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Aquatic foods to nourish nations

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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')[1–4]. Here 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 animal-source food (AASF) production, and a high-production scenario with a 15-million-tonne increased supply of AASFs over the business-as-usual scenario in 2030, driven largely by investment and innovation in aquaculture production. By comparing changes in AASF consumption between the scenarios, we elucidate geographic and demographic vulnerabilities and estimate health impacts from diet-related causes. Globally, we find that a high-production scenario will decrease AASF 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[5,6] while also preventing approximately 166 million cases of inadequate micronutrient intake. This finding provides a broad evidentiary basis for policy makers and development stakeholders to capitalize on the potential of aquatic foods to reduce food and nutrition insecurity and tackle malnutrition in all its forms.

Globally, multiple forms of malnutrition continue to be important and universal. Among children under the age of five, 149 million (22%) are affected by stunting and 45 million by wasting[7]. Among adults globally, 2.1 billion are overweight or obese[8]. Sparse data suggest that vitamin A deficiency is prevalent among children in Africa and South Asia, and zinc deficiency affects half of all children in regions for which information exists[9]. Dietary inadequacies could be the leading reason that people experience multiple nutrient deficiencies and subsequent morbidity and mortality[10]. Cardiovascular diseases, which are largely driven by diet-related factors, are the greatest contributor to global mortality, causing 17.8 million deaths in 2017[11]—greater than the approximately 2 million deaths that were 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[12]. 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 the treatment of AASFs as a homogenous group ('seafood' or 'fish') has limited the potential for their inclusion and recognition in global diets.

Nutrition from aquatic food diversity

Here we reframe the role of aquatic foods in global food systems as a highly diverse food group, which can supply critical nutrients[1–3,13]

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and improve overall health[14]. Aquatic foods are defined as animals, plants and microorganisms, as well as cell- and plant-based foods of aquatic origin emerging from new technologies[15]. They include finfish, crustaceans (such as crabs and shrimp), cephalopods (octopus and squids), other molluscs (clams, cockles and sea snails), aquatic plants (water spinach; *Ipomoea aquatica*), algae (seaweed) and other aquatic animals (mammals, insects and sea cucumbers). Aquatic foods can be farmed or wild-caught, and are sourced from inland (for example, lakes, rivers and wetlands), coastal (estuaries, mangroves and near-shore) and marine waters, producing a diversity of foods across all seasons and geographic regions. Here we focus on AASFs, which constitute the majority of aquatic foods.

Relative to the limited variation in domesticated terrestrial animal-source foods (for example beef, poultry, pork), AASFs present myriad options for supplying nutrients (Fig. 1). Currently, wild fisheries harvest more than 2,370 taxa and aquaculture growers farm approximately 624 species or species-types[16]. To provide evidence of the variability in nutrient composition across this diverse array of aquatic foods, we created the Aquatic Foods Composition Database[17] (AFCD) (Methods), a comprehensive global database that comprises hundreds of nutrients, including minerals (for example, calcium, iron and zinc), vitamins and fatty acids from 3,753 aquatic food taxa. Our analysis indicates that the top 7 categories of nutrient-rich animal-source foods are all aquatic foods, including pelagic fish, bivalves and salmonids (Fig. 1).

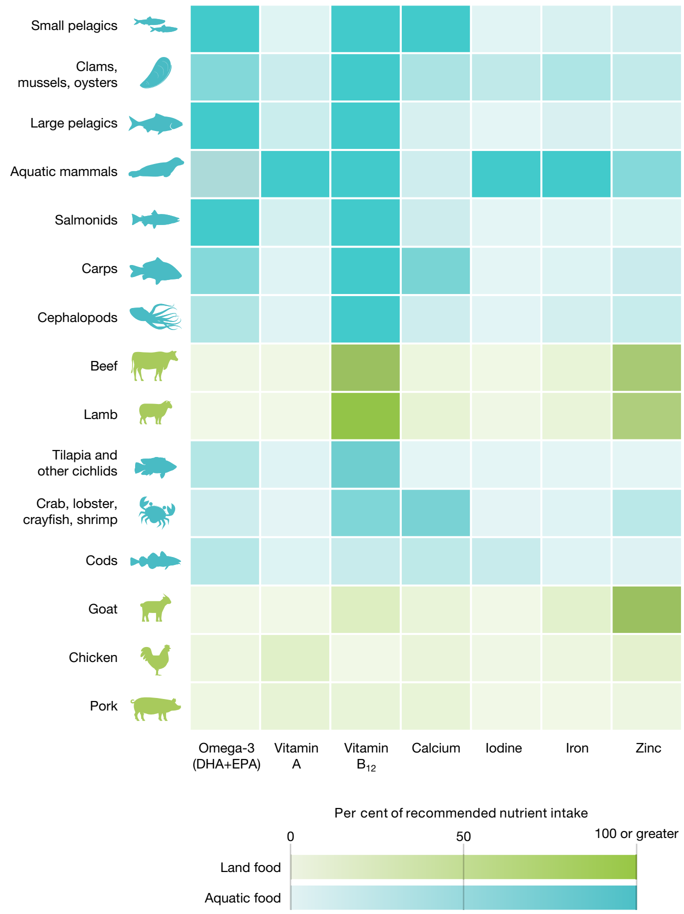

Fig. 1 | Nutrient diversity of aquatic animal-source foods in relation to terrestrial animal-source foods. Aquatic (blue) and terrestrial (green) food richness assessed as a ratio of concentrations of each nutrient per 100 g to the daily recommended nutrient intake. Each shaded box represents the median value of each nutrient in a muscle tissue across all species within each taxonomic group. Food groups were ordered vertically by their mean nutrient richness with higher values meeting a higher percentage of the daily recommended intake. See Supplementary Table 4 for the recommended nutrient intake values and their citations.

Aquatic foods to benefit human health

AASFs improve human health through at least three pathways: by reducing micronutrient (for example, vitamin A, calcium and iron) deficiencies that can lead to subsequent disease; by providing the dominant source of the omega-3 long-chain polyunsaturated fatty acids docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA) (hereafter referred to jointly as DHA+EPA), which may reduce the risk of heart disease and promote brain and eye health; and by displacing the consumption of less-healthy red and processed meats that can cause adverse health outcomes[14]. Any of these three pathways may overlap in an individual, or predominantly target consumers of particular geographies or age–sex groups. The third pathway, specifically, is characteristic of the nutrition transition—the process by which demographic and economic shifts lead to concomitant dietary and epidemiological shifts that often accompany the Westernization of food systems[18]. To better understand these pathways, we examine how aquatic food policy initiatives and investments could improve diets and public health through increasing access to the diversity of aquatic foods and the nutrients that they provide.

We explicitly integrated aquatic and terrestrial food-systems models to evaluate the potential health impacts of increasing global AASF production. This integration enables a more realistic portrayal of the trade-offs made within our global terrestrial and aquatic food systems. To understand the health impacts of increased AASF consumption, we modelled future food systems to 2030. We used an integrated version of the FISH model[19] from the United Nations Food and Agriculture Organization (FAO), and the Aglink–Cosimo model[20], 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 enabled the addition of AASFs and the substitution of aquatic for terrestrial foods within national diets. This affects the supply and demand of a broad range of related food items, particularly terrestrial animal-source foods (such as poultry, pork, beef, eggs and dairy).

We used the integrated model to produce two scenarios: first, a baseline scenario with projections of moderate growth trends in AASF production and expert consensus regarding macroeconomic conditions, agriculture and trade policy settings, long-term productivity, international market developments and average weather conditions; and second, a high-AASF-production scenario that assumes higher growth rates in production as a result of increased financial investment and innovation in aquaculture and improved and effective management in capture fisheries[21] (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 AASFs, and an increase in their production by 15.5 million tonnes (an approximate 8% 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)[22] 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, 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.

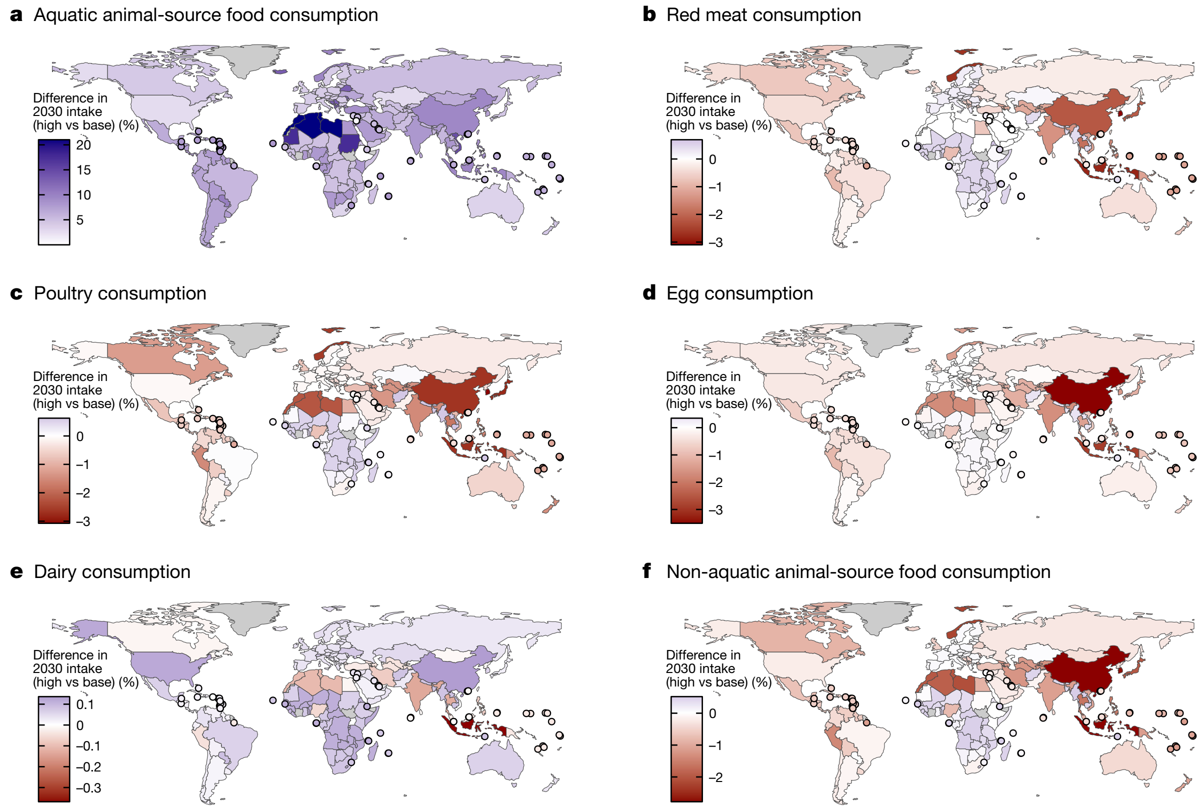

Fig. 2 | Shifts in fish and red meat consumption resulting from an increase in aquatic animal-source foods. a–f, The percentage difference in consumption of mean aquatic animal-source food (**a**), red meat (bovine, ovine and pork) (**b**), poultry (**c**), egg (**d**), dairy (milk, butter and other dairy products) (**e**) and all non-aquatic animal-source food (**f**) in 2030 under the high-production and baseline-production scenarios. Values greater than zero indicate greater consumption under the high-production scenario. Countries smaller than 25,000 km^2 are illustrated as points (small European countries excluded). All European Union member countries have the same value because they are modelled as a single unit in the Aglink–Cosimo model.

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 12 categories explicitly modelled in the GND (for example, demersal fish, pelagic fish and so on). 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 (Methods). Instead of 12 GND categories for aquatic foods, we used supply and nutrient composition values for 2,143 taxa. This comparison enabled us to determine whether incorporating species diversity, as opposed to relying on common commercial species, shifted the levels of nutrients supplied by aquatic foods. The disaggregated model outputs in the baseline scenario resulted in a higher supply of calcium (8% higher; median across countries), iron (4%), DHA+EPA (186%), zinc (4%) and vitamin B_{12} (13%), with a 1% decline in vitamin A (Extended Data Fig. 1). This result provides evidence that narrowly focusing on the nutrient contributions of commercially important species underestimates the nutritional benefits of aquatic foods, especially from diverse small-scale fisheries.

Aquatic foods can reduce meat intake

In addition to the key role of AASFs in providing essential micronutrients, DHA+EPA and protein, AASFs can also prevent diet-related non-communicable diseases. These health benefits are delivered through two mechanisms. First, AASFs directly provide DHA+EPA, which may improve brain function and reduce the incidence of heart disease and certain types of cancer[5,6]. Second, AASFs displace the consumption of more harmful animal-source foods—such as red and processed meats (Fig. 2, Extended Data Figs. 2–4, Supplementary Data 1)—particularly in the global north, or can attenuate their increased consumption in the global south[23,24], in both cases reducing the risk of diet-related non-communicable disease[25].

In much of the global north, an increase in AASF consumption was associated either with reductions in the consumption of red meat, poultry, eggs and dairy, or with no notable impact (that is, no discernible increases; Fig. 2). In the global south, an increase in AASF consumption was not associated with declines in the consumption of red meat, poultry, eggs and dairy. The combined dietary effect of increasing AASFs and reducing red and processed meats may lead to a reduced risk of hypertension, stroke, heart disease, diabetes, colorectal cancer and breast cancer. Countries that are rapidly undergoing the nutrition transition (such as China, India, Philippines, Malaysia, Indonesia, Vietnam, South Korea, Mexico, Brazil, Peru, Chile, Nigeria, Russia, USA and Canada) are most likely to benefit from increases in AASF production, which could avert the trajectory of their populations towards harmful levels of meat consumption (Fig. 2).

Aquatic foods can fill the nutrient gap

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[8]. Further, an estimated 30% of the global population (around 2.3 billion people) have diets that are deficient in at least one micronutrient[8]. Inadequate nutrient intakes can arise from various

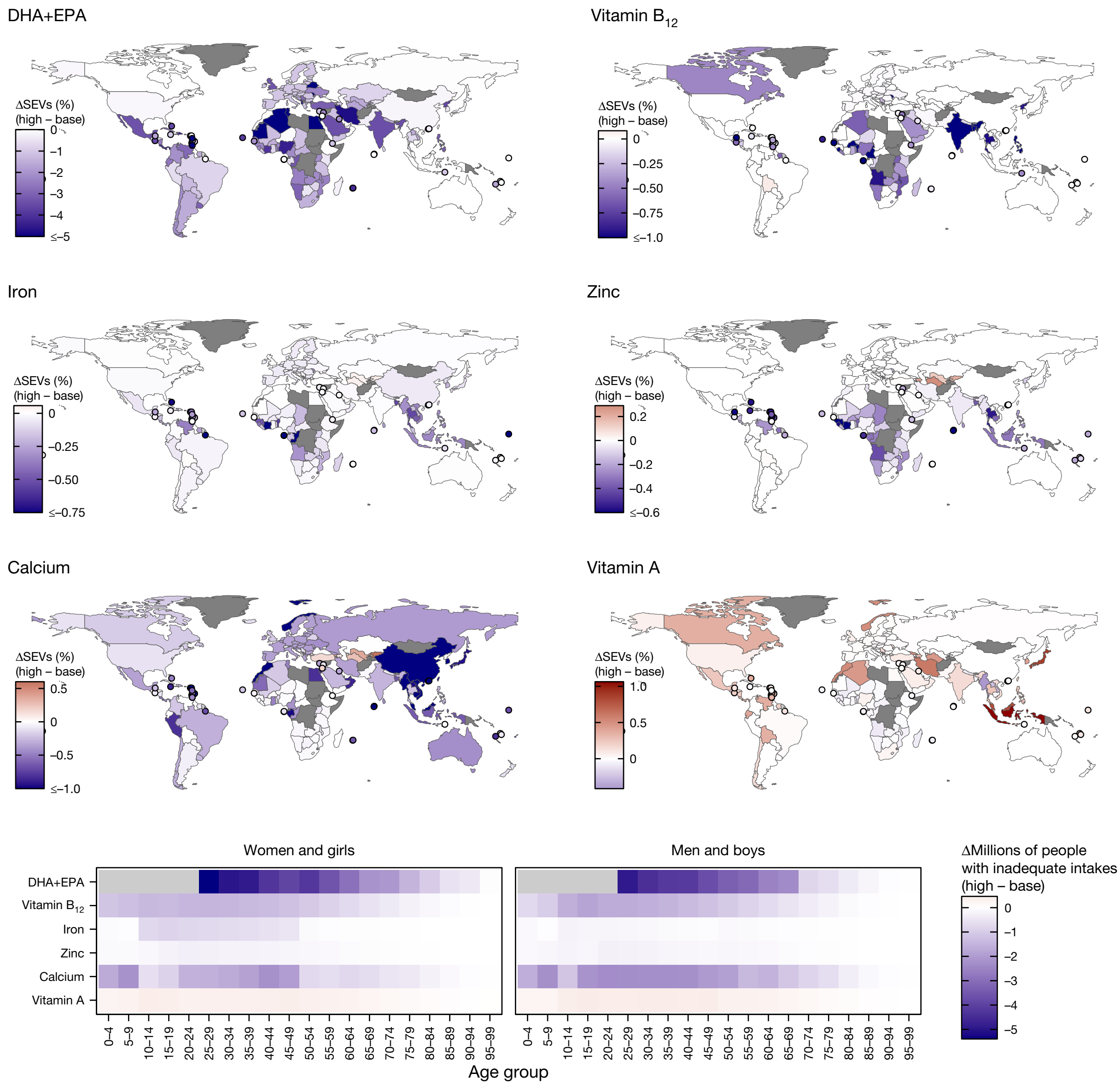

Fig. 3 | Shifts in micronutrient intake resulting from an increase of aquatic animal-source foods. The maps show the difference in SEVs in 2030 under the high-production and baseline-production scenarios by country. Values less than zero indicate reduced risk (lower SEVs) of inadequate intake under the high-production scenarios. The bottom panels show the difference in the number of people with inadequate micronutrient intakes, by age–sex group. Values less than zero indicate fewer inadequate intakes under the high-production scenario. Countries smaller than 25,000 km^2 are illustrated as points (small European countries excluded).

factors: the formulation of food systems, including the availability and accessibility of foods; ecological or environmental conditions—such as soil nutrient loss, drought or fishery declines—that decrease availability; reduced access to markets and natural resources through tariffs, fisheries governance, or other economic incentives; and/or taste preferences, consumer behaviour or other individualized factors[8,26,27]. AASFs have the capability to reduce or fill this nutrient gap with bioavailable forms of micronutrients, particularly in geographies where AASF reliance and nutritional deficiencies are high, such as equatorial regions[1].

Here we focus on nutrient supply to estimate the contribution of AASFs to overall nutrient intake. In the high-production scenario by 2030, AASFs 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 DHA+EPA, an approximate 0–10% increase for each nutrient above 2020 reference values (Extended Data Fig. 5, Supplementary Data 2). For each of the AASF taxa included in the analysis, we used standardized nutrient composition values for muscle tissue because the species coverage was higher than for other parts (such as liver, bones and eyes). Because these other parts are often more nutrient-rich than muscle tissue, our estimates are likely to be conservative, underestimating the true value of AASFs in human diets.

We calculated summary exposure values (SEVs) to assess the excess risk that each country experiences because of inadequate nutrient supply in their overall food systems, comparing the total amount of nutrition derived from apparent consumption against age- and sex-specific nutrient demands (Methods). SEVs range from 0% to 100% and should be viewed as a risk-weighted prevalence, with higher SEVs representing higher risk of inadequate micronutrient intake[28]. The difference in SEVs represents the change in potential risk of inadequate nutritional intake between the two AASF production scenarios in 2030 (Fig. 3, Supplementary Data 3). With overall trends in increasing AASF consumption and concomitant reductions in poultry, eggs, dairy, and red and processed meats (Fig. 2), there are large gains in micronutrient and DHA+EPA consumption (Fig. 3). Globally, the high-production scenario will lead to reductions in inadequate intake across most assessed nutrients (reduction of 8.1 million iron, 5.5 million zinc, 49.3 million calcium, 36.0 million vitamin B_{12}, and 76.8 million DHA+EPA inadequate intakes), while potentially increasing 10.1 million vitamin A inadequate intakes (Extended Data Fig. 6). Particular geographies will also experience small declines in calcium, iron, vitamin A and zinc supply. This phenomenon probably arises from modest reductions in the consumption of iron- and zinc-rich red meat (as shown in historical trends), and large reductions in the consumption of calcium- and vitamin-A-rich dairy, egg and poultry. Notably, certain regions that are characterized by food and nutrition insecurity (for example, sub-Saharan Africa and Southeast Asia) experience increases in intake for all measured nutrients. However, some populations will face increasing risk of inadequate micronutrient intake if consumption of AASFs displaces other foods, as evidenced by reduced calcium intake in Turkey, zinc intake in Azerbaijan, and vitamin A intake in Indonesia and Mexico, among others (Fig. 3). Yet, globally, there is a pattern in which increasing the diversity of aquatic animal-source food consumption leads to reduced micronutrient-inadequate intakes (Extended Data Fig. 7).

Recognition of the diversity of AASFs and their nutrient composition could be harnessed to direct their 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 might be to increase the consumption of pelagic small fish (such as herrings and 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 might 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 support the vulnerable

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 AASFs. AASFs 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 DHA+EPA in fetal 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 AASFs for particular groups. The function of reducing micronutrient deficiencies is more important for children and women of reproductive age, and the function of attenuating morbidity and mortality as a result of chronic disease is more important for adults. For example, older people in Tunisia, Algeria, St Lucia, Iran and Moldova would experience large benefits in reduced inadequate intake of DHA+EPA (ΔSEV of at least −10.0 percentage points) and reduced inadequate intake in iron in Kiribati and the Republic of the Congo (ΔSEV = −3.6 percentage points). In several countries, children would experience large benefits in reduced inadequate calcium intake due to increased AASF 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; −5.1 for 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 from increased DHA+EPA consumption (ΔSEV= −6.7 to −8.6 percentage points). Across all measured nutrients, there were significant sex differences in benefits between the base and the high-production scenario (n = 73 of a total 115 age–nutrient groups), in which increased AASF production and consumption disproportionately improved the intakes of women and girls (average of 51.4% of countries) over men and boys (average of 18.2% of countries; Supplementary Data 4). Thus, there is an almost three times greater likelihood of increased AASF consumption benefitting female nutrition, providing a potential pathway for nutritional equity (Supplementary Methods).

Discussion

We illustrate the role of AASFs in improving the future of human health, focusing on supplying critical micronutrients and attenuating morbidity and mortality from chronic disease that is characteristic of the nutrition transition. Our analyses demonstrate that an increase in production of the rich diversity of AASFs (and the nutrients contained therein) can improve the diets of many nations. Notably, our analysis focuses on the consumption of muscle tissue from AASFs and therefore must be viewed as a probable underestimate of the potential contribution to micronutrient supplies. Our projection of declines in global vitamin A supply may be incorrect, given the high levels of this nutrient in certain fish parts (such as liver) that are not included because of our focus on muscle tissue.

The diversity of aquatic foods highlighted here evidences the limitations of treating them as a homogenous group. The EAT–Lancet Commission Report[12] undervalues the importance of aquatic foods; key food policy dialogues (such as 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 to be 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, forms of culture production, and wild harvest by small-scale fisheries[32]. Second, the nutritional contribution of aquatic foods has traditionally focused on its low contribution to global energy (that is, calories) and protein intake, failing to consider the contribution of aquatic foods to nutrition via highly bioavailable essential micronutrients and fatty acids. The AFCD presented here enables future studies to move beyond this limited view of nutrition from aquatic foods. However, there are still limitations in our current presentation (for example, a lack of focus on vitamin D due to variable intake requirements and a lack of recognition of the nutritional value of small fish and non-muscle fish parts in human nutrition). Vitamin D deficiency is a major health issue in some countries, and an increase in fatty fish intake could reduce this.

It is critical to consider where and how aquatic foods are produced, because environmental, social and economic impacts can vary widely across both the wild-capture and aquaculture sectors (Supplementary Methods). Despite the variability in environmental impacts across animal-source food-production sectors, aquaculture and wild-capture fisheries nearly always produce fewer greenhouse gas emissions and use less land than the farming of red meats, and many AASFs outperform poultry[33]. Sustainably and equitably achieving the human health benefits of expanded aquatic food production will require policies and technologies that mitigate impacts on adjacent ecosystems, industries and communities[21].

Policy translation

Our findings suggest the following strategic research and policy opportunities:

First, in countries in which there are high burdens of micronutrient deficiencies, the 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.

Second, the promotion of 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.

Third, incentivizing access and affordability of aquatic foods in countries experiencing a rapid nutrition transition.

Fourth, prioritizing aquatic foods in social protection programs, including food assistance, school meal programmes, and safety nets for the most nutritionally vulnerable, including pregnant and lactating women, young children in the first 1,000 days of life, and older people.

In line with the Voluntary Guidelines on Food Systems and Nutrition[34] of the Committee on World Food Security, national food and nutrition policy is needed to transform food systems by prioritizing aquatic foods where culturally and socially appropriate. Also, policy may ensure that the governance of and investment in aquatic food systems aims to preserve, support and improve aquatic species diversity; production and harvest methods and practices; and efficient and safe distribution channels. With more than 1.5 billion people unable to afford a healthy and sustainable diet[35], our model results showcase the importance of price and economic policies in creating nutritious diets that are affordable for consumers. These measures should enable aquatic foods to have an important role in nourishing the global population and improving global nutrition and health.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41586-021-03917-1.

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Methods

Food system modelling approach

The FAO FISH[19] and Aglink–Cosimo[20] 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 and FAO FISH are managed by the Secretariats of the OECD and FAO, and used to generate the annual OECD–FAO Agricultural Outlook[20] and other peer-reviewed scenario analyses[36]. The references cited provide full model descriptions.

The FAO FISH model contains 2,019 equations and covers 47 country and/or region endogenous modules. Three products are covered with complete supply-disposition variables and prices: an aggregate of all aquatic animals except mammals; fishmeal; and fish oil. For the aggregate aquatic animals, the model supplies functions for both capture and aquaculture depending on the country or regional aggregate. On the demand side, the model produces one aggregate aquatic animal demand function, but includes 3 different types of use: food; processed into fishmeal and oil; and other uses.

To reflect the fact that fisheries are a renewable natural resource that are fully exploited and regulated or over-exploited, capture fisheries are kept exogenous in most modules of the model as they are controlled under strict fishing quotas and subject to regulations preventing economically driven supply. Therefore, the supply of only 11% of world capture fisheries respond to price for those countries and regions with insufficiently strict regulations. However, it is assumed that their capture production will always stay below the maximum sustainable yield. Conversely, in the model, 99% of world aquaculture production is endogenous and responsive to the price of the output, and 75% of aquaculture is additionally responsive to feed prices. In terms of aquaculture supply, the model contains 115 functions that cover the combination of countries and species. Each species has its specific feed rations (different mix of feed ingredients), production lags driven by the species biology, and elasticities (the level of responsiveness of production to price changes). Ninety seven per cent of the global reduction of fish into fishmeal and oil is endogenous in the model. In 63% of the modules, fishmeal and oil is controlled by a simple technical parameter, whereas in the remaining modules it is price-responsive.

The Aglink–Cosimo model, described as a structural sector model, provides a mathematical representation of the decision processes of producers and consumers of agricultural commodities. The equations relate exogenously provided projections of the macroeconomic environment, such as population growth and gross domestic product (GDP) developments, through commodity- and country-specific parameters to agricultural supply and demand variables. These variables are projected forward in a dynamic-recursive way using prices at domestic and global levels to clear markets at all stages. The demand for food is a function of income, own and cross prices, in which the respective elasticities control the relative strength of each variable. Because Aglink–Cosimo and the FAO FISH model are 'partial-equilibrium' sector models, income does not change in the scenario. The substitution between the various food items is caused by shifts in relative prices.

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 fully integrated into the merged model and the full set of commodities is simulated simultaneously. Per capita food demand of aquatic products is determined by their retail price, retail price of substitutes (mostly beef, pork and poultry), and by real per capita GDP. Typically, consumers from wealthier countries respond less to a change in the retail price of fish expressed in real terms (that is, deflated by the overall consumer price index) than consumers who spend a higher share of their income on food. The retail price of aquatic products is determined by the price of traded products (which can be considered a wholesale price) and the GDP deflator to capture movement in the other costs along the supply chain. The higher the GDP of a country, the smaller the influence of the wholesale price in the calculation of the retail price. Imports and exports are a function of the ratio between the domestic (adjusted by tariff and exchange rate) and world price of aquatic products with different levels of responsiveness depending on the openness of the different countries' aquatic product markets. Finally, the price of traded aquatic products is the market clearing variable of each country component.

Scenario development

Two alternative outlook projections, a baseline and high-production scenario (Supplementary Table 1; Supplementary Fig. 1), were used to represent food production, consumption, and trade to 2030 for 22 food groups. The baseline scenario is driven by the results of the FAO FISH model included in the OECD–FAO Agricultural Outlook 2020–2029, with 2030 data reflecting the UN FAO's best understanding of likely fisheries and aquaculture growth (Supplementary Fig. 2) based on anticipated macroeconomic conditions, agriculture and trade policy settings, fisheries management outcomes, long-term productivity, international market developments and average weather conditions[37]. Aquaculture will be the main driver of the growth up to 2030, while fisheries production is expected to slightly decline. The high-production scenario is not a prediction but represents the UN FAO's specific estimation of the upper limits of aquatic foods growth potential[37], reflecting an imposed change to AASF production. This could be obtained by applying innovative technologies, capacity building, increased and cost-effective financial investment in aquaculture and improved and effective management in fisheries production constrained by estimates of global maximum sustainable yield. Also in the high-production scenario, major growth in production is expected to originate mainly from aquaculture, but fisheries production will slightly grow. The improved and effective management will support the sustainable growth in fisheries production through increased catches in areas recovering from previous overexploitation patterns, as well as underfished resources, and improved utilization of the harvest, including reduced onboard discards, waste and losses.

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 AASF consumption corresponding to marine and freshwater capture and aquaculture production projections in 2030 based on the joint Aglink–Cosimo FISH baseline and high-production outputs.

As the supply of fish is increased relative to the baseline, under the assumption that demand does not shift, a new equilibrium price is found along the demand curve. This new price of fish influences the consumption and production of other agricultural commodities through links on the production and consumption side. The shift in the international reference price of fish, which represents the aggregate behavior of all consumers, leads to changes in individual decisions that are determined by the relative changes in their domestic prices. They, in turn, are determined by the integration of each commodity market into the global trade system and the respective shift of the fish supply in the scenario. Consumers in a fish-producing or importing country will take advantage of the lower fish price and consume more fish and less terrestrial meats, depressing terrestrial meat prices. These prices are also transmitted through trade to countries that do not produce or import a substantial volume of fish. Thus, consumers take advantage of the lower meat prices and increase their meat consumption.

On the production side, similar effects are simulated. As demand for meat declines globally owing to its substitution with cheaper fish, demand for feed also declines, lowering its price. Depending on the production technology, certain producers take advantage of the cheaper feed and increase production of livestock products. As cereals are used as feed and food, the consumption of staples also increases. The relative size of all of these responses culminates in the trade flows. They shift relative to the baseline and a new global market equilibrium is found. A full description of the high-production scenario parameters and assumptions can be found in the Supplementary Methods.

Global Nutrient Database

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[22]. 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. On the basis of 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 (Supplementary Table 1).

Species disaggregation

Aquatic foods in the GND are based on FAO FishStat production data and currently include the following categories: demersal fish; pelagic fish; fish oils; crustaceans; cephalopods; other marine fish; freshwater fish; other molluscs; aquatic mammals; other aquatic animals; and aquatic plants. To derive more resolved consumption estimates, we first assigned fish consumption estimates to freshwater and marine species on the basis of 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 (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 (Supplementary Methods; Supplementary Figs. 3, 4). All commodities were converted to live weights using freshwater conversion factors[38]. The proportion of freshwater species consumed was further disaggregated with household survey data[38], and recreational fishery consumption (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[38]. 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 (Supplementary Methods).

Aquatic Foods Composition Database

The 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 United States Department of Agriculture (USDA), FAO INFOODS and the EU SMILING project in Southeast 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[2].

The search strategy focused on studies between 1990 and 2020, and prioritized specific journals known to include food composition data (for example, *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, the 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 (Supplementary Fig. 5). 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: scientific name, average of species genus, average of species family, common name, average of species order, and average of GND category. In the disaggregation effort, we found 2,143 different aquatic species being consumed globally. We matched nutrient composition values from muscle tissue for protein, iron, zinc, calcium, vitamin A, vitamin B_{12} and DHA+EPA. After this matching process, we updated the estimates of nutrient intake at national levels.

Sub-national intake distributions

To evaluate the health impacts of AASF 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[39], we estimated usual intakes of iron, zinc, calcium, vitamin A, vitamin B_{12}, 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 Supplementary Table 7.

We fit gamma and log-normal distributions to the habitual intake distributions for all available age–sex groups using the fitdistrplus package[40]. 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 national intake distributions

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 (Supplementary Table 5). Second, we disaggregated country-level mean intakes into age–sex-level mean intakes using the Global Expanded Nutrient Supply (GENuS) database[41] for all nutrients except DHA+EPA 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[41]. We used these estimates to calculate scalars for relating country-level availability to age-group-level availability as:

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

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:

$$\mathrm{Intake}_{c,n,a,s} = \mathrm{intake}_{c,n} \times \mathrm{scalar}_{c,n,a,s}$$

We used the same process to disaggregate intakes for DHA+EPA and vitamin B_{12} but used the country-level and age-sex-level means derived from SPADE habitual intakes described above. See Supplementary Table 6 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 (Supplementary Fig. 6) 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 nearest age group within a sex and country; the opposite sex from within a country; and the nearest country geographically and/or socioeconomically (Supplementary Fig. 7). We then mapped these to the rest of the world, based on UN sub-regions, with a few expert-identified modifications (Supplementary Fig. 8).

Health impact modelling approach

SEVs 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 in which everyone is at a maximal risk level, giving values ranging from 0% (no risk) to full population-level risk (100%). For DHA+EPA, we used the updated Institute for Health Metrics and Evaluation relative risk curves that are associated only with ischaemic 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 omega-3 long-chain polyunsaturated fatty acids under 0.4 g per day[28]. For inadequate micronutrient intake risk assessment, we derived continuous relative risk curves for iron, zinc, calcium and vitamin A, based on the probability approach for calculating inadequate intake, often a precursor to micronutrient deficiencies[42]. To evaluate the risk of inadequate micronutrient intake, distributions of intake 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 estimated average requirement (EAR) and zero at large intakes. These absolute risk curves are based on the cumulative normal distribution function of requirements[43] 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[42,44]. The prevalence of risk at the population level is derived by computing the expected micronutrient deficiency across the entire population[43], 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 inadequate intake, 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[45–47]. Because zinc and iron requirements depend on other dietary factors (for example, 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 food intakes[48,49]. We then assigned each country to their proxy zinc and iron values, based on its social development index[50]. For vitamin B_{12}, we used the values used by the Institute of Medicine[51] but acknowledge that uncertainties regarding recommended intakes exist, and used a coefficient of variation of 25% instead of the default 10% in constructing our risk curves[52].

Reporting summary

Further information on research design is available in the Nature Research Reporting Summary linked to this paper.

Data availability

The AFCD is open access and can be found at: https://dataverse.harvard.edu/dataverse/afcd. All other nutrient data were sourced from the USDA FoodData Central (https://fdc.nal.usda.gov/) or the GND as described in Methods. For sub-national data evaluation, data was sourced from the following locations: FAO/GIFT: http://www.fao.org/gift-individual-food-consumption/data-and-indicator/en/; NHANES: https://wwwn.cdc.gov/nchs/nhanes/continuousnhanes/default.aspx?BeginYear=2017; ENSANUT: https://ensanut.insp.mx/encuestas/ensanut2016/descargas.php; China Health and Nutrition Survey: https://www.cpc.unc.edu/projects/china/data/datasets; Uganda: https://doi.org/10.7910/DVN/FOYZBL; Burkina Faso: https://doi.org/10.7910/DVN/5CXCLX. Proprietary input datasets protected by data-sharing agreements (that is, the GND) are not posted in these repositories. All processed outputs and non-proprietary raw inputs are available on GitHub. The data associated with the diversity disaggregation is available at https://github.com/cg0lden/Fisheries-Nutrition-Modeling. The data associated with the SPADE analysis is available at https://github.com/cg0lden/subnational_distributions_BFA. The data associated with the health impacts analysis is available at https://github.com/alonshepon/Health-Benefit-Calculation-BFA.

Code availability

The code associated with the diversity disaggregation is available at https://github.com/cg0lden/Fisheries-Nutrition-Modeling. The code associated with the SPADE analysis is available at https://github.com/cg0lden/subnational_distributions_BFA. The code associated with the health impacts analysis is available at https://github.com/alonshepon/Health-Benefit-Calculation-BFA.

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Author contributions C.D.G. and S.H.T. conceptualized the research idea, with substantial methodological and design input from J.Z.K., A.S., C.M.F., D.F.V. and H.M. Data acquisition and compilation was conducted by subgroups for the Aquatic Foods Composition Database (C.D.G., J.Z.K., C.D., H.K., K.J.F., M.K. and D.F.V.), Global Nutrient Database (H.M.), Aglink–Cosimo model (H.M.), FAO Fish model (P.C., S.V. and M.B.), species disaggregation models (E.F.-C., E.A.N., J.A.G., A.J.L., D.F.V., J.G.E. and C.D.G.), sub-national distribution model (S.P., C.D.G., L.C. and S.B.), and health impact models (A.S., C.D.G., G.D. and E.B.R.). The food systems modelling was led by H.M. and P.C.; sub-national distributions modelling was led by S.P. and S.B.; and the health impact modelling was led by A.S., C.M.F. and G.D. C.D.G. drafted the original manuscript, and all co-authors edited and revised the writing.

Competing interests The authors declare no competing interests.

Additional information
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Correspondence and requests for materials should be addressed to C.D.G.
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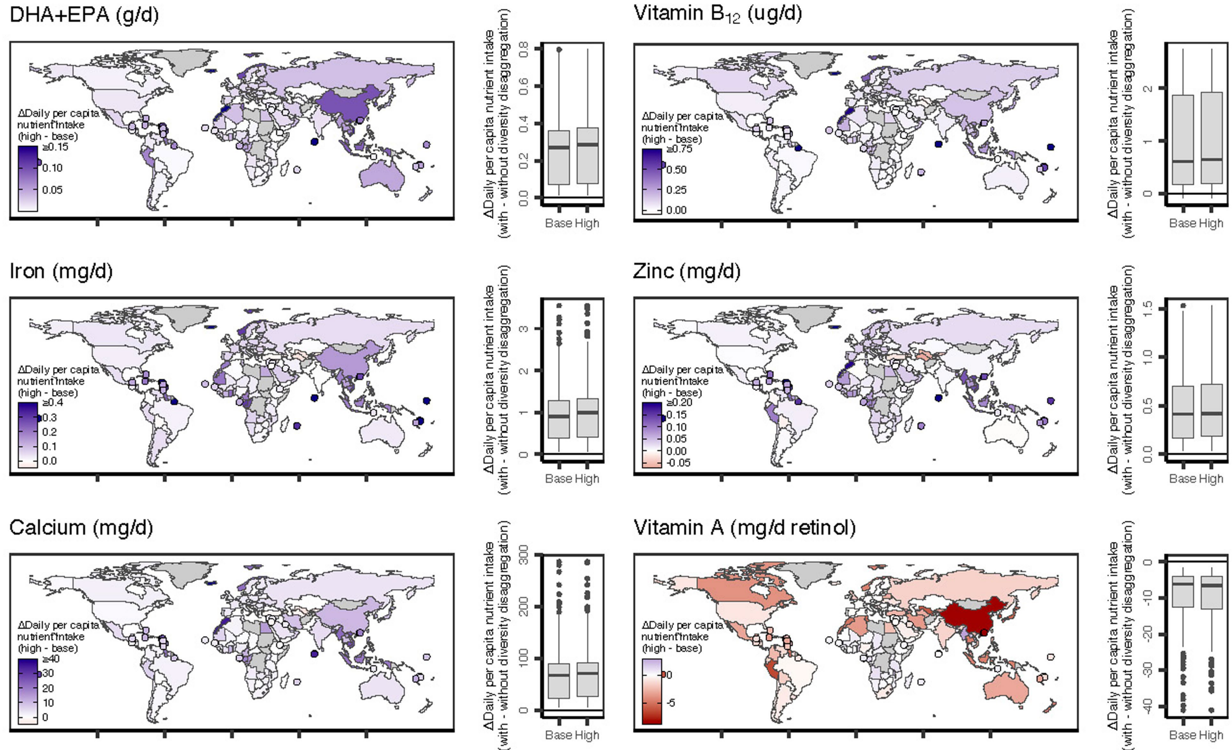
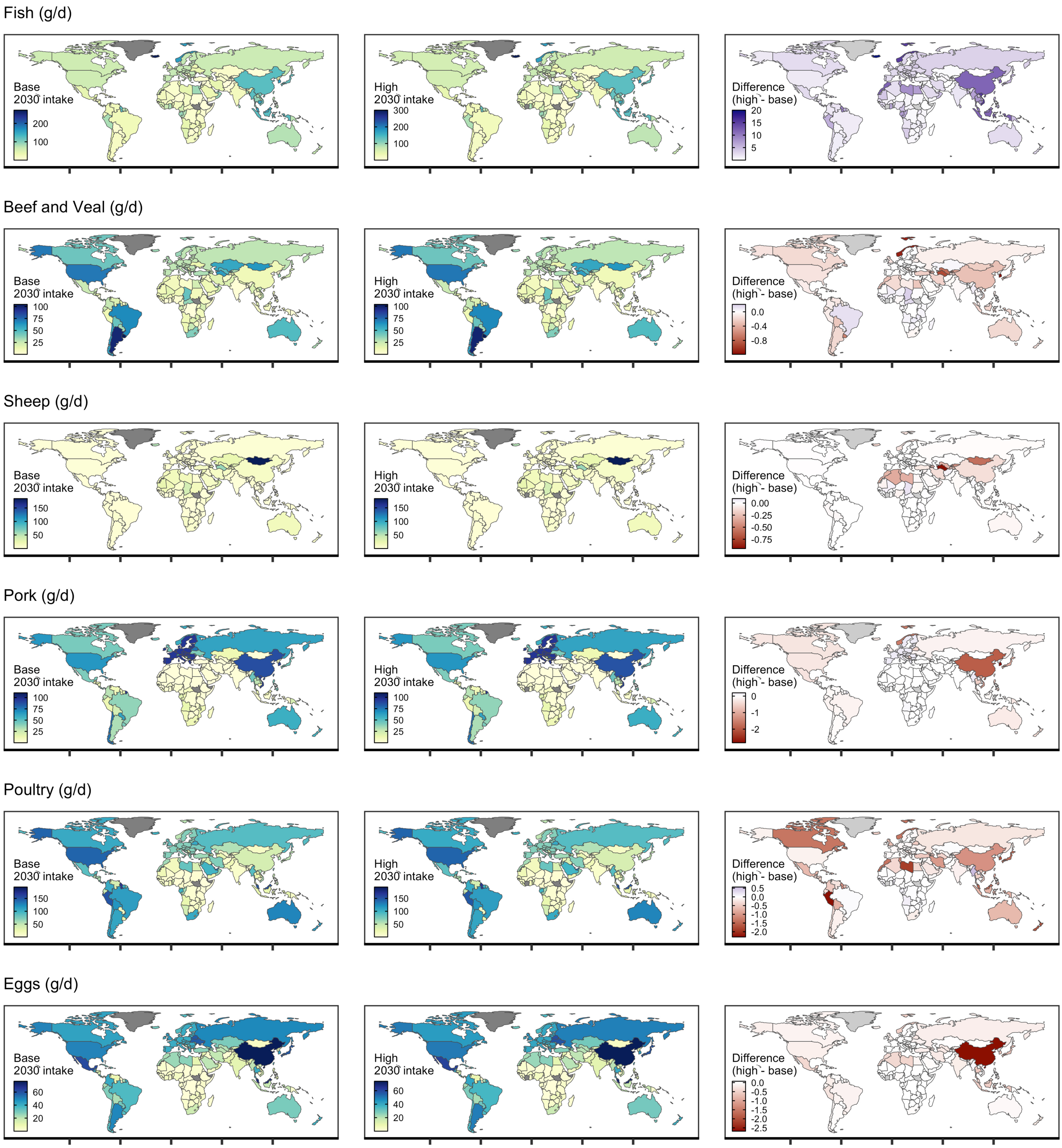
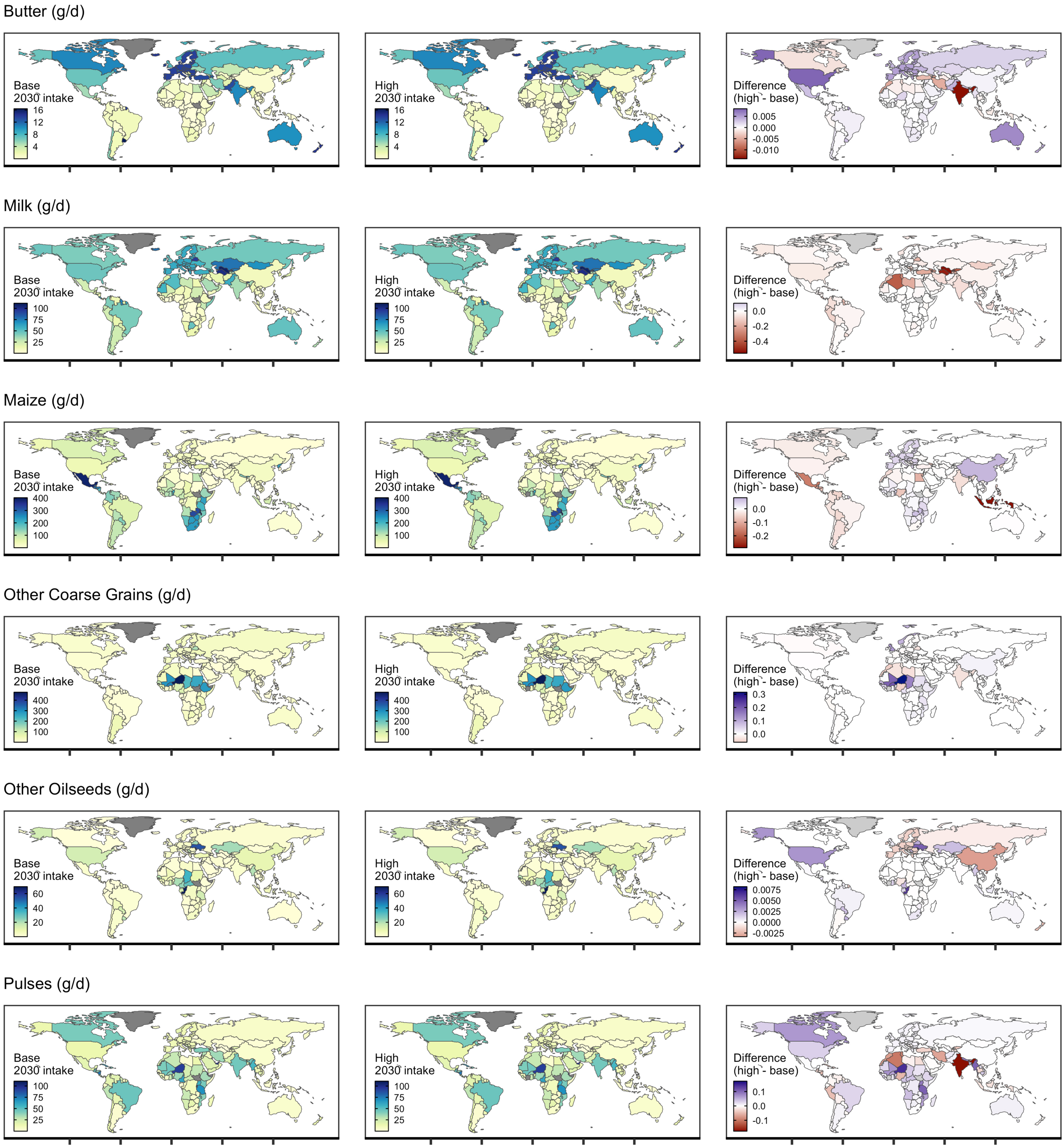


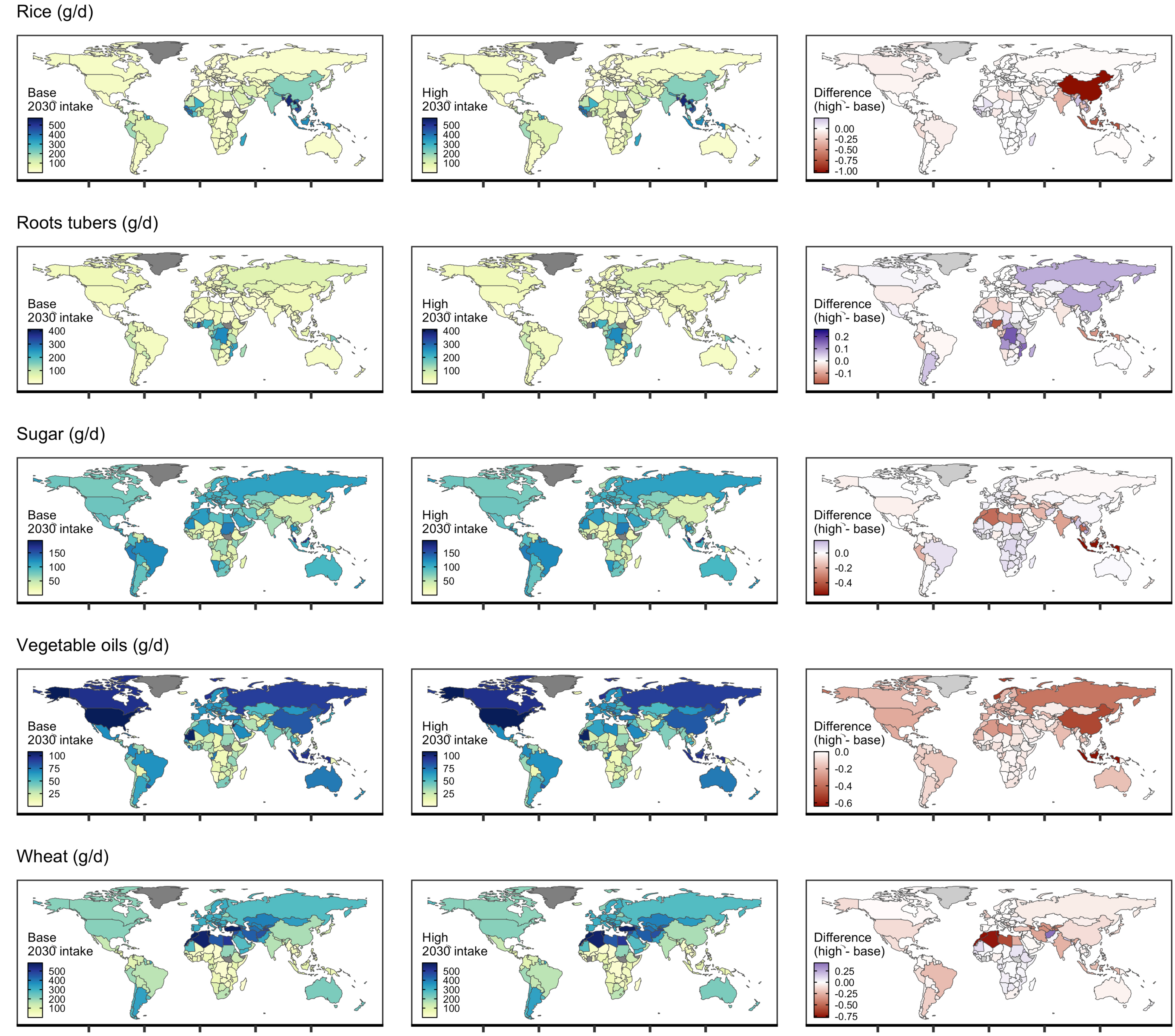
Extended Data Fig. 1 | Difference in daily per capita intake of various nutrients from increasing aquatic animal-source food production and fully accounting for species diversity. The maps show the difference in mean nutrient intakes in 2030 under the high and baseline production scenarios when fully 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 (n=164 independent countries remain for comparison).



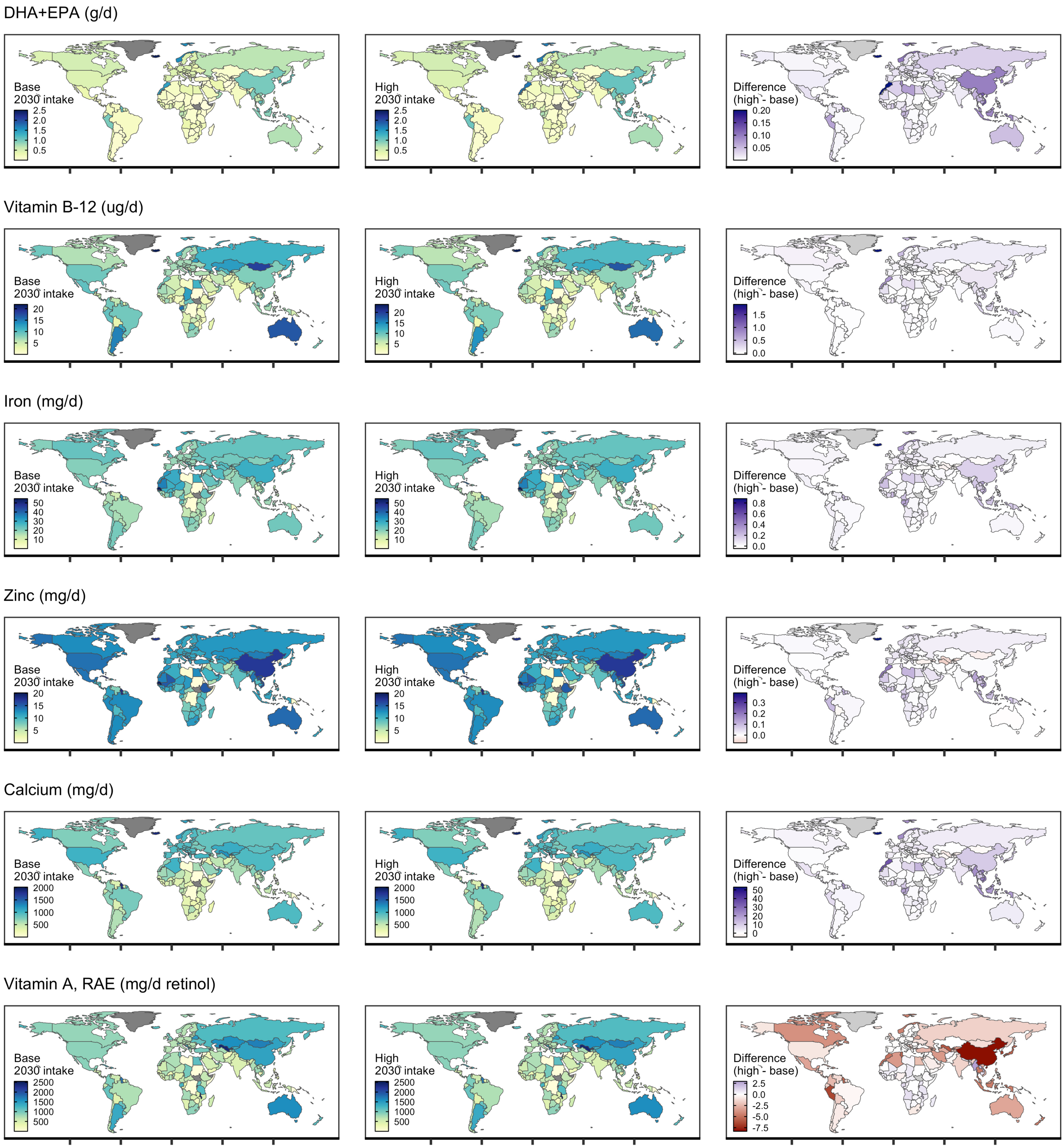
Extended Data Fig. 2 | Difference in 2030 food consumption under the base and high production scenarios (part 1). Mean daily per capita food consumption in 2030 under the (A) base and (B) high production scenarios and (C) the difference in consumption between the high production and base scenarios.



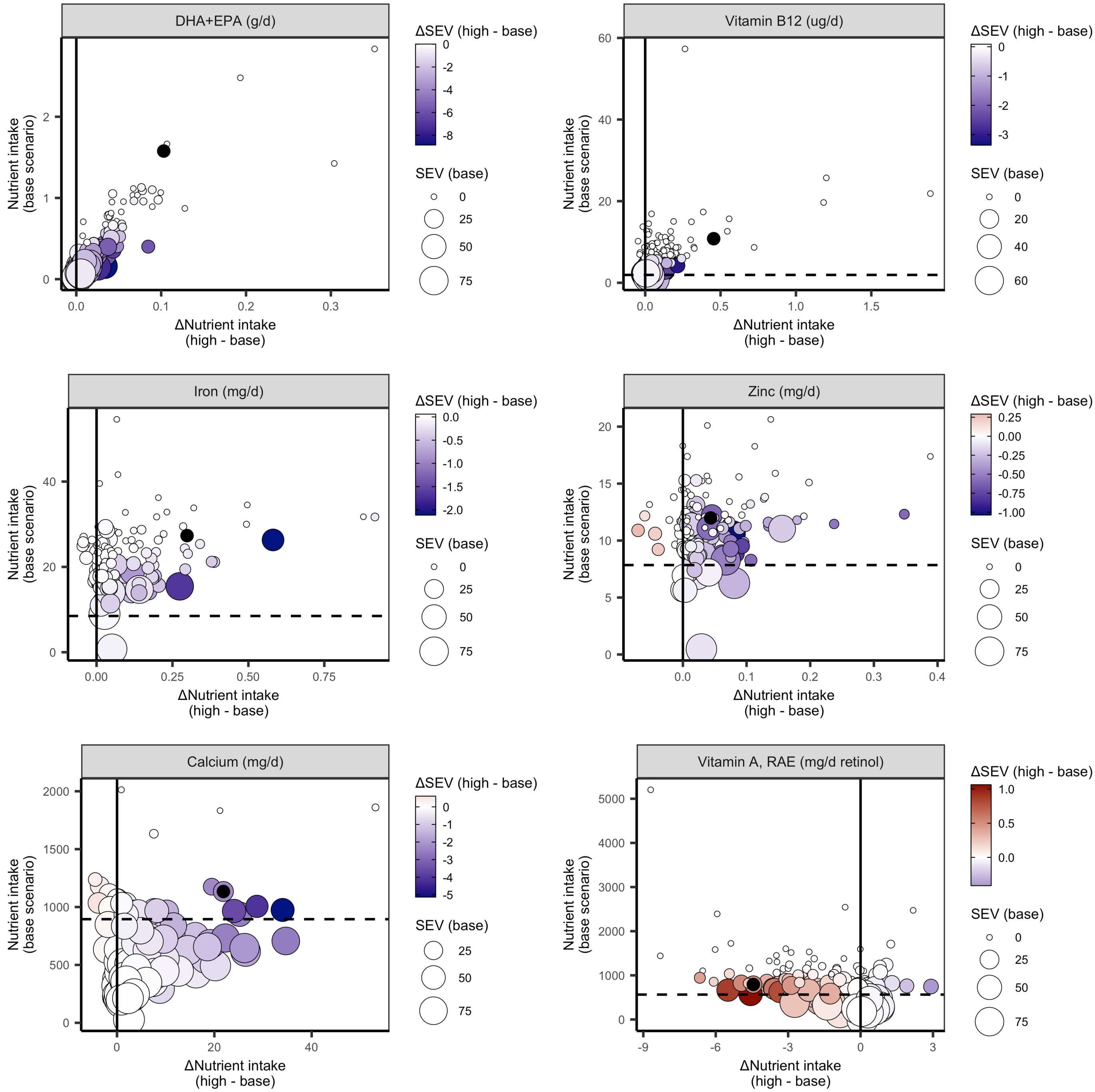
Extended Data Fig. 3 | Difference in 2030 food consumption under the base and high production scenarios (part 2). Mean daily per capita food consumption in 2030 under the (A) base and (B) high production scenarios and (C) the difference in consumption between the high production and base scenarios.



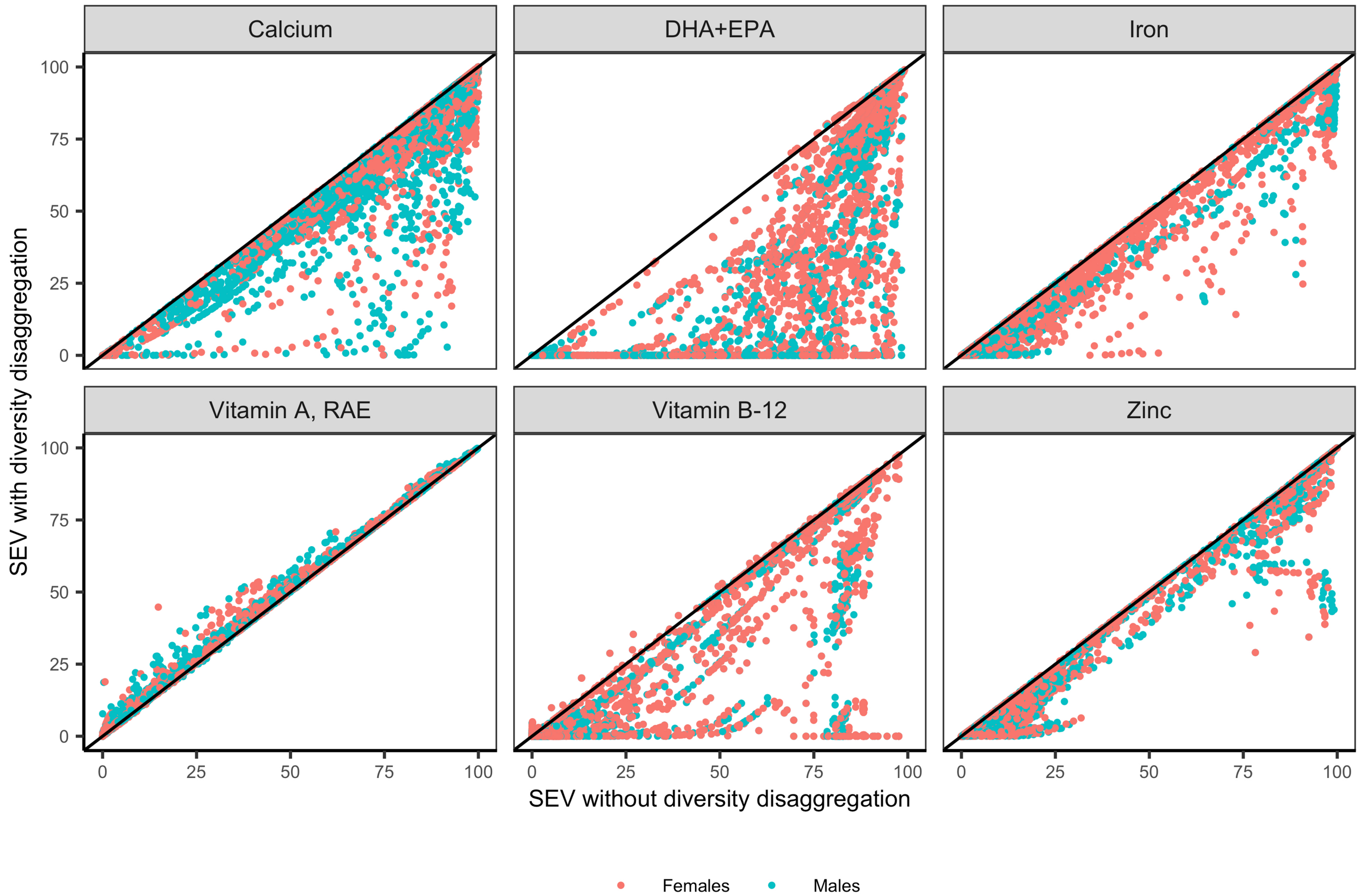
Extended Data Fig. 4 | Difference in 2030 food consumption under the base and high production scenarios (part 3). Mean daily per capita food consumption in 2030 under the (A) base and (B) high production scenarios and (C) the difference in consumption between the high production and base scenarios.



Extended Data Fig. 5 | Difference in 2030 nutrient intakes under the base and high production scenarios accounting for the full diversity of nutrient compositions in seafood. The mean daily per capita nutrient intake in 2030 when accounting for the full diversity of nutrient compositions in seafood under the (A) base and (B) high production scenarios and (C) the difference in intakes between the high production and base scenarios.



Extended Data Fig. 6 | The relationship between the difference in 2030 health outcomes under the high and base production scenarios and base scenario status. Each point represents a country where point color indicates the difference in national micronutrient deficiency averages between the scenarios (blue=reduced deficiencies; red=increased deficiencies) and point size indicates the scale of nutrient deficiencies in the base scenario (small=few deficiencies; large=many deficiencies). The vertical line indicates zero difference in nutrient intakes between the high and base scenarios; positive values indicate increased nutrient intake under the high production scenario and negative values indicate reduced intake. The dashed horizontal line indicates the average Estimated Average Requirement (EAR) for all age-sex groups. Countries falling below this line often have more room for health improvements than countries falling above this line. Counter-clockwise from the top-left, the quadrants of each plot indicate countries with mean 2030 intakes in the base scenario that are: (1) higher than the mean EAR and higher than the high production scenario; (2) higher than the mean EAR but lower than the high production scenario; (3) lower than the mean EAR and lower than the high production scenario; and (4) lower than the EAR but higher than the high production scenario.



Extended Data Fig. 7 | Summary exposure values (SEVs) in the high production scenario with and without the diversity disaggregation. Summary exposure values (SEVs) for each country-age-sex group in the high production scenario with and without the diversity disaggregation. The diagonal line indicates the 1:1 line. Points below this line indicate country-age-sex groups with lower SEVs with the diversity disaggregation. Points above this line indicate country-age-sex groups with higher SEVs with the diversity disaggregation.

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Data collection	No code on collection.
Data analysis	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_BFA The code associated with the health impacts analysis is available in this Github repository: https://github.com/alonshepon/Health-Benefit-Calculation-BFA

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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_BFA
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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Research sample	All countries with available data were included in our food system models. All countries with open-access, nationally representative data were included in our subnational distributions models.
Sampling strategy	All countries with available data were included in our food system models. All countries with open-access, nationally representative data were included in our subnational distributions models. Therefore, the strategy did not include stratification or exclusion.
Data collection	N/A
Timing	N/A
Data exclusions	N/A
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Supplementary information

Aquatic foods to nourish nations

In the format provided by the authors and unedited

Supplementary Information for

Aquatic foods to nourish nations

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Supplementary Methods

1. Overview

The workflow for this research (**Fig. M1**) included the integration of the FAO FISH model into the OECD-FAO Aglink-Cosimo model to allow for simultaneous food system modeling of terrestrial and aquatic sources. The FAO FISH model, although operating independently, was included as a subsumed modular component of the Aglink-Cosimo model to produce an output for 22 food groups, one of which was aquatic foods. The 21 terrestrial food groups were assigned nutrient composition values through the Global Nutrient Database (GND), while aquatic foods were treated separately. To understand the role of diversity in aquatic food consumption, we disaggregated the mix of species available for consumption beyond the typical 12 International standard statistical classification of aquatic animals and plants (ISSCAAP) categories that the GND uses (see below for detailed methods). We then assigned each species (or broad taxa where data was limited) to a matched nutrient composition profile with the Aquatic Food Composition Database (AFCD). By combining the aquatic food nutrient supply with the terrestrial food nutrient supply, we were able to model the total nutrient supply from all food sectors. To understand how these national level aggregated nutrient supplies were distributed subnationally, we used the Statistical Program to Assess Habitual Dietary Exposure (SPADE)- a software that allows for the modeling of subnational habitual intake distributions based on quantitative dietary intake data from repeat 24-hour recalls (Dekkers et al., 2014). This allowed us to estimate nutrient intake per capita, to the resolution of various age-sex groups. We then calculated summary exposure values (SEV) to identify the proportion of the population that would be nutrient deficient in each nation (see below for detailed methods).

This modeling approach was used for a moderate production and high production scenario. The moderate production scenario was driven by the OECD-FAO Agricultural Outlook 2020-2029, and the high production scenario is detailed in depth below.

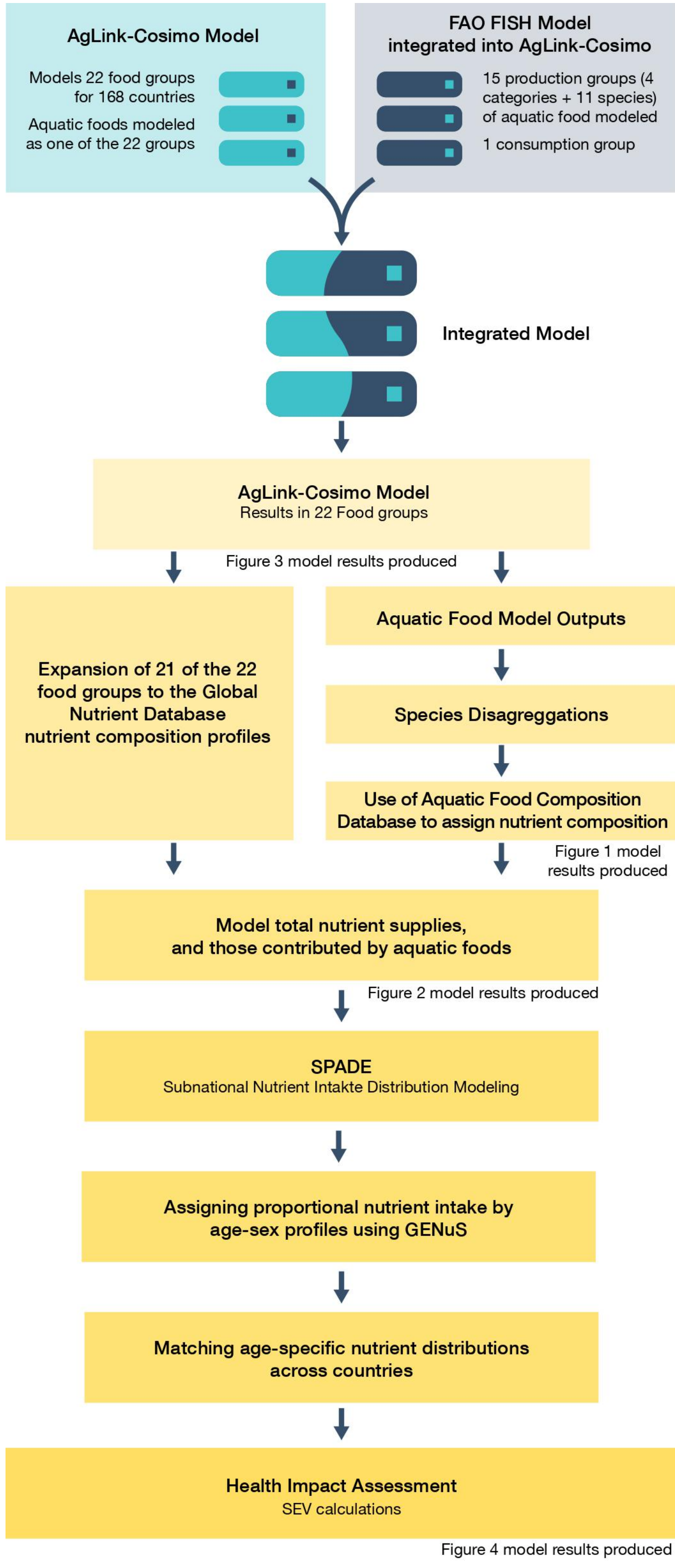

Figure M1: Description of modelling workflow. Conceptual diagram of the modelling components and integrated data sources.

2. Integrated food system model

2.1 Aglink-Cosimo model

Aglink-Cosimo is a structural sector model that simulates supply, demand, and prices of main agricultural and fish commodities (http://www.agri-outlook.org/about/; see **Fig. M2**). It is managed by the Secretariats of the OECD and the Food and Agriculture Organization of the United Nations (FAO), and is used to generate the annual OECD-FAO Agricultural Outlook (e.g., OECD/FAO 2021 is the most recent outlook). The Aglink-Cosimo model provides forward-looking analyses of potential supply and demand shocks caused by alternative policies, technological advances, or natural disasters, among others.

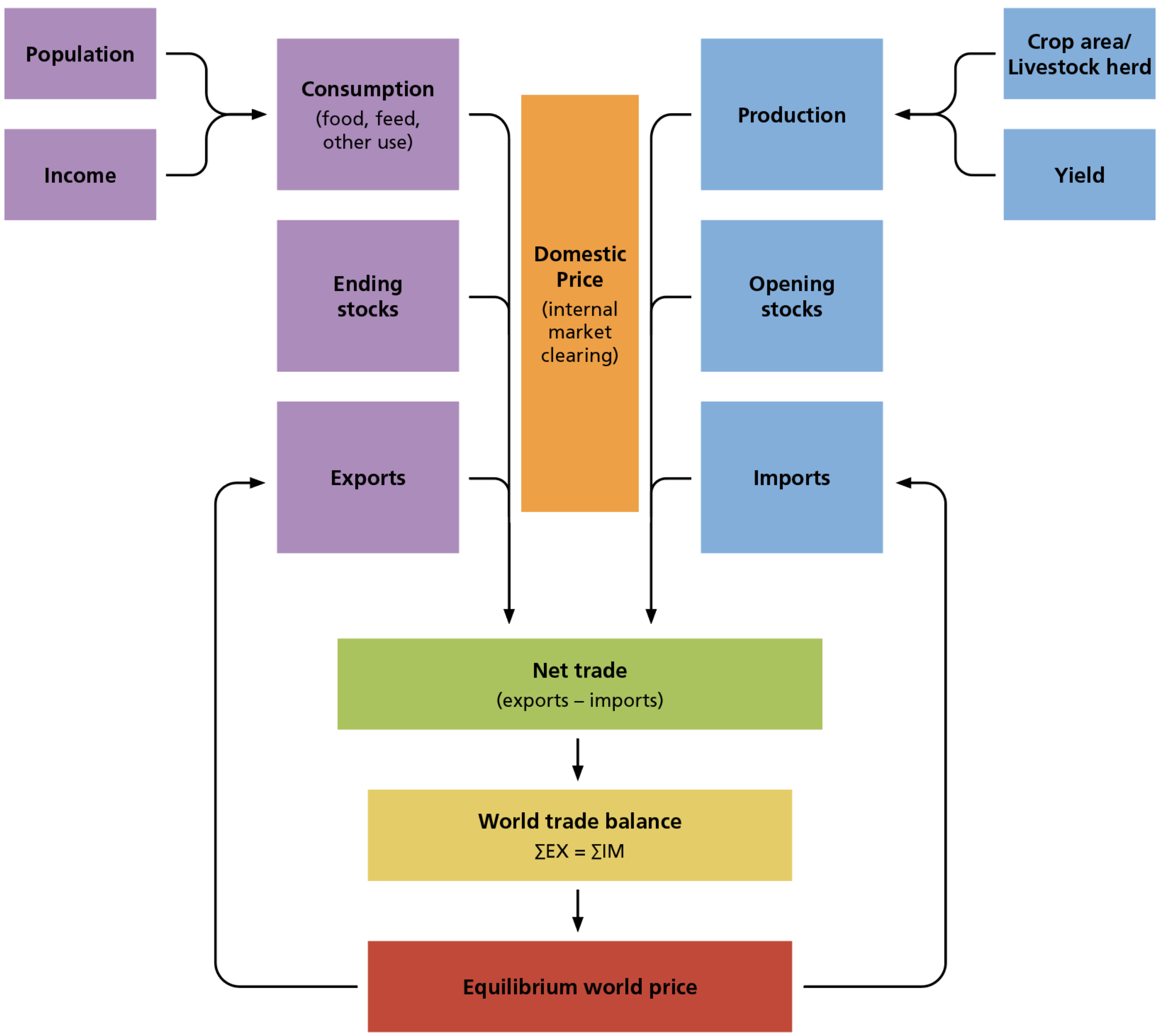

Figure M2: Aglink-Cosimo model description. Conceptual diagram of the modelling components, variables, and integrated data sources.

3. Aquatic animal-source food production scenarios

We used the Aglink-Cosimo model to project changes in human consumption under two potential aquatic animal-source food production futures: 1) a baseline scenario with moderate growth in production; and 2) a high production scenario that assumes higher growth rates in production, largely driven by increased financial investment and innovation in aquaculture (**Table S1; Fig. S1**). The baseline scenario is driven by the results of the FAO FISH model included in the OECD-FAO Agricultural Outlook 2020-2029, with 2030 data reflecting the UN FAO's best understanding of likely fisheries and aquaculture growth based on anticipated macroeconomic conditions, agriculture and trade policy settings, fisheries management outcomes, long-term productivity, international market developments, and average weather conditions (Ahern et al. 2021). It projects a 1.7 mt loss in global fisheries production and a 25.1 mt increase in global aquaculture production relative to 2018, with country-level production trends determined by the Aglink-Cosimo model. The high production scenario, which represents the UN FAO's specific estimation of the upper limits of aquatic animal-source foods growth potential (Ahern et al. 2021), projects a 2.6 mt increase in global fisheries production as a result of improved and effective fisheries management allowing to reach global MSY, with country-level production trends occurring in proportion to estimated benefits of fisheries management reforms from Costello et al. (2016). It projects an increase of 36.2 mt in global aquaculture production based on increased and cost-effective financial investment and innovative technologies and capacity building in aquaculture, with country-level production trends occurring in proportion to the changes derived below.

The high production aquaculture scenario seeks to simulate ambitious yet plausible aquaculture growth resulting from strategic investments in aquaculture production capacity. The scenario is ambitious in that it stimulates growth in countries i) without aquaculture production, ii) with declining aquaculture production, and iii) with slow-growing aquaculture production. The scenario is plausible in that it gently accelerates growth in these three categories of countries and that it reduces growth in the countries exhibiting the fastest growth. We parameterized the scenario by calculating recent (2008-2017) country-level changes (annual percent) in production in five different aquaculture sectors (environment-taxonomic group combinations) and by classifying these changes into five growth categories: a category for declining production and a category for each quartile of historical growth (**Fig. S2**). We then assumed that strategic investments result in the following:

1. **Sectors without production** are developed and exhibit production equivalent to that of the lowest producing country in the 1st quartile of sector-specific historical growth; production grows at the median rate of countries in that quartile.
2. **Sectors with declining production** reverse trends and grow at the median rate of countries in the 1st quartile of sector-specific historical growth.
3. **Sectors with slow production growth** (growth in the 1st quartile of sector-specific historical growth) grow at the median rate of the countries in the 2nd quartile of sector-specific historical growth.

4. **Sectors with moderate production growth** (growth in the 2nd quartile of sector-specific historical growth) maintain their historical growth rates.
5. **Sectors with fast production growth** (growth in the 3rd and 4th quartiles of sector-specific historical growth) grow at the median rate of the countries in the 2nd quartile of sector-specific historical growth.

Country-level changes in food consumption under the two scenarios are shown in **Extended Data Figures 3A-C** and the resulting changes in nutrient intake are shown in **Extended Data Figure 4**.

4. Nutrient composition of foods

The following methodology took place *after* the food systems modeling was complete. Therefore, any species disaggregation or nutrient assignments are separate from the workflow outlined above and do not influence production, trade, or market dynamics.

4.1 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. For both marine and freshwater fish, whether produced domestically or imported, we adjusted the mass estimates of supply by conversion factors for edible weight to account for head removal and gutting. Our adjustments did not account for any within-household processing or waste. 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 the estimates, 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 (**Tables S1 & S2**).

4.2 Species disaggregation

Species disaggregation, disaggregation of marine capture, and freshwater production were based on FAO historical and projected production shares, FAOSTAT production statistics, and FAOSTAT production statistics refined by household survey data and recreational fisheries consumption estimates, respectively. All production was adjusted for trade flows according to FAO trade data and FAO food balance sheets. Aquaculture production was disaggregated based on the most commonly produced species and their projected growth in production (**Figure M3**).

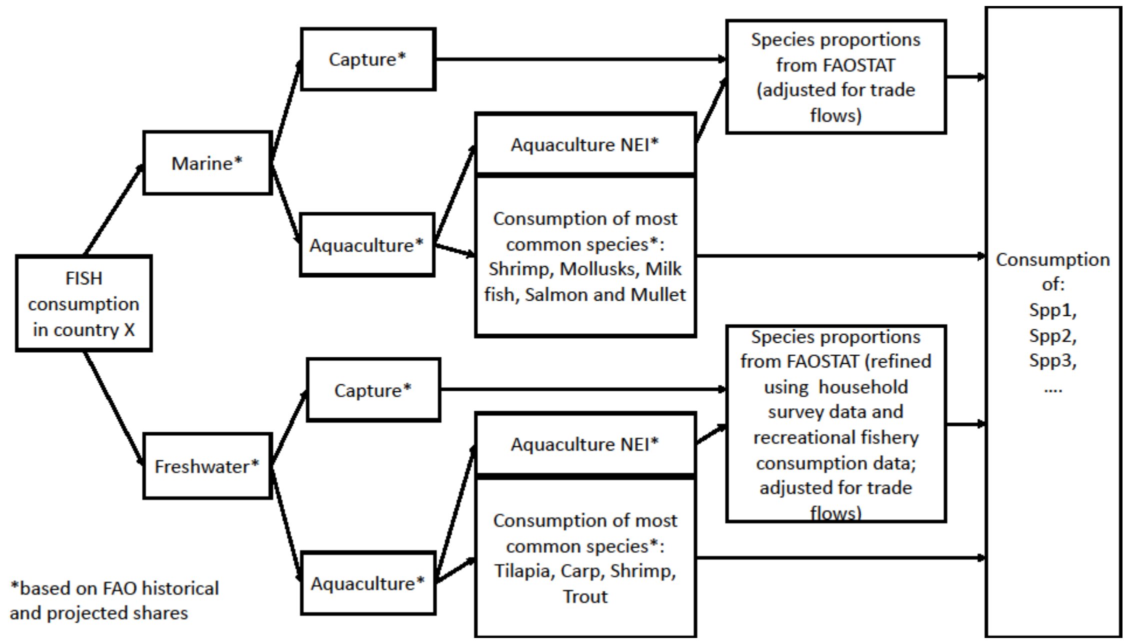

Figure M3: Description of disaggregation workflow. Conceptual diagram describing the marine and freshwater species disaggregation to derive more resolved consumption estimates. The workflow reads left to right with an asterisk representing FAO historical and projected shares. NEI: not enough information.

4.2.1 Taxonomic disaggregation of freshwater fish consumption

We estimated country-level freshwater fish consumption at the highest taxonomic resolution possible by combining three data sources:

1. FAO freshwater capture and aquaculture production data (with matching of FAO FishStat trade labels to account for imports and exports).
2. Household Consumption and Expenditure Surveys (HCES; used to disaggregate species-specific consumption for Bangladesh, Cambodia, Democratic Republic of Congo, Myanmar, and Zambia).
3. Consumption from recreationally harvested fishes used to disaggregate species-specific consumption (for Australia, Belarus, Canada, Iceland, Lithuania, Netherlands, New Zealand, Norway, Sweden, Ukraine, and USA).

The adjusted volumes were converted to a percentage of national consumption before use in the nutritional analysis.

4.2.2 Species-level mass balance from FAO statistics

Species-level aquaculture and capture production statistics were matched with FAO FishStat commodity trade groups to account for fish species produced but not consumed within a country, and *vice versa* (i.e., imports and exports). Trade data are not reported at the species-level, but are instead recorded in broader commodity groups (e.g., 'Carps, Eels, and Snakeheads'), and also labeled based on processing (e.g., fresh, frozen, fillets, etc.). To account for quantities exported, we used a fuzzy matching approach with the Harmonized System (HS) coding structure to add HS codes to the species-specific production table. Species were matched to 6-digit HS codes according to the taxa named in code descriptions, or in a "not elsewhere indicated" (NEI) code, where applicable. Exported commodity weights were converted to live weights using live-weight conversion factors for freshwater fish from Fluet-Chouinard et al. (2018). Where the number of individual aquatic animals (as opposed to tonnes) was reported by FAO, (e.g., crocodiles, alligators, turtles, seals, etc.), these values were converted to tonnes using average wild-caught adult body size from the literature. To reflect that most of these animals' mass is not edible, we applied the highest whole-weight factors from our database (i.e., for fillets).

We subtracted exported weights from production in four sequential steps. First, we assumed that exports and imports of the same species in the same country signified re-exported commodities. Second, we subtracted the exports from the matched aquaculture production to reflect the greater supply chain integration of aquaculture with trade. Exported commodities under generic HS codes (e.g., 'freshwater fish NEI'; not enough information) were matched with every production item falling under that same HS code. Inversely, non-generic (e.g.,'tilapia') export HS codes were matched with generic production items. Third, this process was repeated to subtract unaccounted exports from capture production. Fourth, any remaining exports were assigned exports to all generic production (e.g., all 'NEI' categories) for that country.

Once the exports were subtracted from production, the remaining weight was assumed to represent apparent domestic consumption per commodity group. For imported marine and freshwater fish, the processing level (fillet, canned, smoked, etc.) of most fish commodities was specified and no conversion to edible portions was required. Fish produced domestically or imported for which no processing was specified, were assumed to be consumed fresh, and we estimated edible portions using conversion factors accounting for head removal and gutting (0.8 for freshwater and marine). The conversion factor did not vary by taxa or by geographic region. Moreover, our adjustments did not account for any within-household processing or waste. Our species-level mass balance accounting produced 69 instances of negative consumption in 14 countries. We assigned these as zeros assuming that the negative cases arise from erroneous assumptions regarding exports. Total negative consumption was 6061.5 tonnes, accounting for a negligible 0.014% of total consumption.

4.2.3 Supplementing with HCES and recreational data

The process described above produced species-specific, trade-adjusted FAO capture and aquaculture production estimates, which closely reflect the Food Balance Sheet calculations of FAO. However, it is widely recognized that freshwater fishery production tends to be underreported in most countries. This underreporting exists in both low-income countries where freshwater subsistence and informal artisanal fisheries are geographically dispersed, and in high-income countries where catch from large-scale and intensive recreational fisheries are challenging to monitor and report to FAO. To account for these potential sources of error we 1) scaled up production with under-estimation factors from HCES for 31 countries known to have underreported subsistence production, 2) used HCES data to improve taxonomic resolution of FAO data for five countries in Africa and Asia that had already been scaled up in step 1, and 3) appended estimated consumption from recreational fisheries for 11 countries with high recreational harvest not reported to FAO (**Fig. S3**).

To increase taxonomic resolution of FAO data for five countries (step 2) we first removed all marine species categories from the HCES dataset, and then estimated the freshwater fraction inside categories with mixed marine and freshwater species following proportions in Fluet-Chouinard et al. (2018). Common names of species reported by HCES were converted to scientific names based on FAO reports and FishBase searches for matching with FAO data. To integrate HCES data with FAO, we first checked if the HCES species were already represented within FAO. For species present in both FAO and HCES, we took the higher consumption estimate. For species only present in HCES, we took the sum of all HCES consumption estimates and compared this to the generic 'freshwater fish NEI' FAO category. If the summed HCES consumption estimates were less than consumption of 'freshwater fish nei', we allotted that generic catch to each of the HCES species and left the remainder as 'freshwater fish nei'. If HCES consumption was greater than 'freshwater fish nei', we proportionally allocated the entirety of the FAO capture 'freshwater fish NEI' among the HCES species. Inclusion of upward conversion factors for 31 countries and HCES species disaggregation resulted in a 10.4% increase in overall consumption estimates from FAO data (4,184,717 tonnes).

Data processing of recreational species was led by the U.S. Geological Survey National Climate Adaptation Science Center. Countries were included based on recreational participation rates (i.e., Arlinghaus et al. 2015) and species breakdown availability. Although not fully comprehensive of recreational consumption globally, the additions do include substantial recreational fisheries not otherwise reported in official FAO channels (see supplementary data). Eleven countries were supplemented using these data: Australia, Belarus, Canada, Iceland, Lithuania, Netherlands, New Zealand, Norway, Sweden, Ukraine, and USA. We additionally compiled data for Finland, but since Finland reports recreational fisheries to FAO, our recreational data did not add further detail to the FAO dataset. Recreational fish consumption estimates were added to the dataset using the same protocol as outlined above for HCES data. Inclusion of recreational fish consumption for 11 countries resulted in a 0.17% increase in overall consumption estimates from FAO data (67,840 tonnes).

Finally, to ensure that our supplemented consumption data do not deviate greatly from the official FAO statistics, we compare both sets of per capita consumption of freshwater fish (**Fig. S4**). Notably, some countries had increases in their share of capture fisheries due to the upward adjustment with household surveys (e.g., Zambia, Myanmar, and Cambodia).

4.3 Aquatic Food Composition Database (AFCD)

A systematic literature review was conducted to compile international and national food composition data to supplement the international food composition databases. The search strategy was conducted on Web of Science, binned from 1990 to 2020, and used 20 aquatic and 15 nutritional search terms. Search terms included: *(TI=("aquatic insect*" OR "aquatic plant*" OR "algae" OR "algal" OR "aquatic food*" OR "bivalve*" OR "crustacean*" OR "finfish*" OR "fish" OR "fishes" OR "marine invertebrate*" OR "marine mammal*" OR "mollusc*" OR "mollusk*" OR "sea food*" OR "seafood*" OR "sea weed*" OR "seaweed*" OR "shell fish*" OR "shellfish")) AND (TI=("beta carotene" OR "fat" OR "fats" OR "fatty acid*" OR "iron" OR "lipid*" OR "macro nutrient*" OR "macronutrient*" OR "micro nutrient*" OR "micronutrient*" OR "mineral*" OR (("nutrient*" OR "nutritional" OR "nutritive" OR "proximate") NEAR/3 ("density" OR "composition" OR "value*" OR "profile*")) OR "protein*" OR "vitamin*")) OR (AB=("beta carotene" OR "fat" OR "fats" OR "fatty acid*" OR "iron" OR "lipid*" OR "macro nutrient*" OR "macronutrient*" OR "micro nutrient*" OR "micronutrient*" OR "mineral*" OR ("nutrient*" OR "nutritional" OR "nutritive" OR "proximate") NEAR/3 ("density" OR "composition" OR "value*" OR "profile*") OR "protein*" OR "vitamin*")).*

The following elimination hedges were also applied: *(TI=(antibacterial OR antimicrobial OR microplastic OR genome OR microbiota OR microbacteria OR sediment OR soil OR milk OR chicken OR vegetable OR pathogen)) OR (AB=(antibacterial OR antimicrobial OR microplastic OR genome OR microbiota OR microbacteria OR sediment OR soil OR milk OR chicken OR vegetable OR pathogen)).* Studies were excluded if they did not mention the scientific name of the organism or only assessed aquatic foods destined for fish oil or as an ingredient in processed seafood products (e.g., fish burgers).

Quality checks were conducted on the peer review data to ensure that data were correctly extracted from the literature. Aquaculture feeding trials (i.e., fish nutrition) were excluded. Protein concentration values were used to identify and exclude outliers; especially high or low protein values flagged issues of unit misalignment or of sample preparation, or identifying a broad publication of low quality. Outliers were identified with protein values above 40 g/100g, many of these were reported on a dry weight basis. For observations where moisture content was also available, we converted to wet weight equivalence. In most cases, these studies were deemed low quality if they did not contain sufficient information about the unit of analysis, whether values were given on a weight or dry weight basis or if there were obvious errors reporting data (e.g. fat + protein + ash + moisture = 150 g/100g). While this method was cost-effective given the large number of studies, it does not necessarily specify the accuracy of e.g. instrumentation, sample size and protocols for other nutrients. All units were standardized to those set forth by FAO INFOODS guidelines (FAO/INFOODS 2012).

The AFCD includes 29,912 lines of data and 3,753 unique taxa. Within the analysis, species nutrient composition information was aggregated across analyses in order to complete the nutrient information available for the nutrients of interest for each species (e.g., for species X one study analyzed vitamin A, another study analyzed zinc and iron). When multiple studies analyzed the same species, we took the average for that species. In addition, data entries for internal parts of fish (e.g., liver, roe) were removed for nutrient assignment and nutritional value was averaged across all preparation types (e.g., raw, cooked, baked). Focusing on muscle tissue and ignoring other parts of the fish (e.g., bones, liver, subcutaneous fat) is certainly not a reflection of how cultures consumed these aquatic animal-source foods. However, to standardize these values across the breadth of aquatic animal-source food species, the most pragmatic approach was used. We have retained this important metadata in the AFCD to further explore the nutritional value of these other parts in the future.

For the majority of species consumed globally, AFCD delineated a match for the scientific name, genus, or family (**Fig. S5**). Protein, iron, zinc, and calcium resulted in the greatest number of species with a reliable match, with ~90% of the species being filled by the first three tiers of our hierarchical approach (scientific name, genus, or family). For vitamin B_{12}, DHA + EPA and vitamin A, however, ~20-30% of species nutrient composition was missing at the family level or below, and were thus filled by either the species order or the GND category, decreasing the accuracy of estimates.

4.4 Visualizing nutrient richness across food groups in Figure 1

All aquatic animal-source food composition data was sourced from AFCD. Food composition data for terrestrial animals were downloaded from the USDA Food Composition database (United States Department of Agriculture and Agricultural Research Service 2019) except for iodine, which was sourced from the Norwegian Food Composition Database (2020). Details on the nutrients, units (**Table S2**), and specific products are available in **Table S3**. Data was first standardized to 100 g of raw product. Then any dry-weight observations were converted to a wet weight basis. The ratio of nutrient richness across food categories visualized in Figure 1 was calculated following the methodology outlined by Drewnowski (2009).

First, nutrient information was aggregated up to the taxonomic level of order by taking the median of species or genus-level information. We pooled nutrient concentration values from AFCD across species and filled gaps prior to calculating nutrient richness ratios. Using a median, rather than a mean, helped to address outliers from taxa with especially high or low nutrient concentration belonging to each taxonomic order. Second, the richness ratio of individual nutrients for each taxonomic order was calculated by dividing the nutrient concentration in a given food by the daily recommended nutrient intake (RNI) for that nutrient (see Table S4 for a description of the recommended nutrient intake values and their sources). Third, the *composite* richness across individual nutrient richness ratios for each taxonomic order was calculated using an average across the seven individual nutrient richness values, following Drewnowski (2009). Taking the average for this composite value was chosen over a median for ease of interpretation (e.g., a composite richness of 0. 30 for Cypriniformes or "carps" indicates the average richness was 30% of the RNI across the seven nutrients included). Fourth, the individual and average nutrient richness values were aggregated from taxonomic order to the broad food categories visualized in Fig. 1 by taking the median of the richness values across taxonomic orders within each broad category. Some broad food groups only represented single orders (e.g., the taxonomic order of Gadiformes or Clupeiformes to "Cods" or "Small pelagics", respectively) while others required aggregation by taking the median values for individual and composite richness. (e.g., taking the median of values for Mytiloida, Ostreida, Venerida to aggregate to the single broad category of "Clams, Mussels, Oysters". While most taxa were grouped to taxonomic order, a few needed to be grouped to the level of class. "Cephalopods" were grouped at the higher taxonomic class Cephalopoda because it included all the major food categories for squid, octopus and cuttlefish, whereas "Aquatic mammals" were grouped to class Mammalia because there was no complete dataset of observations at the level of taxonomic order. The same four step process was used to calculate individual and composite nutrient richness ratios for terrestrial ASFs, however, these were not aggregated to higher groupings. At no point were values weighted.

The panels visualized in **Figure 1** represent these richness ratios calculated for each of the seven nutrients (i.e., vitamin A (RAE), vitamin B_{12}, calcium, iodine, iron, zinc, and omega-3 long-chain polyunsaturated fatty acids DHA and EPA). The food categories are ordered by their composite nutrient richness value. High composite nutrient richness was in some cases due to relatively high richness ratios for specific nutrients. For example, small pelagics had very high DHA+EPA (218%) and vitamin B_{12} (416%) percentage values of the total recommended nutrient intake (RNI), but more moderate richness ratios for iodine and iron. In other cases, high composite richness in food categories were driven by a more moderate individual richness ratios across a broader range of nutrients (e.g., aquatic mammals).

5. Subnational intake distributions

5.1 Overview

The Aglink-Cosimo model estimates mean national nutrient intakes, but subnational distributions of nutrient intakes are needed to estimate nutrient deficiencies among sex-age groups with differing nutrient requirements. To disaggregate mean national intakes into subnational intake distributions, we used estimates of mean subnational nutrient supply from the Global Expanded Nutrient Supply (GENuS) database (Smith et al. 2016) to first derive mean subnational nutrient intakes in each country. We then derived the shape of the intake distribution around this mean through analysis of dietary survey data from the country or borrowed from its most similar neighbor. The workflow is visualized in **Figure M4** below. Derivation of subnational nutrient intake means required imputation for 2 nutrients and 56 nations not included in the GENuS database. Derivation of the distribution of subnational nutrient intakes around these means required more imputation due to the limited availability of publicly accessible dietary survey data. To our knowledge, this represents the largest geographical coverage of modelled micronutrient intakes ever created, especially with disaggregation by age and sex.

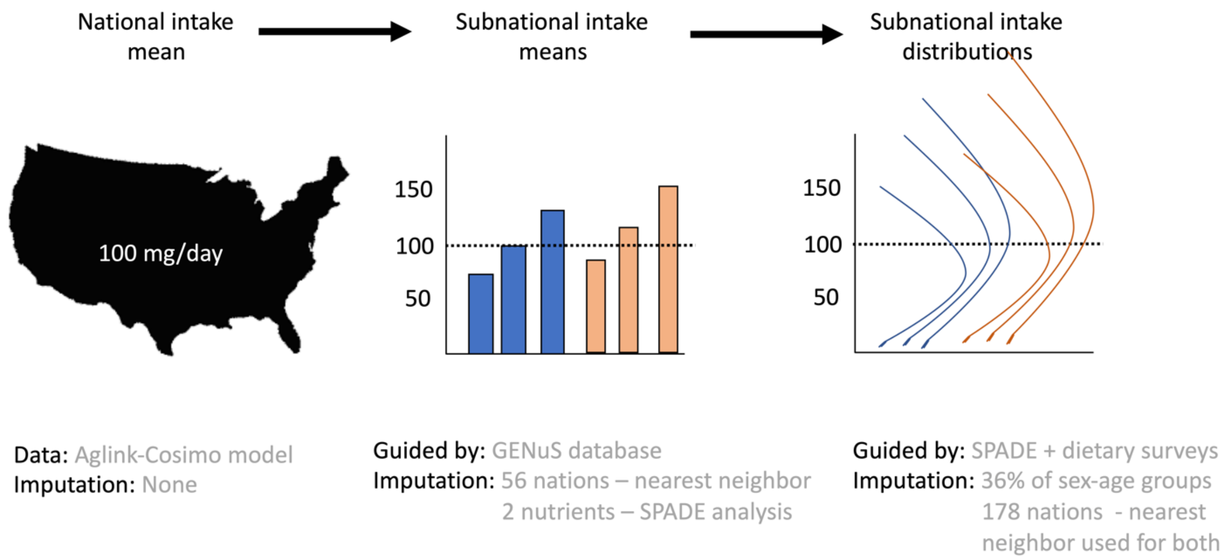

Figure M4. Conceptual schematic illustrating the procedure for disaggregating the mean national nutrient intakes (mg/day) provided by the Aglink-Cosimo model into the subnational nutrient intake distributions required for the health impacts analysis.

5.2 Subnational intake means

We disaggregated mean national intakes into mean subnational intakes in two steps. First, we assigned mean national intakes for the European Union (E.U.), which is modelled as a single entity in the Aglink-Cosimo model, to each of its 27 constituent countries (**Table S5**). Second, we disaggregated this expanded set of mean national intakes into mean subnational intakes using the GENuS database. The GENuS database provides estimates of subnational nutrient supply for 23 nutrients from 225 food categories for 34 age-sex groups in nearly all countries (including the 27 E.U. countries individually) based on historical national dietary trend data (Smith et al. 2016). We used these estimates to calculate scalars for relating national nutrient supply to subnational nutrient supply:

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

Where the scalar for country *c*, nutrient *n*, sex *s*, and age group *a* is calculated by dividing the nutrient supply for each sex-age group by the mean nutrient supply for all sex-age groups. Because the GENuS database includes subnational nutrient supply information for each E.U. country, this procedure produces different scalars for each E.U. country, despite having a common mean national intake across E.U. countries (i.e., the numerator in Eq. 1 changes while the denominator remains constant). We assume these ratios of nutrient supply are proportional to ratios of nutrient intake and scale the country-level mean nutrient intakes as follows:

$$\text{intake}_{c,n,s,a} = \text{intake}_{c,n} * \text{scalar}_{c,n,s,a}$$

The GENuS database does not estimate subnational nutrient supplies for all countries and nutrients. For the 56 nations without GENuS data, we borrowed information from the nearest neighbor with usable data (**Table S6**). We derived mean subnational intakes for DHA+EPA and vitamin B_{12}, which are not included in the GENuS database, using the same process, but applied to the dataset described below.

5.3 Subnational intake distributions

We used surveys of dietary intake to define the *shape* of subnational intake distributions, which are key for accurately calculating population-level risk of inadequate nutrient intake. We assembled a dataset of individual dietary intakes based on variable days of 24-hour recalls for 13 countries with publicly available data: the United States, Zambia, Mexico, China, Lao PDR, Philippines, Uganda, Burkina Faso, Bulgaria, Romania, Italy, Bangladesh, and Bolivia (**Fig. S6; Table S7**). In a handful of cases, nutrient intakes were not already available in the datasets and we had to impute them using information from the USDA Food Data Central Database (United States Department of Agriculture and Agricultural Research Service, 2019), the AFCD database, or the INFOODS databases for Asia (FAO, 2018). This was done for vitamin B_{12} for China; zinc and vitamin B_{12} for Lao PDR and the Philippines; and EPA+DHA for Lao PDR, the Philippines, Uganda, Zambia, Burkina Faso, Bolivia, and Bangladesh. To our knowledge, this is the most extensive empirical dataset used to derive distributions of habitual nutrient intakes on a global scale.

We then used the Statistical Program to Assess Habitual Dietary Exposure (SPADE) to estimate habitual intakes from these data (Dekkers et al., 2014). SPADE requires at least two days of 24-hour recalls, aggregated nutrient or food intakes calculated at the level of each person for each day, age and sex variables, and sample weights, if available. It consists of several steps, including: 1) a transformation of observed data to a normal distribution; 2) removal of the within-person variability resulting in a shrunken distribution at the transformed scale; and 3) a complex back-transformation to the original scale (Dekkers, Verkaik-Kloosterman, and Ocké, 2017).

We then fitted gamma and log-normal distributions to the habitual intake distributions for all available age-sex groups using the *fitdistrplus* package (Delignette-Muller & Dutang 2014) and 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 the best fitting distribution describe the shape of the habitual intake distribution for each sex-age group and can be shifted along the x-axis in response to changing diets. Because the habitual intake data and associated statistical probability distributions were incomplete across all country-nutrient-sex-age combinations (**Fig. S6**), we filled gaps by imputing data from the nearest neighbor (37% of sex-age groups). 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 (**Fig. S7**). We then mapped these to the rest of the world, based on UN sub-regions, with a few expert-identified modifications (**Fig. S8**). Lastly, the shapes of these distributions were used along with the means derived from the Aglink-Cosimo model to describe empirical-based distributions per age-sex group. Because the Aglink-Cosimo model produced only a single mean value for each country, subnational age-sex subgroups were then inferred from that single value based on per country subnational mean intakes fractions per nutrient derived from GENuS (Smith et al. 2016).

6. Exploring sensitivity of health outcome projections

We evaluated the sensitivity of the health outcome projection to the nutrient composition database with the comparison illustrated in **Extended Data Fig. 2**. In general, the use of the disaggregated nutrient composition database (AFCD) decreases micronutrient deficiencies (lowers SEVs) relative to the aggregated nutrient composition database (GND). The exception is for Vitamin A where nutrient deficiencies are higher when using the disaggregated database (AFCD).

We explored the role of baseline nutrient intake and micronutrient deficiency status in determining the difference in micronutrient deficiency status between the two scenarios in **Extended Data Fig. 5**. In general, countries with either low rates of micronutrient deficiencies or with small changes in nutrient intakes exhibited the smallest differences in health outcomes between the two scenarios. Conversely, countries with high rates of micronutrient deficiencies and large changes in nutrient intakes exhibited the largest differences between the two scenarios.

7. Acknowledging limitations of our nutrient projections

Much of our analysis focuses on shifts in production, and how that will influence consumption, without adequate attention to the role of human culture. Cultural norms around consumption of aquatic foods, and indeed what is considered ‘edible,’ are highly variable. Such norms are also subject to change, and linked to both species-size variation and consumer socio-economic status. Often consumption of whole fish can provide more substantial nutritional benefits over, for example, fillets due to the bioavailability of minerals and nutrients in the bones and other parts of the fish commonly discarded with processing (Roos et al. 2007). However, some forms of processing such as drying or fermentation, particularly of small fish, that retain most of the carcass and micronutrients, are sometimes preferred and have nutritional value in traditional diets and food cultures (e.g., fermented fish, Zang et al. 2019; dried kapenta, Haug et al. 2010).

Food cultures, including the processing and cooking of aquatic foods, also impact nutrient availability and uptake. Fish consumption is often limited to fillets, and nutrients are often lost to processing and plate waste. Critically, cooking methods can alter the bioavailability of nutrients, in some cases reducing it (e.g., deep frying fish fillets leading to reduced potassium and magnesium content; Gall et al. 1983), and in other cases increasing it (e.g., grilling and baking salmon to preserve the omega-3 polyunsaturated fatty acid content; Şengör et al. 2013). Further, nutrient analysis often focuses on muscle tissue of raw fish, as is the case for our analyses. Yet, analysis of muscle may miss edible portions of aquatic animal-source foods that are widely consumed, especially for small species often eaten whole, while analysis of whole fish may fail to account for plate waste, such as discarded bones, head, and skin. Additionally, there are considerable differences in nutrient concentrations within different parts of the animal. For example, calcium is higher in the “frame” or bones and Vitamin A concentrates in the liver and eyes (Roos et al. 2007). Focusing exclusively on muscle tissue therefore biases away from nutritious small fish species that are often consumed whole (Thilsted et al. 2016), and it is conceivable that their potential nutrient contribution is even greater.

Lastly, we acknowledge several limitations within our nutrient projection approach. First, the dietary intake data was subject to availability. Thus, the year in which the dietary recalls were conducted varied from as early as 2000 in the case of the Philippines to 2018 in the United States. Although diets may have changed during this time period, we used the estimates of mean intake from the GENuS database, and only derived the shape of the distribution from the dietary recall data. Moreover, we understand that there are substantial differences in nutrient intakes and dietary patterns within individual countries – for example, in rural versus urban populations. Thus, we supplemented the analysis with survey weights and nationally representative dietary data when available. Finally, it is possible that bias may be introduced through our imputation procedure if the population being imputed is dissimilar from the population from which it is borrowing data. In spite of these limitations, incorporating more nuanced information to determine the shape of the distribution around a mean is an advance over previous nutritional epidemiological methods, which tend to assume a shape ex-ante.

8. Synergies with the environment and technology

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. 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, potentially negative interactions with wild fishery populations resulting from nutrient discharge, escapements, and disease (Belton et al. 2020). Increasing dominance of a few species also threatens the sector's resilience (Gephart et al. 2020) and much research is still required in understanding the nutritional impacts of shifting reliance from wild caught fisheries to aquaculture (Karapanagiotidis et al. 2006).

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; Borg et al. 2019; Bogard et al. 2015). 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 longevity of aquatic food products and support nutritionally vulnerable populations. Measures to ensure that these products are safe from contaminants and do not exceed recommended intake of preservatives like salt, for example, are needed.

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Supplementary Figures

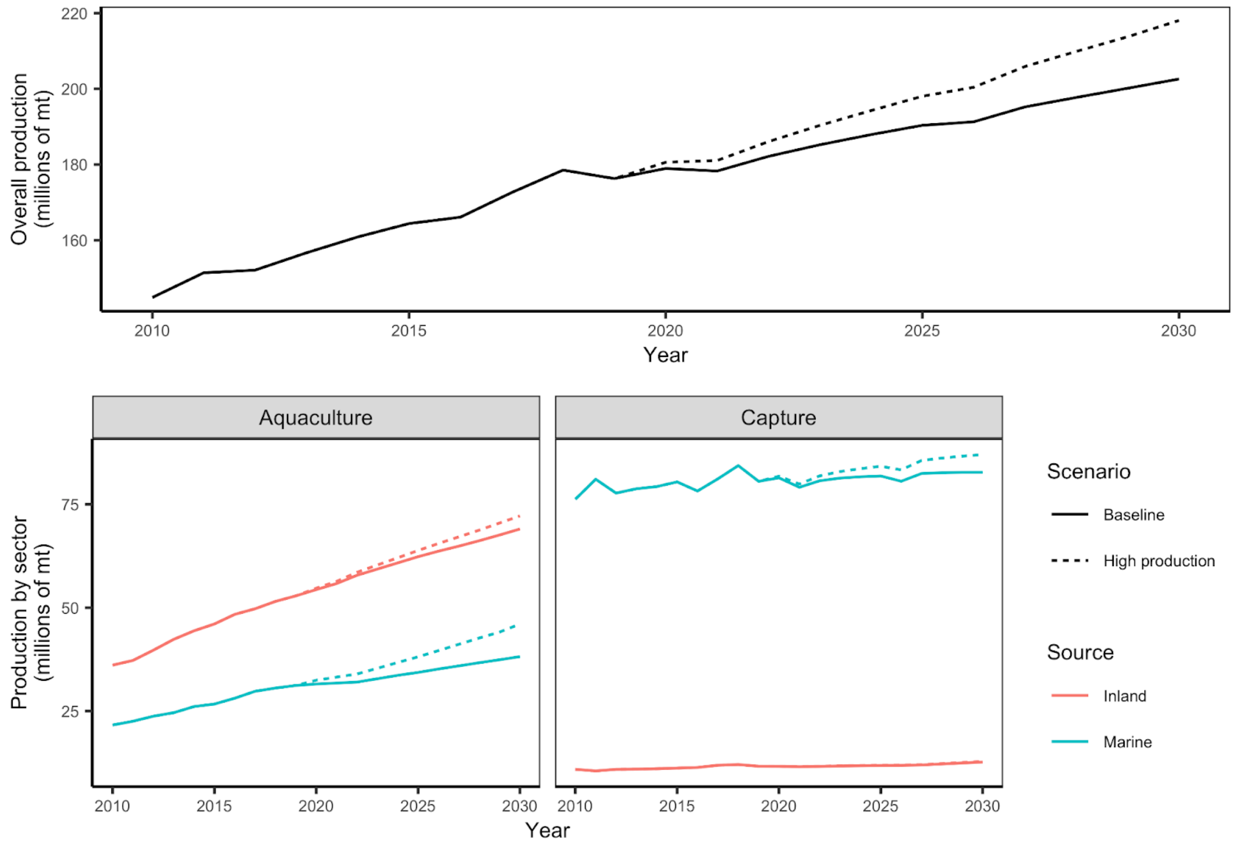

Figure S1. Aquatic animal-source foods production under the baseline and high production scenarios.

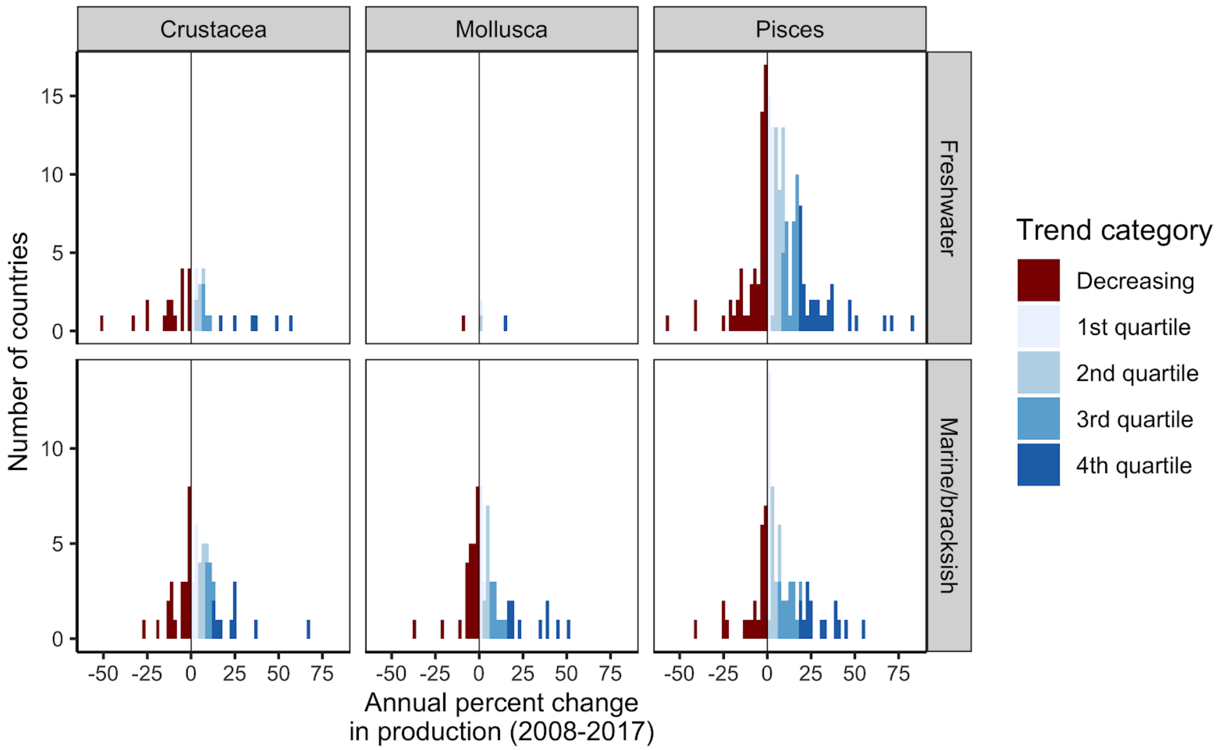

Figure S2. Trends in aquaculture production over the last 10 years. Distribution of recent (2008-2017) country-level trends in aquaculture production by environment (inland, marine/brackish) and major groups (fish, bivalves, crustaceans).

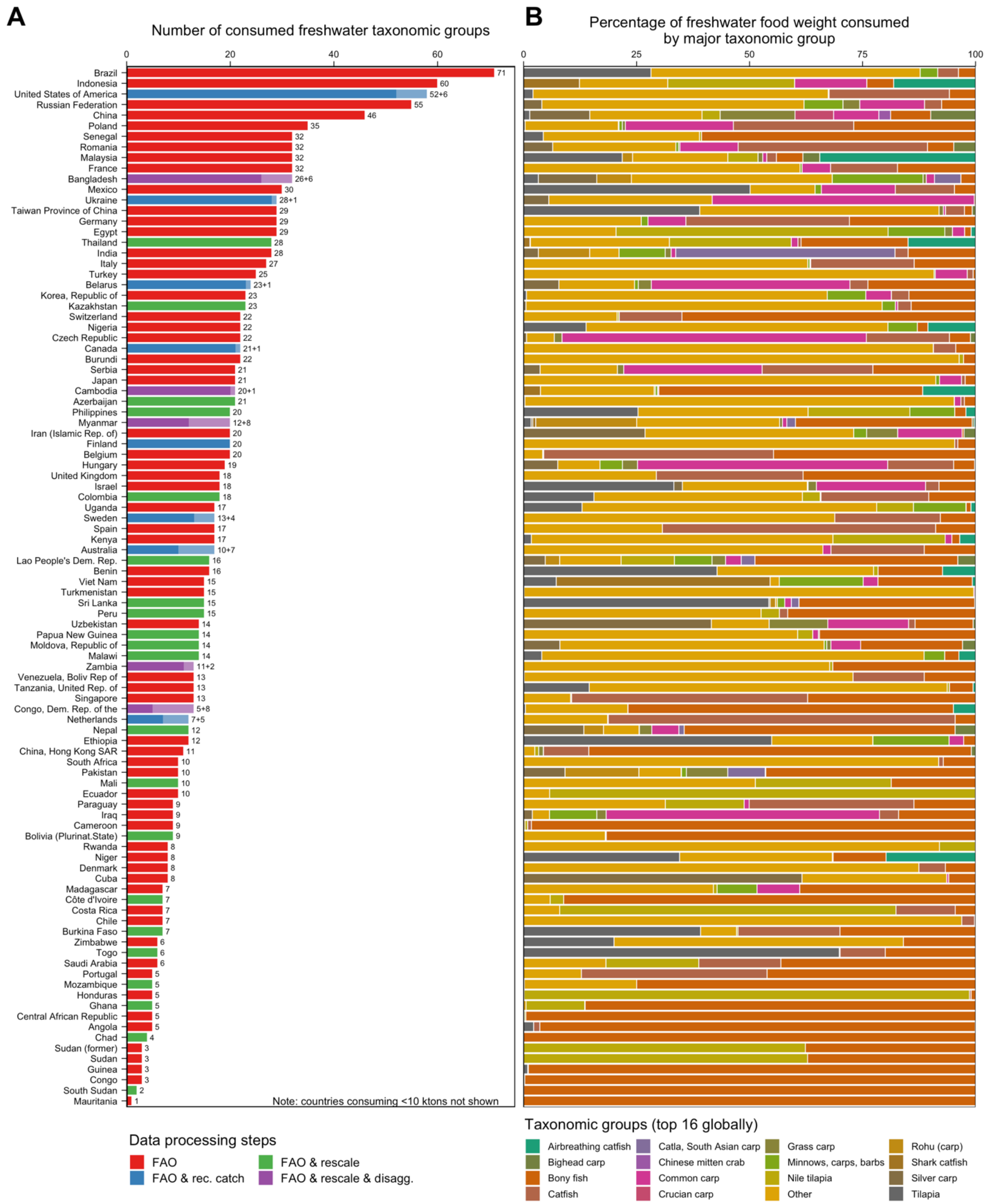

Figure S3. (A) Number of freshwater fish species consumed in each country sorted from highest to lowest. Bar color indicates the processing and data inputs used to generate the final taxonomic list. The darkened section of each bar represents the number of species from FAO data, while the lighter color represents species added from ancillary data. Red - only FAO data; Blue - FAO data further disaggregated with recreational fisheries catch; Green - FAO data whose wild catch was upward-scaled based on HCES underestimation factors; Purple - FAO data that were upward-scaled based on HCES underestimation factors and then disaggregated with HCES data. The exact number of species is labeled next to each bar as: FAO + supplementary (if any). **(B)** Percentage of national consumption across the largest taxonomic group according to global consumption. All other taxonomic groups are lumped into 'Other'. Note that taxonomic groups are not the finest level of consumption data, as a single taxa can be processed into different commodities (dried, filleted, frozen, etc.).

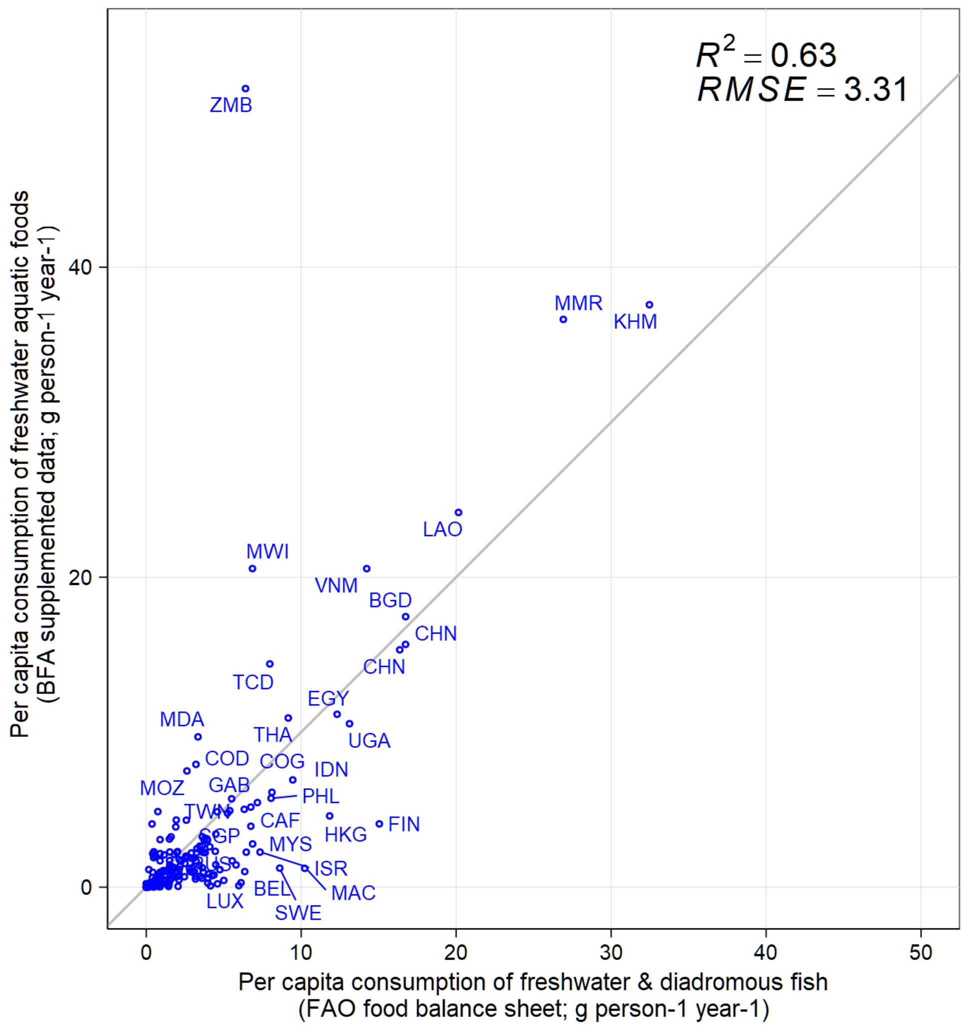

Figure S4. Scatterplot showing the broad alignment (R2=0.63) of the per capita consumption from our species disaggregation against the food supply estimated by the FAO food balance sheets. The diagonal segment represents the 1:1 line.

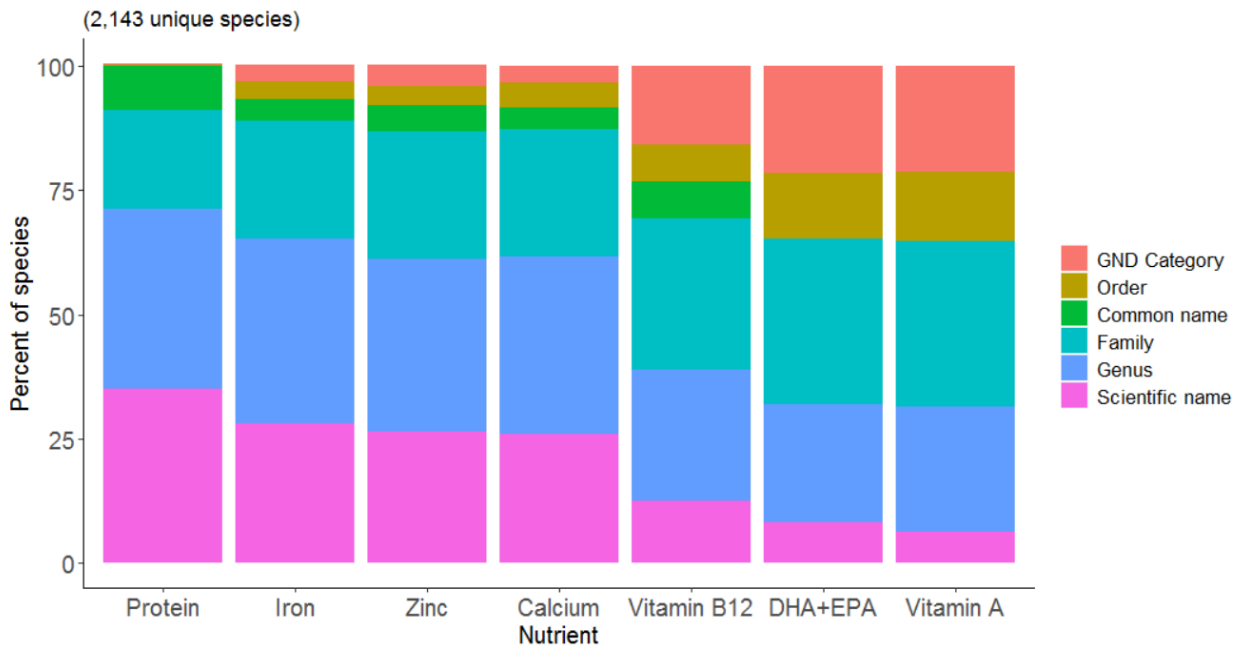

Figure S5. Total number of species per nutrient and criteria used to fill nutritional values from the Aquatic Foods Composition Database (AFCD). For all nutrients, there are a total of 2,143 unique species derived from disaggregation efforts.

Figure S6. Coverage of habitual intake distribution data. Coverage of habitual intake distributions derived using the SPADE algorithm and data from household-level recall surveys by country, sex, and age. Red shading indicates groups with available repeat 24-hour recall data.

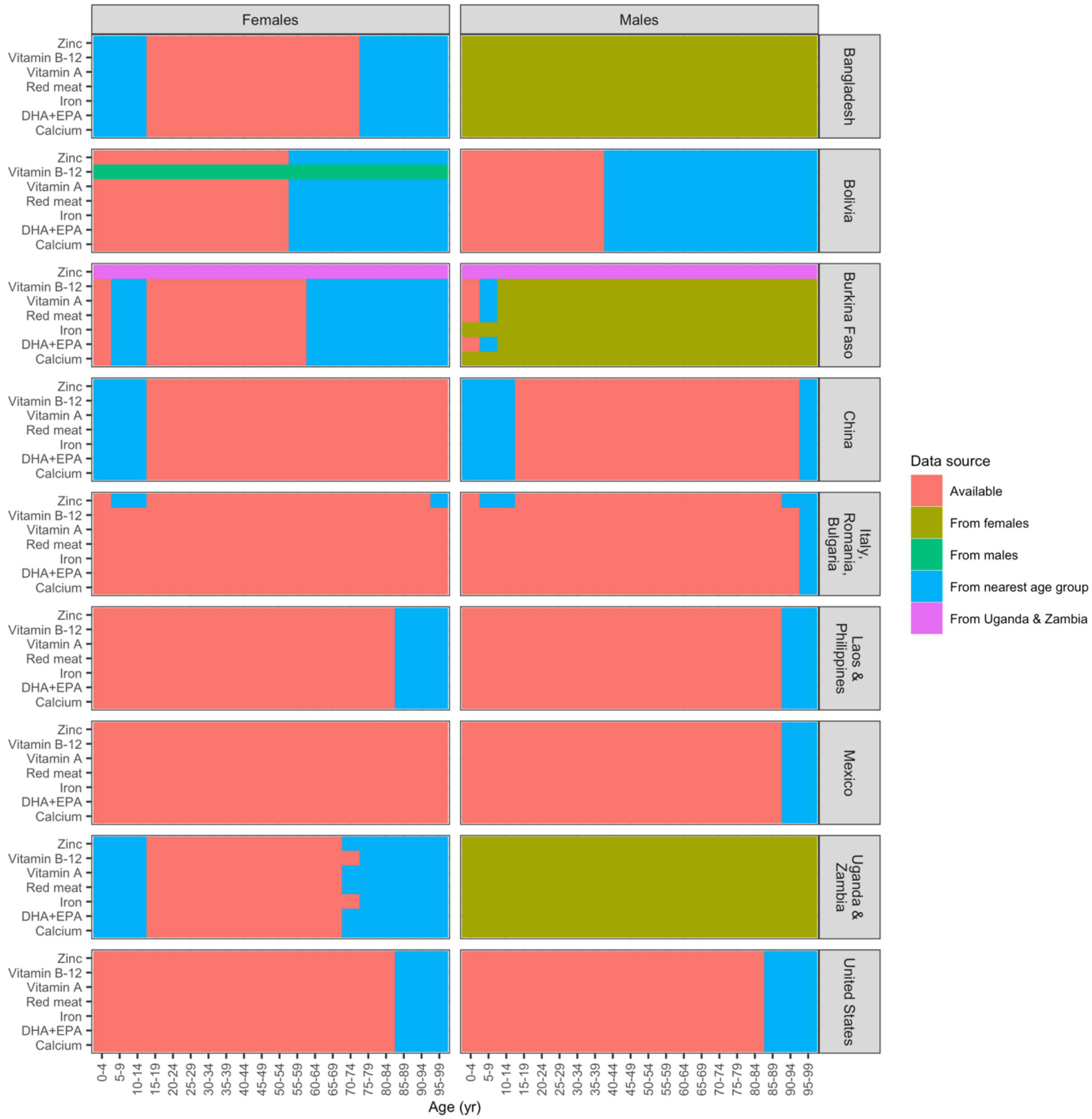

Figure S7. Approach to imputing habitual intake data for age and sex groups without habitual intake data. The red shading indicates age/sex groups with data. Missing data were imputed by borrowing from the nearest neighbor (32% of age-sex groups). We filled within country gaps by borrowing intake distributions, 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.

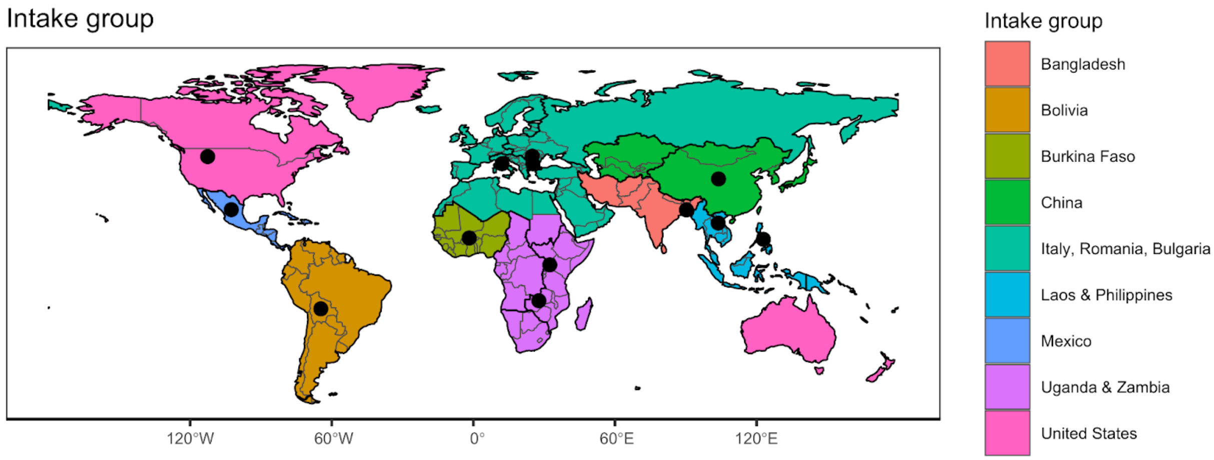

Figure S8. Map of the nutrient intake groups used to scale the subnational habitual intake distributions across countries. These groups are based on U.N. subregions (delineated in thick black lines) with a few expert-identified modifications.

Supplementary Tables

Table S1. Aquatic food production scenarios.

Aquatic animal-source foods production today (2018) and in the future (2030) under two potential production futures derived by the UN FAO (Ahern et al. 2021).

		Aquaculture			**Capture fisheries**			
Scenario	**Year**	**Inland**	**Marine**	**Total**	**Inland**	**Marine**	**Total**	**Overall**
Current (FAO SOFIA)	2018	51.3	30.8	82.1	12.0	84.4	96.4	178.5
Baseline scenario (FAO base)	2030	69.0	38.2	107.2	12.7	82.7	95.4	202.6
High production scenario (FAO high road)	2030	72.2	46.1	118.3	12.8	87.0	99.8	218.1

Table S2. Aglink-Cosimo nutrient intakes and units.
Classifications and units used for the Aglink-Cosimo model.

Type	Nutrient	Units
Fatty acid	Monounsaturated fatty acids	g/d
Fatty acid	Omega-3 fatty acids	g/d
Fatty acid	Polyunsaturated fatty acids	g/d
Fatty acid	Saturated fatty acids	g/d
Macronutrient	Energy	Kcal/d
Macronutrient	Protein	g/d
Macronutrient	Total lipids	g/d
Mineral	Calcium	mg/d
Mineral	Iron	mg/d
Mineral	Zinc	mg/d
Vitamin	Vitamin A	IU/d
Vitamin	Vitamin A, RAE	mg/d retinol
Vitamin	Vitamin B_{12}	ug/d

Table S3. Database description of terrestrial animal food categories. Describes the source and product form for the terrestrial animal food categories visualized in Figure 1. Nutrient data sourced from USDA included vitamin A (RAE), vitamin B_{12}, calcium, iron, zinc, and omega-3 long-chain polyunsaturated fatty acids DHA and EPA. Iodine data was sourced from the Norwegian Food Composition Table.

Food category	USDA [code] description	Norway description (Iodine)
Chicken	[05006] Chicken, broilers or fryers, meat and skin, raw	Chicken with skin, raw
Pork	[10006] Pork, fresh, separable fat, raw	Pork, inside round, raw
Beef	[13002] Beef, carcass, separable lean and fat, select, raw	Beef, inside round, topside, raw
Goat	[17168] Game meat, goat, raw	No Iodine available in Norway's database or elsewhere, assumed to be 0.
Lamb	[17224] Lamb, ground, raw	Lamb, inside round, raw

Table S4. List of nutrients included in Figure 1, with daily recommended nutrient intakes and their source. Describes the recommended nutrient intake (RNI) visualized in **Figure 1**, and used to calculate the ratio of nutrient concentration per 100 gram of each food group for each of the 7 nutrients. Institute of Medicine. 2001. *Dietary Reference Intakes for Vitamin A, Vitamin K, Arsenic, Boron, Chromium, Copper, Iodine, Iron, Manganese, Molybdenum, Nickel, Silicon, Vanadium, and Zinc*. Washington, DC: The National Academies Press. https://doi.org/10.17226/10026.); Murray, C. J. L. et al. 2020. Global burden of 87 risk factors in 204 countries and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019. *Lancet Br. Ed.* **396**, 1223–1249.

Nutrient	**RNI**	**Source**	**Notes**
Vitamin A (RAE)	700 µg/d	Institute of Medicine (2001)	This is a mean value based on RNI requirements for women across age groups 14-18, 19-30, 31-50.
Vitamin B_{12}	2.4 µg/d	Institute of Medicine (2001)	This is a mean value based on RNI requirements for women across age groups 14-18, 19-30, 31-50.
Calcium	1100 mg/d	Institute of Medicine (2001)	This is a mean value based on RNI requirements for women across age groups 14-18, 19-30, 31-50.
Iodine	150 µg/d	Institute of Medicine (2001)	This is a mean value based on RNI requirements for women across age groups 14-18, 19-30, 31-50.
Iron	17 mg/d	Institute of Medicine (2001)	This is a mean value based on RNI requirements for women across age groups 14-18, 19-30, 31-50.
Zinc	8.3 mg/d	Institute of Medicine (2001)	This is a mean value based on RNI requirements for women across age groups 14-18, 19-30, 31-50.
Omega 3 fatty acids (DHA plus EPA)	0.45 g/d	Murray et al. (2020)	Consuming less than 0.43-0.47 grams of eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) is considered low. We used the midpoint value of 0.45 as the RNI. This value is not differentiated by age or sex.

Table S5. EU27 countries.
Countries included in the EU27 in the Aglink-Cosimo model.

ISO3	Country
AUT	Austria
BEL	Belgium
BGR	Bulgaria
CYP	Cyprus
CZE	Czechia
DEU	Germany
DNK	Denmark
ESP	Spain
EST	Estonia
FIN	Finland
FRA	France
GRC	Greece
HRV	Croatia
HUN	Hungary
IRL	Ireland
ITA	Italy
LTU	Lithuania
LUX	Luxembourg
LVA	Latvia
MLT	Malta
NLD	Netherlands
POL	Poland
PRT	Portugal
ROU	Romania
SVK	Slovakia
SVN	Slovenia
SWE	Sweden

Table S6. Cross-walking GENuS database and Aglink-Cosimo output.

The following countries with output from the Aglink-Cosimo model do not have information on subnational mean intakes in the GENUS database. To fill this gap, we used subnation mean intakes from the nearest neighbor with information in the GENUS database.

Aglink-Cosimo country		GENuS country	
ISO3	Country	ISO3	Country
AFG	Afghanistan	PAK	Pakistan
ANT	Netherlands Antilles	VEN	Venezuela
BDI	Burundi	RWA	Rwanda
BHR	Bahrain	SAU	Saudi Arabia
BLX	Belgium-Luxembourg	BEL	Belgium
BMU	Bermuda	USA	United States
BTN	Bhutan	NPL	Nepal
COD	Congo - Kinshasa	COG	Congo
COM	Comoros	MDG	Madagascar
CZ2	Czechoslovakia	CZE	Czech Republic
DMA	Dominica	LCA	Saint Lucia
ERI	Eritrea	DJI	Djibouti
ESH	Western Sahara	MAR	Morocco
ET2	Ethiopia PDR	ETH	Ethiopia
FSM	Micronesia (Federated States of)	FJI	Fiji
GAB	Gabon	COG	Congo
GNQ	Equatorial Guinea	CMR	Cameroon
HKG	Hong Kong SAR China	CHN	China
KHM	Cambodia	THA	Thailand
KIR	Kiribati	PYF	French Polynesia
KNA	St. Kitts & Nevis	ATG	Antigua and Barbuda
LBR	Liberia	CIV	Côte d'Ivoire
LSO	Lesotho	ZAF	South Africa
MAC	Macau SAR China	CHN	China
MHL	Marshall Islands	FJI	Fiji
MMR	Myanmar (Burma)	LAO	Laos
OMN	Oman	YEM	Yemen
PLW	Palau	PHL	Philippines
PNG	Papua New Guinea	IDN	Indonesia
PRI	Puerto Rico	CUB	Cuba
PRK	North Korea	KOR	South Korea
QAT	Qatar	ARE	United Arab Emirates
SGP	Singapore	MYS	Malaysia
SLB	Solomon Islands	NCL	New Caledonia
SLE	Sierra Leone	GIN	Guinea
SMR	San Marino	ITA	Italy
SOM	Somalia	ETH	Ethiopia
SRM	Serbia and Montenegro	SRB	Serbia
STP	São Tomé and Príncipe	CMR	Cameroon
SYC	Seychelles	MDG	Madagascar
TCD	Chad	SDN	Sudan
TGO	Togo	BEN	Benin

TKM	Turkmenistan	UZB	Uzbekistan
TLS	Timor-Leste	IDN	Indonesia
TON	Tonga	FJI	Fiji
TUV	Tuvalu	FJI	Fiji
TWN	Taiwan	CHN	China
UGA	Uganda	KEN	Kenya
USR	USSR	RUS	Russia
VNM	Vietnam	LAO	Laos
VUT	Vanuatu	FJI	Fiji
WSM	Samoa	FJI	Fiji
YUG	Yugoslav SFR	SRB	Serbia
ZMB	Zambia	ZWE	Zimbabwe

Table S7. Data sources used for estimation of habitual intake.
Description of datasets with repeat 24-hour recalls that were used to determine habitual intake distributions in SPADE.

Dataset	Data source	Age/sex groups	Number of recall days	Sample size	Year	Nutrients available	Representa-tiveness
Bangladesh	FAO/WHO GIFT	Female, ages 16-70	2	475	2007-2008	DHA+EPA, red meat, calcium, vitamin A, iron, vitamin B_{12}	Two rural upazillas
Bolivia	FAO/WHO GIFT	Female/male, ages 4-52	3	153	2009-2012	DHA+EPA, red meat, calcium, vitamin A, iron, vitamin B_{12}	One rural tropical area
Bulgaria	FAO/WHO GIFT	Girls/boys, ages 0-4	2	1723	2007	DHA+EPA, zinc, red meat, calcium, vitamin A, iron, vitamin B_{12}	National
Burkina Faso	HarvestPlus	Female, ages 19-55; girls/boys 1-4	2	960	2010	DHA+EPA, red meat, calcium, vitamin A, iron, vitamin B_{12}	Two rural provinces
China	China Health and Nutrition Survey/ Carolina Population Center	Female/male, ages 15-	3	10197	2009	DHA+EPA, zinc, red meat, calcium, vitamin A, iron	National
Italy	FAO/WHO GIFT	Female/male, ages 0-89	3	3323	2005-2006	DHA+EPA, red meat, calcium, vitamin A, iron, vitamin B_{12}	National
Lao	FAO/WHO GIFT	Female/male, ages 0-89	2	2045	2016-2017	DHA+EPA, zinc, red meat, calcium, vitamin A, iron, vitamin B_{12}	National
Mexico	ENSANUT	Female/male, ages 0-97	2	4343	2016	DHA+EPA, zinc, red meat, calcium, vitamin A, iron, vitamin B_{12}	National
Philippines	FAO/WHO GIFT	Female, lactating, ages 15-47	2	1205	2002	DHA+EPA, zinc, red meat, calcium, vitamin A, iron, vitamin B_{12}	National
Romania	FAO/WHO GIFT	Female/male. ages 19-92	7	1382	2011-2012	DHA+EPA, zinc, red meat, calcium, vitamin A, iron, vitamin B_{12}	National
Uganda	HarvestPlus	Female, ages 20-73	2	554	2006-2007	DHA+EPA, zinc, red meat, calcium, vitamin A, iron, vitamin B_{12}	National
USA	NHANES	Female/male, ages 0-80	2	7640	2017-2018	DHA+EPA, zinc, red meat, calcium, vitamin A, iron, vitamin B_{12}	National

Zambia	FAO/WHO GIFT	Female, ages 18-67	2	374	2009	DHA+EPA, zinc, red meat, calcium, vitamin A, iron, vitamin B_{12}	Two rural regions

Supplementary Datasets

Dataset 1. Mean national per capita food consumption in 2030 under the base and high production scenarios.

Dataset 2. Mean national per capita nutrient intakes in 2030 under the base and high production scenarios.

Dataset 3. Mean national per capita inadequate nutrient intakes (SEVs) in 2030 under the base and high production scenarios.

Dataset 4. Two-tailed t-test comparison by sex of changes in age-group inadequate nutrient intakes (SEVs) in response to increased production of aquatic foods.