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Journal

Nature, 598(7880)

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Publication Date

2021-10-01

DOI

10.1038/s41586-021-03917-1

Published in final edited form as:
Nature. 2021 October ; 598(7880): 315–320. doi:10.1038/s41586-021-03917-1.

Aquatic foods to nourish nations

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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.

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

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.

Competing interests The authors declare no competing interests.

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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] 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).

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.

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 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.

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:

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

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

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

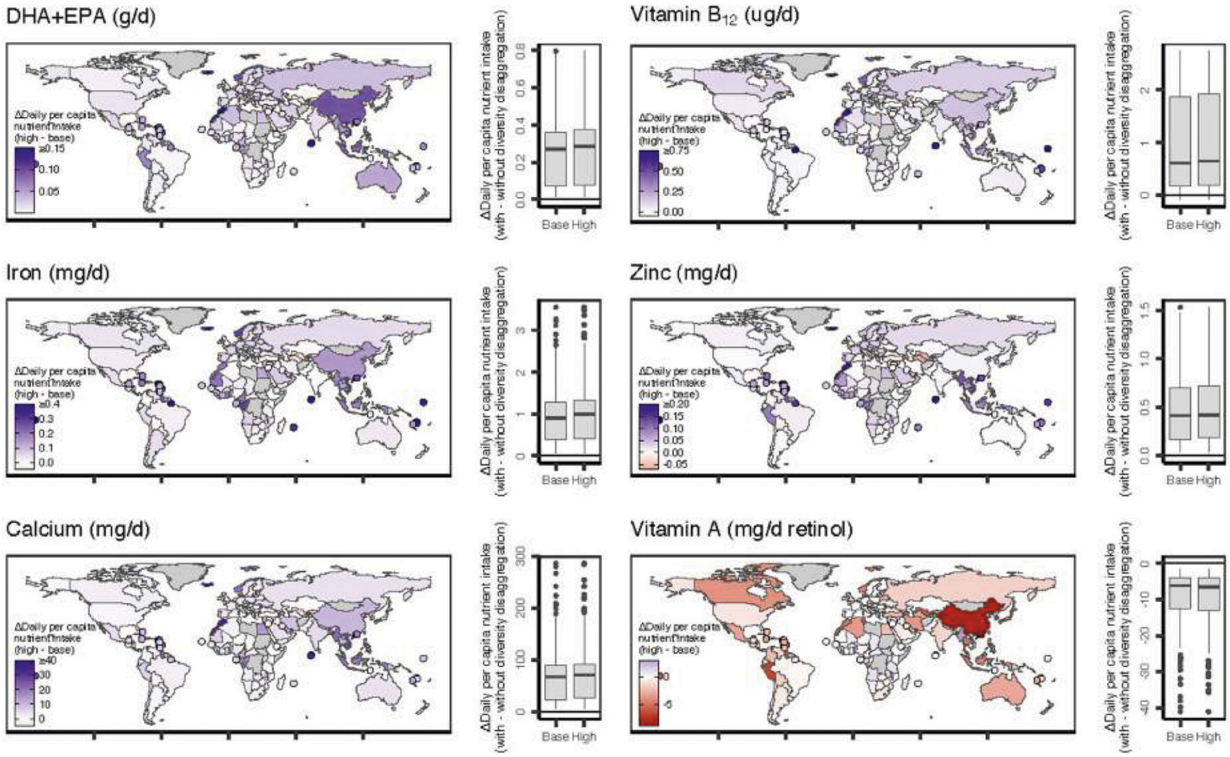
We used the same process to disaggregate intakes for DHA+EPA and vitamin B_{12} but used the country-level and age-sex-level means derived from SPADE habitual intakes described above. See Supplementary Table 6 for details on crosswalking the Aglink–Cosimo and GENuS outputs.

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

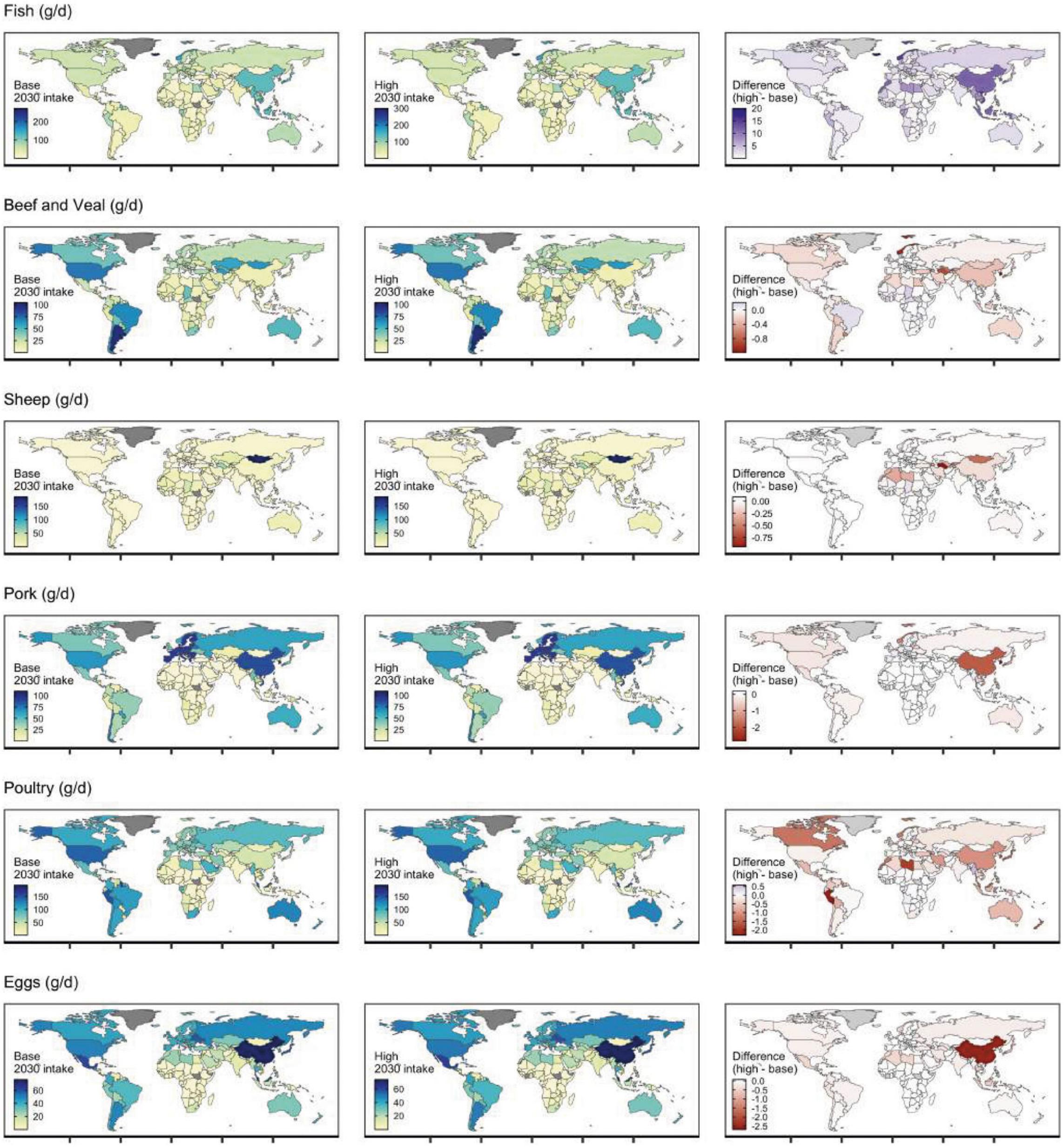
SEVs integrate relative risks of sub-optimal diets with actual intake distributions[28]. They estimate the population-level risk related to diets and compare it to a population in which everyone is at a maximal risk level, giving values ranging from 0% (no risk) to full population-level risk (100%). 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].

Extended Data



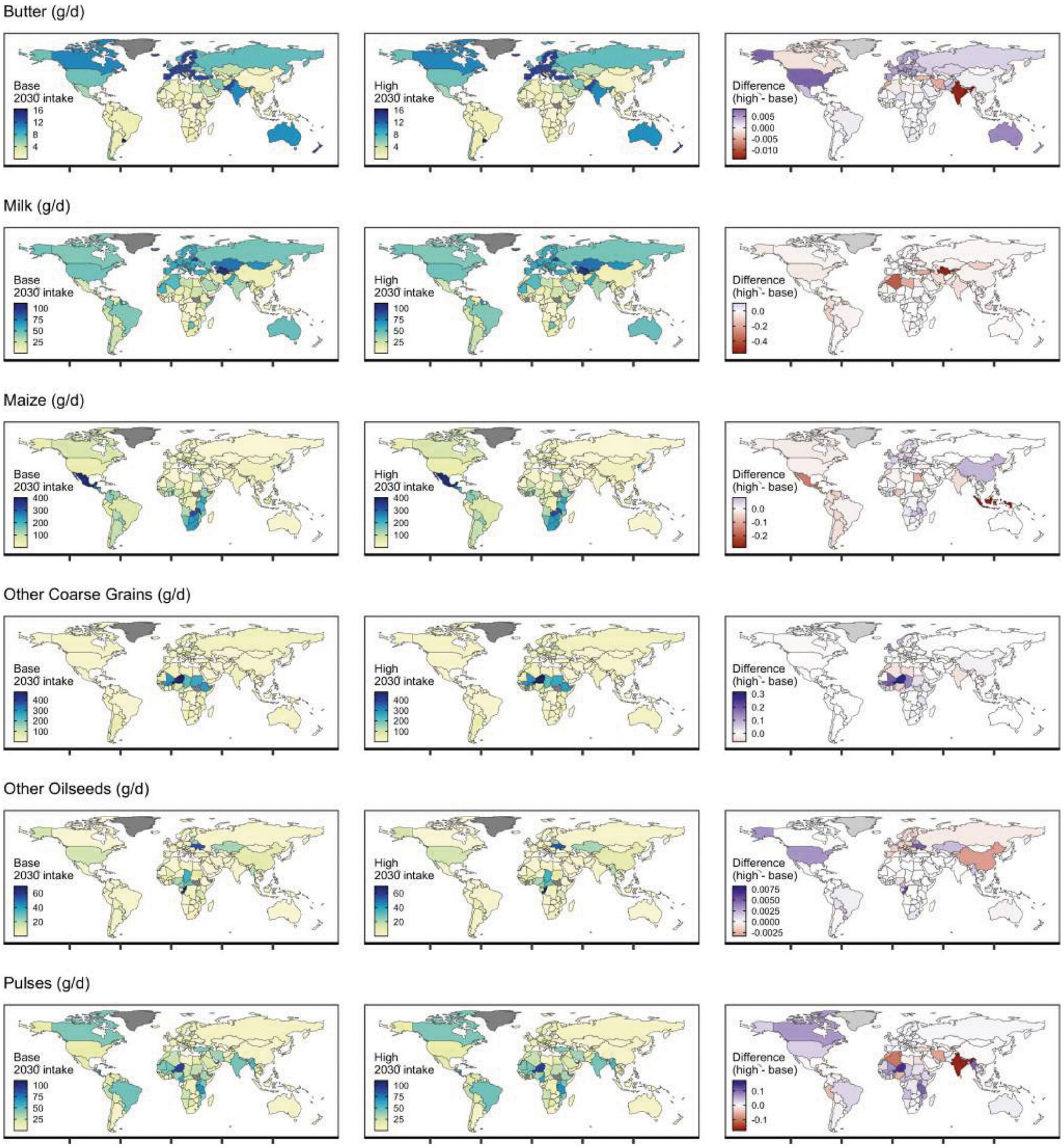
Extended Data Fig. 1 |. Difference in daily per capita intake of various nutrients from increasing aquatic animal-source food production and fully accounting for species diversity

. 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).



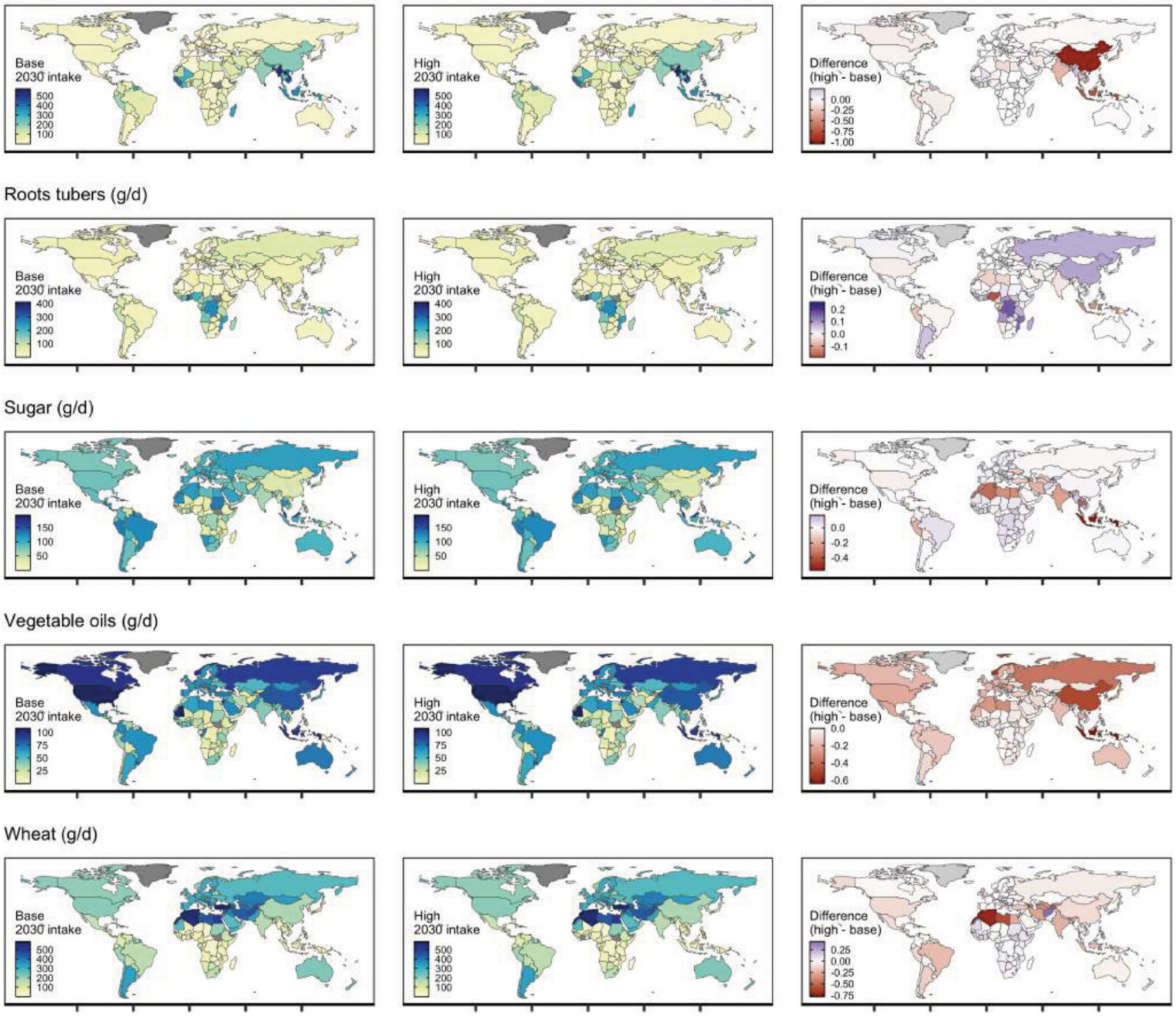
Extended Data Fig. 2 |. Difference in 2030 food consumption under the base and high production scenarios (part 1)

. 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.



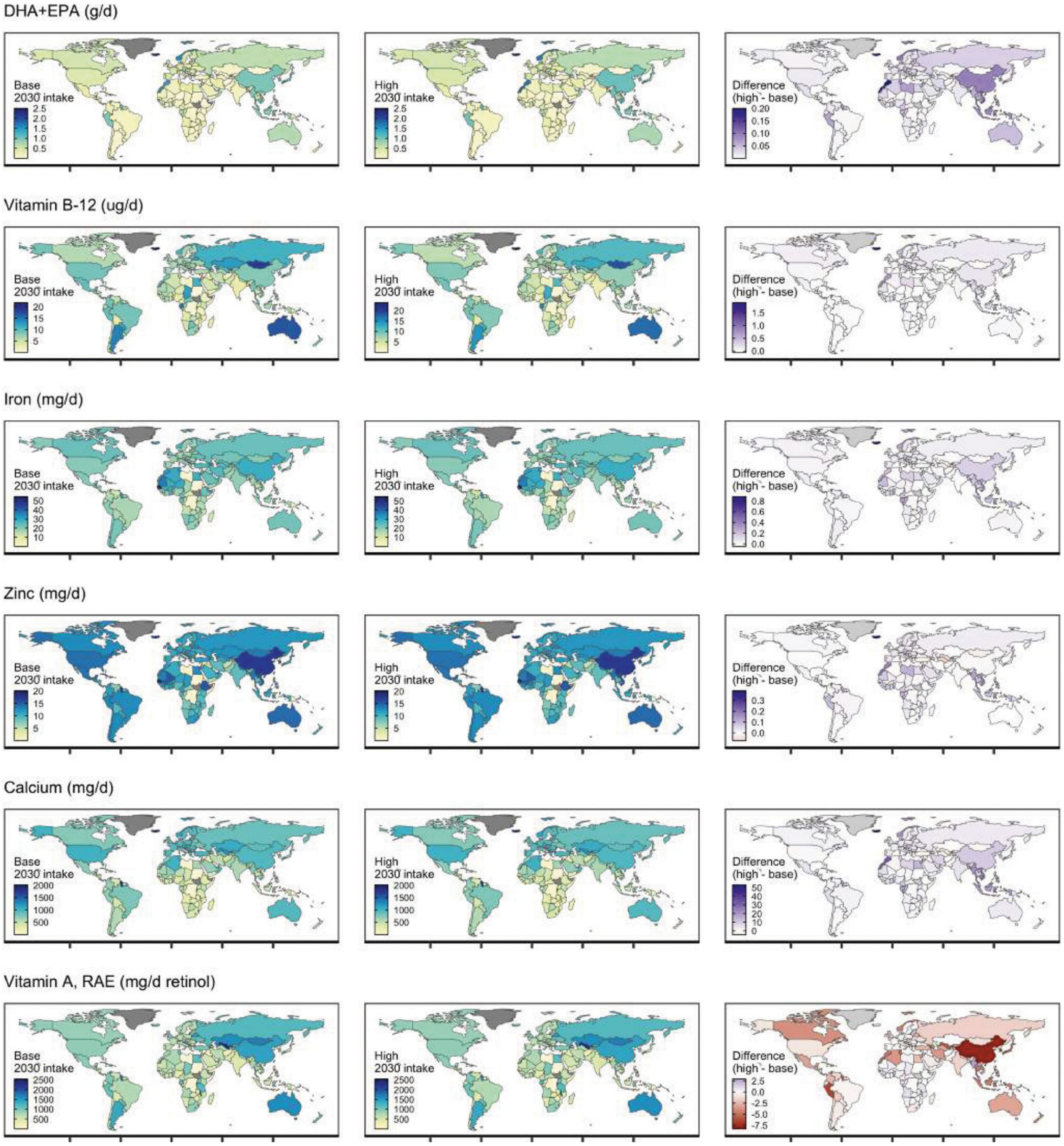
Extended Data Fig. 3 |. Difference in 2030 food consumption under the base and high production scenarios (part 2)

. 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.



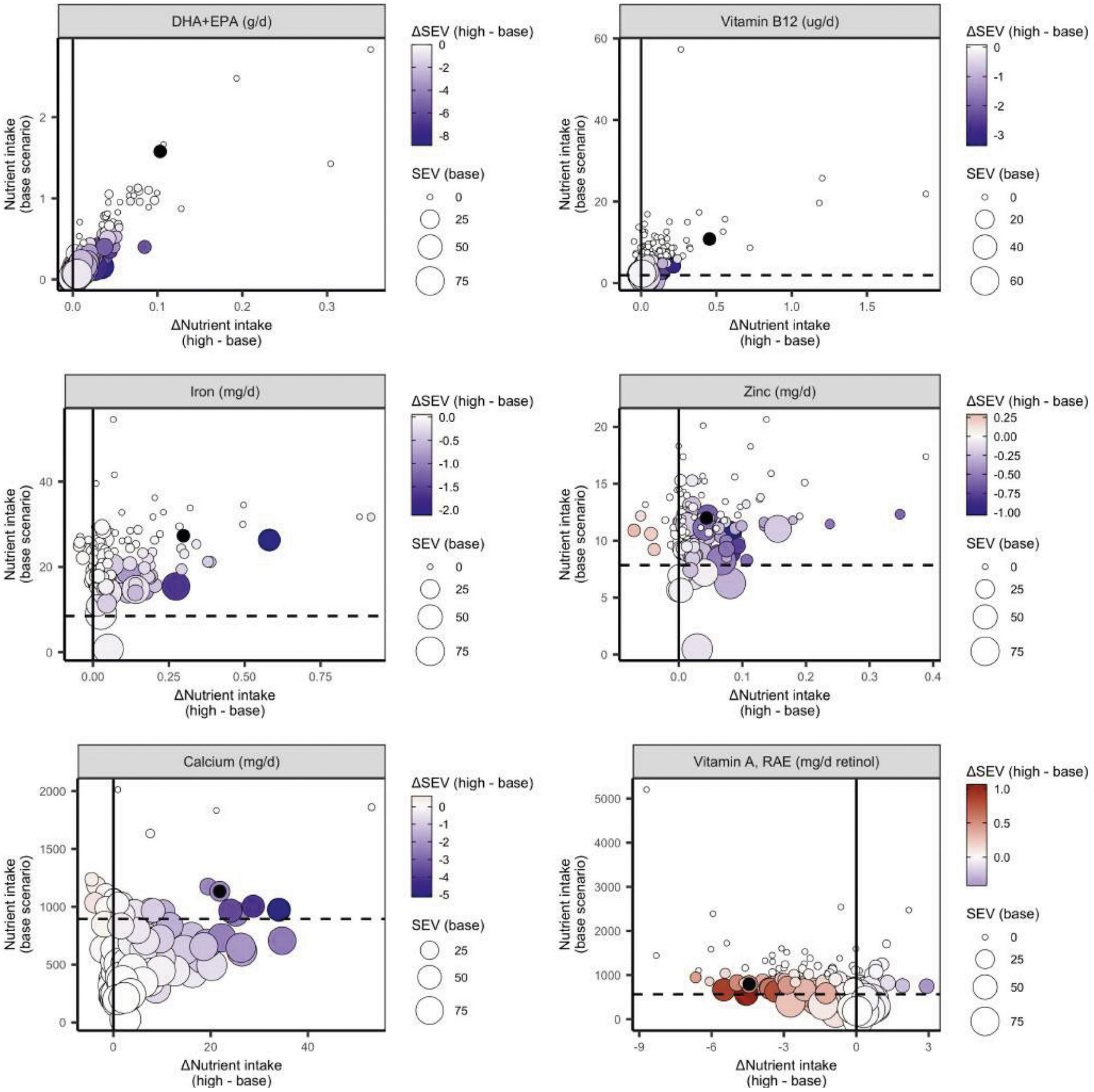
Extended Data Fig. 4 |. Difference in 2030 food consumption under the base and high production scenarios (part 3)

. 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.



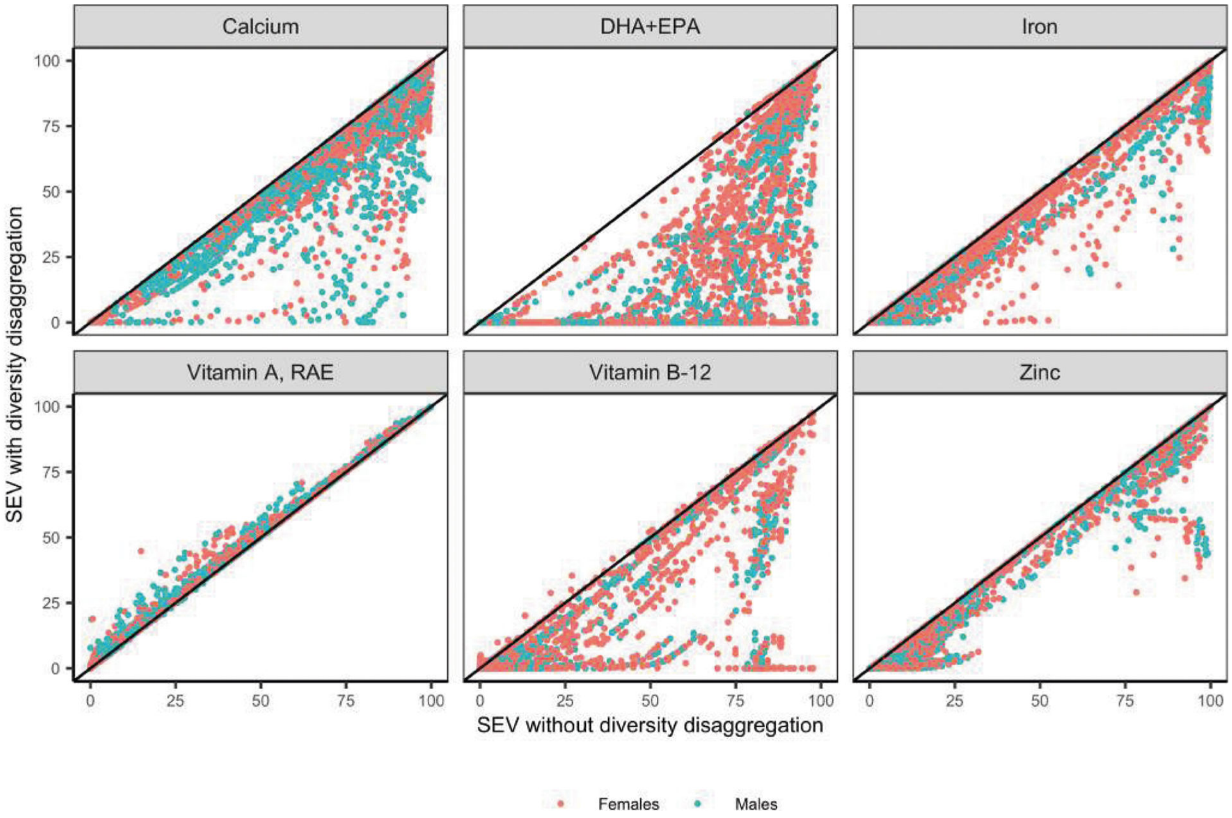
Extended Data Fig. 5 |. Difference in 2030 nutrient intakes under the base and high production scenarios accounting for the full diversity of nutrient compositions in seafood

. 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.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgements

This paper is part of the Blue Food Assessment (BFA) (https://www. bluefood.earth/), a comprehensive examination of the role of aquatic foods in building healthy, sustainable and equitable food systems. The BFA was supported financially by the Builders Initiative, the MAVA Foundation, the Oak Foundation and the Walton Family Foundation, and has benefitted from the intellectual input of the wider group of scientists leading other components of the BFA. We are also grateful for the financial support of the National Science Foundation (CNH 1826668 to C.D.G., J.A.G. and J.G.E.) and the John and Katie Hansen Family Foundation (C.D.G. and D.F.V.). Support was provided to SP and HK by a National Institutes of Health Departmental Training Grant in Academic

Nutrition (2T32DK007703-26). This work was also undertaken as part of the CGIAR Research Program (CRP) on Fish Agri-Food Systems (FISH), led by WorldFish and contributing to the WorldFish 2030 Research and Innovation Strategy: Aquatic Foods for Healthy People and Planet and the One CGIAR. This work is a product of the new Planetary Health laboratory at the Harvard T. H. Chan School of Public Health. For data sharing, visualization support and comments on study design, analysis and early drafts of writing, we thank J. Schmidhuber, H. Lescinsky, A. Afshin, T. Beal, S. Pires, L. Jakobsen, C. Costello, S. Funge-Smith, A. Castellanos, C. Batis, J. Rivera, Y. Li, W. Willett, A. Dekkers, M. Moursi, H. Embke, A. Robertson, J. J. Hallo and K. Manning. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the US Government.

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.

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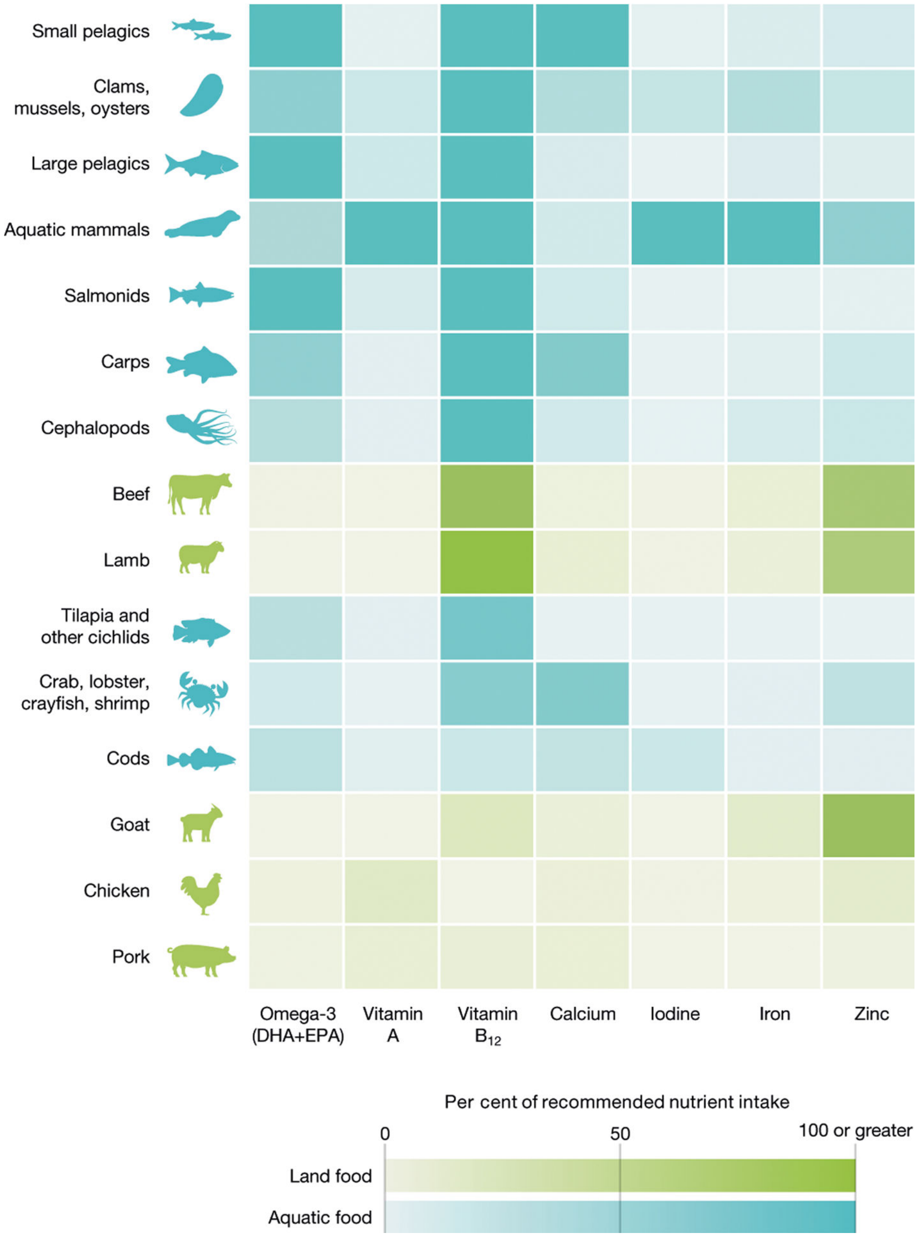

Fig. 1 |. Nutrient diversity of aquatic animal-source foods in relation to terrestrial animal-source foods

. 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.

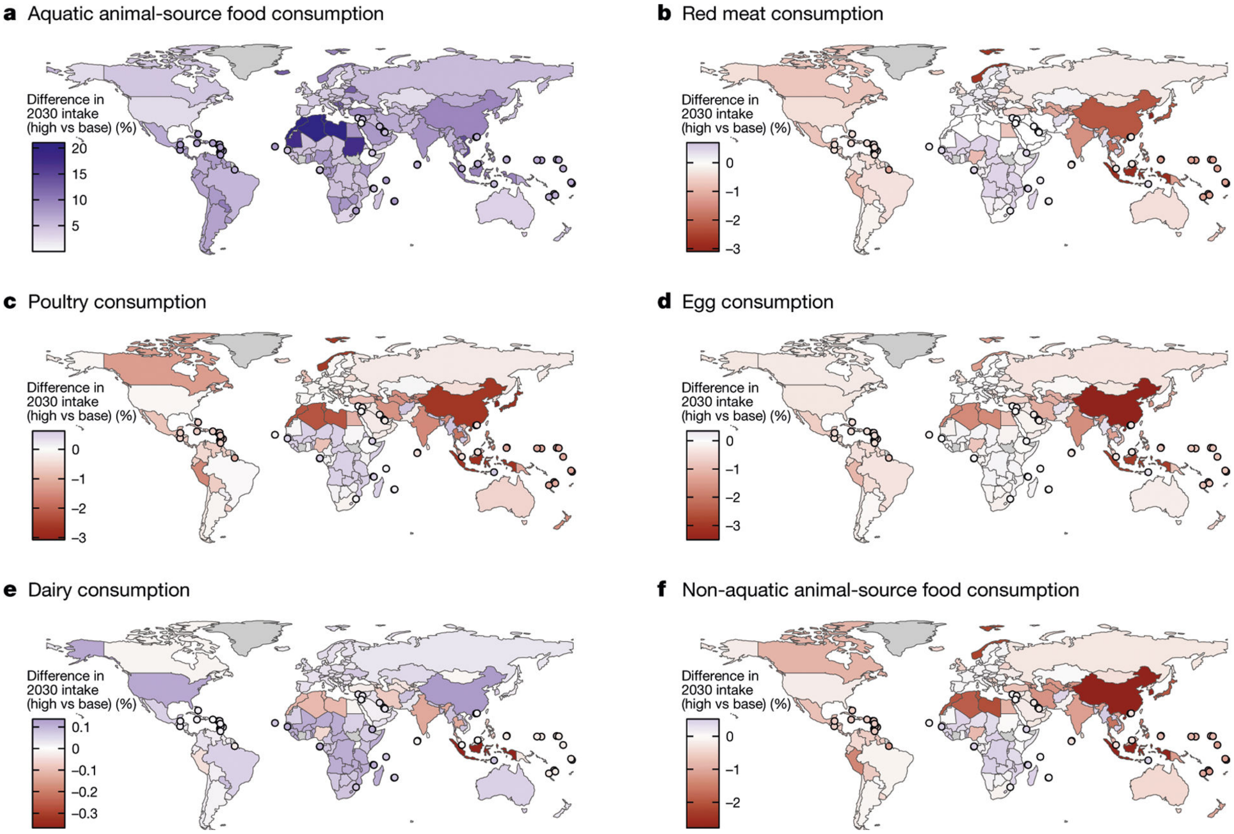

Fig. 2 |. Shifts in fish and red meat consumption resulting from an increase in aquatic animal-source foods.

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.

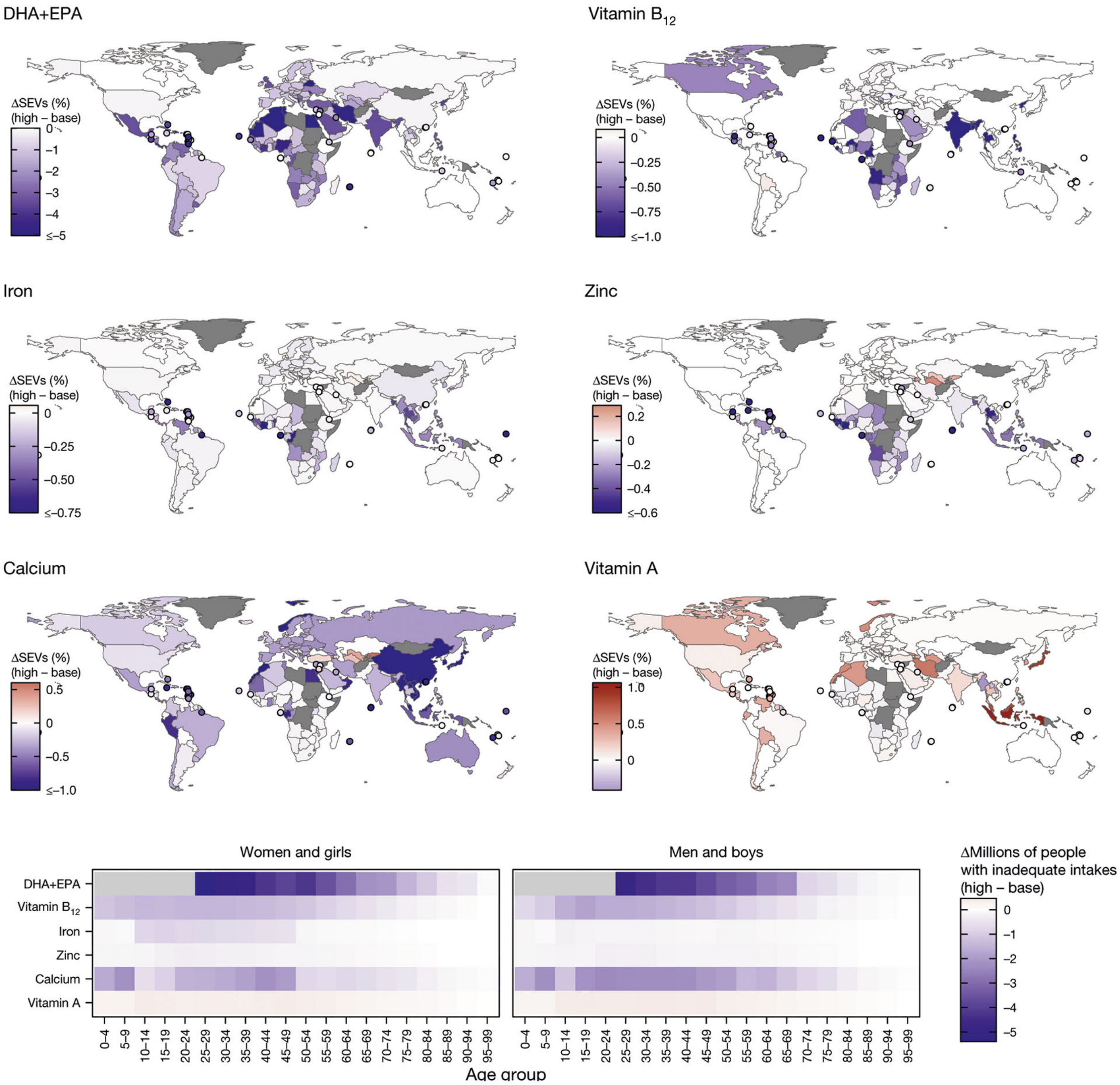

Fig. 3 |. Shifts in micronutrient intake resulting from an increase of aquatic animal-source foods. The maps show the difference in SEVs in 2030 under the high-production and baseline-production scenarios by country. Values less than zero indicate reduced risk (lower SEVs) of inadequate intake under 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).