Aquatic Foods to Nourish Nations

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55   **Summary**
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57   Despite contributing to healthy diets for billions of people, aquatic foods are often undervalued
58   as a nutritional solution because their diversity is often reduced to the protein and energy value
59   of a single food type ('seafood' or 'fish')[1–4]. For the first time, we create a cohesive model that
60   unites terrestrial foods with nearly 3,000 taxa of aquatic foods to understand the future impact of
61   aquatic foods on human nutrition. We project two plausible futures to 2030: a baseline scenario
62   with moderate growth in aquatic animal-source food (hereafter, AASF) production, and a high
63   production scenario with a 15-million-ton increased supply of AASFs over the business-as-usual
64   scenario in 2030, driven largely by investment and innovation in aquaculture production. By
65   comparing changes in AASF consumption between the scenarios, we then illuminate geographic
66   and demographic vulnerabilities and estimate health impacts from diet-related causes. Globally,
67   we find that a high production scenario will decrease AASF prices by 26% and increase their
68   consumption, thereby reducing the consumption of red and processed meats that can lead to diet-
69   related non-communicable diseases[5,6], while also preventing approximately 166 million people
70   from inadequate micronutrient intake. This finding provides a broad evidentiary basis for policy
71   makers and development stakeholders to capitalize on the vast potential of aquatic foods to
72   reduce food and nutrition insecurity and tackle malnutrition in all its forms.
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Main text

Globally, multiple forms of malnutrition continue to be significant and universal. Among children under the age of five, 149 million (22%) suffer from stunting and 45 million from wasting[7]. Among adults globally, 2.1 billion are overweight and obese[8]. Patchy data suggest that vitamin A deficiency is high among children in Africa and South Asia, and zinc deficiency affects half of all children where information exists[9]. Dietary inadequacies may be the leading reason people suffer from multiple nutrient deficiencies and subsequent morbidity and mortality[10]. Cardiovascular diseases, largely driven by diet-related factors, are the greatest contributor to global mortality, causing 17.8 million deaths in 2017[11], greater than the approximate 2 million deaths caused by COVID-19 in 2020.

To address these multiple forms of malnutrition, contemporary food policy discourses centre on the role of sustainable and healthy diets in improving human nutrition. The EAT-Lancet Commission report detailed a strategy to transform the global food system into one that could nourish the world without exceeding planetary boundaries[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, treatment of AASFs as a homogenous group ('seafood' or 'fish') limited the potential of their inclusion and recognition in global diets.

Nutrition from aquatic food diversity

Here, we reframe aquatic foods' role 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 (e.g., crabs, shrimp), cephalopods (e.g., octopus, squids), other mollusks (e.g., clams, cockles, sea snails), aquatic plants (e.g., water spinach, *Ipomoea aquatica*), algae (e.g., seaweed), and other aquatic animals (e.g., mammals, insects, sea cucumbers). Aquatic foods can be farmed or wild-caught, and are sourced from inland (e.g., lakes, rivers, wetlands), coastal (e.g., estuaries, mangroves, near-shore) and marine waters, producing a diversity of foods across all seasons and geographic regions. Here, we focus on AASFs, which constitute the majority.

Relative to the limited variation in domesticated terrestrial animal-source foods (e.g., 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; see Methods), a comprehensive global database comprising hundreds of nutrients, inclusive of minerals (e.g., calcium, iron, 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, shellfish, and salmonids (Fig. 1).

Aquatic foods to benefit human health

131 AASFs improve human health through at least three pathways: 1) by reducing micronutrient
132 (e.g., vitamin A, calcium, iron) deficiencies that can lead to subsequent disease; 2) by providing
133 the dominant source of omega-3 long-chain polyunsaturated fatty acids docosahexaenoic acid
134 (DHA) and eicosapentaenoic acid (EPA; hereafter referred to jointly as DHA+EPA), which may
135 reduce the risk of heart disease and promote brain and eye health; and 3) by displacing the
136 consumption of less healthy red and processed meats that can cause adverse health outcomes[14].
137 Any of these three pathways may overlap in an individual, or predominantly target consumers of
138 particular geographies or age-sex groups. The third pathway, specifically, is characteristic of the
139 nutrition transition (i.e., the process by which demographic and economic shifts lead to
140 concomitant dietary and epidemiological shifts often accompanying the Westernization of food
141 systems)[18]. To better understand these pathways, we examine how aquatic food policy initiatives
142 and investments could improve diets and public health through increasing access to the diversity
143 of aquatic foods and the nutrients they provide.
144
145 We explicitly integrated aquatic and terrestrial food systems models to evaluate potential health
146 impacts of increasing global AASF production. This integration enables a more realistic
147 portrayal of the trade-offs made within our global terrestrial and aquatic food systems. To
148 understand the health impacts of increased AASF consumption, we modelled future food
149 systems to 2030, using an integrated version of the United Nations Food and Agriculture
150 Organization's (FAO) FISH model[19] and the Aglink-Cosimo model[20], which is jointly
151 maintained by the Organization for Economic Cooperation and Development (OECD) and the
152 FAO. The embedded budgeting framework and price elasticities across foods allowed for
153 additions of AASFs and substitutions of aquatic for terrestrial foods within national diets. This
154 affects the supply and demand of a broad range of related food items, particularly terrestrial
155 animal-source foods (e.g., poultry, pork, beef, eggs, and dairy).
156
157 We used the integrated model to produce two scenarios: 1) a baseline scenario with projections
158 of moderate growth trends in AASF production and expert consensus regarding macroeconomic
159 conditions, agriculture and trade policy settings, long-term productivity, international market
160 developments, and average weather conditions; and 2) a high AASF production scenario that
161 assumes higher growth rates in production as a result of increased financial investment and
162 innovation in aquaculture and improved and effective management in capture fisheries[21] (see
163 Methods). The projections are not forecasts about the future, but rather plausible scenarios based
164 on a set of internally-consistent assumptions. Increases in aquaculture and capture fisheries in the
165 high production scenario led to a 26% decrease in the international reference price of AASFs,
166 and an increase in their production by 15.5 million tons (an approximate 8% increase in annual
167 global production) in 2030 as compared to the baseline scenario. In each scenario, we calculated
168 the nutrients supplied to 191 countries from the projected composition of the food system models
169 by assigning nutrient composition values to the suite of foods being consumed within 22 food
170 commodity categories, using the Global Nutrient Database (GND)[22] and the AFCD. For 21 of the
171 22 food commodity categories (all terrestrially produced foods), the GND was used as the source
172 of nutrient composition data. For the one commodity category containing aquatic foods, the
173 AFCD nutrient composition values were used. A set of refuse factors is applied to all foods,
174 highly specific to individual foods and their respective forms of preparation. Within the food
175 group of fish and seafood, these refuse factors vary from 55% for fresh crustaceans to 10% for
176 fresh cephalopods.

177
178 To assess the role of diversity in the aquatic food system, we compared estimated nutrient
179 outputs with and without species diversity fully disaggregated at national levels. The GND uses
180 relatively similar nutrient composition values across all aquatic foods, varying only for the
181 twelve categories explicitly modelled in the GND (e.g., demersal fish, pelagic fish, etc.). We
182 disaggregated national consumption to the species level in proportion to species-specific
183 aquaculture and capture fisheries production reported by the FAO, and linked these
184 disaggregated species to the AFCD (see Methods). Instead of twelve GND categories for aquatic
185 foods, we used supply and nutrient composition values for 2,143 taxa. This comparison allowed
186 us to determine whether incorporating species diversity, as opposed to relying on common
187 commercial species, shifted the levels of nutrients supplied by aquatic foods (Extended Data Fig.
188 1). The disaggregated model outputs in the baseline scenario resulted in a significantly higher
189 supply of calcium (8% higher; median across countries), iron (4%), DHA+EPA (186%), zinc
190 (4%), and vitamin B_{12} (13%), with a 1% decline in vitamin A (Extended Data Fig. 2). This result
191 provides evidence that narrowly focusing on the nutrient contributions of commercially
192 important species underestimates the nutritional benefits of aquatic foods, especially from
193 diverse small-scale fisheries.
194
195 *Aquatic foods can reduce meat intake*
196
197 In addition to the key role of AASFs in providing essential micronutrients, DHA+EPA, and
198 protein, AASFs can also prevent diet-related non-communicable diseases. These health benefits
199 are delivered through two mechanisms. First, AASFs directly provide DHA+EPA, which may
200 improve brain function and reduce the incidence of heart disease and certain types of cancers[5,6].
201 Second, AASFs displace the consumption of more harmful animal-source foods such as red and
202 processed meats (Fig. 2; Extended Data Fig. 3-5; Dataset 1), particularly in the Global North, or
203 can attenuate their increased consumption in the Global South[23,24], in both cases reducing the risk
204 of diet-related non-communicable disease[25].
205
206 In much of the Global North, an increase in AASF consumption was associated either with
207 reductions in red meat, poultry, eggs, and dairy consumption, or with no significant impact (i.e.,
208 no discernible increases; Fig. 2). In the Global South, an increase in AASFs consumption was
209 not associated with declines in the consumption of red meat, poultry, eggs, and dairy. The
210 combined dietary effect of increasing AASFs and reducing red and processed meats may lead to
211 a reduced risk of hypertension, stroke, heart disease, diabetes, colorectal cancer, and breast
212 cancer. Countries that are rapidly undergoing the nutrition transition (e.g., China, India,
213 Philippines, Malaysia, Indonesia, Vietnam, South Korea, Mexico, Brazil, Peru, Chile, Nigeria,
214 Russia, USA, Canada) are most likely to benefit from increases in AASFs production, which
215 could avert their population's trajectory towards harmful levels of meat consumption (Fig. 2).
216
217 *Aquatic foods can fill the nutrient gap*
218
219 Deficiencies in key micronutrients, such as iron, zinc, calcium, iodine, folate, vitamins A, B_{12},
220 and D, have led to 1 million premature deaths annually[8]. Further, an estimated 30% of the global
221 population (≈2.3 billion people) have diets deficient in at least one micronutrient[8]. Inadequate
222 nutrient intakes can arise from a variety of factors: 1) the formulation of food systems including

223 the availability and accessibility of foods; 2) ecological or environmental conditions—such as
224 soil nutrient loss, drought, or fishery declines—that decrease availability; 3) reduced access to
225 markets and natural resources through tariffs, fisheries governance, or other economic
226 incentives; and/or 4) taste preferences, consumer behaviour, or other individualized factors[8,26,27].
227 AASFs have the capability to reduce or fill this nutrient gap with bioavailable forms of
228 micronutrients, particularly in geographies where AASF reliance and nutritional deficiencies are
229 high (e.g., equatorial regions)[1].
230
231 Here, we focus on nutrient supply to estimate the contribution of AASFs to overall nutrient
232 intake. In the high production scenario by 2030, AASFs may contribute a global average of 2.2%
233 of energy, 13.7% of protein, 8.6% of iron, 8.2% of zinc, 16.8% of calcium, 1.1% of vitamin A,
234 27.8% of vitamin B_{12}, and 98-100% of DHA+EPA, an approximate 0-10% increase for each
235 nutrient above 2020 reference values (Extended Data Fig. 6; Dataset 2). For each of the AASF
236 taxa included in the analysis, we used standardized nutrient composition values for muscle tissue
237 because the species coverage was significantly higher than for other parts (e.g., liver, bones,
238 eyes). Because these other parts are often more nutrient rich than muscle tissue, our estimates are
239 likely conservative, underestimating the true value of AASFs in human diets.
240
241 We calculated summary exposure values (SEVs) to assess the excess risk each country
242 experiences because of inadequate nutrient supply in their overall food systems, comparing the
243 total amount of nutrition derived from apparent consumption against age- and sex-specific
244 nutrient demands (see Methods). SEVs range from 0% to 100% and should be viewed as a risk-
245 weighted prevalence, with higher SEVs representing higher risk of inadequate micronutrient
246 intake[28]. The difference in SEVs represents the change in potential risk of inadequate nutritional
247 intake between the two AASF production scenarios in 2030 (Fig. 3; Dataset 3). With overall
248 trends in increasing AASF consumption and concomitant reductions in poultry, eggs, dairy, and
249 red and processed meats (Fig. 2), there are large gains in micronutrient and DHA+EPA
250 consumption (Fig. 3). Globally, the high production scenario will lead to reductions in
251 inadequate intake across most assessed nutrients (i.e., 8.1 million iron, 5.5 million zinc, 49.3
252 million calcium, 36.0 million vitamin B_{12}, and 76.8 million DHA+EPA inadequate intakes),
253 while potentially increasing 10.1 million vitamin A inadequate intakes (Extended Data Fig. 7).
254 Particular geographies will also experience small declines in calcium, iron, vitamin A, and zinc
255 supply. This phenomenon likely arises from modest reductions in iron- and zinc-rich red meat
256 consumption (as shown in historical trends), and large reductions in calcium- and vitamin A-rich
257 dairy, egg, and poultry consumption. Notably, certain regions characterized by food and nutrition
258 insecurity (e.g., sub-Saharan Africa and Southeast Asia) experience increases in intake for all
259 measured nutrients. However, some populations will face increasing risk of inadequate
260 micronutrient intake if consumption of AASFs displaces other foods, as evidenced by reduced
261 calcium intake in Turkey, zinc intake in Azerbaijan, and vitamin A intake in Indonesia and
262 Mexico, among others (Fig. 3).
263
264 Recognition of the diversity of AASFs and their nutrient composition could be harnessed to
265 direct their production and consumption across a range of deficient minerals, fatty acids, and
266 vitamins. For instance, if calcium deficiency is an issue in Turkey, one prudent option may be to
267 increase the consumption of pelagic small fish (e.g., herrings, sardines)[29]. Similarly, if vitamin A
268 deficiency is an issue in Brazil, then efforts to promote the production of oysters or the

269   consumption of sardines may be appropriate[30]. These types of food system solutions will require
270   sub-national targeting of vulnerable populations and will rely on efforts to increase both
271   production and consumption.
272

273   ***Aquatic foods support the vulnerable***

274

275   Diets are shaped by the structure of food systems. Access to the foods produced by these systems
276   can vary by age, sex, culture, socio-economic status, and geography, as does a given
277   population's reliance on AASFs. AASFs are important for both sexes and all ages, but
278   particularly so for young children, pregnant women, and women of childbearing age due to the
279   critical role of micronutrients and DHA+EPA in foetal and child growth and development[30].

280

281   Because different age-sex groups have different vulnerabilities to certain health outcomes, a
282   disproportionate benefit is associated with consuming AASFs for particular groups. The function
283   of reducing micronutrient deficiencies is more important for children and women of reproductive
284   age, and the function of attenuating chronic disease morbidity and mortality is more important
285   for adults. For example, elderly in Tunisia, Algeria, St. Lucia, Iran, and Moldova would
286   experience large benefits in reduced inadequate intake of DHA+EPA (ΔSEV > -10.0 percentage
287   points) and reduced inadequate intake in iron in Kiribati and the Republic of Congo (ΔSEV =
288   -3.6 percentage points). In several countries, children would experience large benefits in reduced
289   inadequate calcium intake due to increased AASFs consumption (ΔSEV percentage points for 5-
290   9 year-olds = -6.0 for girls and -5.5 for boys in Myanmar; -5.9 for girls in Vietnam and
291   Cambodia; -5.1for girls in Morocco; and -4.5 for boys and girls in Gabon; and ΔSEV percentage
292   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
293   for girls in Kiribati). In Panama, Iran, Moldova, Dominica, and Egypt, a segment of
294   reproductive-aged women (25-49 years) would receive a large health benefit for increased
295   DHA+EPA consumption (ΔSEV= -6.7 - -8.6 percentage points). Across all measured nutrients,
296   there were significant sex differences in benefits between the base vs. high road scenario (n = 73
297   of a total 115 age-nutrient groups), where increased AASF production and consumption
298   disproportionately improved the intakes of females (average of 51.4% of countries) over males
299   (average of 18.2% of countries; Dataset 4). Thus, there is nearly a 3 times greater likelihood of
300   increased AASF consumption benefitting female nutrition, providing a potential pathway for
301   nutritional equity (see Supplementary Methods).

302

303   ***Discussion***

304

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

314

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 (e.g., the UN Sustainable Development Goal 2: Zero Hunger) ignore aquatic foods completely; and funding for the aquatic foods sector from the World Bank and Regional Development Banks lack targeted support[31]. Two main issues seem pervasive in misunderstanding the importance of aquatic foods. First, a very narrow view of the diversity of 'fish' and 'seafood' is often taken, with a focus on a set of commercially grown or wild-harvested finfish and bivalves. This classification ignores the vast diversity of other species, forms of culture production, and wild harvest by small-scale fisheries[32]. Second, nutritional contribution of aquatic foods has traditionally focused on its low contribution to global energy (i.e., calories) and protein intake, failing to consider the contribution of aquatic foods to nutrition via highly bioavailable essential micronutrients and fatty acids. The Aquatic Foods Composition Database presented here enables future studies to move beyond this limited view of nutrition from aquatic foods. Yet, there are still limitations in our current presentation (e.g., 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, as environmental, social, and economic impacts can vary widely across both the wild capture and aquaculture sectors (see 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 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].

Synthesis

Our findings suggest strategic research and policy opportunities:

1) in countries where there are high burdens of micronutrient deficiencies, supply chains and availability of aquatic foods may be strengthened by improving fisheries management; enhancing sustainable aquaculture; and building more equitable national and regional trade networks;

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

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

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

361
362 In line with the Committee on World Food Security's Voluntary Guidelines on Food Systems
363 and Nutrition[34], national food and nutrition policy is needed to transform food systems by
364 prioritizing aquatic foods where culturally and socially appropriate. Also, policy may ensure that
365 the governance of and investment in aquatic food systems aim to preserve, support and improve:
366 aquatic species diversity; production and harvest methods and practices; and efficient and safe
367 distribution channels. With more than 1.5 billion people unable to afford a healthy and
368 sustainable diet[35], our model results showcase the importance of price and economic policies in
369 creating nutritious diets that are affordable for consumers. These measures should enable aquatic
370 foods to play an important role in nourishing nations and improving global nutrition and health.
371
372 **Figure Captions**
373
374 *Fig. 1: Nutrient diversity of aquatic animal-source foods in relation to terrestrial animal-*
375 *source foods*
376 Aquatic (blue) and terrestrial (green) food richness assessed as a ratio of concentrations of each
377 nutrient per 100 grams to the daily recommended nutrient intake (RNI). Each shaded box
378 represents the median value of each nutrient in a muscle tissue across all species within each
379 taxonomic group. Food groups were ordered vertically by their mean nutrient richness with
380 higher values meeting a higher percentage of the daily recommended intake. See Table S5 for the
381 RNI values and their citations.
382
383 *Fig. 2. Fish and red meat consumption shifts resulting from an increase of aquatic animal-*
384 *source foods.* The percent difference in mean **(A)** aquatic animal-source food, **(B)** red meat (i.e.,
385 bovine, ovine, and pork), **(C)** poultry, **(D)** egg, **(E)** dairy (milk, butter, and other dairy products),
386 and **(F)** all non-aquatic animal-source food consumption in 2030 under the high and baseline
387 production scenarios. Values greater than zero indicate higher consumption under the high
388 production scenario. Countries smaller than 25,000 km^2 illustrated as points (small European
389 countries excluded). All European Union member countries have the same value because they
390 are modelled as a single unit in Aglink-Cosimo model.
391
392 *Fig. 3 Shifts in micronutrient intakes resulting from an increase of aquatic animal-source*
393 *foods.* The maps show the difference in Summary Exposure Values (SEVs) in 2030 under the
394 high and baseline production scenarios by country. Values less than zero indicate reduced risk
395 (lower SEVs) of inadequate intake under the high production scenarios. The bottom panel shows
396 the difference in the number of people with inadequate micronutrient intakes, by age-sex group.
397 Values less than zero indicate fewer inadequate intakes under the high production scenario.
398 Countries smaller than 25,000 km^2 are illustrated as points (small European countries excluded).
399
400 **METHODS**
401
402 *Food System Modelling Approach*
403
404 The FAO FISH[19] and Aglink-Cosimo[20] models are recursive-dynamic, partial equilibrium
405 models used to simulate developments of annual market balances and prices for the main
406 agricultural commodities produced, consumed, and traded worldwide. Aglink-Cosimo and FAO

407   FISH are managed by the Secretariats of the OECD and FAO, and used to generate the annual
408   OECD-FAO Agricultural Outlook[20] and other peer-reviewed scenario analyses[36]. The referenced
409   citations provide full model descriptions.
410
411   The FAO FISH model contains 2019 equations and covers 47 country and/or region endogenous
412   modules. Three products are covered with complete supply-disposition variables and prices: 1)
413   an aggregate of all aquatic animals except mammals, 2) fishmeal, and 3) fish oil. For the
414   aggregate aquatic animals, the model supplies functions for both capture and aquaculture
415   depending on the country or regional aggregate. On the demand side, the model produces one
416   aggregate aquatic animal demand function, but includes 3 different types of use: 1) food, 2)
417   processed into fishmeal and oil, and 3) other uses.
418
419   To reflect the fact that fisheries are a renewable natural resource that are fully exploited and
420   regulated or over-exploited, capture fisheries are kept exogenous in most modules of the model
421   as they are controlled under strict fishing quotas and subject to regulations preventing
422   economically driven supply. Therefore, the supply of only 11% of world capture fisheries
423   respond to price for those countries and regions with insufficiently strict regulations. However, it
424   is assumed that their capture production will always stay below the maximum sustainable yield
425   (MSY). Conversely, in the model, 99% of world aquaculture production are endogenous and
426   responsive to price of output, and 75% of aquaculture are additionally responsive to feed prices.
427   In terms of aquaculture supply, the model contains 115 functions which cover the combination of
428   countries and species. Each species has its specific feed rations (i.e. different mix of feed
429   ingredients), production lags driven by the species biology, and elasticities (i.e. the level of
430   responsiveness of production to price changes). Ninety seven percent of global reduction of fish
431   into fishmeal and oil is endogenous in the model. In 63% of the modules, fishmeal and oil is
432   controlled by a simple technical parameter, while in the remaining modules, it is price
433   responsive.

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

445   The FAO FISH model was integrated into Aglink-Cosimo to represent the aquatic foods
446   component of the overall global food and agriculture system. Once integrated, the fish, fishmeal,
447   and fish oil of the FISH model become fully integrated into the merged model and the full set of
448   commodities is simulated simultaneously. Per capita food demand of aquatic products is
449   determined by their retail price, retail price of substitutes (mostly beef, pork and poultry), and by
450   real per capita gross domestic product (GDP). Typically, consumers from wealthier countries
451   respond less to a change in the retail price of fish expressed in real terms (i.e. deflated by the

452 overall consumer price index) than consumers who spend a higher share of their income on food.
453 The retail price of aquatic products is determined by the price of traded products (which can be
454 considered a wholesale price) and the GDP deflator to capture movement in the other costs along
455 the supply chain. The higher the GDP of a country, the smaller the influence of the wholesale
456 price in the calculation of the retail price. Imports and exports are a function of the ratio between
457 the domestic (adjusted by tariff and exchange rate) and world price of aquatic products with
458 different levels of responsiveness depending on the openness of the different countries' aquatic
459 product markets. Finally, the price of traded aquatic products is the market clearing variable of
460 each country component.
461
462 ***Scenario Development***
463 Two alternative outlook projections, a baseline and high production scenario (Table S1; Fig. S1),
464 were used to represent food production, consumption, and trade to 2030 for 22 food groups. The
465 baseline scenario is driven by the results of the FAO FISH model included in the OECD-FAO
466 Agricultural Outlook 2020-2029, with 2030 data reflecting the UN FAO's best understanding of
467 likely fisheries and aquaculture growth based on anticipated macroeconomic conditions,
468 agriculture and trade policy settings, fisheries management outcomes, long-term productivity,
469 international market developments, and average weather conditions[37]. Aquaculture will be the
470 main driver of the growth up to 2030, while fisheries production is expected to slightly decline.
471 The high production scenario is not a prediction but represents the UN FAO's specific estimation
472 of the upper limits of aquatic foods growth potential[37], reflecting an imposed change to AASF
473 production. This could be obtained by applying innovative technologies, capacity building,
474 increased and cost-effective financial investment in aquaculture and improved and effective
475 management in fisheries production constrained by estimates of global MSY. Also in the high
476 road scenario, major growth in production is expected to originate mainly from aquaculture, but
477 fisheries production will slightly grow. The improved and effective management will support the
478 sustainable growth in fisheries production through increased catches in areas recovering from
479 previous overexploitation patterns, as well as underfished resources, and improved utilization of
480 the harvest, including reduced onboard discards, waste and losses.
481
482 Although the high production scenario is optimistic, it is within the realm of possible futures, and
483 is used to explicitly highlight the potential nutritional and health gains that could arise from
484 targeted interventions. Species composition of broad commodity categories and feed
485 composition (which could affect nutrient composition of products) were left unchanged between
486 the present and 2030. We estimated country-level AASF consumption corresponding to marine
487 and freshwater capture and aquaculture production projections in 2030 based on the joint Aglink-
488 Cosimo FISH baseline and high production outputs.
489 As the supply of fish is increased relative to the baseline, under the assumption that demand does
490 not shift, a new equilibrium price is found along the demand curve. This new price of fish
491 influences the consumption and production of other agricultural commodities through links on
492 the production and consumption side. The shift in the international reference price of fish, which
493 represents the aggregate behavior of all consumers, leads to changes in individual decisions that
494 are determined by the relative changes in their domestic prices. They, in turn, are determined by
495 the integration of each commodity market into the global trade system and the respective shift of
496 the fish supply in the scenario. Consumers in a fish-producing or importing country will take
497 advantage of the lower fish price and consume more fish and less terrestrial meats, depressing

498 terrestrial meat prices. These prices are also transmitted through trade to countries that do not
499 produce or import a substantial volume of fish. Thus, consumers take advantage of the lower
500 meat prices and increase their meat consumption.

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

509
510 *Global Nutrient Database (GND)*

511
512 The GND matched over 400 food and agricultural commodities from the FAO's Supply and
513 Utilization Accounts to food items in the United States Department of Agriculture Food
514 Composition Database and obtained data on nutrient composition of the Supply and Utilization
515 Accounts food items[22]. After adjusting for the inedible portion of each food item, the GND can
516 estimate the national availability of macronutrients and micronutrients in a given year. Based on
517 this, the 22 food group model outputs from the Aglink-Cosimo model were cross-walked to the
518 GND, and nutrient supply was estimated for each scenario (Table S1).

519
520 *Species Disaggregation*

521
522 Aquatic foods in the GND are based on FAO FishStat production data and currently include the
523 following categories: i) demersal fish; ii) pelagic fish; iii) fish oils; iv) crustaceans; v)
524 cephalopods; vi) other marine fish; vii) freshwater fish; viii) other molluscs; ix) aquatic
525 mammals; x) other aquatic animals; and xi) aquatic plants. To derive more resolved consumption
526 estimates, we first assigned fish consumption estimates to freshwater and marine species based
527 on historical shares. Within these broad categories, consumption was then assigned to capture
528 and aquaculture sources to allow for future projections to reflect increased share (for some key
529 species) in aquaculture production. Next, we used FAO FishStat production data to predict which
530 species are actually being consumed in each country, adjusting for trade flows. We assumed that
531 future diets preserved the current taxonomic make-up within each of these categories.

532
533 For marine species disaggregation, we used country-specific FAO FishStat historical catch and
534 production data from 2014 to proportionally assign consumption projections to the Aglink-
535 Cosimo outputs. Freshwater species, with the exception of salmon which were calculated
536 separately using FAO trade data, and any fish destined to fishmeal, fish oil, or discards were
537 removed. National apparent consumption of marine seafood by species from all producing
538 sectors and sources (aquaculture, capture, and import) was calculated by subtracting exports
539 from production, using FAO food balance sheets (according to the proportion of species within
540 each seafood commodity category), and adding imports (assuming a species mix within trade
541 codes proportional to trade partner production). Negative apparent consumption was assumed to
542 be zero. Finally, we scaled total harvest by the edible portion of each species.

543

544 Consumption of freshwater taxa was generated by matching FAO FishStat production and trade
545 labels nested in the same commodity group (see Supplementary Methods). All commodities were
546 converted to live weights using freshwater conversion factors[38]. The proportion of freshwater
547 species consumed was further disaggregated with household survey data[38], and recreational
548 fishery consumption (see Supplementary Methods). Household surveys were used to adjust the
549 volume of capture fishery relative to aquaculture in 31 countries and disaggregated unidentified
550 commodity groups for five countries[38]. Recreational fisheries data from ancillary sources were
551 included for 11 countries that have high but potentially under-reported recreational participation.
552 Finally, we estimated consumable harvest by scaling total harvest by edible proportion (see
553 Supplementary Methods).
554
555 ***Aquatic Foods Composition Database***
556 The Aquatic Foods Composition Database (AFCD) synthesizes information from international
557 and national food composition tables and peer-reviewed literature. Food composition tables were
558 assumed to be correct and directly integrated. Data were sourced from international food
559 composition databases from the USDA, FAO INFOODS and the EU SMILING project in SE
560 Asia, as well as individual food composition tables from Australia, New Zealand, Pacific Islands,
561 South Korea, India, Bangladesh, West Africa, Canada, Norway, and Hawaii, and previous
562 reviews of peer-reviewed literature[2].
563
564 The search strategy focused on studies between 1990 and 2020, and prioritized specific journals
565 known to include food composition data (e.g., Food Chemistry, Journal of Food Composition
566 and Analysis). A broader search was also conducted using Web of Science including 20 aquatic
567 and 15 nutritional search terms, with elimination hedges to avoid irrelevant studies (see
568 Supplementary Methods for full terms). Peer-reviewed data were collected from 1,063 individual
569 studies. In total, AFCD contains 29,912 lines of data representing 3,753 unique taxa.
570
571 We estimated the likely mix of species consumed as described above and then matched these
572 individual species identities with the AFCD. To link disaggregated species to the AFCD, we
573 used a hierarchical approach to assign the nutritional value for all 7 nutrients to all species
574 consumed globally (Supplemental Fig. S7). When multiple entries were present for a single
575 species, we took the mean of all entries. We built this hierarchy according to the following order:
576 1) scientific name, 2) average of species genus, 3) average of species family, 3) common name,
577 4) average of species order, and 5) average of GND category. In the disaggregation effort, we
578 found 2,143 different aquatic species being consumed globally. We matched nutrient
579 composition values from muscle tissue for protein, iron, zinc, calcium, vitamin A, vitamin B_{12},
580 and DHA+EPA. After this matching process, we updated the estimates of nutrient intake at
581 national levels.
582
583 ***Sub-national Intake Distributions***
584
585 To evaluate the health impacts of AASF consumption, we first modelled the distribution of
586 habitual dietary intake across age-sex groups and geographies. Using SPADE (Statistical
587 Program to Assess Habitual Dietary Exposure), an R-base package that uses 24-hour recall data
588 to remove within-person variability and estimate habitual intake distributions[39], we estimated
589 usual intakes of iron, zinc, calcium, vitamin A, vitamin B_{12}, DHA+EPA, and red meat. These

590 distributions relied on the availability of individual dietary intake data with variable days of 24-
591 hour recalls, which were available in 13 datasets to which we had access, including: United
592 States, Zambia, Mexico, China, Lao PDR, Philippines, Uganda, Burkina Faso, Bulgaria,
593 Romania, Italy, Bangladesh, and Bolivia. A summary of the datasets used to estimate the sub-
594 national intake distributions is available in Supplemental Table S7.
595
596 We fit gamma and log-normal distributions to the habitual intake distributions for all available
597 age-sex groups (Figures S9-S15) using the *fitdistrplus* package[40]. We selected the distribution
598 with the best Kolmogorov-Smirnov (KS) goodness-of-fit statistic (0.002-0.373) as the final
599 distribution for each group. The parameters of this best fitting distribution describe the shape of
600 habitual intake distribution for each age-sex group and can be shifted along the x-axis in
601 response to changing diets.
602
603 *Assigning National Intake Distributions*
604
605 We disaggregated country-level intakes into sub-national distributions of intake in three steps.
606 First, we disaggregated the European Union, which is modelled as a single entity in the
607 integrated model, into its 27 constituent countries (Table S5). Second, we disaggregated country-
608 level mean intakes into age-sex-level mean intakes using the Global Expanded Nutrient Supply
609 (GENuS) database[41] for all nutrients except DHA+EPA and vitamin B_{12}, which are not included
610 in the GENuS database. We used the SPADE habitual intake output to derive age-sex-level mean
611 intakes for these two nutrients. Finally, we used the SPADE habitual intake output to describe
612 the shape of intake distribution for each age-sex group.
613
614 The GENuS database uses historical national dietary trend data to estimate the availability of 23
615 individual nutrients across 225 food categories for 34 age-sex groups in nearly all countries in
616 2011[41]. We used these estimates to calculate scalars for relating country-level availability to age-
617 group-level availability as:
618
619 $$\text{scalar}_{c,n,a,s} = \text{availability}_{c,n,a,s} / \text{mean}(\text{availability}_{c,n})$$
620
621 Where the scalar for country *c*, nutrient *n*, age group *a*, and sex *s* is calculated by dividing the
622 nutrient availability for each age-sex group by the mean nutrient availability for all age-sex
623 groups. We assume these ratios of nutrient availability are proportional to ratios of nutrient
624 intake and scale the country-level mean nutrient intakes as follows:
625
626 $$\text{intake}_{c,n,a,s} = \text{intake}_{c,n} * \text{scalar}_{c,n,a,s}$$
627
628 We used the same process to disaggregate intakes for DHA+EPA and vitamin B_{12} but used the
629 country-level and age-sex-level means derived from SPADE habitual intakes described above.
630 See Table S6 for details on crosswalking the Aglink-Cosimo and GENuS outputs.
631
632 We then used the SPADE habitual intake outputs to characterize the distribution of nutrient
633 intakes within each age-sex group. The habitual intake data and associated statistical probability
634 distributions are incomplete across all country-nutrient-age-sex combinations (Figure S8) so we
635 filled gaps by imputing data from the nearest neighbour (37% of age-sex groups). First, we filled

636 within-country gaps by borrowing intake distributions, in order of preference, from the: (i)
637 nearest age group within a sex and country; (ii) the opposite sex from within a country; and (iii)
638 the nearest country geographically and/or socioeconomically (Figure S16). We then mapped
639 these to the rest of the world, based on UN sub-regions, with a few expert-identified
640 modifications (Figure S17).
641
642 *Health Impact Modelling Approach*
643
644 Summary exposure values (SEV) integrate relative risks of sub-optimal diets with actual intake
645 distributions[28]. They estimate the population level risk related to diets and compare it to a
646 population where everyone is at a maximal risk level, giving values ranging from 0% (no risk) to
647 full population-level risk (100%). For DHA+EPA, we used the updated IHME relative risk
648 curves that are only associated with ischemic heart disease and have different values for
649 adolescent and adult subpopulations (with no risk for children). These relative risk curves
650 capture mild risk associated with consumption of omega-3 long-chain polyunsaturated fatty acids
651 under 0.4 g/d[28]. For inadequate micronutrient intake risk assessment, we derived continuous
652 relative risk curves for iron, zinc, calcium, and vitamin A, based on the probability approach for
653 calculating inadequate intake, often a precursor to micronutrient deficiencies[42]. To evaluate the
654 risk of inadequate micronutrient intake, distributions of intake are compared against
655 requirements. The latter is defined as a continuous risk curve that has a value of 1 at low intakes,
656 0.5 at the relevant EAR (estimated average requirement) and zero at large intakes. These
657 absolute risk curves are based on the cumulative normal distribution function of requirements[43]
658 with a mean at the EAR and a coefficient of variation of 10%. The latter value is used when
659 more information on exact nutrient requirement is unavailable[42,44]. The prevalence of risk at the
660 population level is derived by computing the *expected* micronutrient deficiency across the entire
661 population[43], by applying an integral of the intake distribution per age-sex-location-nutrient
662 multiplied by its specific relative risk. The values derived range from 0 to 1, and evaluates the
663 risk of inadequate intake, as SEV, on a population level from no risk (0) to maximal (1; everyone
664 is at risk). Estimated average requirements were derived from several sources[45–47]. Because zinc
665 and iron requirements depend on other dietary factors (e.g., inhibitors such as phytate), we used
666 three levels for each nutrient, based on overall diets, which crudely divide between diets based
667 on their cereals and animal-source foods intakes[48,49]. We then assigned each country to their
668 proxy zinc and iron values, based on its Social Development Index[50]. For vitamin B_{12}, we use the
669 values used by the Institute of Medicine[51] but acknowledge that uncertainties regarding
670 recommended intakes exist, and use a coefficient of variation of 25% instead of the default 10%
671 in constructing our risk curves[52].
672
673 *Extended Data Fig. 1 Difference in daily per capita intake of various nutrients from*
674 *increasing aquatic animal-source food production and fully accounting for species diversity.*
675 The maps show the difference in mean nutrient intakes in 2030 under the high and baseline
676 production scenarios when fully accounting for species diversity. Values greater than zero
677 indicate higher nutrient intake under the high production scenario. Values less than zero indicate
678 lower nutrient intake under the high production scenario. The boxplots show the difference in
679 mean nutrient intakes in 2030 under both production scenarios, with and without fully
680 accounting for species diversity. In the boxplots, the solid line indicates the median, the box
681 indicates the interquartile range (IQR; 25th and 75th percentiles), the whiskers indicate 1.5 times

682   the IQR, and the points beyond the whiskers indicate outliers. Countries smaller than 25,000 km^2
683   are illustrated as points (small European countries excluded). All European Union (EU) member
684   countries have the same value because they are modelled as a single economic unit in the
685   Aglink-Cosimo model (n=164 independent countries remain for comparison).
686
687   **Extended Data Fig. 2. Summary exposure values (SEVs) in the high production scenario**
688   **with and without the diversity disaggregation.** Summary exposure values (SEVs) for each
689   country-age-sex group in the high production scenario with and without the diversity
690   disaggregation. The diagonal line indicates the 1:1 line. Points below this line indicate country-
691   age-sex groups with lower SEVs with the diversity disaggregation. Points above this line indicate
692   country-age-sex groups with higher SEVs with the diversity disaggregation.
693
694   *Extended Data Fig. 3 Difference in 2030 food consumption under the base and high*
695   *production scenarios.* Mean daily per capita food consumption in 2030 under the (A) base and
696   (B) high production scenarios and (C) the difference in consumption between the high
697   production and base scenarios.
698
699   *Extended Data Fig. 4 Difference in 2030 food consumption under the base and high*
700   *production scenarios.* Mean daily per capita food consumption in 2030 under the (A) base and
701   (B) high production scenarios and (C) the difference in consumption between the high
702   production and base scenarios.
703
704   *Extended Data Fig. 5. Difference in 2030 food consumption under the base and high*
705   *production scenarios.* Mean daily per capita food consumption in 2030 under the (A) base and
706   (B) high production scenarios and (C) the difference in consumption between the high
707   production and base scenarios.
708
709   *Extended Data Fig. 6 Difference in 2030 nutrient intakes under the base and high production*
710   *scenarios accounting for the full diversity of nutrient compositions in seafood.* The mean daily
711   per capita nutrient intake in 2030 when accounting for the full diversity of nutrient compositions
712   in seafood under the (A) base and (B) high production scenarios and (C) the difference in intakes
713   between the high production and base scenarios.
714
715   *Extended Data Fig. 7 The relationship between the difference in 2030 health outcomes under*
716   *the high and base production scenarios and base scenario status*
717   Each point represents a country where point color indicates the difference in national
718   micronutrient deficiency averages between the scenarios (blue=reduced deficiencies;
719   red=increased deficiencies) and point size indicates the scale of nutrient deficiencies in the base
720   scenario (small=few deficiencies; large=many deficiencies). The vertical line indicates zero
721   difference in nutrient intakes between the high and base scenarios; positive values indicate
722   increased nutrient intake under the high production scenario and negative values indicate reduced
723   intake. The dashed horizontal line indicates the average Estimated Average Requirement (EAR)
724   for all age-sex groups. Countries falling below this line often have more room for health
725   improvements than countries falling above this line. Counter-clockwise from the top-left, the
726   quadrants of each plot indicate countries with mean 2030 intakes in the base scenario that are: (1)
727   higher than the mean EAR and higher than the high production scenario; (2) higher than the

728 mean EAR but lower than the high production scenario; (3) lower than the mean EAR and lower
729 than the high production scenario; and (4) lower than the EAR but higher than the high
730 production scenario.
731
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864   deriving recommendations on vitamin B12 intake with the factorial approach. *Ann. Nutr.*
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866

867   **Data Availability Statement**
868
869   Code

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

872   The code associated with the SPADE analysis is available in this Github
873   repository: https://github.com/cg0lden/subnational_distributions_BFA
874
875   The code associated with the health impacts analysis is available in this Github
876   repository: https://github.com/alonshepon/Health-Benefit-Calculation-BFA

877   Data

878   The Aquatic Foods Composition Database is open access and can be found at:
879   https://dataverse.harvard.edu/dataverse/afcd

880   All other nutrient data was sourced from the USDA FoodData Central (https://fdc.nal.usda.gov/)
881   or the Global Nutrient Database (GND) as described in the Methods.

882   For sub-national data evaluation, data was sourced from the following locations:

883   FAO/GIFT: http://www.fao.org/gift-individual-food-consumption/data-and-indicator/en/

884   NHANES: https://wwwn.cdc.gov/nchs/nhanes/continuousnhanes/default.aspx?BeginYear=2017

885   ENSANUT: https://ensanut.insp.mx/encuestas/ensanut2016/descargas.php

886   China Health and Nutrition Survey: https://www.cpc.unc.edu/projects/china/data/datasets
887

888   Uganda: https://doi.org/10.7910/DVN/FOYZBL

889

890   Burkina Faso https://doi.org/10.7910/DVN/5CXCLX

891

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

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

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

897   The data associated with the SPADE analysis is available in this Github
898   repository: https://github.com/cg0lden/subnational_distributions_BFA

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

901

902   **Acknowledgements**

926 **Competing Interests Statement**
927
928 All authors declare that we have no competing financial or non-financial interests to disclose.
929
930 **Author Contributions**

931 CDG and SHT conceptualized the research idea, with significant methodological and design
932 input from JZK, AS, CMF, DV, and HM. Data acquisition and compilation was conducted by
933 subgroups for the Aquatic Foods Composition Database (CDG, JZK, CD, HK, KJF, MK, DV),
934 Global Nutrient Database (HM), Aglink-Cosimo model (HM), FAO Fish model (PC, SV, MB),
935 species disaggregation models (EFC, EAN, JAG, AJL, DV, JGE, CDG), sub-national
936 distribution model (SP, CDG, LC, SB), and health impact models (AS, CDG, GD, ER). The food
937 systems modelling was led by HM and PC; sub-national distributions modelling was led by SP
938 and SB; and the health impact modelling was led by AS, CF, and GD. CDG drafted the original
939 manuscript, and all co-authors edited and revised the writing.
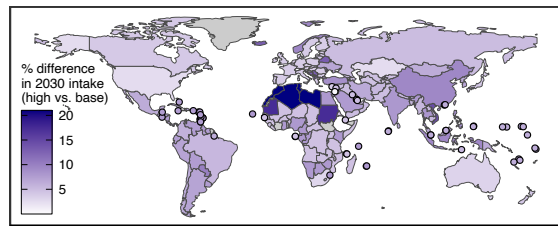940
941 **Additional Information:**

942 Supplementary Information is available for this paper.
943 Correspondence and requests for materials should be addressed to Christopher Golden at
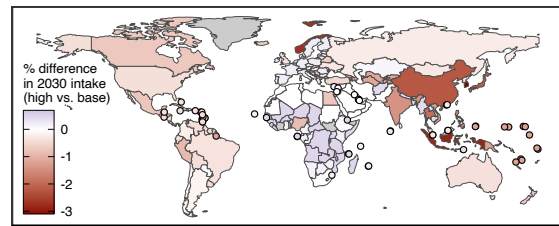944 golden@hsph.harvard.edu
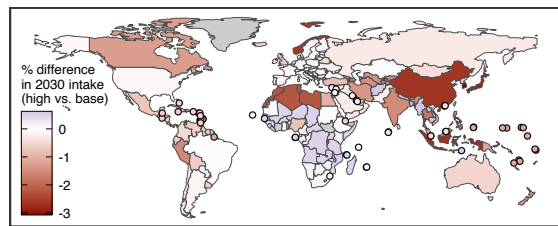945 Reprints and permissions information is available at www.nature.com/reprints

	Omega-3 (DHA+EPA)	Vitamin A	Vitamin B12	Calcium	Iodine	Iron	Zinc
Small pelagics							
Clams, Mussels, Oysters							
Large pelagics							
Aquatic mammals							
Salmonids							
Carps							
Cephalopods							
Beef							
Lamb							
Tilapia & other Cichlids							
Crab, Lobster, Crayfish, Shrimp							
Cods							
Goat							
Chicken							
Pork							

% of recommended nutrient intake

0%   50%   100% or greater

Land food

Aquatic food

A. Aquatic animal-source food consumption

% difference in 2030 intake (high vs. base)
20
15
10
5

B. Red meat consumption

% difference in 2030 intake (high vs. base)
0
-2
-3

C. Poultry consumption

% difference in 2030 intake (high vs. base)
0
-1
-2
-3

D. Egg consumption

% difference in 2030 intake (high vs. base)
0
-1
-2
-3

E. Dairy consumption

% difference in 2030 intake (high vs. base)
0.1
0.0
-0.1
-0.2
-0.3

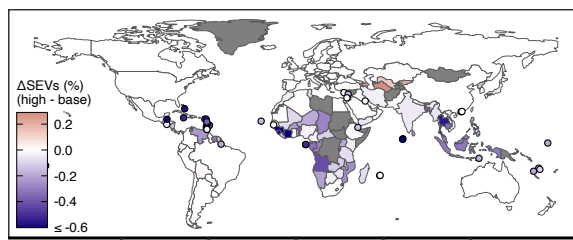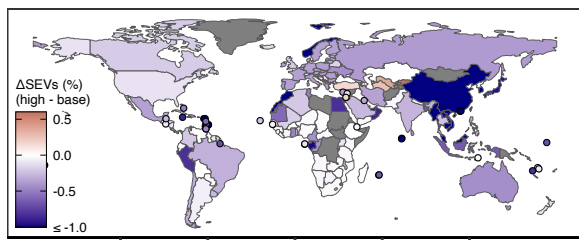F. Non-aquatic animal-source food consumption

% difference in 2030 intake (high vs. base)
0
-1
-2

DHA+EPA

Vitamin B₁₂

Iron

Zinc

Calcium

Vitamin A

ΔSEVs (%)
(high - base)

ΔMillions of people
with inadequate intakes
(high - base)

Females

Males

Age group