Supplementary Information for

Aquatic foods for nourishing nations

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The Supplementary Information includes:

- Supplementary Methods and Figures M1 to M4
- Supplementary References
- Supplemental Data Figures S1 to S19
- Supplemental Data Tables S1 to S7

Supplementary Methods

1. Overview

The workflow for this research (**Fig. M1**) included the integration of the FAO FISH model into the 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.

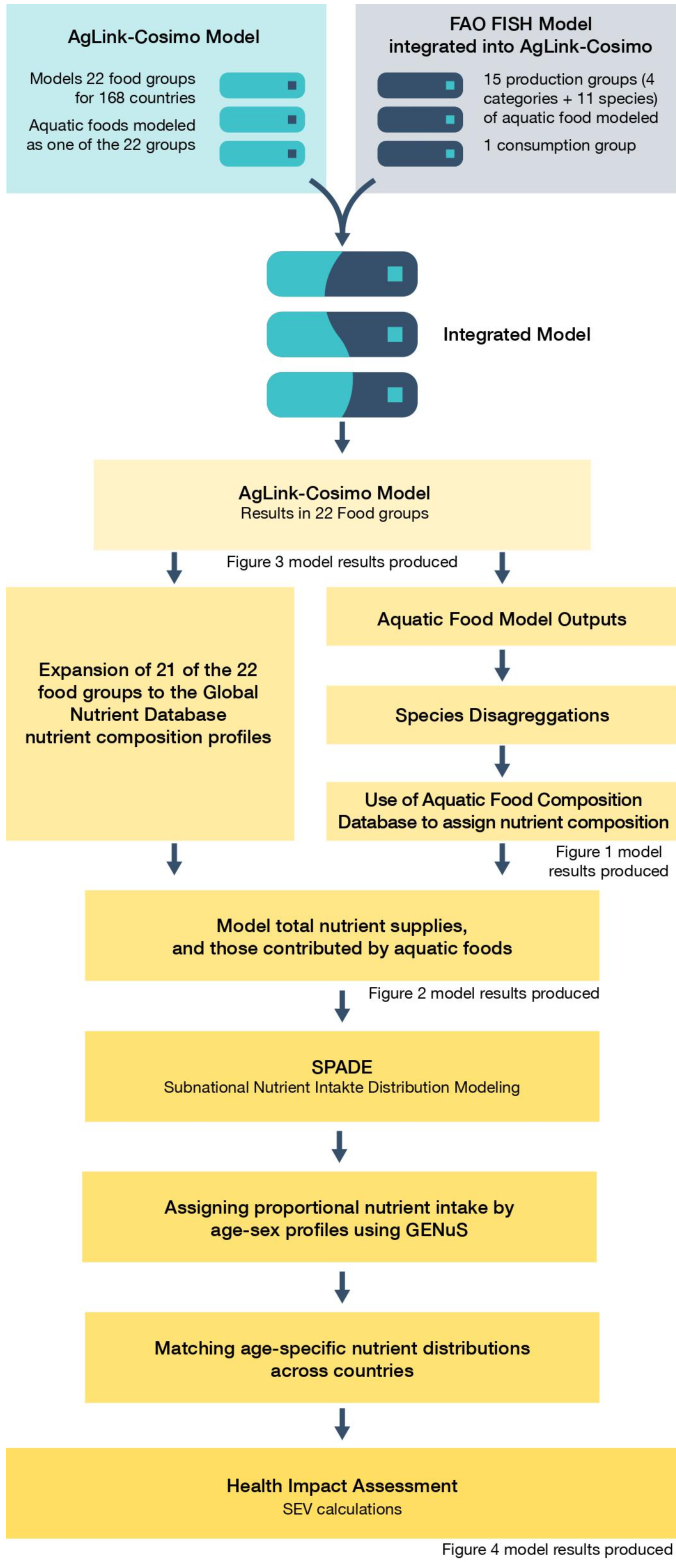

Figure M1: Description of modelling workflow. Conceptual diagram of the modelling components and integrated data sources.

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 2020 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.

Further, 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, where the respective elasticities control the relative strength of each variable. Because Aglink-Cosimo is a "partial-equilibrium" agricultural-fish model, income does not change in the scenario. The substitution between the various food items is caused by shifts in relative prices. We applied a scenario (described in detail below) whereby the global supply function of aquatic foods shifts outward due to technology improvements. 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 due 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.

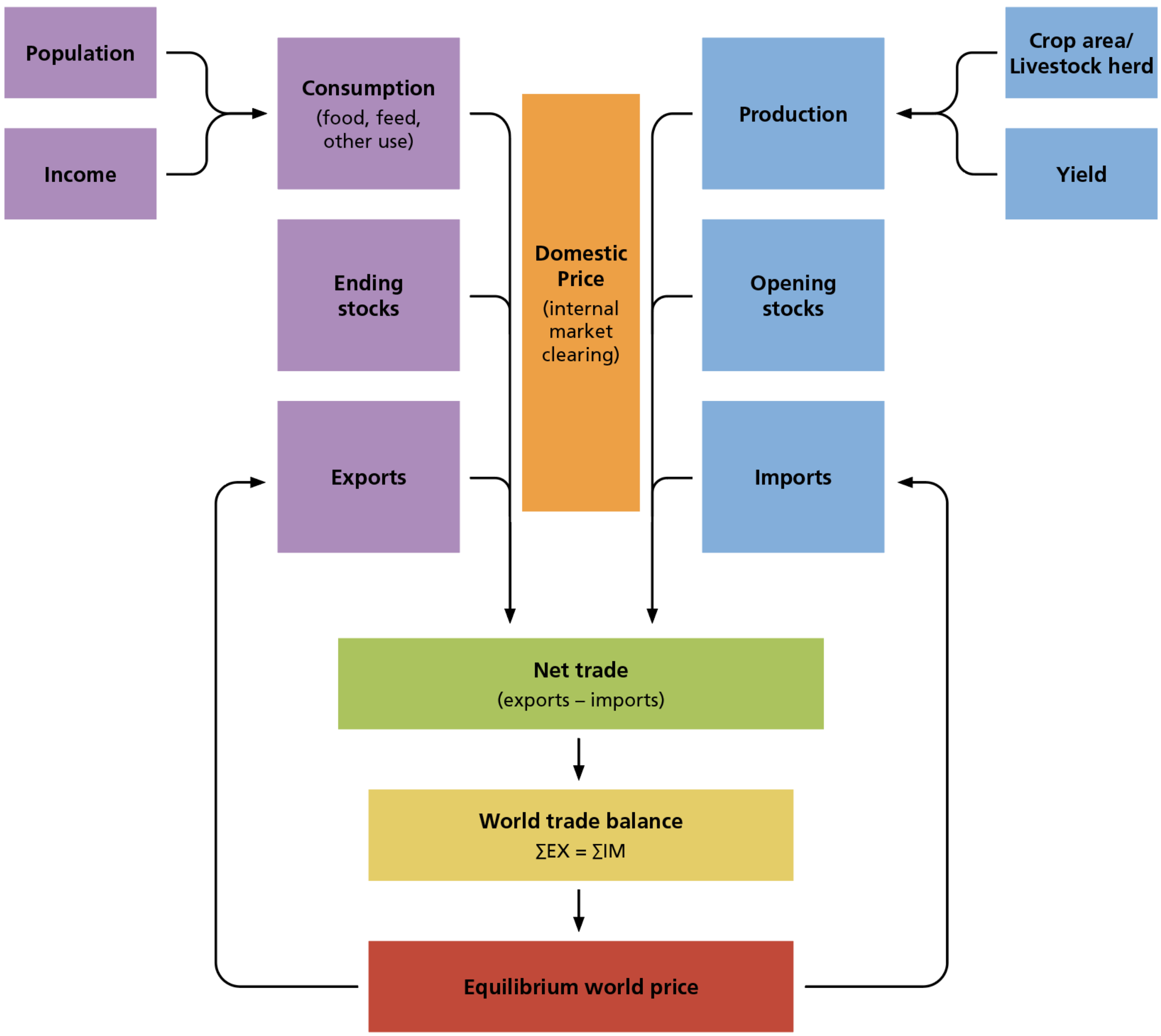

Figure M2: Aglink-Cosimo model description. Conceptual diagram of the modelling components, variables, and integrated data sources.

2.2 FAO FISH model

The FAO FISH model contains 2019 equations and covers 47 country and/or region endogenous modules. Three products are covered with complete supply-disposition variables and prices: 1) an aggregate of all aquatic animals except mammals, 2) fishmeal, and 3) fish oil. For the aggregate aquatic animals, the model supplies functions for both capture and aquaculture depending on the country. On the demand side, the model produces one aggregate aquatic animal demand function, but includes 3 different types of use: 1) food, 2) processed into fishmeal and oil, and 3) other uses.

Capture fisheries, which are controlled under strict fishing quotas, are kept exogenous in most countries of the model. In the model, only 15% of world capture fisheries respond to price. Ninety nine percent of world aquaculture fisheries are endogenous and responsive to price of output, and 75% of aquaculture are responsive to feed prices. The model contains 115 aquaculture supply functions resulting from the combination of countries and species, with species specific feed ration, production lag, and elasticities (level of responsiveness in production to change in the different prices).

Ninety seven percent of world reduction of fish in fishmeal and oil is endogenous but only 37 percent responds to output prices and to the opportunity cost represented by the fish price. The remainder is tied to capture fisheries, which are controlled and exogenous in the model. Fishmeal and oil production from fish residue is also endogenous and tied to fish production used for food consumption.

Per capita food demand is determined by the retail price of aquatic products, retail price of substitutes (mostly beef, pork and poultry), and by per capita gross domestic product (GDP). Typically, consumers from wealthier countries respond less to a change in price and GDP. The retail price of aquatic products is determined by the price of traded products and the GDP deflator to capture movement in the other costs along the supply chain. Higher GDP countries are influenced more by the size of the GDP deflator in these equations. 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.

3. Aquatic food production scenarios

We used the Aglink-Cosimo model to project changes in human consumption under two potential aquatic 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 reflects the UN FAO's best understanding of likely fisheries and aquaculture growth based on anticipated macroeconomic conditions, agriculture and trade policy settings, 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 today, with country-level production trends determined by the Aglink-Cosimo model. The high production scenario, which represents the UN FAO's best understanding of the upper limits of aquatic foods growth potential (Ahern et al. 2021), projects a 2.6 mt increase in global fisheries production as a result of improved fisheries management, 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 investment and innovation 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 **Fig. S3** and the resulting changes in nutrient intake are shown in **Fig. S4**.

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. 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**).

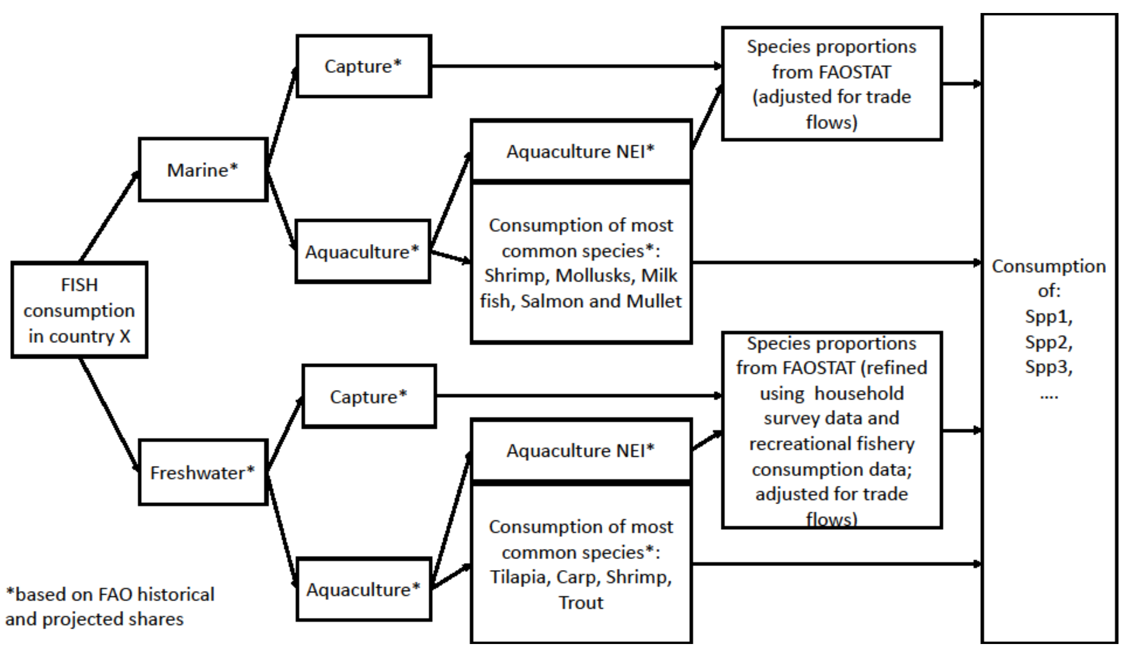

Figure M3: Description of disaggregation workflow. Conceptual diagram describing the marine and freshwater species disaggregation to derive more resolved consumption estimates. The workflow reads left to right with an asterisk representing FAO historical and projected shares. NEI: not enough information.

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. Processed weights were converted to consumed weights using a conversion factor of 0.8 to generate estimates of freshwater fish species consumption. 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 developed 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. S5**).

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. S6**). 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 is certainly not a reflection of how cultures consumed these aquatic foods. However, to standardize these values across the breadth of aquatic 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. S7**). 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 were filled by either the species order or the GND category, which decreases accuracy of estimates.

4.4 Visualizing nutrient richness across food groups in Figure 1

All aquatic 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 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 was calculated following the methodology outlined by Drewnowski (2009). First, the richness ratio of individual nutrients was calculated by dividing nutrient density in a given food by the daily recommended intake for that nutrient (see **Table S4** for a description of the recommended nutrient intake values and their sources). A richness ratio of 1.0 for an individual nutrient indicates that 100% of the daily requirement of that nutrient is met by eating 100 g of the food product. Once each of the individual nutrient richness ratios were calculated, the mean richness across the food was calculated. Richness ratios of individual nutrients as well as the mean richness were calculated for individual foods at the taxonomic level of order *before* being aggregated to create the broader categories in **Figure 1**. Aquatic mammals were an exception, where none of the observations included complete data. For aquatic mammals, the median value across each of the richness ratios for each nutrient was first aggregated across all aquatic mammals, and then the mean richness was calculated.

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 fatty acids DHA and EPA). The food categories are ordered by their mean nutrient richness value. High mean nutrient richness was in some cases due to relatively high richness ratios for specific nutrients. For example, small pelagics had very high omega-3 (218%) and vitamin B_{12} (416%) percentage values of the total recommended nutrient intake (RNI), but more moderate richness ratios for iodine and iron, while other food categories were driven by a more moderate richness ratio 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.

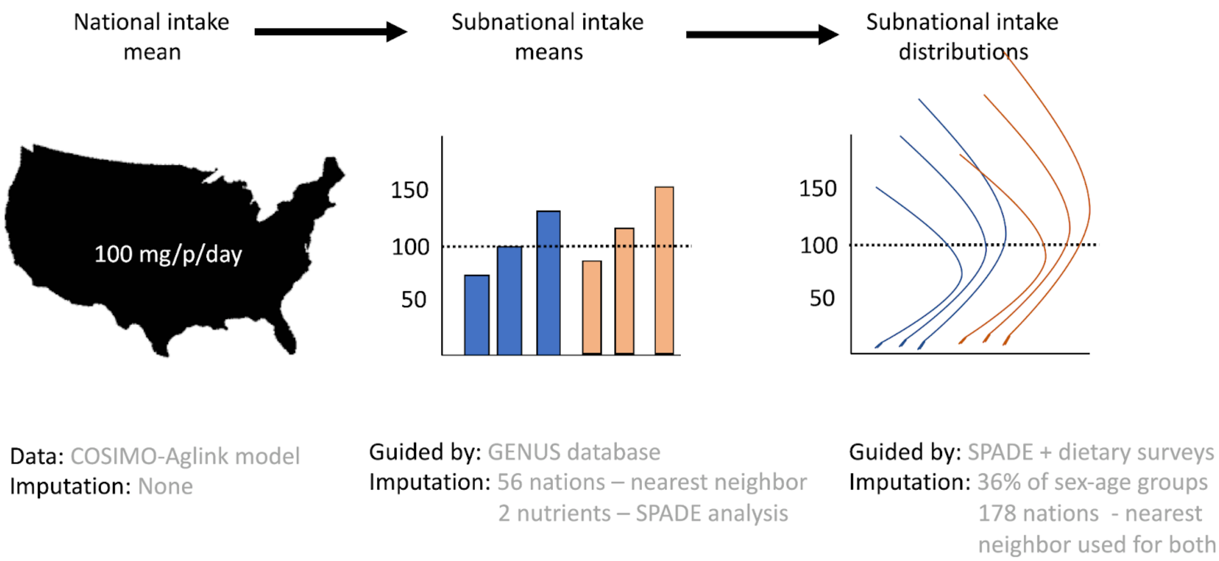

Figure M4. Conceptual schematic illustrating the procedure for disaggregating the mean national nutrient intakes (mg/p/day) provided by the AgLink-Cosimo model into the subnational nutrient intake distributions required for the health impacts analysis.

5.2 Subnational intake means

We disaggregated mean national intakes into mean subnational intakes in two steps. We first disaggregated the European Union, which is modelled as a single entity in the Aglink-Cosimo model, into its 27 constituent countries (**Table S5**). We disaggregated the 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 across 225 food categories for 34 age-sex groups in nearly all countries 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. We assumed 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 omega-3 fatty acids 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. S8; 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 (**Fig. S9-S15**) 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. S8**), 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. S16**). We then mapped these to the rest of the world, based on UN sub-regions, with a few expert-identified modifications (**Fig. S17**). 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 **Fig. S18**. 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 **Fig. S19**. 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 n-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 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 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.

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Supplemental Figures

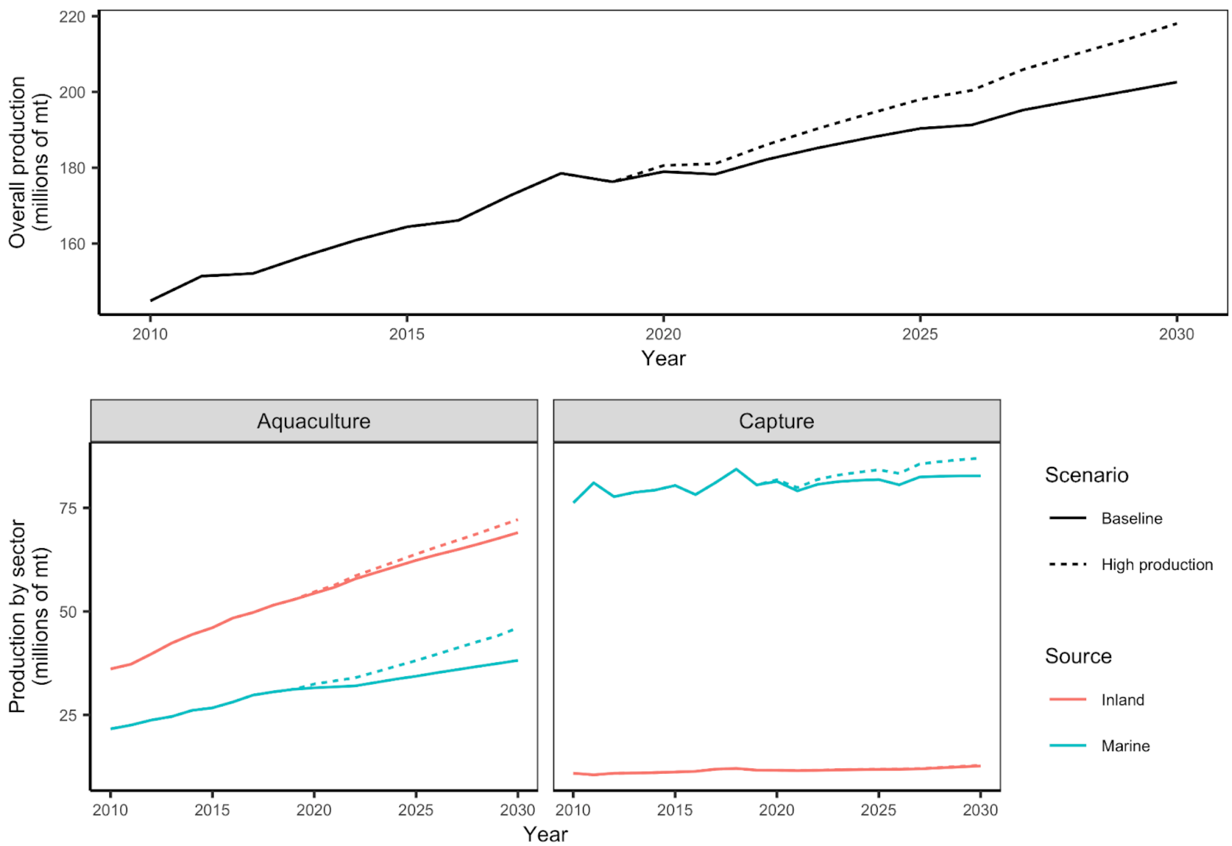

Figure S1. Aquatic foods production under the baseline and high production scenarios.

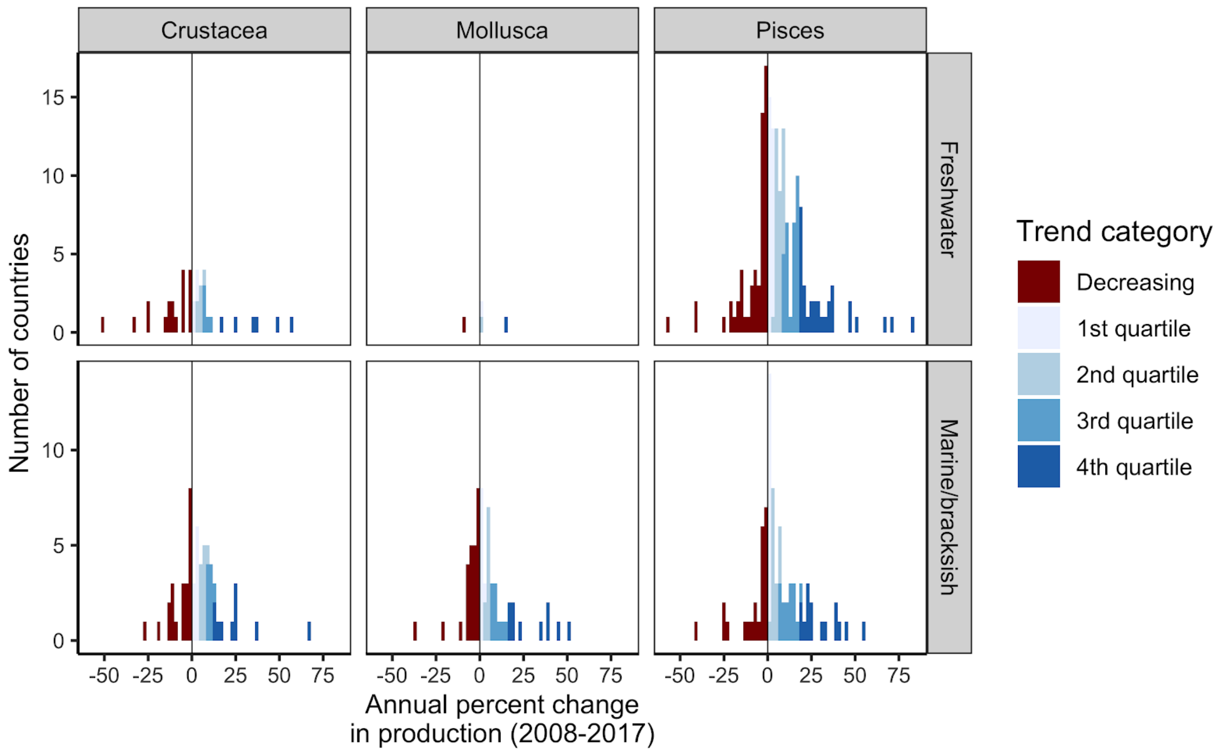

Figure S2. Trends in aquaculture production over the last 10 years. Distribution of recent (2008-2017) country-level trends in aquaculture production by environment (inland, marine/brackish) and major groups (fish, bivalves, crustaceans).

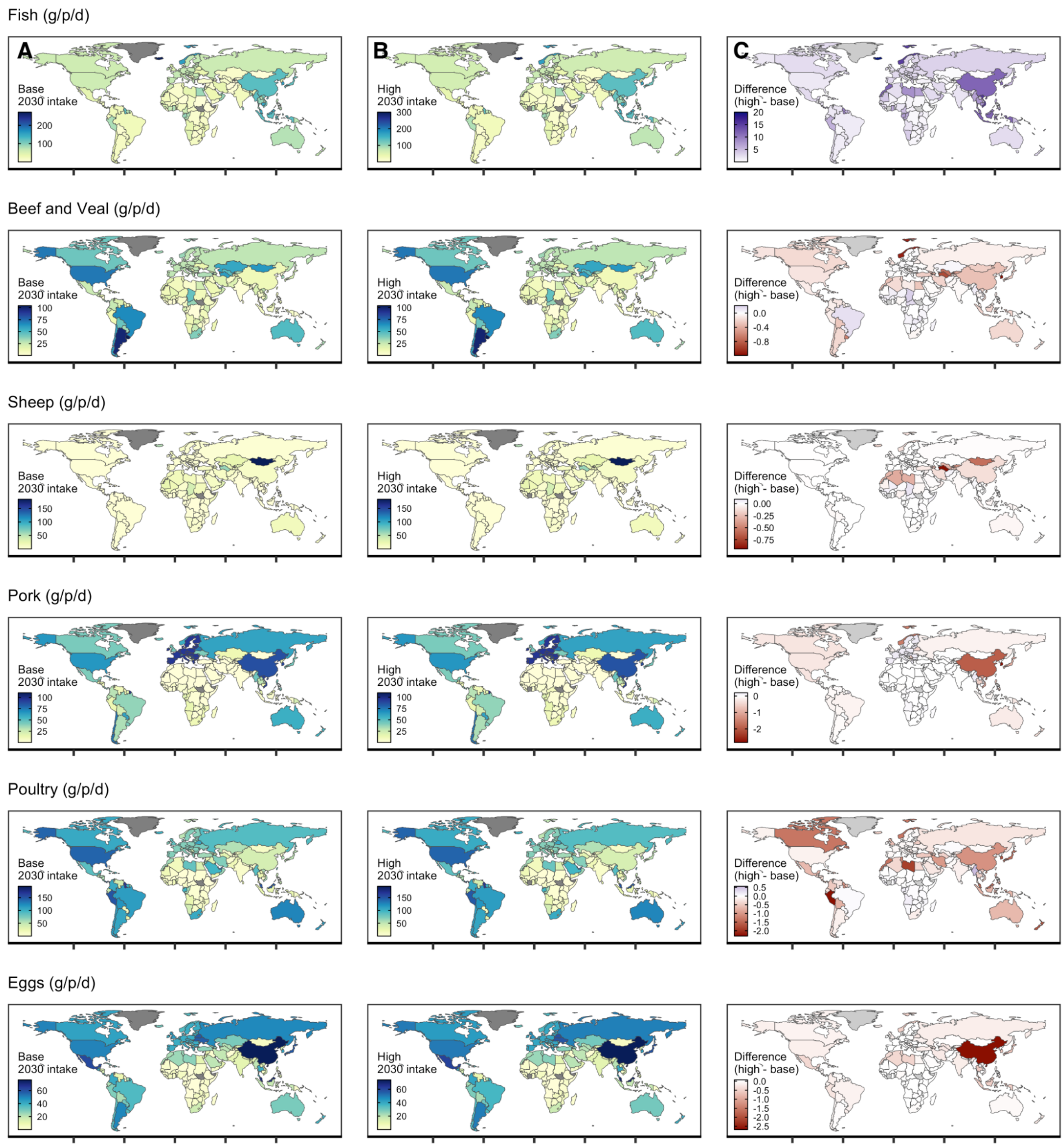

Figure S3. Difference in 2030 food consumption under the base and high production scenarios. Mean daily per capita food consumption in 2030 under the (A) base and (B) high production scenarios and (C) the difference in consumption between the high production and base scenarios.

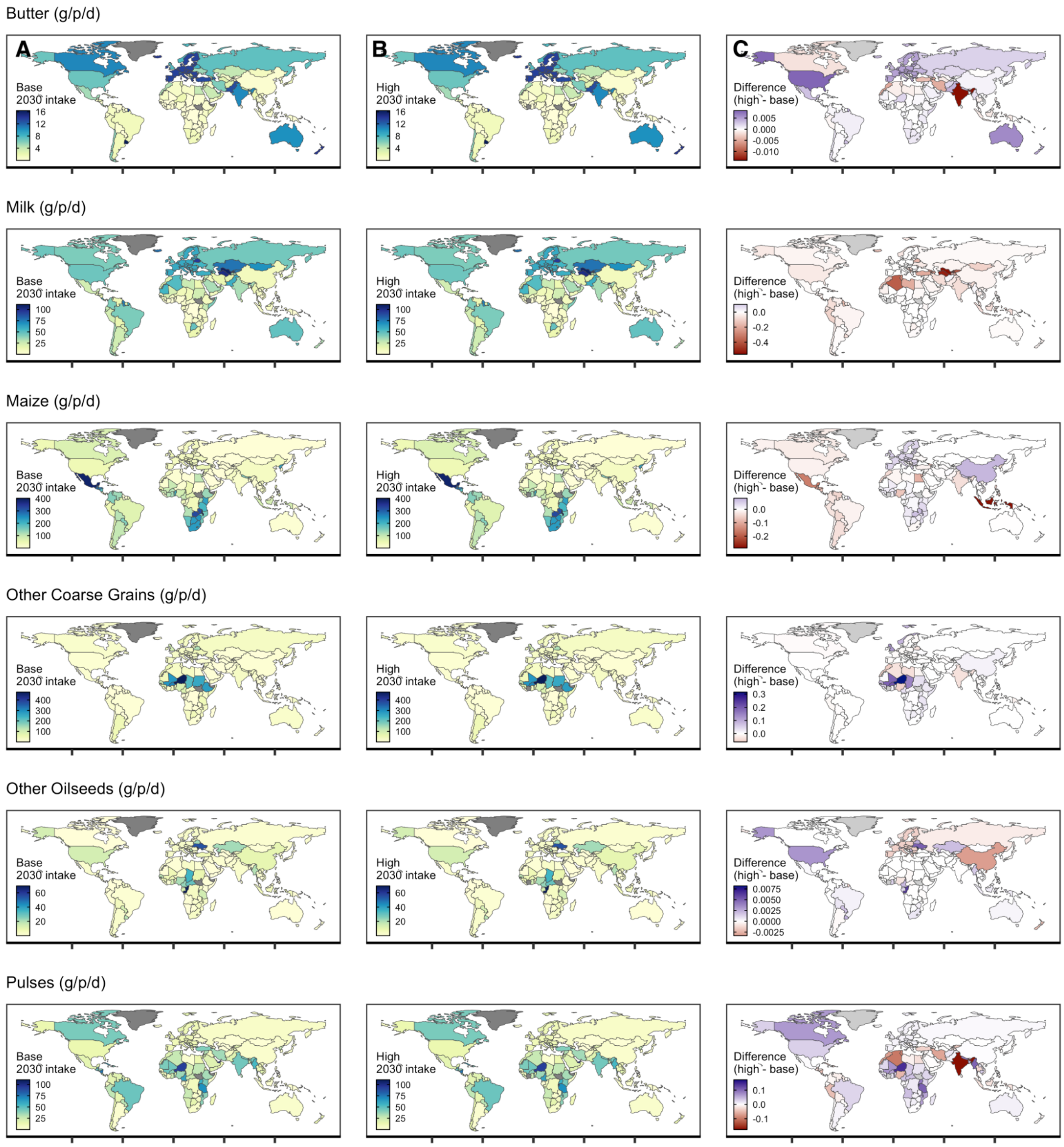

Figure S3 (continued). Difference in 2030 food consumption under the base and high production scenarios. Mean daily per capita food consumption in 2030 under the (A) base and (B) high production scenarios and (C) the difference in consumption between the high production and base scenarios.

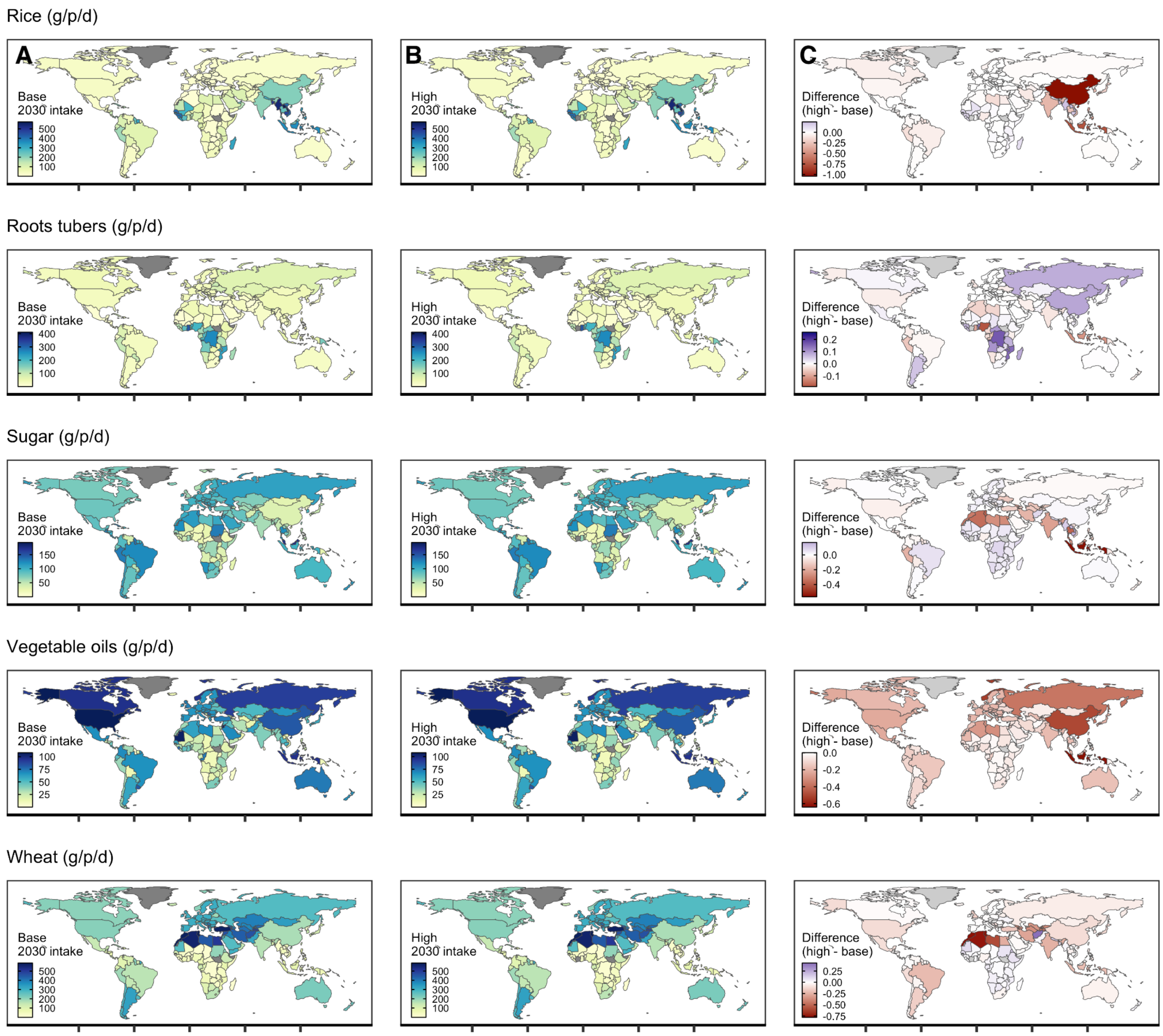

Figure S3 (continued). Difference in 2030 food consumption under the base and high production scenarios. Mean daily per capita food consumption in 2030 under the (A) base and (B) high production scenarios and (C) the difference in consumption between the high production and base scenarios.

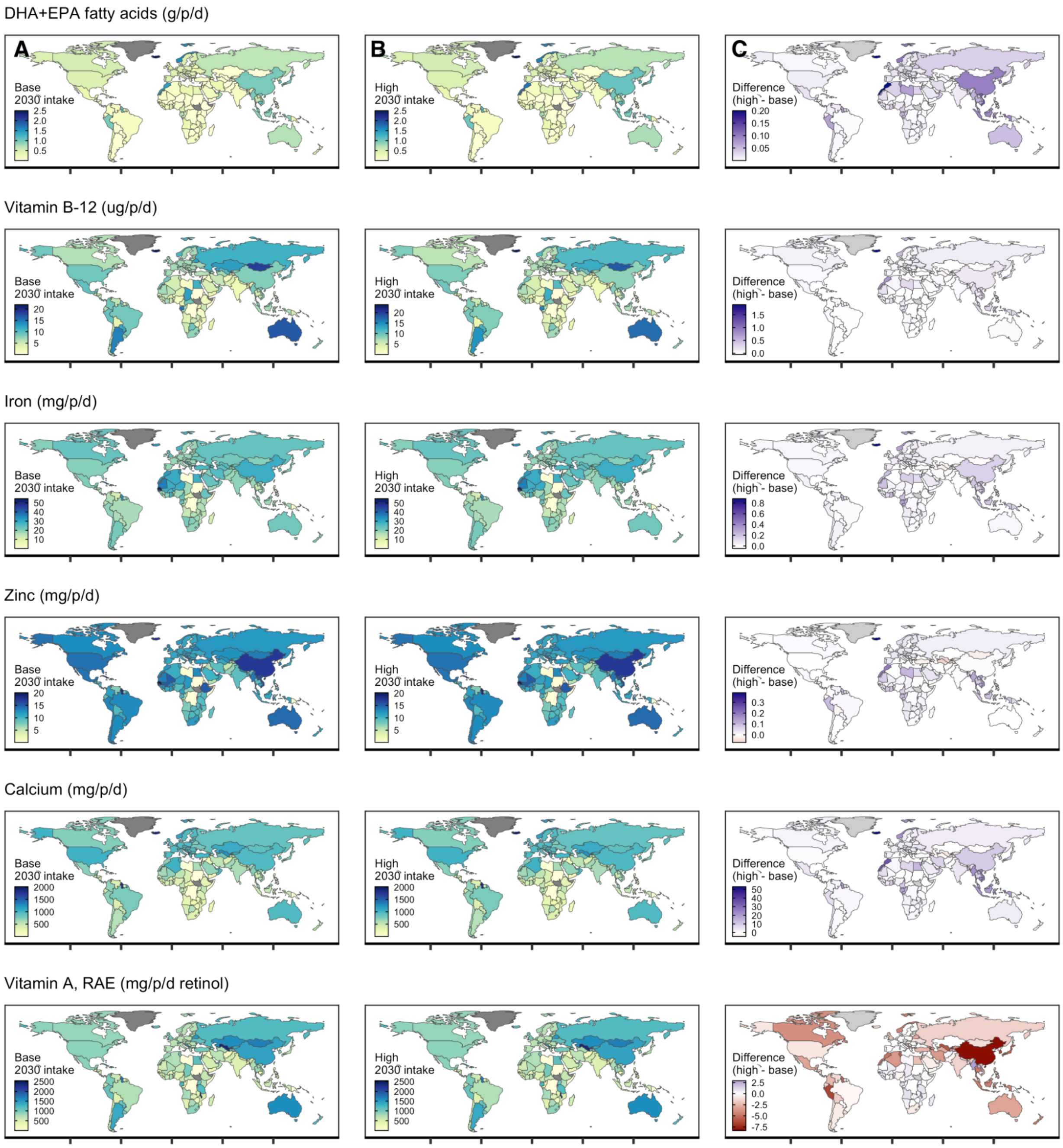

Figure S4. Difference in 2030 nutrient intakes under the base and high production scenarios accounting for the full diversity of nutrient compositions in seafood. The mean daily per capita nutrient intake in 2030 when accounting for the full diversity of nutrient compositions in seafood under the (A) base and (B) high production scenarios and (C) the difference in intakes between the high production and base scenarios.

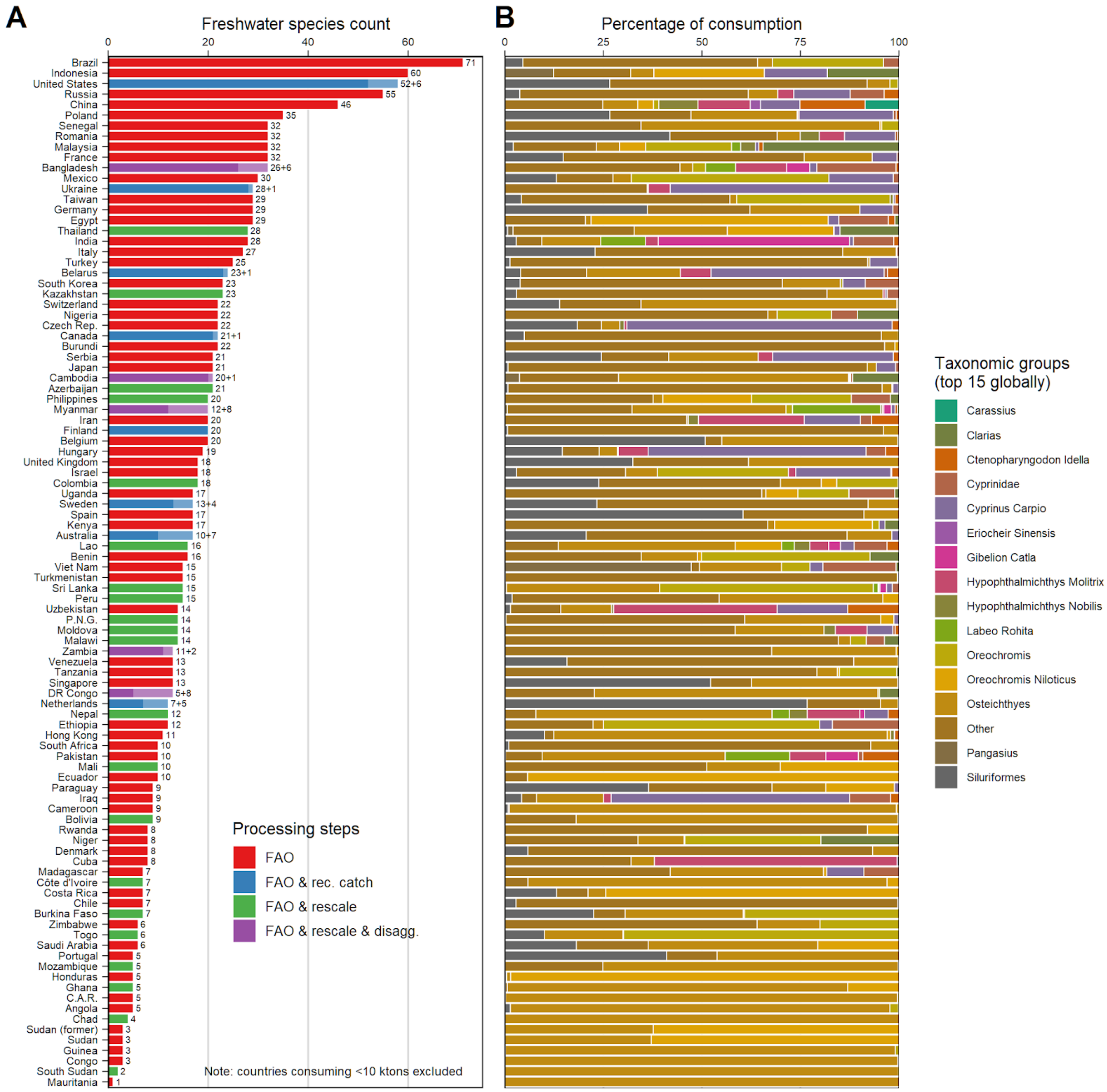

Figure S5. (A) Number of freshwater fish species consumed in each country sorted from highest to lowest. Bar color indicates the processing and data inputs used to generate the final taxonomic list. The darkened section of each bar represents the number of species from FAO data, while the lighter color 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.).

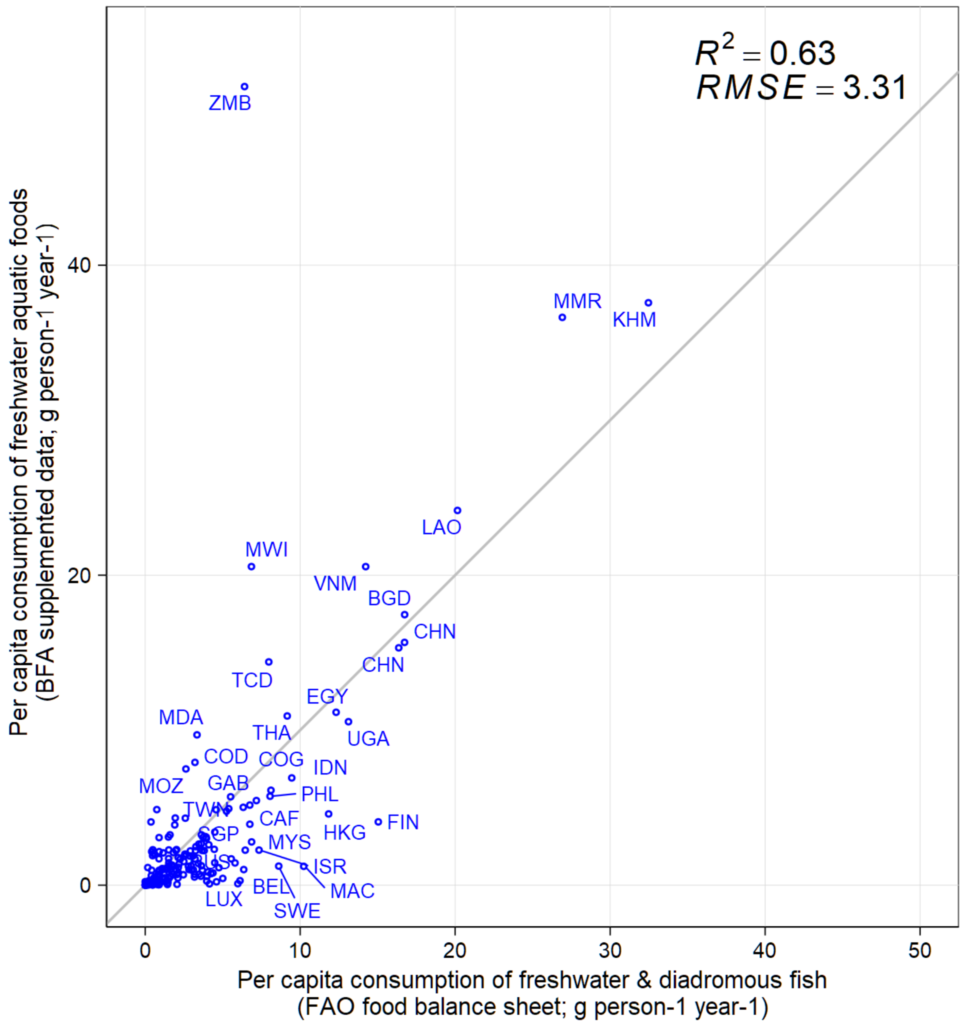

Figure S6. Scatterplot showing the broad alignment (R2=0.63) of the per capita consumption from our species disaggregation against the food supply estimated by the FAO food balance sheets. The diagonal segment represents the 1:1 line.

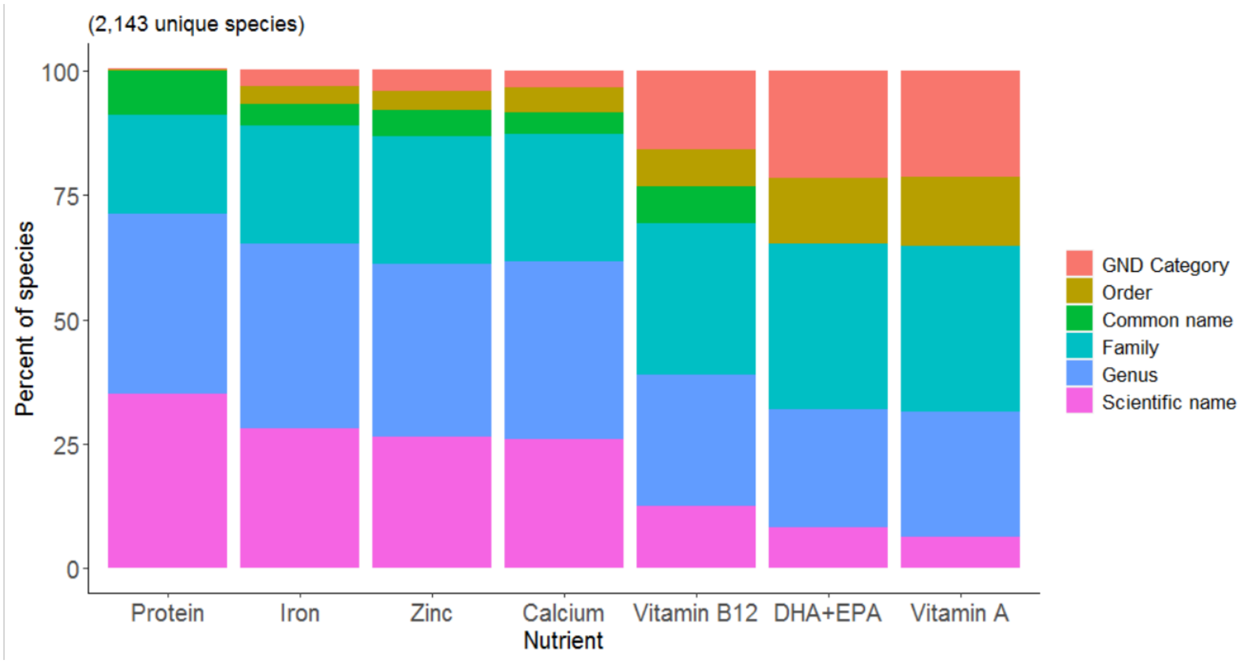

Figure S7. Total number of species per nutrient and criteria used to fill nutritional values from the Aquatic Foods Composition Database (AFCD). For all nutrients, there are a total of 2,143 unique species derived from disaggregation efforts.

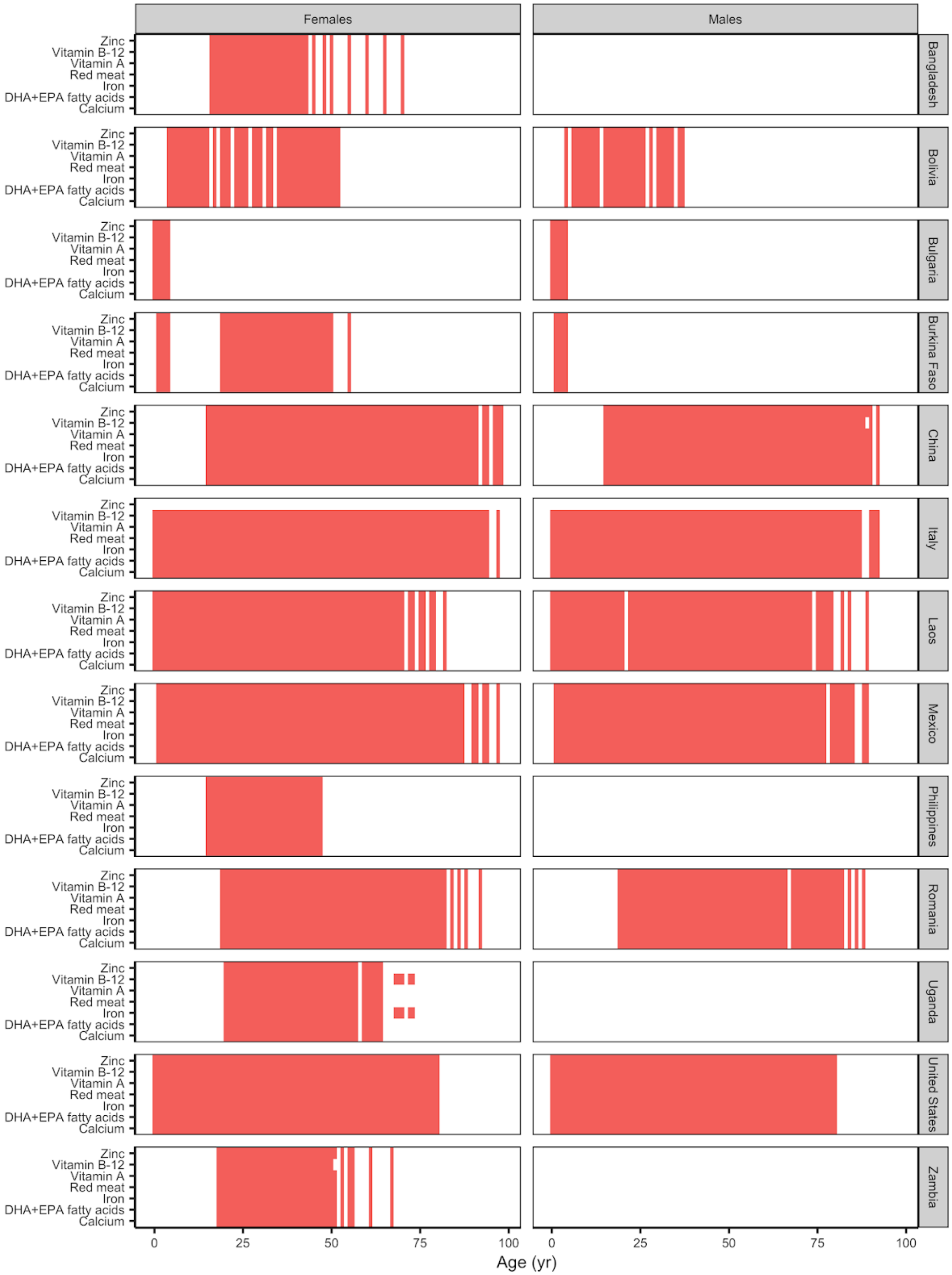

Figure S8. Coverage of habitual intake distribution data. Coverage of habitual intake distributions derived using the SPADE algorithm and data from household-level recall surveys by country, sex, and age. Red shading indicates groups with available repeat 24-hour recall data.

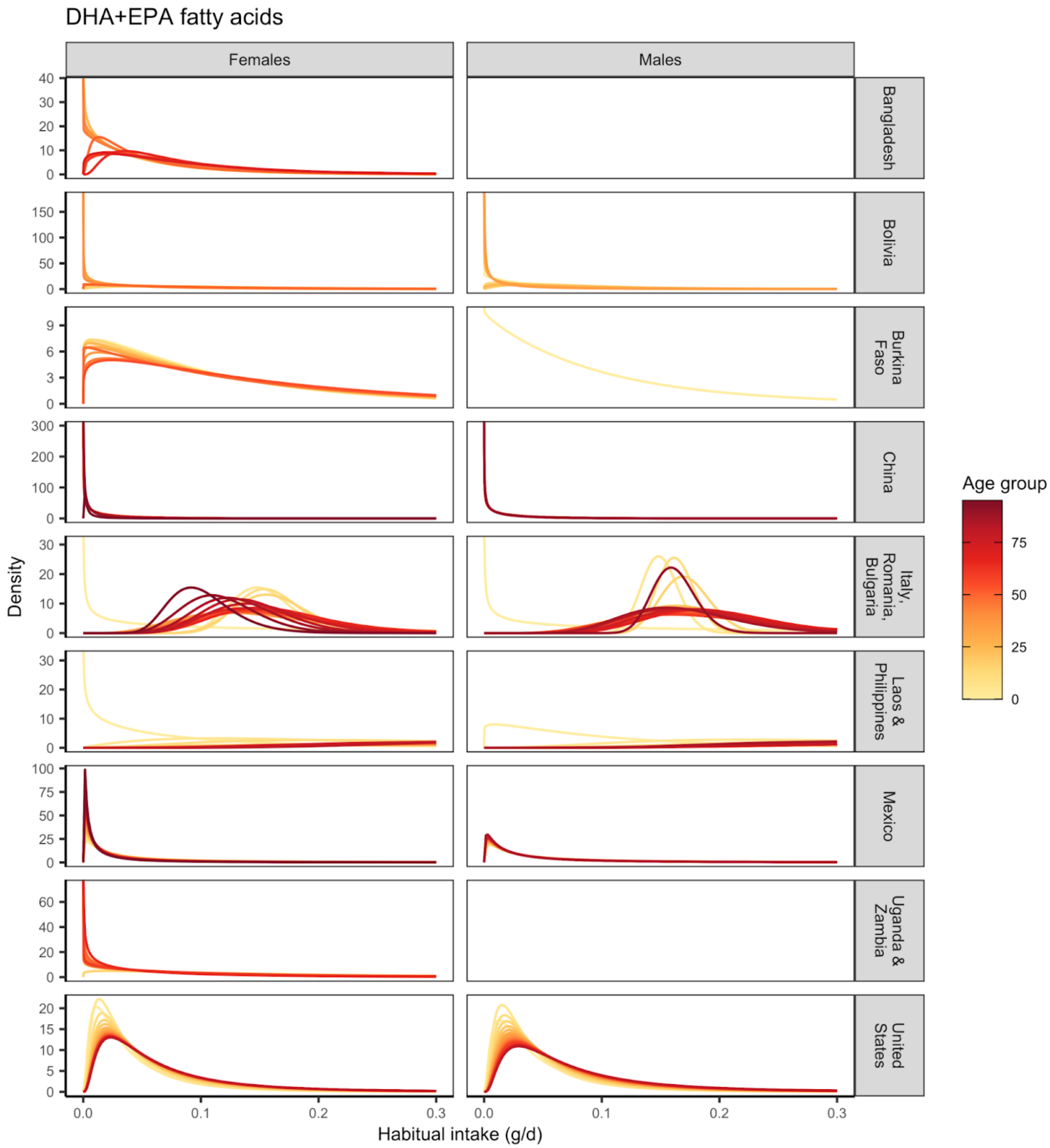

Figure S9. DHA+EPA fatty acid habitual intake distributions by country, sex, and age group. The best statistical distribution (either a log-normal or a gamma distribution) for each country group, sex, and age group is shown. The family of distribution may differ among age groups within a country and sex.

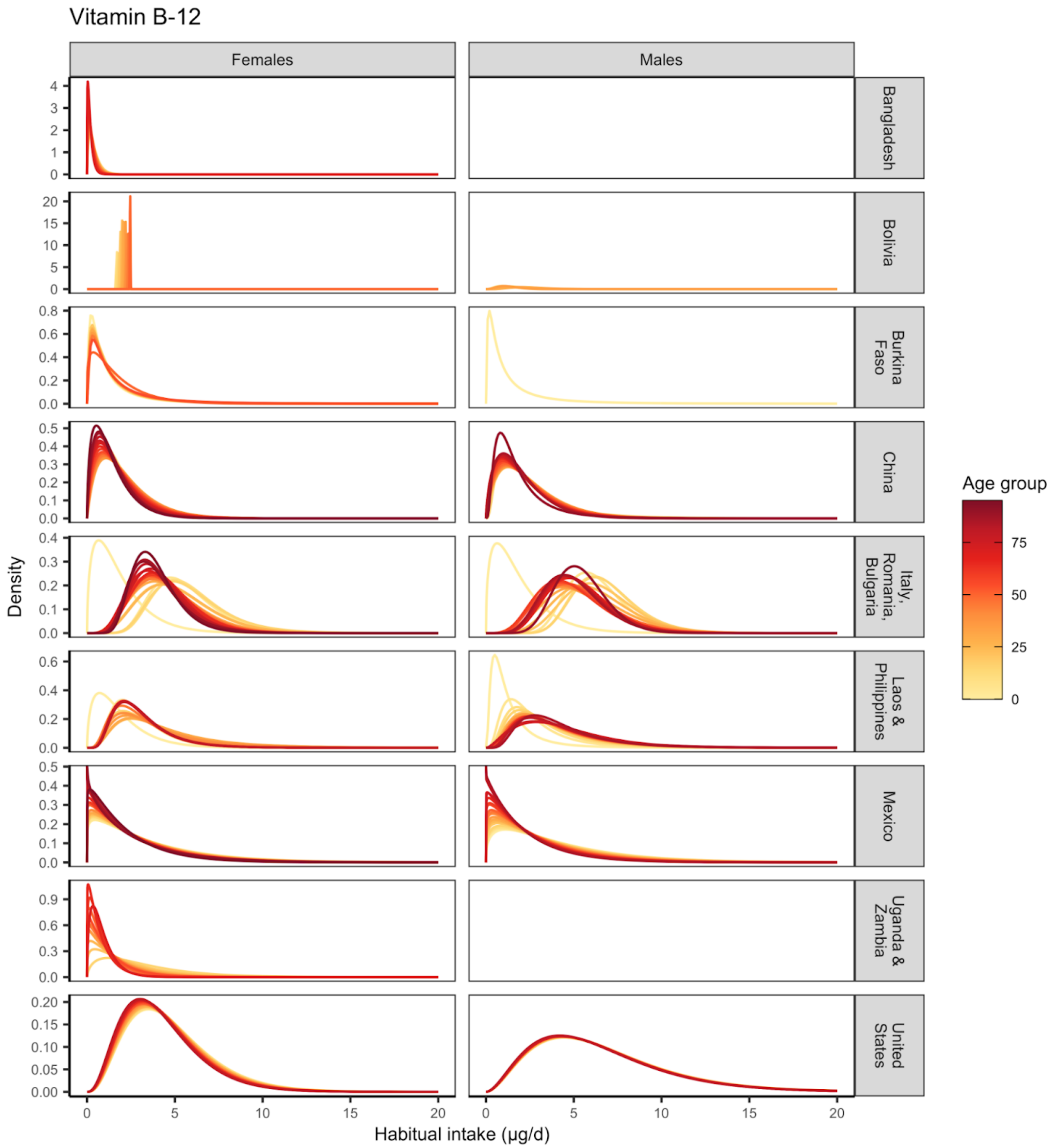

Figure S10. Vitamin B12 habitual intake distributions by country, sex, and age group. The best statistical distribution (either a log-normal or a gamma distribution) for each country group, sex, and age group is shown. The family of distribution may differ among age groups within a country and sex.

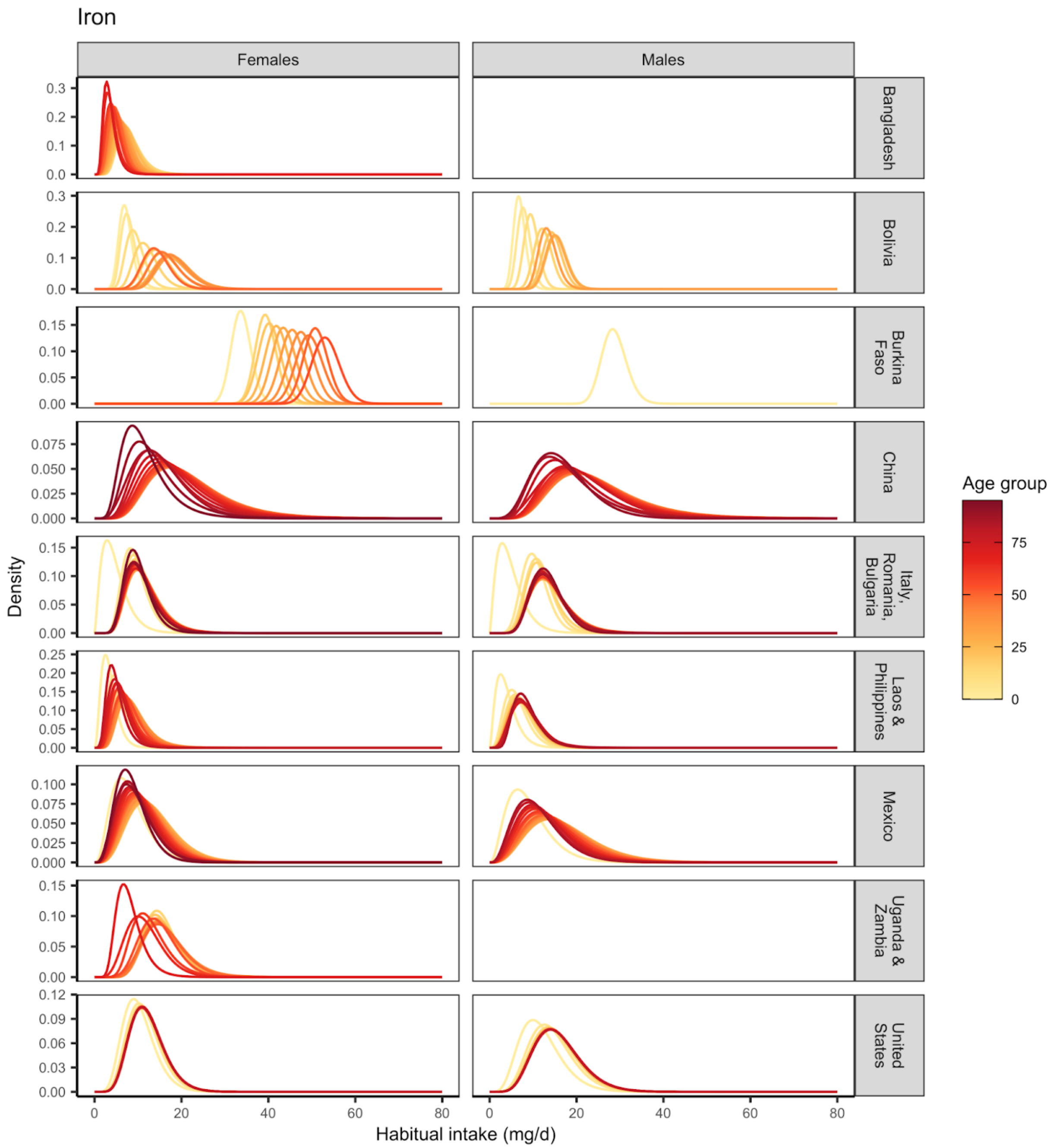

Figure S11. Iron habitual intake distributions by country, sex, and age group. The best statistical distribution (either a log-normal or a gamma distribution) for each country group, sex, and age group is shown. The family of distribution may differ among age groups within a country and sex.

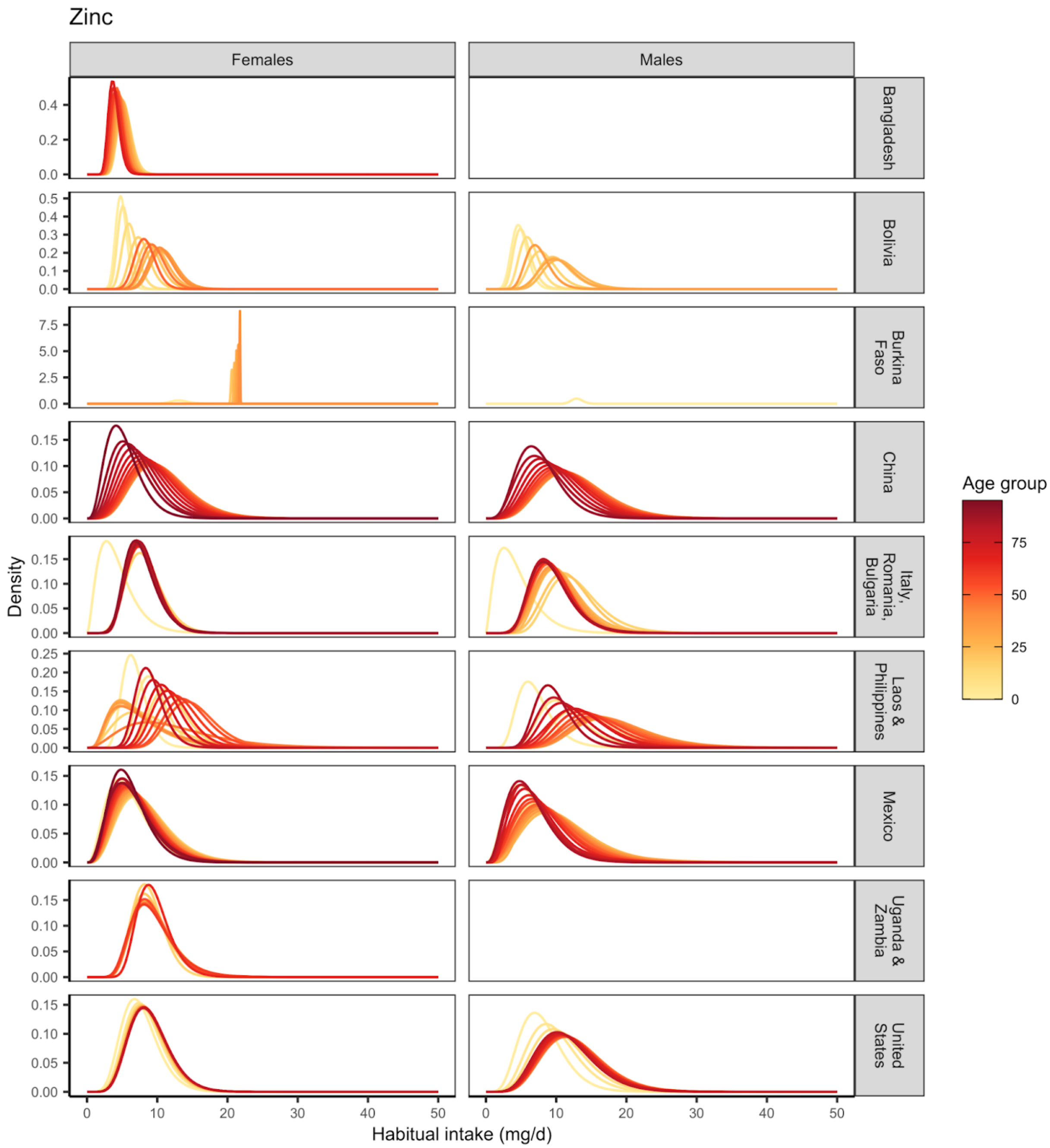

Figure S12. Zinc habitual intake distributions by country, sex, and age group. The best statistical distribution (either a log-normal or a gamma distribution) for each country group, sex, and age group is shown. The family of distribution may differ among age groups within a country and sex.

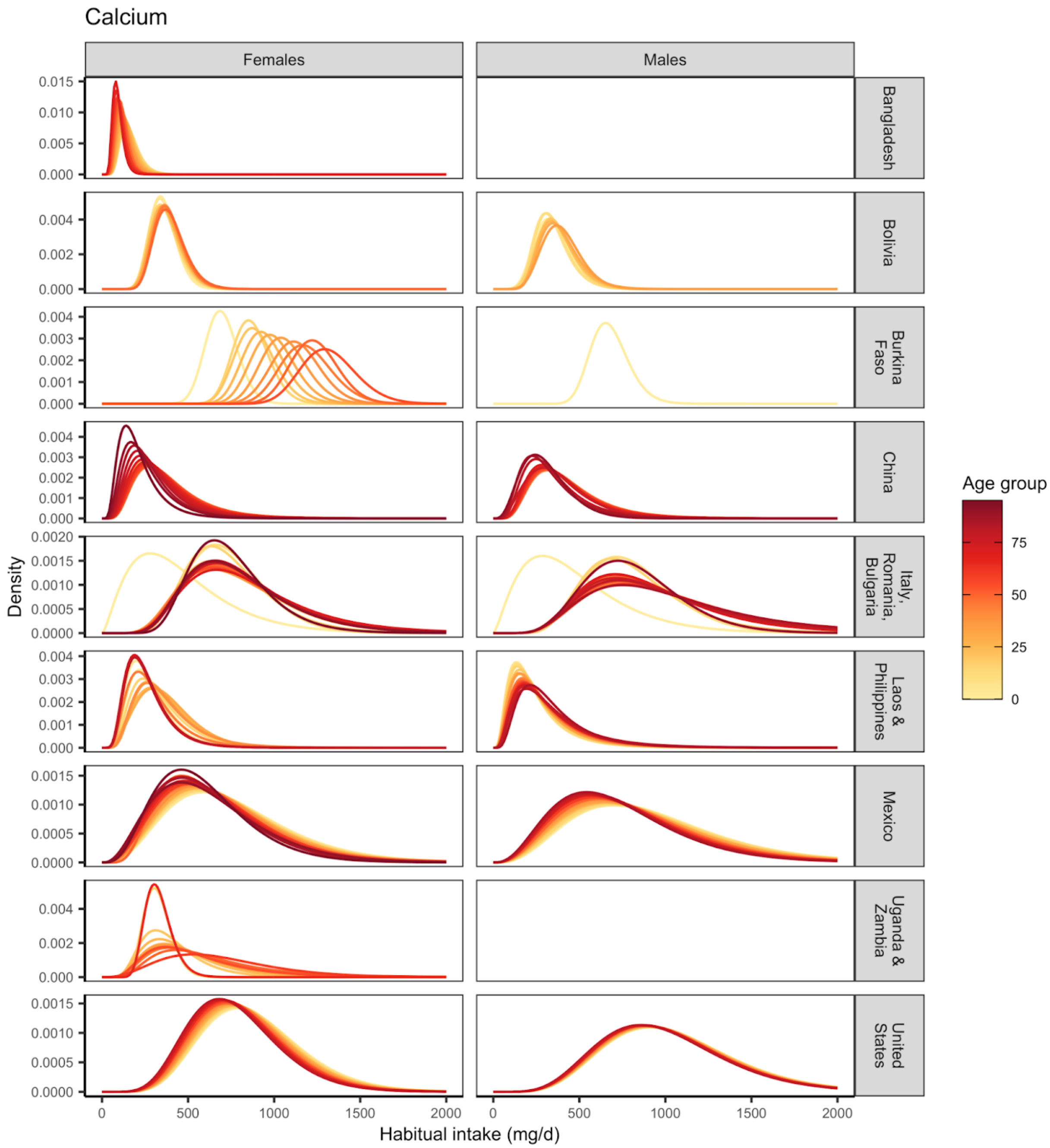

Figure S13. Calcium habitual intake distributions by country, sex, and age group. The best statistical distribution (either a log-normal or a gamma distribution) for each country group, sex, and age group is shown. The family of distribution may differ among age groups within a country and sex.

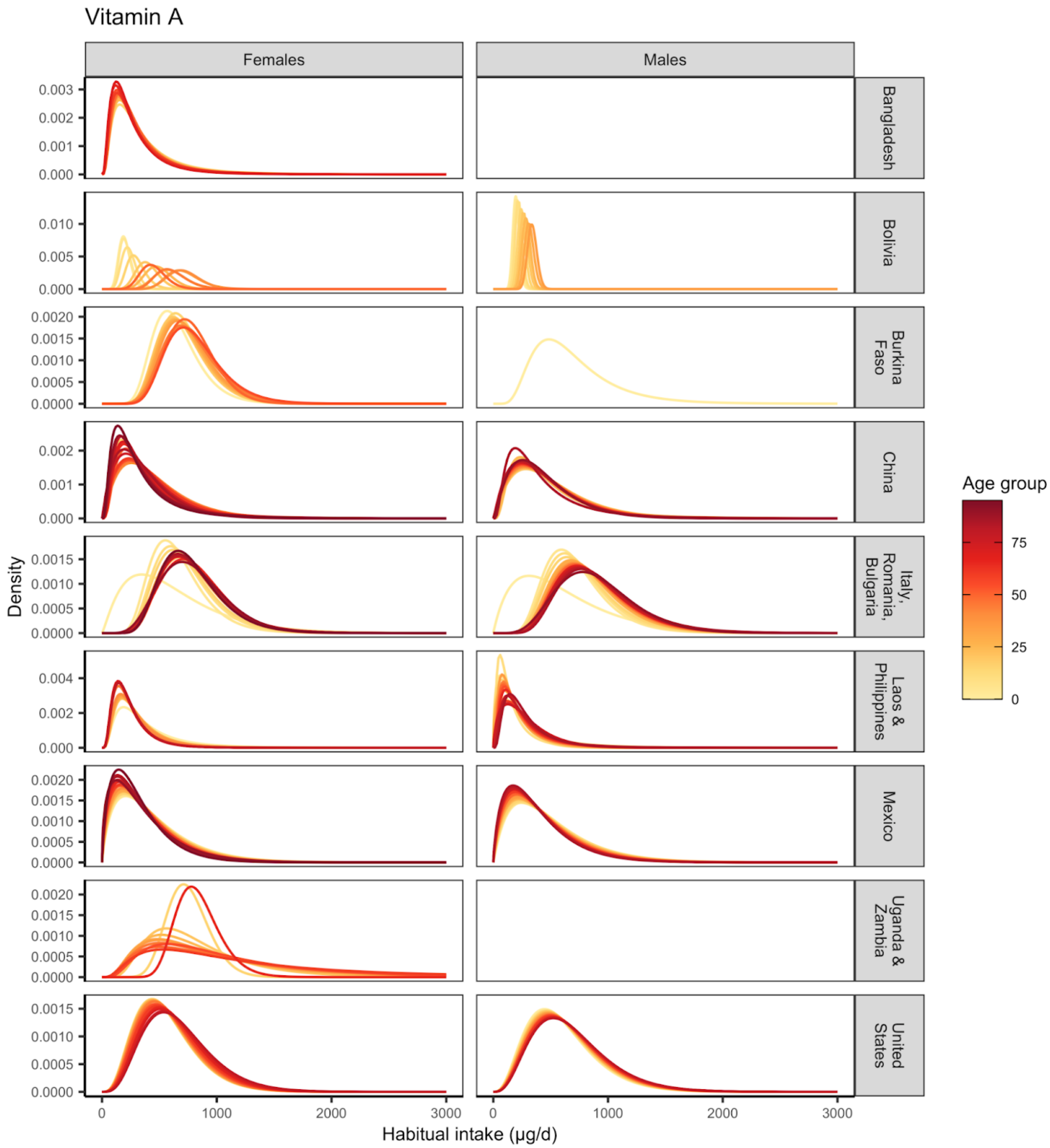

Figure S14. Vitamin A habitual intake distributions by country, sex, and age group. The best statistical distribution (either a log-normal or a gamma distribution) for each country group, sex, and age group is shown. The family of distribution may differ among age groups within a country and sex.

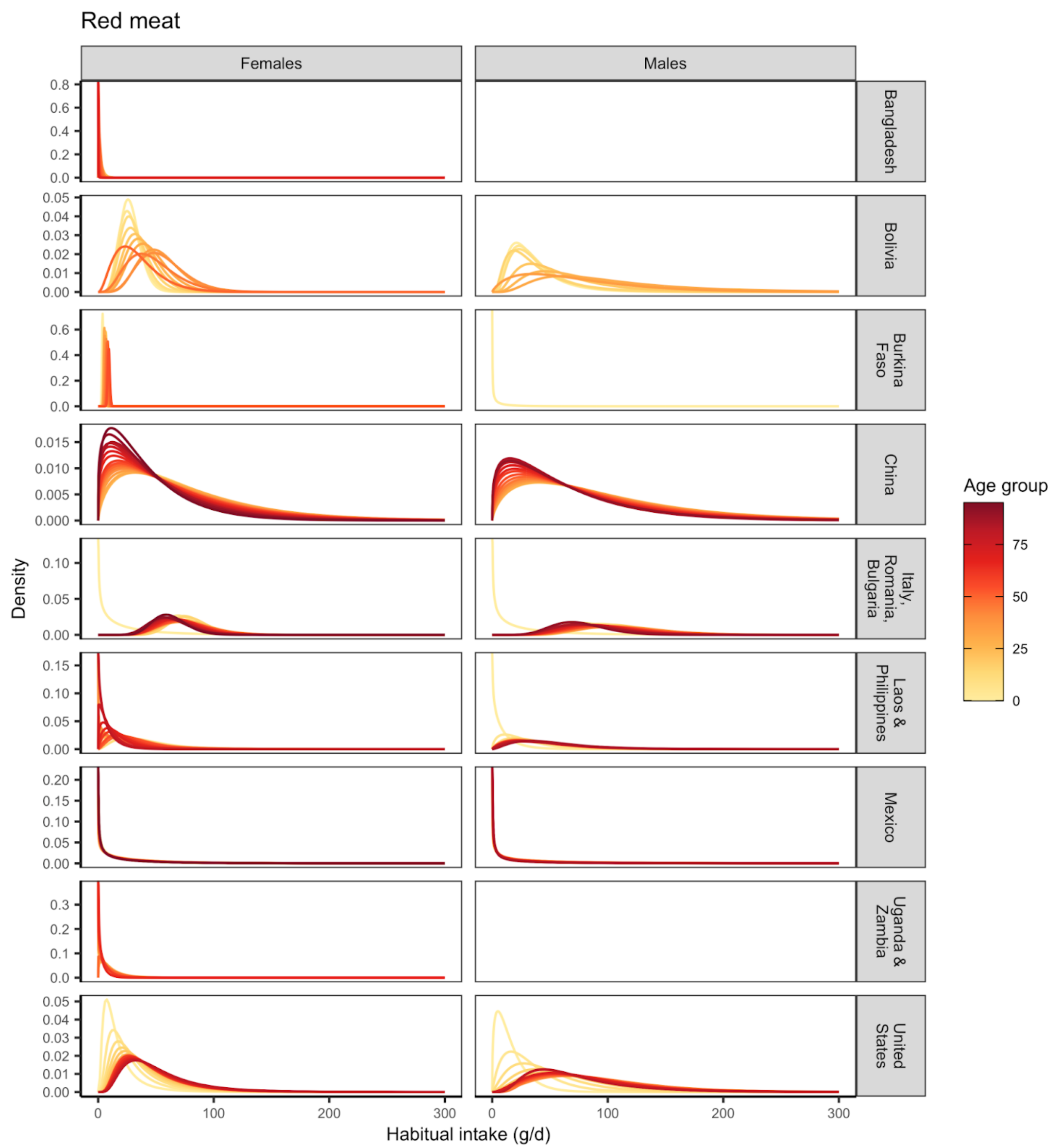

Figure S15. Red meat (i.e., beef/veal, pork, sheep) habitual intake distributions by country, sex, and age group. The best statistical distribution (either a log-normal or a gamma distribution) for each country group, sex, and age group is shown. The family of distribution may differ among age groups within a country and sex.

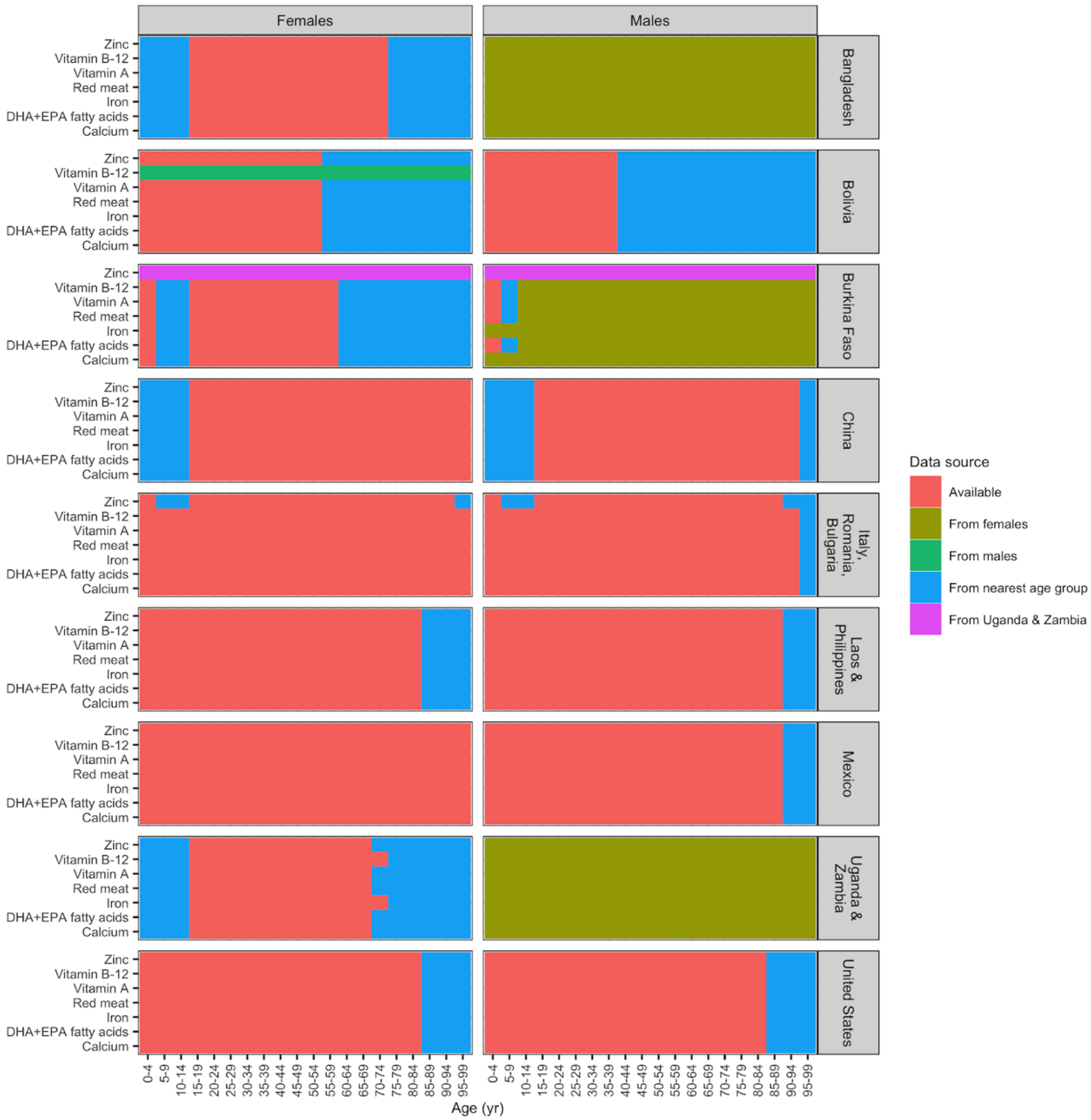

Figure S16. Approach to imputing habitual intake data for age and sex groups without habitual intake data. The red shading indicates age/sex groups with data. Missing data were imputed by borrowing from the nearest neighbor (32% of age-sex groups). We filled within country gaps by borrowing intake distributions, 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.

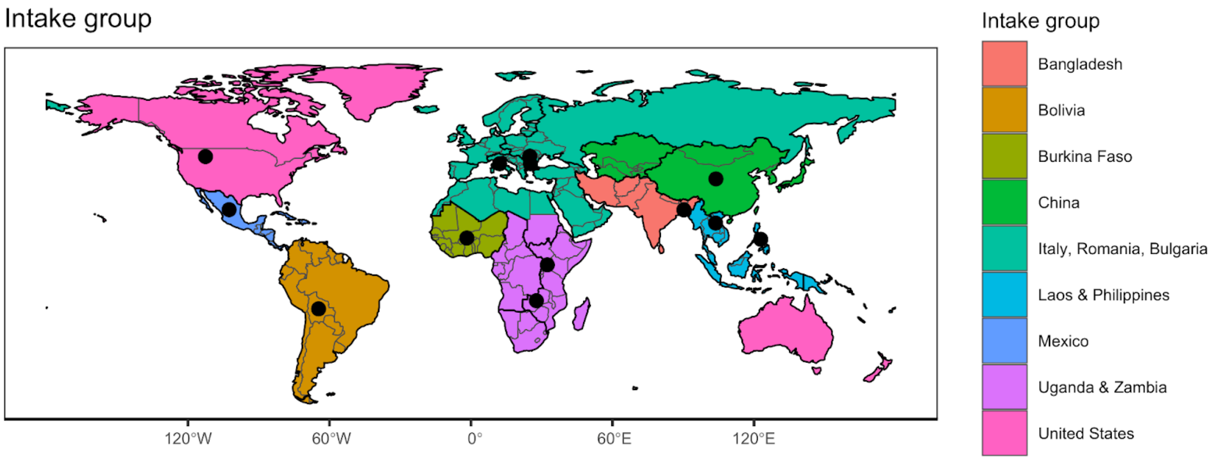

Figure S17. Map of the nutrient intake groups used to scale the subnational habitual intake distributions across countries. These groups are based on U.N. subregions (delineated in thick black lines) with a few expert-identified modifications.

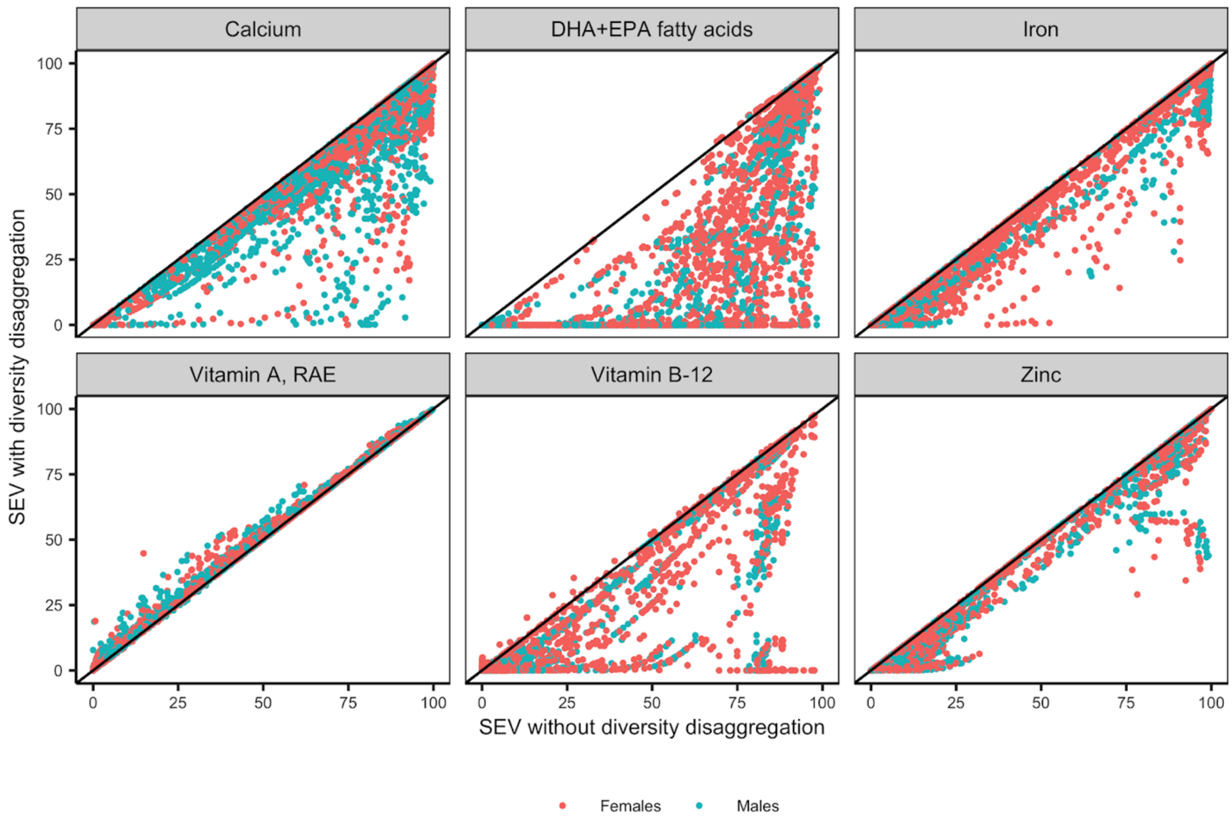

Figure S18. Summary exposure values (SEVs) in the high production scenario with and without the diversity disaggregation. Summary exposure values (SEVs) for each country-age-sex group in the high production scenario with and without the diversity disaggregation. The diagonal line indicates the 1:1 line. 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.

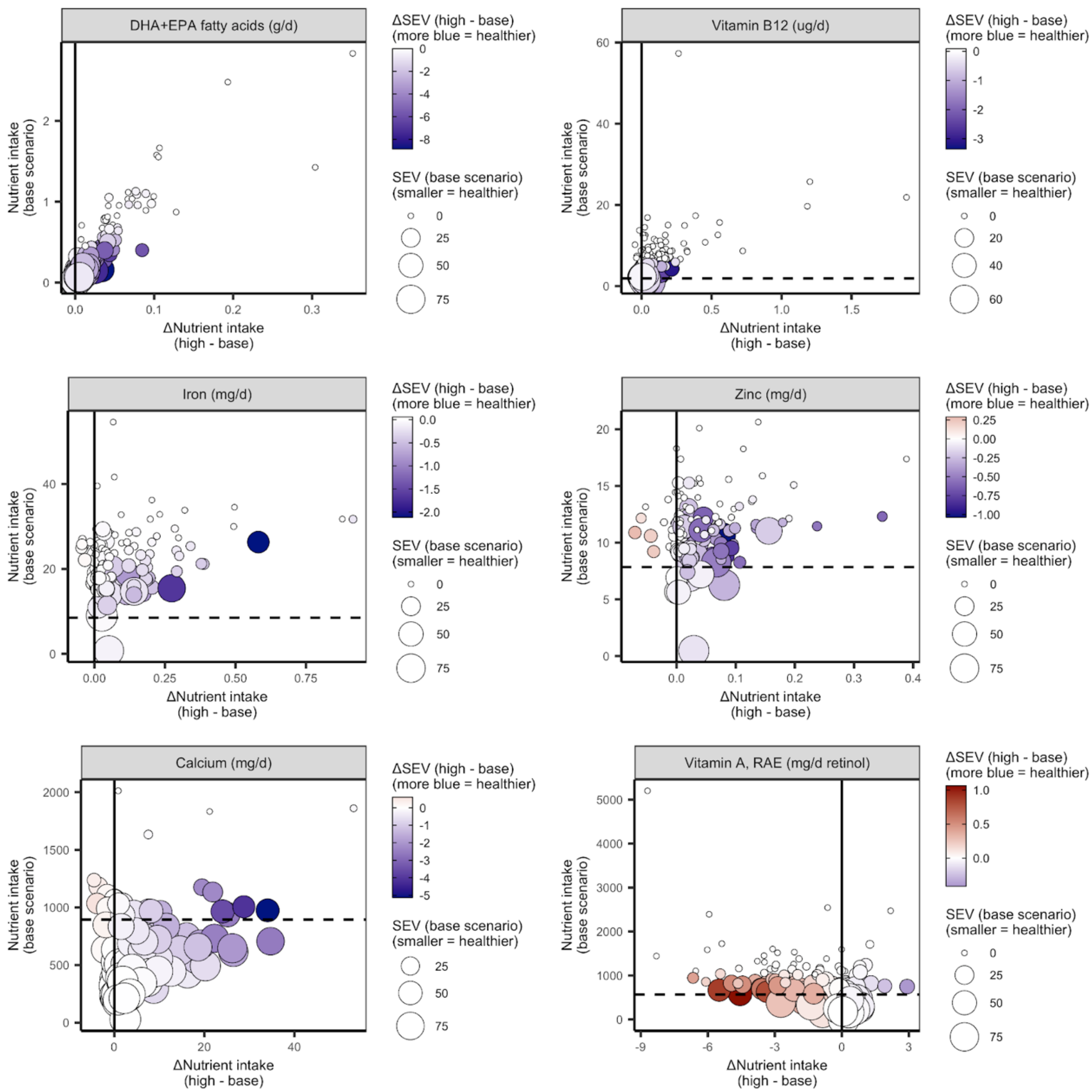

Figure S19. The relationship between the difference in 2030 health outcomes under the high and base production scenarios and base scenario status Each point represents a country where point color indicates the difference in national micronutrient deficiency averages between the scenarios and point size indicates the scale of nutrient deficiencies in the base scenario. 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.

Supplemental Tables

Table S1. Aquatic food production scenarios.

Aquatic 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/p/d
Fatty acid	Omega-3 fatty acids	g/p/d
Fatty acid	Polyunsaturated fatty acids	g/p/d
Fatty acid	Saturated fatty acids	g/p/d
Macronutrient	Energy	Kcal/p/d
Macronutrient	Protein	g/p/d
Macronutrient	Total lipids	g/p/d
Mineral	Calcium	mg/p/d
Mineral	Iron	mg/p/d
Mineral	Zinc	mg/p/d
Vitamin	Vitamin A	IU/p/d
Vitamin	Vitamin A, RAE	mg/p/d retinol
Vitamin	Vitamin B_{12}	ug/p/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 fatty acids DHA and EPA. Iodine data was sourced from the Norwegian Food Composition Table.

Food category	USDA [code] description	Norway description (Iodine)
Eggs	[01123] Egg, whole, raw, fresh	Eggs, raw
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
Cow Milk	[01211] Milk, whole, 3.25% milkfat, without added vitamin A and vitamin D	Milk , cultured, plain, organic
Butter	[81101000] Butter	Butter
Veal	[17104] Veal, loin, separable lean and fat, raw	Veal, chops, 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. FAO and WHO 1998: FAO and World Health Organization 1998 Vitamin and mineral requirements in human nutrition Second edition (Bangkok) Online: www.who.org

Nutrient	**Daily Value**	**Source**	**Notes**
Vitamin A (RAE)	45 mg	FAO and WHO 1998	Value based on requirements for a female aged 19-50
Vitamin B_{12}	2.4 mcg	FAO and WHO 1998	Value based on requirements for an adult 19-65+
Calcium	1000 mg	FAO and WHO 1998	Value based on requirements for a female aged 19-50
Iodine	150 mcg	FAO and WHO 1998	Value based on requirements for adolescents and adults from 13-65+
Iron	29.4 mg	FAO and WHO 1998	Value based on requirements for a female aged 19-50
Zinc	4.9 mg	FAO and WHO 1998	Value based on requirements for a female aged 19-50
Omega 3 fatty acids (DHA plus EPA)	0.5 g	Cunnane S, Drevon C A, Harris B, Sinclair A and Spector A 2004 Recommendations for intakes of polyunsaturated fatty acids in healthy adults. ISSFAL Newsletter, 11, 12-25.	Expected to significantly reduce risk for death from coronary heart disease in healthy adults.

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 intakes 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	omega-3, 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	omega-3, 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	omega-3, 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	omega-3, 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	omega-3, zinc, red meat, calcium, vitamin A, iron	National
Italy	FAO/WHO GIFT	Female/male, ages 0-89	3	3323	2005-2006	omega-3, red meat, calcium, vitamin A, iron, vitamin B_{12}	National
Lao	FAO/WHO GIFT	Female/male, ages 0-89	2	2045	2016-2017	omega-3, zinc, red meat, calcium, vitamin A, iron, vitamin B_{12}	National
Mexico	ENSANUT	Female/male, ages 0-97	2	4343	2016	omega-3, zinc, red meat, calcium, vitamin A, iron, vitamin B_{12}	National
Philippines	FAO/WHO GIFT	Female, lactating, ages 15-47	2	1205	2002	omega-3, zinc, red meat, calcium, vitamin A, iron, vitamin B_{12}	National
Romania	FAO/WHO GIFT	Female/male. ages 19-92	7	1382	2011-2012	omega-3, zinc, red meat, calcium, vitamin A, iron, vitamin B_{12}	National
Uganda	HarvestPlus	Female, ages 20-73	2	554	2006-2007	omega-3, zinc, red meat, calcium, vitamin A, iron, vitamin B_{12}	National

USA	NHANES	Female/male, ages 0-80	2	7640	2017-2018	omega-3, zinc, red meat, calcium, vitamin A, iron, vitamin B_{12}	National
Zambia	HarvestPlus	Female, ages 18-67	2	374	2009	omega-3, zinc, red meat, calcium, vitamin A, iron, vitamin B_{12}	Two rural regions

Data Appendices

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

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

Appendix C. Mean national per capita nutrient deficiencies (SEVs) in 2030 under the base and high production scenarios.