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Aquatic Animal Foods for Nutrition Security and Child Health

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Abstract

Background: Aquatic animal source foods (AASF) can provide vital nutrients and bioactive factors essential for human health, yet disparities in consumption patterns prevail globally. Limited evidence exists for the implications of AASF access on child health outcomes.

Objective: This study aimed to examine global AASF intakes longitudinally in association with critical nutrient intakes and childhood stunting and anemia.

Methods: The analysis draws from compiled longitudinal country data (1993-2013) based on a constructed conceptual framework encompassing social and ecological factors that influence fish consumption and human health. Longitudinal generalized linear models were used to estimate the association of apparent AASF intake on country-level nutrient availability (docosahexaenoic acid [DHA], choline, vitamin B_{12}, iron, and zinc) and prevalence of undernourishment, child stunting, and child anemia.

Results: Across 175 countries, the median per capita daily apparent intake of all AASF was 37.87 g, with marginally significant differences observed between countries with low (46.65 g) versus high child mortality (23.50 g). The combined category of all AASF was significantly associated with increased total apparent intakes of DHA, choline, and vitamin B_{12} and reduced child stunting. Finfish (pelagic and demersal) and crustaceans inversely correlated with child stunting, while apparent intakes of mollusks and crustaceans were associated with reduced child anemia.

Conclusions: This study uniquely showed that AASF were associated with improved child health outcomes and the critical nutrients necessary for growth, development, and maintaining health throughout the life course. Policies should ensure increased access to AASF across food systems and within sustainable healthy diets globally.

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Introduction

Globally, aquatic animal food consumption provides 17% of human dietary intake of animal protein, with large disparities apparent across regions and countries.[1] Aquatic animal source foods (AASF), here, refer to edible species of finfish (demersal, pelagic), mollusks, crustaceans, and cephalopods as a category of other mollusks including squids, cuttlefish, and octopus. Recent dietary guidelines recommend fish as part of sustainable healthy diets, up to 28 g/d, with mussels and oysters suggested as preferred examples of sustainable alternatives.[2] These guidelines may, however, not be viable in certain regions where availability and access are limited. Large disparities exist in apparent consumption of AASF and the critical nutrients they contain.[3] While the world average for annual per capita consumption of fish was 20.2 kg in 2015, low-income, food-deficit countries averaged only 7.7 kg per capita.[1] Disparities persist among and within countries but also across the life course, with gaps in fish consumption for vulnerable groups such as infants and young children.[4]

Dietary fish consumption has been linked to human health outcomes, but evidence is lacking for some populations. A recent review of the literature highlighted the need for greater regional representation outside Asia and for comparisons across regions in terms of the relative importance of fish in providing critical nutrients.[5] Meta-analyses and large-scale epidemiological studies have focused on dietary fish among adults and associated chronic disease outcomes of stroke and cardiovascular disease,[6] as well as fish during pregnancy and links to offspring neurodevelopment.[7-9] In the United States, a committee convened by the Institute of Medicine applied risk–benefit analyses to make recommendations on the importance of seafood consumption in particular populations: pregnant and lactating women, children younger than 12 years, and adults at risk for cardiovascular disease.[10] Few studies have examined fish and other AASF in relation to childhood stunting or anemia, 2 of the leading contributors to the global burden disease.[11,12]

Hidden hunger—or nutrient deficiencies arising from poor-quality diets—increases the risks for infectious and chronic diseases, and impaired brain development and function.[11] AASF providing several nutrients in highly bioavailable forms could play a greater role in mitigating these risks.[13] Recently published studies provided population-level evidence for the links between AASF and adequacies of nutrient intakes, highlighting calcium, vitamin A, iron, and zinc.[13,14] In this study, we also focus on iron and zinc but add other nutrients that are both concentrated in AASF and likely more deficient in child diets—docosahexaenoic acid (DHA), choline, and vitamin B_{12}.[11,15] Other nutrients such as vitamin A, calcium, and selenium, among others are also concentrated in AASF but were considered a lower priority due to high coverage of supplementation programs globally or a lack of evidence showing deficiencies in children.[16, 17]

Evidence supports the critical role played by each of the 5 nutrients selected for this study in child health and development. The macronutrient DHA is critical for brain development and largely derived from aquatic foods.[18] Choline has been less well studied, but emerging evidence shows its importance during pregnancy and early childhood, particularly when derived from animal source foods.[19-21] Animal source foods broadly are the predominant dietary source vitamin B_{12}, which is a nutrient critical for early growth and development.[22] The minerals zinc and iron were selected in recognition that iron deficiency anemia and zinc deficiency are widely prevalent globally.[23-25] Evidence suggests that zinc and iron are more bioavailable in animal source foods than in plant-based foods, and this particularly has implications for complementary feeding guidelines and practices in low-income settings where zinc and iron deficiency are more rampant.[26] Zinc,

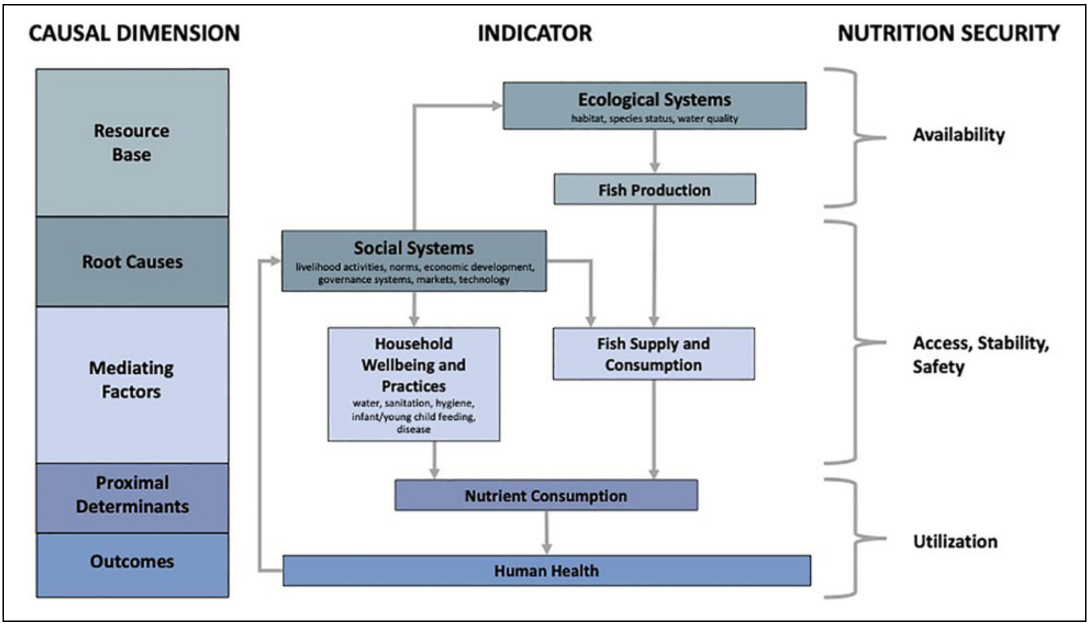

Figure 1. A conceptual framework for aquatic animal source foods and nutrition security.

in particular, is crucial for linear growth, brain development, and immune system processes, yet an estimated 17.3% of the world's population are at risk of zinc deficiency.[25]

Despite our focus on these 5 specific nutrients, we acknowledge that, ultimately, it is the animal food matrix of nutrients and a multitude of bioactive compounds that function synergistically to protect child health and promote growth and development. This study uniquely examines the contribution of different AASF to critical nutrient access and child health outcomes over time. We hypothesized that apparent aquatic animal consumption would be positively associated with apparent nutrient intake levels of DHA, choline, vitamin B_{12}, zinc, and iron and negatively associated with population undernourishment, child stunting, and anemia after adjusting for confounding factors.

Methods

Framework

Drawing from the evidence base, a theoretical framework was derived to illustrate pathways to human health and nutrition security (Figure 1).[27-31] A unique feature of the framework is its representation of both the social and ecological facets that link natural resource health and improved human health outcomes. The framework also highlights the cyclical feedback loop between environmental and human pathways, underlining the importance of taking a transdisciplinary food systems approach when designing and implementing interventions directed at nutrition security. Though not all the linkages and pathways depicted in the framework are explored in this article due to data limitations, it serves to illustrate how our nutrition focused analysis is positioned within a broader, complex socio-ecological system that impacts aquatic animal availability, access, and utilization.

Humans have a high degree of dependence on aquatic based goods and services, and the vitality of these ecosystems plays a direct role in the volume of fish and seafood that is available for harvest.[29,32,33] Thus, the pathway to human health begins with the natural *resource base* and the biophysical conditions, including habitat condition, species status, and water quality. These are all factors that impact fish production and, thus, the availability of AASF.

The quantity of fish produced in each localized ecosystem impacts community access to AASF and the stability of consumption levels, a mediating factor in the amount of nutrient intake linked to fish. Though production is a primary driver of availability, consumption of aquatic foods is also affected by postharvest losses of fish due to poor infrastructure and limited supply chains.[1,34,35] Additionally, social norms and behavior such as beliefs, food preferences, and feeding practices drive fish consumption at the individual level, constituting yet another linkage between the social and ecological drivers of access, safety, and stability. Aquatic foods could improve the quality of diets, particularly for vulnerable populations, if barriers to availability and access are addressed.

The social systems component of the framework highlights the range of complex social factors that can influence the vitality of the ecological system as well as household well-being and practices, which impact nutrient consumption and, ultimately, human health. A range of social factors, including governance systems, social norms, economic development, markets, and technology, directly influence the resource bases that are vital to aquatic ecosystem health and fish production.[28,29] Of particular importance is the level of knowledge and resources available for proper environmental management.[28,29,36] Additionally, human economic activities directly and indirectly alter aquatic ecosystems through pollutant and nutrient runoff, resource extraction, and changes in species composition.[37] The degree of socioeconomic development also influences the ability of families to access safe water, sanitation, and hygiene (WASH) conditions, practice appropriate infant and young child feeding (IYCF), and prevent and address disease. Unsafe WASH practices and inadequate IYCF impact the intake and utilization of key nutrients necessary for improved health outcomes.[38] This is particularly important for children younger than 5 years of age, as they are highly susceptible to enteric diseases.[39,40]

Nutrient intakes may serve as *proximal determinants* of health outcomes, particularly those limited in the diets of malnourished populations. Deficiencies in key nutrients such as DHA, choline, vitamin B_{12}, iron, and zinc are implicated in stunted growth and anemia, health outcomes examined in this study, as well as other multiple global health challenges.[11,41-43] Inadequate nutrient intakes are associated with poor cognitive and educational outcomes, which in turn can have significant adverse economic consequences for the individual, their household, community, and country.[44] This feedback is represented in the framework by the linkage back to social systems.

Data

Data were identified and extracted for all indicators that were available within the 5 casual dimensions of the framework: (1) resource base, (2) root causes, (3) mediating factors, (4) proximal determinants, and (5) outcomes. Data were merged into a compiled data set and disaggregated by country.

The *resource base* dimension includes ecological and fish production indicators that influence fish availability. We had hoped to use the Ocean Health Index (OHI) (https://github.com/OHI-Science/ohi-global/releases), which provides a score for overall ocean health and marine biodiversity, coastal protection, and clean waters, as a proxy measure for the broader aquatic ecological system.[45] However, OHI was only available in recent years (2012-2019), so we were unable to include it in the longitudinal models. Another resource base proxy measure we explored including are exclusive economic zone areas (km^2) from the Sea Around Us (SAU) database (http://www.seaaroundus.org/data). Exclusive economic zone areas are included in the summary statistics table, but not in the longitudinal models, due to limited data.

Fish production in the *resource base* dimension refers to the capture fisheries landings reported for each country (marine and freshwater), as well as aquaculture production. We acquired these data through the FAOSTAT data portal (http://www.fao.org/faostat/en/#data). Data were available from 1960 to 2016 for up to 175 countries. We also used data from the SAU database for years 2010 to 2014 to determine the leading fish species caught and farmed globally and examined the variability of nutrient concentrations by representative fish type (Supplemental Tables 1-2). The SAU data use Food and Agriculture Organization (FAO) production data but refine estimates to incorporate the informal sector and unreported catch. The U.S. Department of Agriculture (USDA) FoodData Central site (https://fdc.nal.usda.gov/) was used to estimate fish nutrient content per raw 100 g.

The primary *root cause* indicator used as a proxy for social systems is the Human Development Index (HDI) (http://hdr.undp.org/en/data). The Human Development Index is a measure, on a scale of 0 to 1, of average achievement in key areas of human development including life expectancy at birth, expected and mean years of schooling, and per capita gross national income. The HDI data are available from 1980 to 2017 for up to 168 countries. Another social system proxy measure included in the data set are country-level Gini coefficients from the World Bank (https://databank.worldbank.org/home.aspx). We had hoped to include the Gini coefficient variable in the longitudinal models and summary statistics table as a way to assess the potential differences in and impacts of income inequality; however, sample sizes were not large enough.

Mediating factors include indicators linked with the HDI as well as the OHI and fish production. Data for fish supply and consumption were extracted from FAOSTAT and the Global Dietary Database (https://www.globaldietarydatabase.org/). Food supply data from FAOSTAT serve as the basis for food balance sheets as well as estimates of undernourishment. Several studies have applied the FAO Food Balance sheet data to estimate population-level access to AASF and validated with actual intake levels at individual levels.[1,14,25,46]

Food supply data are derived by adding the total quantity of foodstuff produced to the total quantity imported, accounting for quantities exported, nonhuman uses such as feed for agriculture, and postharvest losses during storage and transportation. The net supply is then divided by the population. For our data set, we downloaded supply data (g/capita/d) for 175 countries from years 1961 to 2013, where available, on the following AASF: total AASF, pelagic fish (marine), demersal fish (marine), other marine fish, crustaceans, mollusks, squid/octopus, and freshwater fish. Eggs, milk, and meat supply data (g/capita/d) were also included to account for any confounding associated with consumption of animal source foods.

Mediating health indicator data for up to 168 countries from 2000 to 2013 were drawn from a UNICEF compiled Data Warehouse site (https://data.unicef.org/dv_index/) and the World Bank indicator data portal. We selected basic sanitation services (% of population) because of its known association with enteric disease and malnutrition.[47] Mortality datum was included for deaths under 5 years and deaths among children aged 5 to 14 years.

Proximal determinants in our model include the total and fish-specific nutrient availability or utilization. We extracted these data from the Global Nutrient Database.[48] A total of 394 food items from this database were matched to individual raw food items in the USDA Food and Nutrient Database for Dietary Studies and adjusted for inedible portions to derive nutrient concentrations in 195 countries from 1980 to 2013.[48] For this analysis, we included energy (kcal/capita/d), DHA (g/capita/d), choline (mg/capita/d), vitamin B_{12} (μg/capita/d), iron (mg/capita/d), and zinc (mg/capita/d). Nutrients selected for this analysis were based on the following criteria: concentrations of limiting nutrients in fish; evidence for population nutrient deficiencies, particularly in young child; and data availability.

The human health *outcomes* of population undernourishment and child anemia were most widely available across countries and years of analysis. Undernourishment (% of the population) data were downloaded from the FAO data portal for 165 countries between 2000 and 2013. The undernourishment indicator measures the proportion of the population whose dietary energy intake is insufficient to provide minimum energy requirements. The prevalence of anemia (% of children younger than 5) variable was extracted from the World Bank indicator database for 167 countries between 1993 and 2013. Anemia is defined as hemoglobin (Hb) levels $<$11.0 g/dL and severe anemia as Hb $<$ 7.0 g/dL.[49] Stunting prevalence, defined as percentage of children less than 5 years with height-for-age *Z* score <-2,[50] was extracted from UNICEF's Multi Indicator Country Survey data repository. These data were available from 120 countries, with an average of 3.2 observations per country over the time span studied. Although limited relative to the other health outcomes, it was determined to be sufficient for longitudinal modeling purposes.[51]

Analyses

The first step in the analytical process was examining the summary statistics for all variables to assess the availability of data longitudinally and determine indicator distributions. For variables that lacked a normal distribution, median values were reported in place of the mean and standard deviation. We then applied univariate statistics to examine the variables by child mortality ($\geq$50 deaths per 1000 live births) as has previously been applied in global modeling analyses to examine inequities in health and income.[40] This indicator allowed for an examination of preliminary associations between AASF intakes, confounding or exposure variables, and a critical child health outcome. In addition to the descriptive statistics reported in the main body of the manuscript, nutrient concentrations in representative AASF were provided in Supplemental Table 1 to compare nutrient levels across different AASF. Aquatic animal source foods were identified from the SAU database. Species from each category were selected to be "representative" based the highest volume catch data from fisheries and aquaculture, including formal/informal sectors and unreported catch for the years 2010 to 2014. Next, we reported the percentage of Dietary Reference Intakes (DRI) met by the representative AASF in Supplemental Table 2 in order to provide a frame of reference for how important the nutrient concentrations are relative to nutrition requirements.

For regression modeling, we applied generalized linear models (GLM) to test the hypothesis of apparent fish consumption's effects on health and nutrition outcomes while adjusting for multiple factors represented in the conceptual framework (Figure 1). The longitudinal GLMs that generate a matrix-weighted average of the between and within results are considered highly robust for examining temporal changes in AASF intakes in relation to nutrient and health outcomes.[51-53] Initially, we generated random-effect regression models to enable time-invariant factors and a more efficient estimator of the slope coefficients. However, fixed-effect models were instead applied after results from the Hausman specification test showed significant differences in the slope coefficients. Country identification was set as the panel variable and year, the time variable. In the first set of models, we examined total apparent per capita daily nutrient consumption as the dependent variable (DHA, choline, vitamin B_{12}, iron, and zinc) and apparent per capita daily consumption of various AASF types (all AASF, pelagic fishes, demersal fishes, mollusks, crustaceans, cephalopods, and freshwater fishes) as the independent variable. The consumption unit was consistent for all AASF types (g/capita/d), but varied by nutrient: DHA (g/capita/d); choline, iron, and zinc (mg/capita/d); and vitamin B_{12} (µg/capita/d).

In the second set of models, we tested 3 health outcomes (prevalence of undernourishment, prevalence of child stunting, and prevalence of child anemia) as the dependent continuous variables and, again, AASF type as the independent variables. All models included the same set of factors from the conceptual framework which were identified as potential confounders: apparent per capita consumption of other animal source foods (meat, milk, eggs), per capita kilocalorie energy supply, region, access to basic sanitation, and HDI. Per capita kilocalorie energy supply was included to isolate the effects of the micronutrients relative to macronutrients.[54] All non-normally distributed variables were first transformed to the natural logarithmic scale and then included in models, and regression diagnostics were run and inspected to ensure fit and assumptions were met. The Benjamini-Hochberg approach was applied to correct *P* values, accounting for risk of false discovery rate in multiple comparisons.[55] Maps were generated using ArcGIS software (ArcGIS Pro version: 2.2, Esri), and charts with longitudinal trends were generated using R software (version 3.6.2; R Foundation for Statistical Computing). Univariate and multivariate regression analyses were run in Stata software (version 16.0; Stata-Corp, College Station, TX, USA).

Results

In univariate analyses, countries with high mortality rates ($\geq$50 deaths to children younger than 5 years per 1000 live births) showed significant differences from countries with low child mortality rates (<50 deaths to children younger than 5 years per 1000 live births) across all categories of apparent fish consumption, except freshwater (Table 1). These differences were evident across all health outcomes and nutrient intakes, with the exception of protein. Although protein intake (which includes protein from plants and animal source foods) was generally lower in countries with high mortality, the difference with low mortality countries was not statistically significant. Aquaculture production was significantly greater in the low mortality group, but capture fisheries was nonsignificant.

Globally, the proportion of critical nutrients provided by AASF varied across countries and regions, but also showed different ranges in the quintiles (Figure 2A-E). In some countries, DHA and vitamin B_{12} were predominantly provided by AASF in the diet, evident in higher percentages. By contrast, iron, zinc, and choline showed lower ranges across countries globally, suggesting higher percentages of these nutrients derived from foods other than fish. Nutrient concentrations varied across the commonly produced fishes globally, with some fishes providing over the total daily DRI in 100 g (Supplemental Tables 1-2). The representative pelagic fish, clams, and mussels (100 g) exceeded 100% of the DRI for vitamin B_{12} in both men and women aged 19 to 30 years; all other AASF met greater than 50% of vitamin B_{12} requirements. Representative AASF (100 g) met choline DRI at lower percentages, though crustaceans met 19% of DRI for women, and 14.7% for men. Similarly for iron and zinc, there were differences observed across AASF with higher percentages of DRI met by mussels, all crustaceans but especially lobster, squid, carp, mackerel, and herring (Supplemental Table 2).

Data were available for 164 countries for temporal analyses and longitudinal modeling from 1993 to 2013, with 2241 observations (Table 2). Again, regional differences in the proportion of nutrient intakes provided by AASF were evident across the time frame (Figure 3A-E). Latin America and the Caribbean experienced declines in average apparent DHA intakes from AASF from 2002 to 2003, while South Asia saw marked increases in this time frame (Figure 3A). Higher proportions of choline intakes were observed in the East Asia and Pacific region comparatively, though all regions generally showed declining contributions from AASF for this nutrient (Figure 3B). Vitamin B_{12} averages were relatively constant across time and regions, with some fluctuation evident in South Asia and slight increases in North America (Figure 3C). The average percentage of iron and zinc apparent intakes from AASF was low, below 10%, across regions with constant levels in most regions observed over time (Figure 3d and e). North America showed a slight increase from 1999 to 2003 for iron, while the levels for both iron and zinc intakes in South Asia dropped from 2002 to 2003 but increased again around 2010.

After adjusting for covariates and correcting for multiple comparisons, apparent consumption of all AASF types were significantly associated with apparent DHA intakes. Apparent choline intakes showed positive associations with the combined category of AASF and all other types except mollusks. The combined AASF was significantly and positively associated with apparent vitamin B_{12} intakes, as were pelagic and demersal fishes and cephalopods. For apparent zinc intakes, all AASF, crustaceans, and cephalopods were significantly associated with the outcome. For iron, negative associations were evident for crustaceans and freshwater fishes, and positively associated with pelagic fish intakes. Nonsignificant associations were shown for zinc.

While there were fewer observations available for stunting prevalence (385 observations in 120 countries), adequate frequencies of statistics (3.2) per country were available for longitudinal modeling (Table 3). The combined AASF category and individual AASF types of pelagic, demersal, crustaceans, and mollusks showed inverse correlations with child stunting. Child anemia observations (2200 observations) were available for 163 countries. Crustaceans and mollusks showed negative associations with anemia, while pelagic and demersal fishes were positively correlated with the child health marker. We found a nonsignificant relationship between apparent aquatic animal food types and prevalence of undernourishment (proportion of the population meeting minimum caloric requirements).

Discussion

Drawing from a conceptual framework built from the evidence base, this study showed significant positive associations between apparent AASF consumption and vital nutrient intakes—DHA, choline, vitamin B_{12}, and zinc. Specific AASF types were also observed to correlate highly with apparent nutrient intakes: DHA (pelagic fishes, demersal fishes, crustaceans, mollusks, cephalopods, freshwater fishes), choline (pelagic fishes, demersal fishes, crustaceans, cephalopods, freshwater fishes), vitamin B_{12} (pelagic fishes, demersal fishes, cephalopods), and iron (pelagic fishes). The findings also revealed important relationships between apparent fish consumption and child health outcomes of anemia and stunting—not otherwise recognized in evidence base. Our results reinforced previous evidence for inequitable access to AASF and the need for policy supports to increase access across food systems.

We hypothesized that access to AASF at the national level would increase the total nutrient levels available for human nutrition. Although additional nutrients such as selenium, iodine, vitamins A and D, and calcium—which are all concentrated in AASF—would have merited investigation in this study, we selected DHA, choline, vitamin B_{12}, iron, and zinc for analyses due to concentrations of these limiting nutrients in AASF, evidence for nutrient inadequacies across populations, particularly in young children, and data availability. Moving forward, as data become available, additional nutrients could be added to these findings, as well as health outcomes for other vulnerable groups, including pregnant and lactating women and the elderly. Bioactive factors in AASF, beyond essential nutrients, are likely also important for human health outcomes and merit future study.[56] Nonetheless, these findings suggest AASF can play an important role in reaching World Health Assembly targets and the United Nations Sustainable Development Goals (SDGs), in particular those centered around ending hunger, improving nutrition, ensuring healthy lives, and promoting well-being (SDGs 2 and 3).

Docosahexaenoic acid, a predominant long-chain fatty acid in the brain, is important for brain development, anti-inflammatory processes, and other metabolic functions throughout the life course.[57,58] Aquatic foods are uniquely concentrated in DHA, though some animal source foods such as eggs have also been linked to DHA nutrient status.[20] From 1993 to 2013, AASF contributed to more than 60% of all DHA intake across all global regions (Figure 3A). Current dietary patterns with high ratios of n-6 to n-3 fatty acids may necessitate more dietary DHA to meet requirements for long-chain fatty acids and overcome the competition for enzymes needed in endogenous production.[59] Our findings showed a strong association across all AASF groups with apparent intakes of this nutrient. Animal foods broadly are the predominant source of vitamin B_{12} globally, though seaweed and mushrooms can also deliver this nutrient. Vitamin B_{12} is necessary for neurological functions and child growth, among other processes.[41] After adjusting for apparent consumption of meat, milk, and eggs, the combined AASF category, pelagic fishes, demersal fishes, and cephalopods were positively correlated with vitamin B_{12}. Several countries in Asia rely heavily on AASF for vitamin B_{12}, providing up to 72% of total intake in the region (Figure 2C).

Choline has more recently garnered attention for its importance in child growth and development.[60] The nutrient and downstream metabolites are necessary for cell membrane integrity, neurotransmission, and multiple methylation processes, among others. While animal source foods such as eggs and beef are recognized for being concentrated in choline, AASF are referenced to a lesser extent.[61] Trimethylamine *N*-oxide, a choline metabolite needed for osmoregulatory functions, has been studied in some fish.[62] Our analyses showed that 100 g of commonly caught AASF

Table 1. Summary Statistics (2013).[a]

	Global All Countries		Low child mortality (<50 deaths per 1000 live births)		High child mortality (>50 deaths per 1000 live births)		Low/high child mortality difference
	Obs.	Median or mean (SD)	Obs.	Median or mean (SD)	Obs.	Median or mean (SD)	*P* value
Health outcomes							
Undernourishment (% of population)	165	6.50	118	4.40	47	20.10	.000
Child anemia (% of children younger than 5)	167	25.70	124	23.20	43	62.50	.000
Child stunting (% of children younger than 5)	28	27.15 (14.55)	15	17.67 (11.82)	13	37.70 (9.35)	.000
Nutrient intake, apparent (per capita)							
Energy, kcal/d	171	119.68 (14.20)	123	123.12 (13.21)	48	110.88 (12.89)	.000
Protein, g/d	171	75.30	123	77.70	48	64.70	.065
DHA, g/d	173	0.08	124	0.09	49	0.05	.001
Choline, mg/d	173	237.91	124	263.33	49	169.23	.000
Vitamin B_{12}, μg/d	173	5.86	124	6.66	49	3.44	.000
Iron, mg/d	172	0.31	125	0.35	47	0.19	.053
Zinc, mg/d	173	10.35	124	10.70	49	9.77	.008
Fish consumption, apparent (g/capita/d)							
All aquatic animal source foods	175	37.87	125	46.65	50	23.50	.045
Pelagic	174	9.65	125	12.00	49	4.51	.001
Demersal	174	4.94	125	6.70	49	1.25	.000
Crustacean	173	1.27	125	2.05	48	0.13	.000
Mollusks	173	0.53	125	1.01	48	0.02	.000
Cephalopods	172	0.14	124	0.36	48	0.01	.000
Freshwater	175	5.63	125	5.36	50	7.14	.244
Other animal source food consumption, apparent g/d							
Meat	175	138.00	125	167.00	50	49.60	.000
Eggs	175	17.70	125	23.30	50	4.49	.000
Milk	175	262.00	125	358.00	50	82.10	.000
Fish production (metric tons)							
Aquaculture	175	3705.00	125	9080.00	50	713.90	.001
Capture fisheries	175	51724.00	125	51724.00	50	59058.50	.963
Water, sanitation, and hygiene							
Deaths due to diarrhea	168	3.27	125	1.48	43	9.61	.000

(continued)

Table 1. (continued)

	Global All Countries		Low child mortality (<50 deaths per 1000 live births)		High child mortality (>50 deaths per 1000 live births)		Low/high child mortality difference
	Obs.	Median or mean (SD)	Obs.	Median or mean (SD)	Obs.	Median or mean (SD)	*P* value
(% of children younger than 5)							
Access to basic sanitation (% of population)	172	87.85	125	93.90	47	33.10	.000
Aquatic health							
Ocean Health Index (scale of 0-100)	133	64.88 (8.61)	102	66.55 (7.72)	31	59.75 (9.21)	.000
Biodiversity	135	87.75	102	88.75	33	83.51	.000
Habitat conservation	135	92.31	102	93.89	33	84.85	.000
Species conservation	135	84.64	102	85.89	33	81.78	.014
Coastal protection	107	86.70	76	88.71	31	82.18	.249
Clean water	135	56.28 (14.51)	102	58.05 (14.21)	33	50.80 (14.27)	.003
Exclusive economic zone (km^2)	174	100282.00	125	127772.00	49	23112.00	.001
Human Development							
Human Development Index (scale of 0-1)	168	0.73	123	0.77	45	0.50	.000

Data sources: World Bank, FAO, UNICEF, Global Dietary Database, Sea Around Us, and Ocean Health Index.

[a]Median values were used when the data were not normally distributed.

Table 2. Summary Table for Longitudinal Models of Total Nutrient Intakes, 1993 to 2013.[a]

	DHA, g/capita/d (observations, n = 2193) (groups, n = 162)			Choline, mg/capita/d (observations, n = 2241) (groups, n = 164)			Vitamin B_{12}, μg/capita/d (observations, n = 2241) (groups, n = 164)			Iron, mg/capita/d (observations, n = 2,241) (groups, n = 164)			Zinc, mg/capita/d (observations, n = 2241) (groups, n = 164)		
	Coef (SE)	*P* value (corrected[b])	Overall model R^2	Coef (SE)	*P* value (corrected[b])	Overall model R^2	Coef (SE)	*P* value (corrected)	Overall model R^2	Coef (SE)	*P* value (corrected[b])	Overall model R^2	Coef (SE)	*P* value (corrected[b])	Overall model R^2
Fish consumption, apparent (g/capita/d)															
All aquatic animal source foods	0.571 (0.111)	.000	0.865	0.037 (0.010)	.000	0.561	0.057 (0.011)	.000	0.668	−0.010 (0.007)	.129	0.343	0.003 (0.004)	.435	0.526
Pelagic fishes	0.145 (0.008)	.000	0.387	0.016 (0.005)	.001	0.547	0.028 (0.006)	.000	0.662	0.007 (0.003)	.045	0.344	0.002 (0.002)	.405	0.519
Demersal fishes	0.046 (0.006)	.000	0.299	0.007 (0.004)	.050	0.545	0.008 (0.004)	.042	0.639	−0.003 (0.002)	.248	0.338	−0.001 (0.002)	.500	0.583
Crustaceans	0.016 (0.005)	.002	0.221	0.009 (0.003)	.003	0.559	0.001 (0.004)	.894	0.636	−0.006 (0.002)	.005	0.373	0.001 (0.001)	.470	0.566
Mollusks	0.021 (0.005)	.000	0.228	0.002 (0.003)	.436	0.532	−0.007 (0.004)	.045	0.579	−0.004 (0.002)	.056	0.327	−0.002 (0.001)	.218	0.562
Cephalopods	0.011 (0.005)	.013	0.156	0.007 (0.003)	.032	0.550	0.012 (0.004)	.002	0.566	0.001 (0.002)	.556	0.376	−0.002 (0.002)	.266	0.586
Freshwater fishes	0.093 (0.006)	.000	0.319	0.012 (0.004)	.001	0.544	0.007 (0.004)	.137	0.659	−0.007 (0.003)	.006	0.340	−0.002 (0.002)	.210	0.514

Abbreviations: AASF: aquatic animal source foods; DHA: docosahexaenoic acid.

[a]Generalized linear models (GLM) with fixed effects were applied for longitudinal modeling. Separate models were run for each AASF represented in the first column with outcome nutrients (total per capita consumption of nutrient) in the first row. Data were log-transformed where necessary to meet normality assumptions. All models adjusted for per capita meat consumption (g/d), milk consumption (g/d), egg consumption (g/d), total energy supply (kcal/d), region, access to basic sanitation, and Human Development Index (0-1).

[b]Coefficient for AASF apparent intakes was corrected for multiple comparisons.[55]

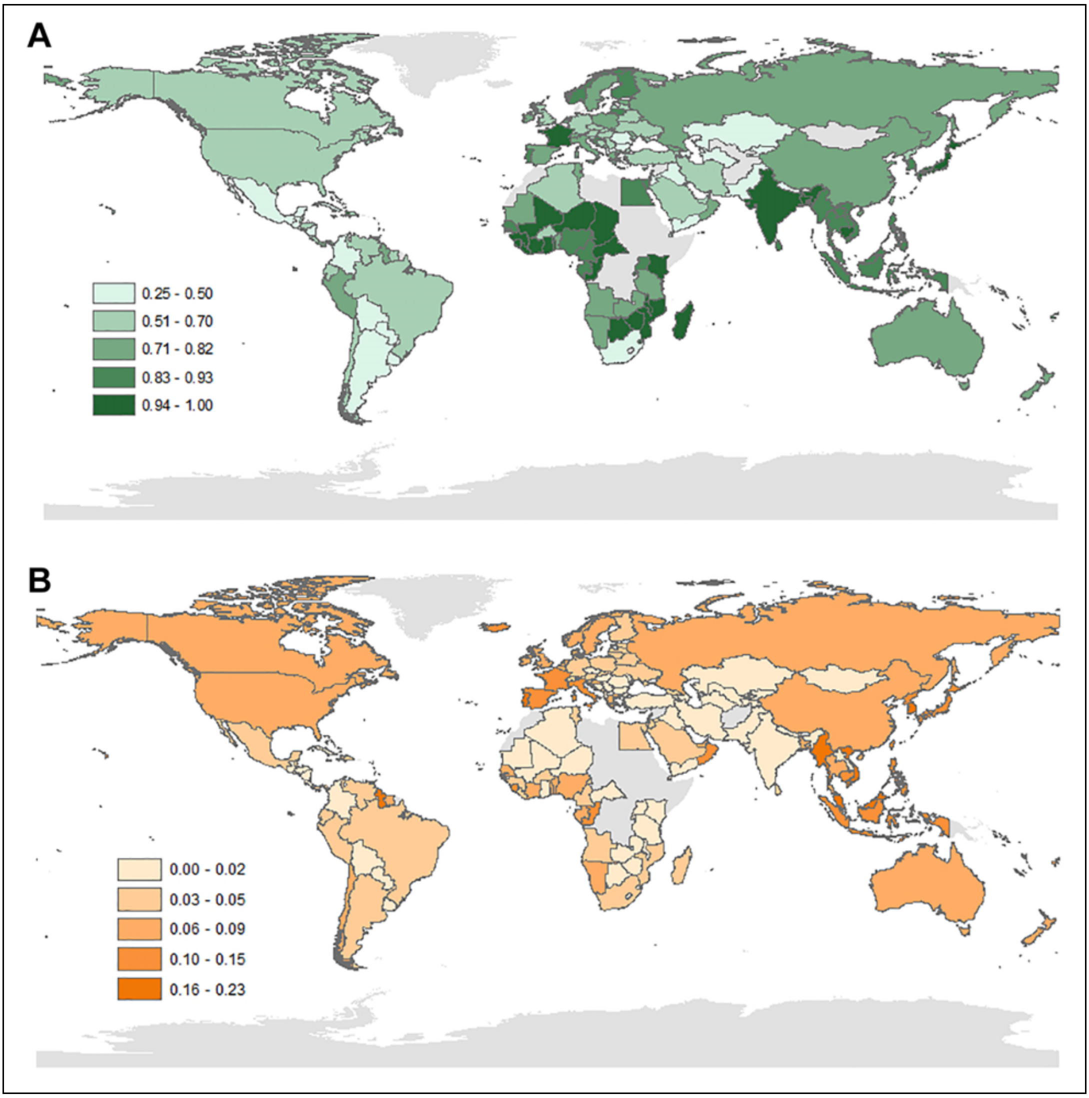

Figure 2. A, Proportion of total apparent docosahexaenoic acid intake provided by all aquatic animal source foods (AASF) by country. B, Proportion of total apparent choline intake provided by all AASF foods by country. C, Proportion of total apparent vitamin B_{12} intake provided by all AASF by country. D, Proportion of total apparent iron intake provided by all AASF by country. E, Proportion of total apparent zinc intake provided by all AASF by country. All maps represent apparent intake data from 2013.

types met adult requirements for choline at relatively high levels ranging from 7.7% (tilapia for men) up to 22.3% (salmon for women) (Supplemental Table 2). We hypothesized positive correlations for AASF and iron and zinc, but found largely nonsignificant findings. This might be in part explained by the mineral levels provided for plant-based foods in food composition databases that do not fully represent bioavailability or diet matrix dynamics. Moreover, iron levels are controlled homeostatically in fish and may not be found concentrated in the edible portions of fish represented in the data, for example, muscle tissue.[63]

Recent studies have recognized the potential for AASF and child nutrition.[13,14] We build on

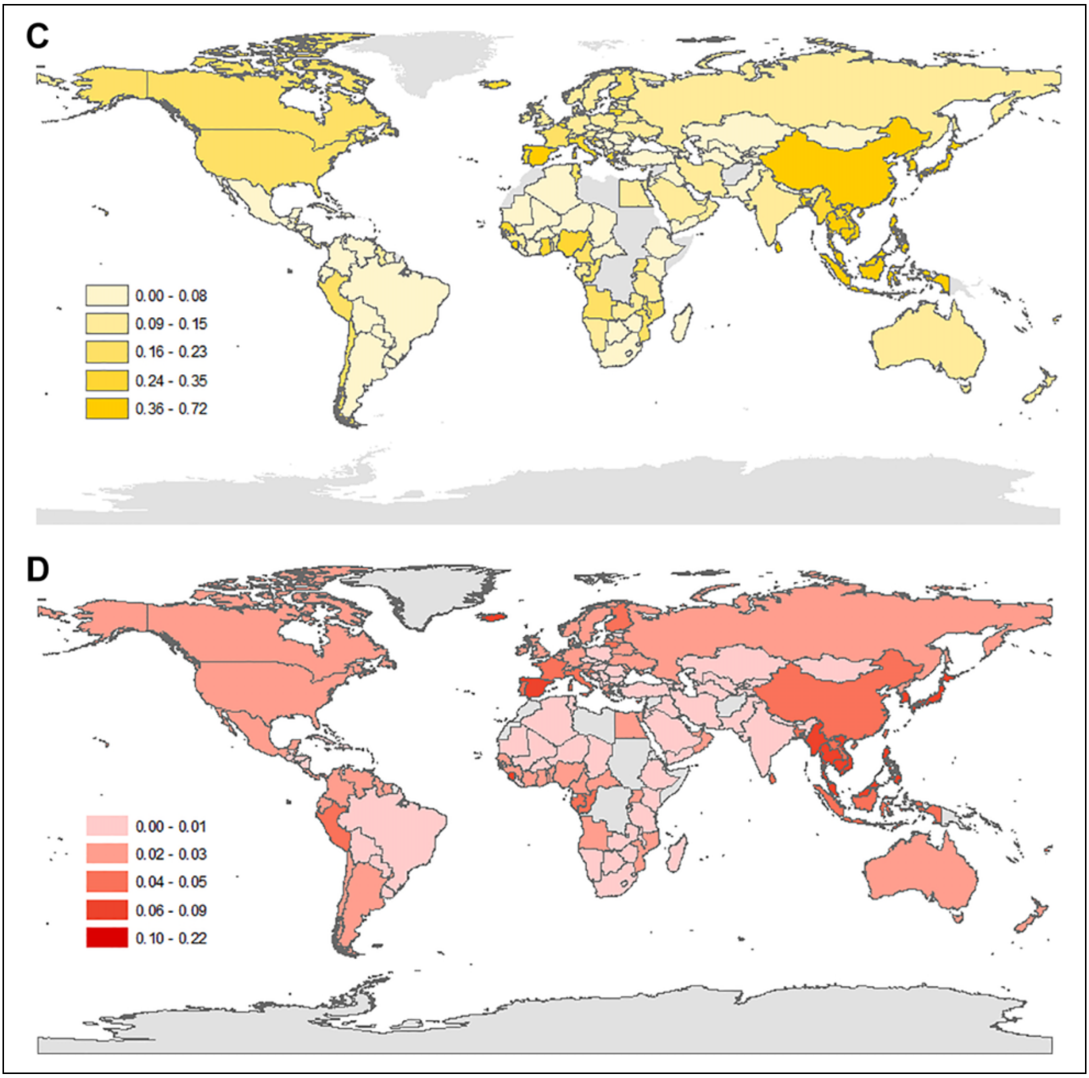

Figure 2. (Continued).

this evidence by uniquely showing positive associations with AASF and improved child health outcomes even after adjusting for factors known to influence health outcomes such as access to basic sanitation and HDI. Stunted growth affects 144 million young children around the world,[27] and over 250 million children are at risk of stunted development.[64] Stunting ranks as the highest priority nutrition target established by the World Health Assembly, yet few studies have successfully identified solutions to the multifactorial public health problem. Our study showed 3 AASF types (pelagic, demersal fishes, and crustaceans) and the combined category reduced prevalence of stunting over time, backed by biological plausibility. Anemia, prevalent in 2.63 billion people around the world, may be caused by deficiencies in nutrients concentrated in AASF, such as zinc, iron, copper, and vitamins A and B_{12}.[65] Our finding for crustaceans and mollusks as protective against child anemia merits further consideration in policy and programming. The nonsignificant finding for AASF and undernourishment is likely a result of the nutrition

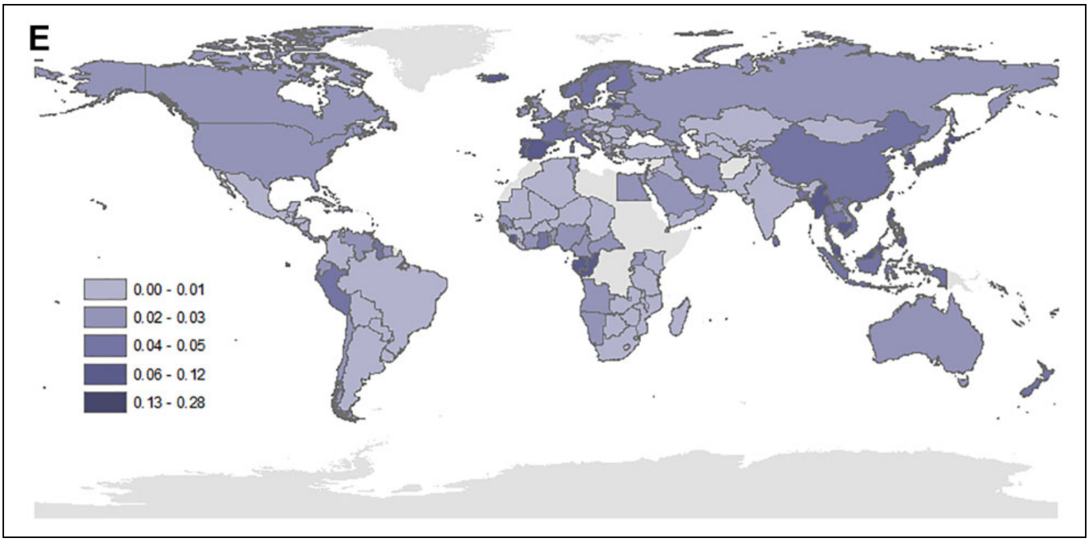

Figure 2. (Continued).

transition in many countries and a more stable, sufficient supply of calories for consumption in populations.[27]

Integral to our original study aims was the investigation of pathways from aquatic health to human health, as represented in our conceptual framework (Figure 1). Unfortunately, nationally representative data such as the Ocean Health Index were available only in recent years and not representative of aquatic health in landlocked nations. In our view, there is an imperative to consider sustainable aquatic food production systems in tandem with human nutrition recommendations, a neglected area in the evidence base.[30] One-third of global fisheries are harvested at biologically unsustainable levels,[1] and biodiversity has seen marked declines in aquatic ecosystems over the past 3 centuries.[66,67] Two recent studies related to nutrition and the environment concur on the importance of AASF. The EAT-Lancet commission recommended fish but covered more extensively the climate change and environmental impacts of livestock-derived foods and agriculture.[2] Another study showed variability in crucial fish nutrients may be driven by ecosystem characteristics such as fish diet, thermal regime, and energetic demand, though nutritional relevance of these differences was not fully addressed.[13]

Small pelagic fish offer an opportunity to both meet nutrient needs in low-resource populations[68,69] and have a lesser environmental impact relative to other animal source foods.[70] We showed that pelagic fish consistently predicted increased critical nutrient intakes and reduced child stunting, suggesting potential for this AASF type in sustainable, healthy food systems. Increasing sustainable production in small- and medium-scale fisheries could lead to improved access in vulnerable populations. Mollusks also showed positive effects on nutrient intakes and child health in our study. These organisms provide critical ecosystem services, and production systems impose lesser environmental impacts.[70] Questions remain about the accuracy of mollusk production data[71] as well as palatability for infants and young children.[72] More research is needed at the intersection of aquatic health and human health.

We acknowledge there were limitations present in this study. First, our models were likely not inclusive of all the factors driving the complex health conditions of stunting and anemia.

Although we aimed to build a data set based on existing evidence, some determinants were not available longitudinally with sufficient frequencies. We explored inclusion of other factors likely mediating pathways to health and nutrition

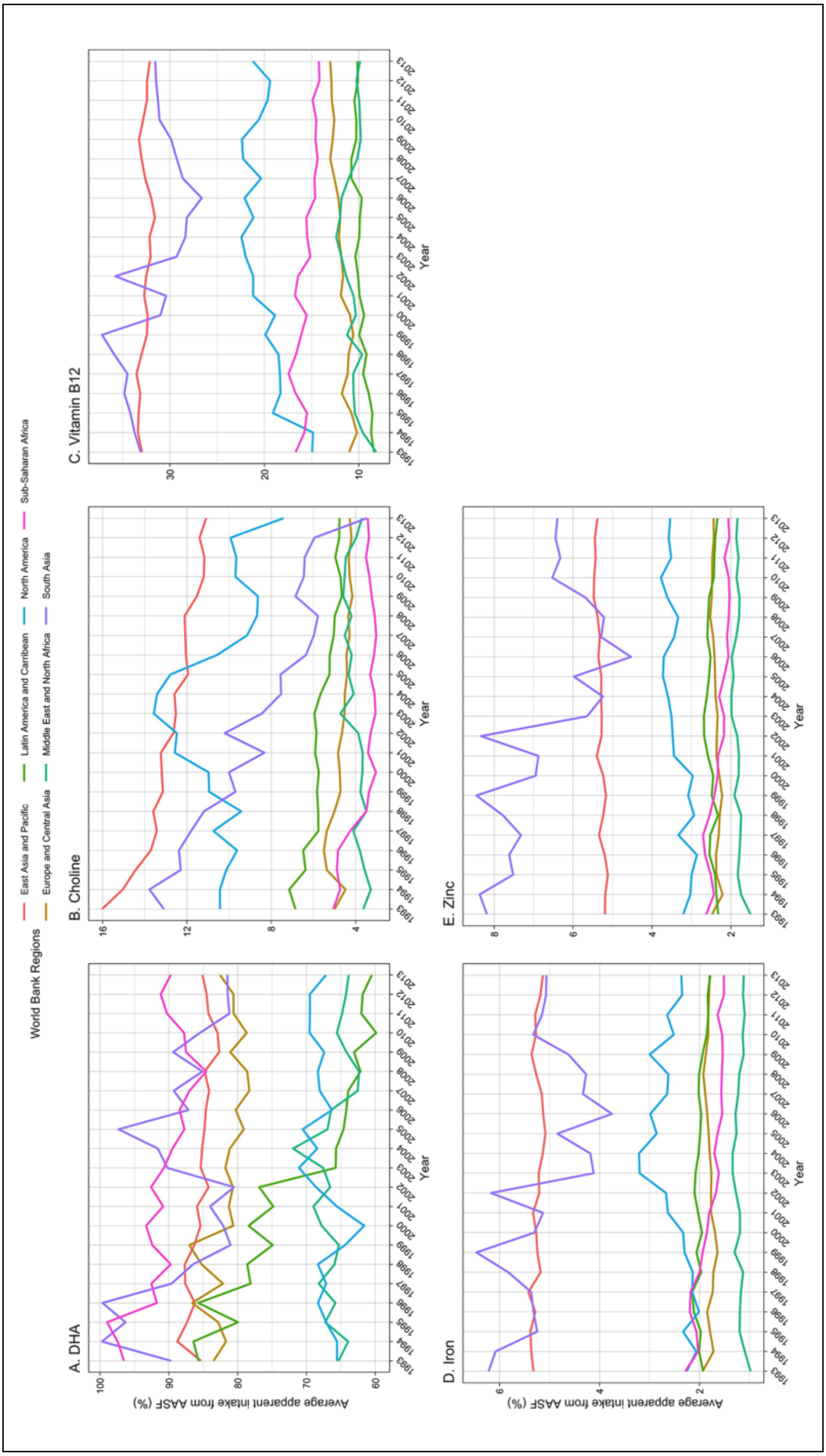

Figure 3. A-E, Regional trends in apparent nutrient intakes provided by all aquatic animal source foods (1993-2013).

Table 3. Summary Table for Longitudinal Models of Health Outcomes, 1993 to 2013.[a]

	Undernourishment (observations, n = 2135) (groups, n = 158)			Child stunting (observations, n = 385) (groups, n = 120)			Child anemia (observations, n = 2200) (groups, n = 163)		
	Coef (SE)	*P* value (corrected[b])	Overall model R^2	Coef (SE)	*P* value (corrected[b])	Overall model R^2	Coef (SE)	*P* value (corrected)	Overall model R^2
Fish consumption (g/capita/d)									
All aquatic animal source foods	−0.009 (0.010)	.411	0.799	0.949 (0.844)	.262	0.617	−0.004 (0.009)	.567	0.520
Pelagic	−0.006 (0.005)	.260	0.795	0.229 (0.357)	.521	0.630	0.004 (0.004)	.397	0.530
Demersal	0.001 (0.004)	.810	0.776	0.146 (0.312)	.641	0.699	0.008 (0.003)	.010	0.600
Crustaceans	−0.001 (0.003)	.866	0.788	−0.582 (0.283)	.041	0.622	−0.005 (0.003)	.006	0.521
Mollusks	0.001 (0.003)	.761	0.783	0.075 (0.306)	.806	0.649	−0.007 (0.003)	.008	0.430
Cephalopods	0.004 (0.004)	.225	0.740	0.669 (0.342)	.052	0.620	0.003 (0.003)	.342	0.546
Freshwater	−0.002 (0.004)	.636	0.791	−0.349 (0.342)	.309	0.646	0.001 (0.003)	.845	0.525

[a]Generalized linear models (GLM) were applied for longitudinal modeling. Separate models were run for each AASF represented in the first column with outcome nutrients (total per capita consumption of nutrient) in the first row. Data were log-transformed where necessary to meet normality assumptions. All models adjusted for per capita meat consumption (g/capita/d), milk consumption (g/capita/d), egg consumption (g/capita/d), total energy supply (kcal/capita/d), region, access to basic sanitation, and Human Development Index (0-1).

[b]Coefficient for AASF apparent intakes was corrected for multiple comparisons.[55]

outcomes, such as markers of breastfeeding and complementary feeding variables. However, these data were not available at sufficiently high frequencies for use in longitudinal modeling (3+ observations per country over time).[51] Another example related to limited data availability would be the Gini coefficient, which is used as a proxy marker of economic inequality. The HDI index, however, allowed for some analyses of economic disparities.

Second, AASF consumption and nutrient intakes could more ideally be modeled at the individual level with considerations of inter- and intra-household food allocations. However, several recent analyses of dietary intakes of AASF have used similar data from food balance sheets to estimate population-level access,[1,13,14] and others have validated these data against actual individual-level intakes for estimating nutrient intakes.[46] We also recognize that apparent consumption data may not include production from small- and medium-sized fishers or may underestimate certain AASF types.[71] Finally, as noted above, our team initially aimed to examine aquatic health in the pathways to human nutrition, but data were only available in recent years. Despite these limitations, the robust longitudinal models, accounting for important confounding factors (observed and residual) and conservatively estimated, suggested an important role for AASF in human health and nutrition.

The world has achieved progress in human health indicators and livelihoods over the past century, though there have been major setbacks by the unprecedented COVID-19 pandemic.[27] Our findings highlight how AASF can make crucial contributions to human health and development but also the significant differences that persist between countries and regions. These differences reinforce the need for renewed global and national efforts to enact policies and support programs focused on strengthening aquatic food availability, access, stability, safety, and utilization.[73] Such efforts could include bolstering biodiversity and habitat preservation initiatives, supporting integrated localized livelihood programs that help small-scale fishers increase income and take home catch while mitigating ecological impacts, and reinforcing and expanding aquatic food value chains.[74,75] Nutrition-focused social marketing could be employed to expand awareness around the importance to fish consumption, increase utilization of specific species to address localized health conditions, and foster sustained behavior change.[76]

Additional research and policies are needed to address cost barriers for low-income communities, reduce postharvest loss and contamination issues, and increase access to production inputs for small fishers and farmers.[4,71,77,78] Ultimately, convergence around aquatic and human health goals will be necessary to ensure fish in sustainable healthy diets globally.

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Authors' Contribution

LI, IB, and AH conceived and designed the study. FC compiled and conducted some data analyses. LI wrote the manuscript with contributions made by IB and AH. RC, MC, and EAG supported the data analyses and editing processes. All authors have read and approved the final manuscript.

Declaration of Conflicting Interests

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Supplemental Material

Supplemental material for this article is available online.

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