LETTER

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Harnessing global fisheries to tackle micronutrient deficiencies

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Micronutrient deficiencies account for an estimated one million premature deaths annually, and for some nations can reduce gross domestic product[1,2] by up to 11%, highlighting the need for food policies that focus on improving nutrition rather than simply increasing the volume of food produced[3]. People gain nutrients from a varied diet, although fish—which are a rich source of bioavailable micronutrients that are essential to human health[4]—are often overlooked. A lack of understanding of the nutrient composition of most fish[5] and how nutrient yields vary among fisheries has hindered the policy shifts that are needed to effectively harness the potential of fisheries for food and nutrition security[6]. Here, using the concentration of 7 nutrients in more than 350 species of marine fish, we estimate how environmental and ecological traits predict nutrient content of marine finfish species. We use this predictive model to quantify the global spatial patterns of the concentrations of nutrients in marine fisheries and compare nutrient yields to the prevalence of micronutrient deficiencies in human populations. We find that species from tropical thermal regimes contain higher concentrations of calcium, iron and zinc; smaller species contain higher concentrations of calcium, iron and omega-3 fatty acids; and species from cold thermal regimes or those with a pelagic feeding pathway contain higher concentrations of omega-3 fatty acids. There is no relationship between nutrient concentrations and total fishery yield, highlighting that the nutrient quality of a fishery is determined by the species composition. For a number of countries in which nutrient intakes are inadequate, nutrients available in marine finfish catches exceed the dietary requirements for populations that live within 100 km of the coast, and a fraction of current landings could be particularly impactful for children under 5 years of age. Our analyses suggest that fish-based food strategies have the potential to substantially contribute to global food and nutrition security.

Uneven progress in tackling malnutrition has kept food and nutrition security high on the development agenda globally[1,3]. Micronutrients, such as iron and zinc, are a particular focus; it is estimated that nearly 2 billion people lack key micronutrients[1], underlying nearly half of all deaths in children under 5 years of age[1] and reducing gross domestic product in Africa[2,3] by estimates of up to 11%. Consequently, efforts to tackle malnutrition have shifted from a focus on increasing energy and macronutrients (for example, protein) to ensuring sufficient consumption of micronutrients[3]. People gain nutrients from a mixture of locally produced and imported food products. Fish, which are harvested widely and traded both domestically and internationally, are a rich source of bioavailable micronutrients; these micronutrients are often deficient in diets that rely heavily on plant-based sources[6,7]. Fish could therefore help to address nutritional deficiencies if there are sufficient quantities of fishery-derived nutrients accessible in places in which deficiencies exist. However, addressing this major food policy frontier has been complicated, in part because the nutrient composition of fish varies considerably among species and data remain sparse for most species[5].

Here we determine the contribution that marine fisheries can make to addressing micronutrient deficiencies. First, using strict inclusion protocols, we developed a database of 2,267 measures of nutrient composition from 367 fish species for 43 countries for 7 nutrients that are essential to human health: calcium, iron, selenium, zinc, vitamin A, omega-3 fatty acids (n-3 fatty acids) and protein. We then gathered species-level environmental and ecological traits that capture elements of diet, thermal regime and energetic demand in fish[8,9] to develop a series of Bayesian hierarchical models that determine drivers of nutrient content (Methods).

Our models successfully predicted nutrient concentrations, with posterior predictive distributions consistently capturing both the observed overall mean and individual values of each nutrient[10] (Extended Data Figs. 1, 2 and Methods). We show that calcium, iron and zinc—nutrients that are critical for growth, health and human capital[11,12]—were found at higher concentrations in tropical fishes (Fig. 1). Tropical soils are often zinc- and calcium-deficient, because these nutrients are easily exported from land to sea during the strong pulse rainfall events that are common in the tropics; this process may increase the levels of these nutrients in marine foodwebs[13]. Higher concentrations of calcium, zinc and omega-3 fatty acids were found in small fish species. Consumption of small fishes is promoted, particularly in Asia and Africa[14,15], as a rich source of micronutrients and, although these high concentrations are often linked to the practice of consuming whole fish[15], we also detected elevated levels of these nutrients in muscle tissue of smaller fish.

Higher concentrations of omega-3 fatty acids—which support neurological function and cardiovascular health[16]—were found in species that are pelagic feeders, from cold regions and approach their maximum size more slowly (Fig. 1). Pelagic feeders consume plankton, the main source of omega-3 fatty acids in aquatic systems[17], whereas species adapted to a colder thermal regime have a greater need for energy storage compounds and fat, including fatty acids[18]. Selenium concentrations were higher in species found at greater depths and lower for species found in tropical waters, whereas lower concentrations of vitamin A were found in species from cold regions, with high trophic levels and short, deep body shapes. Concentrations of protein were greater in species with higher trophic levels and those with a pelagic feeding pathway, and lower in species found in cold regions and with a flat or elongated body shape (Fig. 1).

Given the alignment between our posterior predictions and observed data (Extended Data Fig. 2), we used our trait-based models of nutrient concentration, and traits for species within the landed catch of the world's marine fisheries[19], to produce global estimates for nutrient concentrations (Fig. 2) and nutrient yields (Extended Data Fig. 3) of

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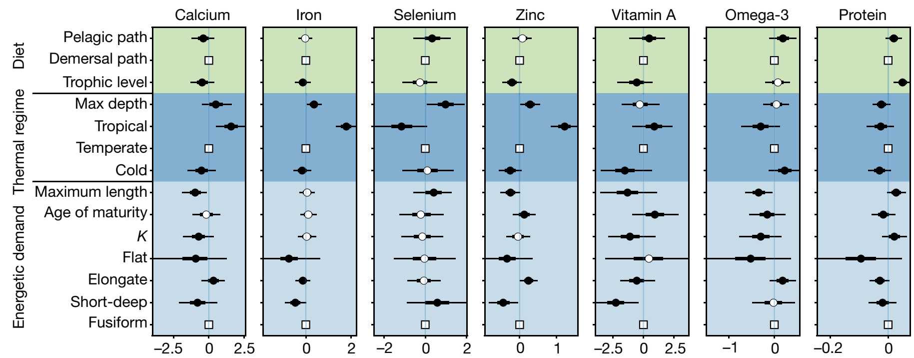

Fig. 1 | Bayesian hierarchical predictive model of nutrient concentrations in fish. Standardized effect sizes for environmental and ecological drivers of nutrient concentrations for diet, thermal regime and energetic demand. Parameter estimates are Bayesian posterior median values, 95% highest posterior density uncertainty intervals (thin lines) and 50% uncertainty intervals (thick lines). Black dots indicate that the 50% uncertainty intervals do not overlap zero, indicating that more than 75% of the posterior density was either positive or negative, whereas open circles indicate that the 50% uncertainty intervals overlap zero. Open squares indicate the baseline category in the statistical model. *K* denotes parameter *K* of the von Bertalanffy growth equation. Underlying sample sizes are as follows: calcium, $n = 170$ biologically independent samples; iron, $n = 173$; selenium, $n = 134$; zinc $n = 196$; vitamin A, $n = 69$; omega-3 fatty acids, $n = 176$; protein, $n = 627$. Effect sizes are not on a common *x*-axis scale for clarity of presentation.

marine fisheries (Methods). These data reflect catches from within the economic exclusive zone (EEZ) of each country that are landed and consumed domestically, landed outside the country by foreign fleets or traded internationally[19]. We include both officially recorded and reconstructed unrecorded catches (see Methods for comparisons), but do not include discards. There was no correlation between the concentration of nutrients per unit catch and either total nutrient yield or total fishery yield (Extended Data Fig. 4), suggesting that the nutrient quality of fishery landings is influenced by species composition rather than simply by quantity landed. Therefore, fish-based food policy guidelines[20] should specify the types of fish that should be consumed.

High concentrations of iron and zinc (>2.5 mg per 100 g and >1.8 mg per 100 g, respectively, of the raw, edible portion of the fish) are found in species caught in a number of African and Asian countries (Fig. 2 and Extended Data Table 1)—the same regions that are at greatest risk of deficiencies in these nutrients[11,12]. This suggests that, in areas with critical public health concerns, a single portion (100 g) of an average fish could provide approximately half of the recommended dietary allowance (RDA) of iron and zinc for a child under 5 years of age. Calcium concentrations are high (>200 mg per 100 g of the raw, edible portion of the fish) in species caught in the Caribbean region, an area in which there is a high prevalence of deficiency[11], again highlighting

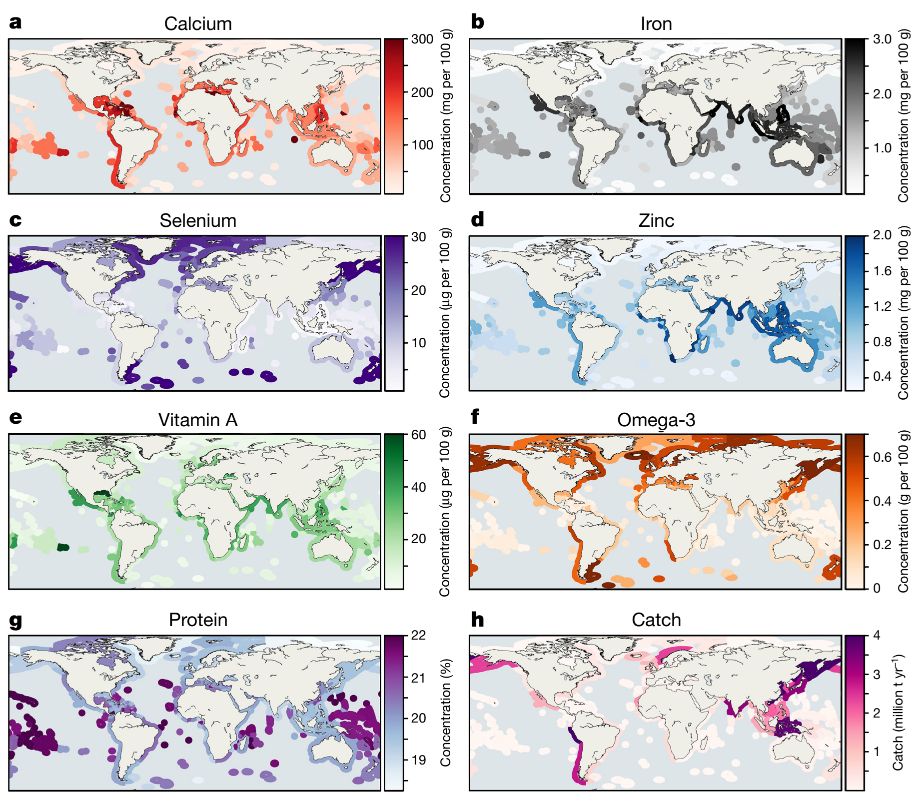

Fig. 2 | Nutrient concentration of fisheries and total catch by EEZ. Data are based on annual catch composition[19] between 2010 and 2014. **a**–**g**, Plots show the concentrations of calcium (in mg per 100 g), iron (in mg per 100 g), selenium (in µg per 100 g), zinc (in mg per 100 g), vitamin A (µg per 100 g), omega-3 fatty acids (g per 100 g) and protein (%) in each EEZ. **h**, Total catch (in million tonnes (t) per year (yr)). Data are plotted at the scale of EEZ areas as previously defined[19]. Base maps were generated using the matplotlib library[31] (https://matplotlib.org) in Python.

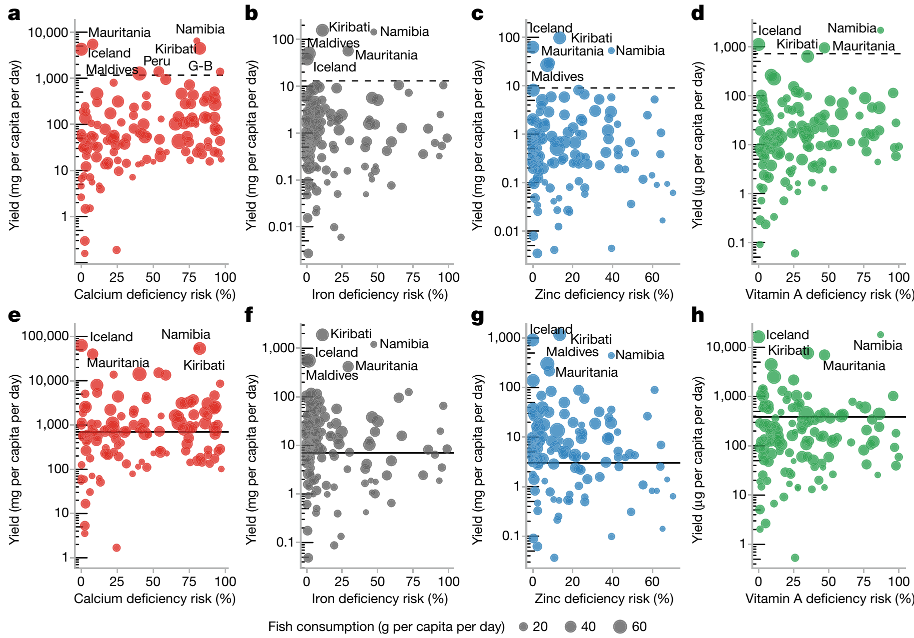

Fig. 3 | The contribution that fisheries could make to closing dietary nutrient gaps. a–h, Nutrient yield per capita for coastal residents (**a**–**d**) and per capita for coastal residents under 5 years old (**e**–**h**) by dietary deficiency risk[12] for all coastal countries on the basis of the concentrations of calcium (**a**, **e**), iron (**b**, **f**), zinc (**c**, **g**) and vitamin A (**d**, **h**). The size of the circle indicates the national consumption of seafood (g per capita per day)[25]. Solid horizontal lines denote the RDA for children under 5 years of age; dotted horizontal lines denote the RDA for the rest of the population[26]. G-B, Guinea-Bissau.

the potential contributions fish can make to targeted health interventions in these areas. Concentrations of selenium and omega-3 fatty acids are high (>25 µg per 100 g, >0.5 g per 100 g, respectively, of the raw, edible portion of the fish) in fish species caught from high-latitude regions, including parts of Russia, Canada, Northern Europe and Alaska (Fig. 2 and Extended Data Table 1). This is consistent with the observation that omega-3 fatty acids are abundant in marine foods consumed by Arctic indigenous populations such as the Inuit of Nunavik, Canada[21]. Furthermore, these high selenium concentrations are found in some of the areas in which selenium deficiencies are common[22], yet a single portion of an average fish (Methods) from these waters contains enough selenium to meet the daily RDA for a child under 5 years of age, and nearly half of the selenium required by adults.

Although we recognize the challenges of the sustainability of fisheries and potential climate-driven declines in yields[23], the availability of high concentrations of key nutrients in areas that are at risk of nutrient deficiencies suggests that marine fisheries could be critical in helping to close nutrient gaps. To assess this, we calculated nutrient yields per capita using the estimated national nutrient yield in our models and the human population living within 100 km of the coast (which represents 39% of the global population[24]; Methods). We focus on calcium, iron, zinc and vitamin A, which constitute a major burden of malnutrition, particularly within low-income countries[1,11,12]. For each nutrient and country, we compare this to published dietary deficiency risks[12], seafood consumption rates[25] and RDA[26] (Methods). We specify RDA averaged for the population aged 5 years and older, and for children between 6 months and 4 years of age (Fig. 3). Children under 5 years of age represent a vulnerable proportion of the population, in which interventions have the greatest potential long-term effects on growth, development and health.

Fish-derived contributions of calcium, iron, zinc and vitamin A, for a large number of countries, could provide a considerable proportion of the RDA for their coastal populations. For eight countries, these yields exceed requirements for at least one of these nutrients (Fig. 3a–d). Of those countries, only Iceland has mild dietary deficiency risks (<20%)[12,27] (Fig. 3a–d). Very high nutrient yields and prevalence of dietary deficiency risk coincide for at least two nutrients in Namibia, Mauritania and Kiribati (Fig. 3a–d). In these countries, a small fraction of the available production from fisheries has the potential to close nutrient gaps. For example, the dietary risk of iron deficiency in Namibia is severe (47%)[12]; however, only 9% of the fish caught in the EEZ of Namibia is equivalent to the dietary iron requirements for the entire coastal population.

Fisheries clearly have an important place in food and nutrition policies. This contribution could be particularly important if targeted to the most vulnerable groups within society, such as children under 5 years of age, capturing the period when most of the faltering growth occurs. More than 50% of coastal countries have moderate-to-severe deficiency risks (>20%)[12,27] and nutrient yields that exceed the necessary RDA for all children under 5 years of age in the coastal population (Fig. 3e–h). Notably, in Kiribati the dietary risk of calcium deficiency is severe (82%)[12]; however, only 1% of fish caught in the EEZ of Kiribati is equivalent to the calcium requirements for all children under 5 years of age. For a further 22 countries, predominantly in Asia and west Africa, the dietary requirements for all children under 5 years of age is equivalent to 20% or less of current catches. The fact that targeted approaches could require only a fraction of current landings to alleviate nutrient deficiencies suggests that a nutrition-sensitive fishery approach could align with environmental efforts to reduce current harvest levels.

Nutrient surpluses of some coastal countries in which nutritional needs are not being met highlight that large yields do not necessarily lead to food and nutrition security. International fishing fleets and trade deals[19], physical, economic or institutional access to the right food[28], food preferences and cultures, waste and reduction to fish oil for animal feed[29] can all act as barriers or avenues to these resources meeting local nutritional needs. For example, international trade and foreign fishing are dominant in countries with large nutrient yields, in which high rates of dietary deficiency risks exist (Extended Data Table 2 and Methods). Understanding why, when there is an adequate supply of nutrients, populations are still at risk of dietary deficiency will require a multiscale socio-economic research agenda that situates fish in the broader food system and accounts for patterns of production, distribution, preparation and consumption.

Our results identify the current world distribution of nutrients from the catches of fisheries. In doing so, we demonstrate that, for a number of nutrients that are essential to human health, current production has the potential to considerably and positively influence the nutritional status of some of the most nutrient-deficient countries globally, even at reduced catch levels. Given that fish are in many instances a more affordable animal-based food source[4] with a lower environmental impact[20], and the fact that nutrient supplies from fisheries are comparable to those from other animal-based food sources[30], fisheries should be a core component of food and nutrition policies. However, current fishery policies remain orientated towards maximizing profit or yield. Reorientating fisheries policies towards a more efficient and equitable distribution of consumption, aimed at meeting local nutritional needs, could close nutrient gaps in geographies of critical food and nutrition concern such as west and sub-Saharan Africa. Achieving this will require concerted efforts to scale approaches that protect local nutritional benefits, and to understand how policies can be redirected towards desired food and nutrition outcomes. Ultimately, multiple approaches and actors must work together to tackle malnutrition[20]. Fisheries should therefore form part of an integrated approach that is informed by health, production, development and environmental sectors.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41586-019-1592-6.

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METHODS

Data reporting. No statistical methods were used to predetermine sample size. The experiments were not randomized, and investigators were not blinded to allocation during experiments and outcome assessment.

Finfish nutrient content database. We compiled a database of 4,188 measures of nutrient composition from 419 finfish species for 45 countries, based on the following sources. (1) Thomson Reuters Web of Science search of the scientific literature published between the years 1980 and 2015, using the search terms 'content' or 'compos*', and 'nutrition* NEAR content NEAR fish* AND Marine*'. (2) FAO/INFOODS food composition for biodiversity databases[32–34] produced by the Food and Agriculture Organisation (FAO) of the United Nations. (3) Key informant grey literature sources of finfish nutrient composition databases identified through snowballing of nutrition experts.

We extracted quantitative nutrient data from these sources on 14 nutrients essential to human health[35]; including, protein, minerals (iron, calcium, zinc, phosphorous, magnesium and selenium), vitamins (vitamin A and B12) and fatty acids (polyunsaturated fatty acid (PUFA); the PUFA subsidiaries (omega-6 and omega-3), and the omega-3 subsidiaries (eicosapentaenoic acid and docosahexaenoic acid). We included only sources in English that were fully traceable and accessible and based on wild caught, marine finfish species, and in which analyses were conducted on fresh samples, the nutrient content was reported as a quantitative measure and samples were taken from either the muscle, fillet, 'edible portion' or whole body.

Where necessary, nutrient quantities were standardized into g per 100 g, mg per 100 g or μg per 100 g. We followed the FAO/INFOODS guidelines[36] for fatty acid conversions from percentage of total fatty acids to g per 100 g. Differences in sampling (for example, wet weight, dry weight, whole, whole minus parts or muscle) were recorded and controlled for in our analyses (Extended Data Fig. 5).

Of the 14 nutrients of interest, 7 had sufficient replication for our analyses: calcium, iron, selenium, zinc, vitamin A, PUFAs and protein. We focused our PUFA on n-3 fatty acids (that is, omega-3 fatty acids) because fish are known to be the richest source of omega-3 fatty acids, and few other sources exist[37]. The final database for the 7 nutrients used here consisted of 2,267 individual samples, from 367 species of finfish, spanning 43 countries.

Traits database. Drawing on a body of theoretical, analytical and empirical research in fish ecology[8,9,38–40], we identified characteristics related to diet, energetic demand and thermal regime that are likely to influence nutrient quality in fish. We selected a trait-based approach to enable mechanisms of nutrient concentrations to be explored. However, we also allowed for inter-order variation among species in the structure of our hierarchical model to account for phylogeny[5].

We used FishBase[41] to source trait data on the identified characteristics for fish species in our nutrient database and the 'Sea Around Us Project' (SAUP) landings data. An underlying assumption of this approach is that trait values are fixed for a species and do not change in time or space. Thus, spatial trends in nutrient concentrations are representative of shifts in the composition of the catch. Where trait data were missing for a particular species, genus-level averages were calculated (mean for continuous traits and mode for categorical traits). Where genus-level averages were not available owing to missing data, family-level average values were calculated. Traits were selected carefully to capture distinct elements of the diet, energy demand and thermal regime of a species.

Diet. Diet directly influences the nutrient content of organisms through the concentration of bioavailable nutrients in their food[9,42]. Two diet variables were sourced for each species: feeding pathway and trophic level. For feeding pathway, each species was first categorized based on their food source, as listed under 'ecology', 'diet' and 'food items' in FishBase[41]. These food sources were then classified as either from a predominantly pelagic pathway (for example, planktonic feeding) or benthic pathway (for example, benthic algae and crustaceans). For carnivores, the prey items needed to be assessed in the same way to see whether they reflect pelagic or benthic pathways. This represents the two dominant energy pathways for fish feeding in the marine environment, which are likely to influence the accumulation of nutrients[43]. Trophic level, directly extracted from FishBase[41], indicates how high in the foodweb a species is feeding, which can be important for the bioaccumulation or bioreduction of some nutrients[44].

Thermal regime. The thermal regimes of water depth and the major geographical zones of the world influence a range of processes that may determine the assimilation or availability of nutrients (for example, metabolism of organisms[45], and precipitation-driven run-off of terrestrial nutrient sources[46]). We capture maximum depth and geographical zone for each species. Because temperature declines with depth, the maximum depth trait is correlated with temperature requirements[47]. Geographical zone was captured with four thermal regimes; tropical, subtropical, temperate and cold. The 'cold' category includes polar and deep-water specialist species that are adapted to very cold water.

Energetic demand. The allocation of energy and resources, including nutrients, to different aspects of life history—for example growth, reproduction or somatic storage—is fundamental in animals[48]. Four variables were included to represent energetic demand: maximum length, which is allometric with a range of characteristics such as home range and metabolism; age at maturity, which captures the age at which resources are allocated to reproduction; K, which captures the rate at which maximum size is approached and thus how energy is dedicated to body mass accumulation; and body shape, which influences how a fish moves through its environment. All variables were extracted from FishBase[41]. Four categories of body shape were used; flat, elongate, short and deep, and fusiform. Eel-like species ($n = 5$ in our data) were grouped with elongate. Natural mortality and reproductive guild were not included owing to limited data on these life-history traits across species.

Control variables. Although fish trait covariates were of substantial interest, other covariates related to sampling were not. However, we included these 'nuisance parameters', because they could have potentially biased our results owing purely to sampling (Extended Data Fig. 5). Therefore we controlled for variability in reported preparation (wet weight or dry weight) and sampling (whole, whole minus parts or muscle), source (Web of Science, key informant grey literature or FAO/INFOODS), by representing these conditions as covariates in our model. Finally, although multiple habitat categories are recorded in FishBase, it was unclear how this covariate would determine nutrient yield within a given ecosystem; however, we believe it might affect sampling and therefore chose to include it as a nuisance parameter.

Predictive model of nutrient concentrations. We developed a series of Bayesian hierarchical models to predict the nutrient quality of marine finfish species, based on their environmental and ecological traits. None of the traits was sufficiently collinear to be problematic for the model. In cases in which nutrient data were recorded at the genus level, these data were retained in the analysis if there were no species data for that genus within the dataset. If species-level data were available from a given genus, any genus-level data were removed owing to non-independence among data points. We ran two sets of models, one in which covariates were unstandardized and a second set in which continuous explanatory variables were standardized by subtracting their mean and dividing by two standard deviations. The dependent variables and maximum depth, maximum length and growth rate were log-transformed to normalize the spread of these highly skewed distributions. Our statistical models were hierarchically structured, allowing for inter-order differences that were otherwise unaccounted for in our trait-focused models; this also provided posterior predictive distributions for unobserved species that represented the full uncertainty underlying their estimation. For each nutrient, our basic linear model structure was:

$$\mu = \beta_{0,\mathrm{ORD}} + \beta_{1,\mathrm{HAB}} + \beta_{2,\mathrm{TR}} + \beta_3\mathrm{MAD} + \beta_4\mathrm{TL} + \beta_5\mathrm{PEL} + \beta_6\mathrm{LMX} + \beta_{7,\mathrm{BOD}} \\ + \beta_8 K + \beta_9\mathrm{AM} + \beta_{10,\mathrm{FOS}} + \beta_{11,\mathrm{SPM}} + \beta_{12,\mathrm{SEA}}$$

in which the β_x values represent covariate parameters for taxonomic order (ORD), thermal regime (TR), maximum depth (MAD), total length (TL), pelagic (PEL), maximum length (LMX), body type (BOD), growth parameter (K) and age at maturity (AM). It also included nuisance parameters for habitat category (HAB), the form of sample (FOS), sample preparation method (SPM) and the database used to acquire the data (SEA). This linear model was itself hierarchical, with the order-level intercepts (β_0) allowing for phylogenetic variation among groups.

Depending on assessed levels of fit to the model for each nutrient (see posterior checks below), we used this linear model in combination with one of three data likelihoods—that is, normal($Y_i \sim N(\mu, \sigma)$) for calcium, omega-3 fatty acids, and selenium, non-central t ($Y_i \sim T(\nu, \mu, \sigma)$) for protein and vitamin A or Gamma ($Y_i \sim \Gamma(\alpha, \alpha/e^{\mu})$) for zinc and iron. The priors and hyperpriors for the various parameters were:

$$\beta_0 \sim N(\gamma_0, \sigma_\gamma)$$

$$\gamma_0,\ \beta_{1\ldots13} \sim N(0, 1{,}000)$$

$$\sigma_\gamma, \sigma,\ \alpha \sim U(0, 1{,}000)$$

$$\nu \sim U(0, 4)$$

Models were all run in PyMC3[49] for 5,000 iterations of the automatically assigned No-U-Turn sampler. We examined posterior traces and Gelman–Rubin statistics[50] for evidence of model convergence and used posterior predictive distributions to check for model fit. Beginning with an assumed normal data likelihood, if we found evidence for lack of convergence or poor model fit, we tried the alternative non-central t and Gamma likelihoods instead. Final models all had stable traces and Gelman–Rubin statistics very close to one, supporting convergence, and posterior predictive distributions consistent with the observed data, supporting accurate predictions under each model (Extended Data Figs. 1, 2).

Mapping nutrient yields from global fisheries. Using the SAUP catch reconstruction database[19], we extracted catches from EEZ of each country in tonnes and by species group for the period 2010–2014. Reported and unreported catches are generally available for consumption, but discards are not. We therefore extracted data on reported and unreported catches from the EEZ of each country, and excluded discards from these data. Insufficient trait data exist for crustaceans[51] and the majority of landed catch are finfish. Therefore, all crustaceans, freshwater species and cephalopods were removed from the database. We used the top 20 remaining species in our SAUP database, which represent 100% of the catch of 31% of EEZs, more than 90% of 74% of EEZs, and 75% of 95% of EEZs, to calculate the nutrient concentration of the catch from each EEZ over the 5-year period. The same procedure as used for the nutrient database was used to assign the environmental and ecological traits to the species in the landed catch. Where SAUP data were reported at family or genus level, we used the average trait value for that family or genus. All higher-level groupings (for example, order and mixed categories), representing 18% of the finfish catch, were removed for the purpose of calculating EEZ nutrient concentrations. Higher level groupings were then reintroduced to calculate the EEZ nutrient yields. Our nutrient database included 17% of the species in the landed catch and we used the predictive capability of the trait-based model (Extended Data Figs. 1, 2) for the remaining catch. Using the trait covariates from our predictive model, we calculated expected nutrient concentrations (per 100 g raw, edible portion) based on the top 20 caught taxon groupings in the SAUP database and the posterior distributions from our model. We then multiplied these values by total catch to estimate total nutrient yield per EEZ, based on reported SAUP catches. There is some debate about the validity of the reconstructed unreported portion of these data, we therefore repeated all of the analysis using only the reported catch and used correlation analyses to establish whether any bias was introduced. The spatial patterns in nutrient yields and nutrient concentrations are extremely similar between the reported and unreported data and only reported data (Extended Data Figs. 3, 6–8). All nutrient yield correlation coefficients are >0.98 (Extended Data Fig. 7) and nutrient concentrations are >0.89 (Extended Data Fig. 8); reported and unreported nutrient yields are 19–29% greater than only reported nutrient yields.

There was no correlation between the concentration of nutrients per unit catch and either total nutrient yield or total fishery yield (Extended Data Fig. 4). This suggests that nutrient concentrations are independent of total yield and that the nutrient quality of fishery landings is influenced by species composition rather than the quantity landed. Food policy guidelines[20] should therefore specify the types of fish that should be consumed.

Fishery contributions to meeting nutritional needs. *Coastal population.* We gathered data[52] on the coastal population of each country within a 100-km coastal band and the population age structure of each country in 2015. To calculate coastal proportion, we created a 100-km buffer along the coastline of each country based on the Global Administrative Areas database (GADM v.2.8) and used this to calculate total human population and population under 5 years of age within the 100-km coastal band of each country in 2015 based on the Socioeconomic Data and Application Centre-gridded population of the world database[53] and population age structure of each country[52]. In 2010, 39% of the world's population lived within 100 km of the coast[24], and within our study the coastal population captured on average 74% of the population of each country (ranging from 2% to 100%), or 49% of the population of all countries considered.

Nutrient yields and reference points. We focused on calcium, iron, zinc and vitamin A, which are of great public health concern globally, and especially in low-income countries[11,12]. We calculated the per capita nutrient yield of each country for the entire coastal population and separately for children under 5 years using the calculated fishery-derived nutrient yields and respective populations within the 100 km coastal band. We use RDA for calcium, iron, zinc and vitamin A as our dietary reference intake values. RDA is the intake level at which the dietary needs of nearly all (97% to 98%) of the population are met. We calculated the average RDA for children under 5 years of age and for the rest of the population[26]. To calculate average RDA for children under 5 years of age, we assumed infants between birth and 6 months of age were exclusively breastfed, and would thus not consume fishery-derived nutrients directly. We then calculated the average RDA for children between 6 months and 4 years (that is, children <5 years), assuming the population of each country was evenly distributed across the first 5 years of life[26].

Prevalence of inadequate intake. We extracted data on the prevalence of inadequate intake of calcium, iron, zinc and vitamin A for each country in 2011 from a previously published study[12]. In this study[12], food balance sheets from the FAO, UN population data, and nutrient intake and requirement data were combined to calculate the prevalence of inadequate intake based on the population-weighted estimated average requirement and the distribution of the availability of each micronutrient.

Fish consumption rates. We extracted data on seafood consumption rates[25] as an indicator of how likely fish-based nutrition strategies were to be locally and culturally acceptable[29]. Countries that do not consume seafood are likely to face social, cultural or religious barriers to the introduction of fish as a source of nutrients.

Role of trade and foreign fishing. Fish trade could act as an engine of growth[54], enabling the import of large volumes of nutritious foods. Alternatively, in the absence of fair returns[55], fish trade could exacerbate food and nutrition insecurity[56]. Recent global analyses demonstrate that the volume of fish exported from developing countries is equal to the volume imported, with developed countries importing high-priced seafood in exchange for low-priced seafood[57]. This study thus suggests that developing countries are compensated for the quantities of seafood that they export with income; however, what remains unclear is whether the income from trade translates to the consumption of nutrient-rich foods, and how this pattern plays out in different countries. To address this gap, we analyse the role of trade and foreign fishing in the countries with potential nutrient supply and high prevalence of deficiencies.

For the countries in which nutrient yields (from catches in their EEZs) exceed the RDA for their coastal populations, and for the same 5-year period (2010–2014), we use the FAO fishery statistical collections[58] (http://www.fao.org/fishery/statistics/global-commodities-production/en) to extract data on marine finfish imports and exports to examine the patterns of marine finfish trade and the SAUP catch reconstructions data to examine the prevalence of foreign fishing in their waters to together establish how trade may affect food and nutrition security.

Domestic fleets account for the greatest volumes of finfish catches (>79%) in Iceland, Maldives and Namibia, whereas foreign fleets account for most of the fish caught in Kiribati and Mauritania (>69%). Namibia and Kiribati subsequently export most of their fish landings (>90%), whereas the other nations export approximately half. For all countries, fish imports amount to a small fraction (<5%) of fish exports. Taken together, Namibia, Mauritania and Kiribati, countries with high prevalence of nutritional deficiencies, have the equivalent of <13% of the fish caught in their waters available for domestic markets, whereas Iceland and Maldives, countries with low prevalence of nutritional deficiencies, have 68% and 39% available, respectively (Extended Data Table 2). Any income gained from the large quantities of fish trade and foreign fishing in Namibia, Mauritania and Kiribati does not appear to substitute for the nutrients lost. These countries could benefit from policies that seek to divert a greater portion of fish for local consumption.

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

Data availability

Data used to produce our nutrient models and estimated global catch can be found at https://github.com/mamacneil/GlobalFishNutrients.

Code availability

Code for Bayesian hierarchical model used to predict nutrient concentrations from standardized covariates and code used to produce our estimated global catch can be found at https://github.com/mamacneil/GlobalFishNutrients.

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Author contributions C.C.H. conceived the study with P.J.C., N.A.J.G., K.L.N., A.L.T.-L., C.D'L., E.H.A., S.H.T. and D.J.M.; C.C.H., P.J.C., N.A.J.G., K.L.N., C.D'L. and M.R. collected the data; C.C.H., M.A.M. and K.L.N. developed and implemented the analyses; C.C.H. led the manuscript with input from all authors.

Competing interests The authors declare no competing interests.

Additional information

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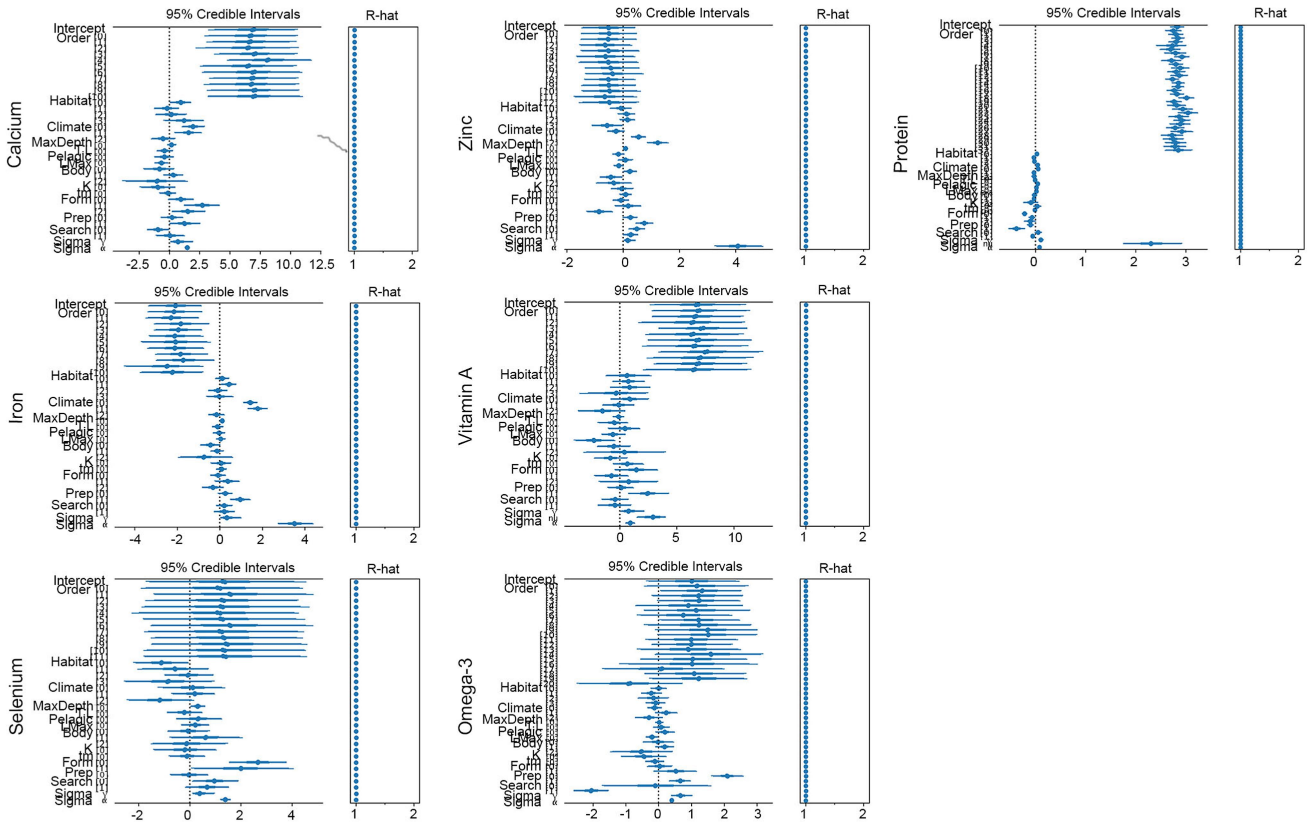
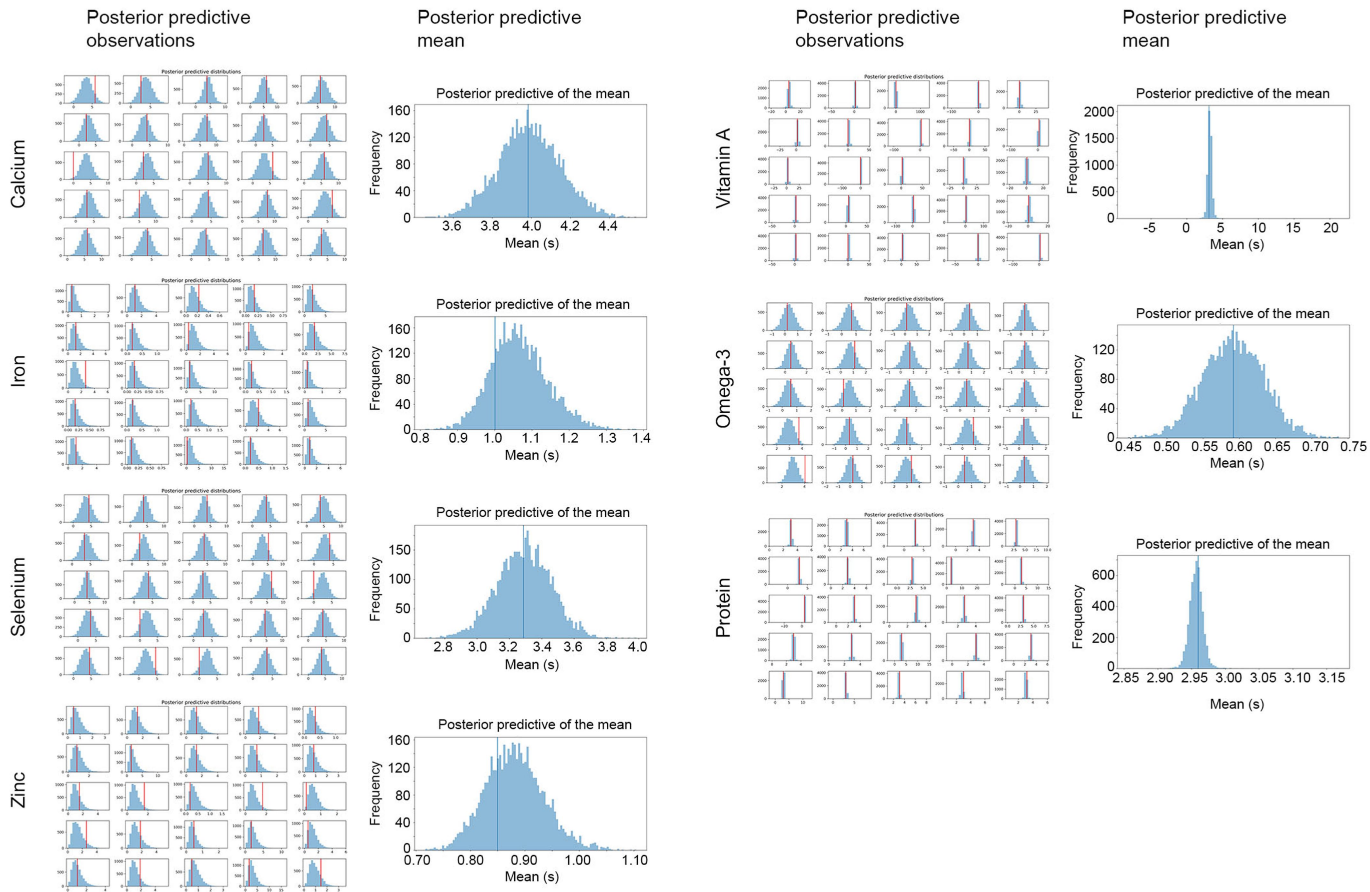
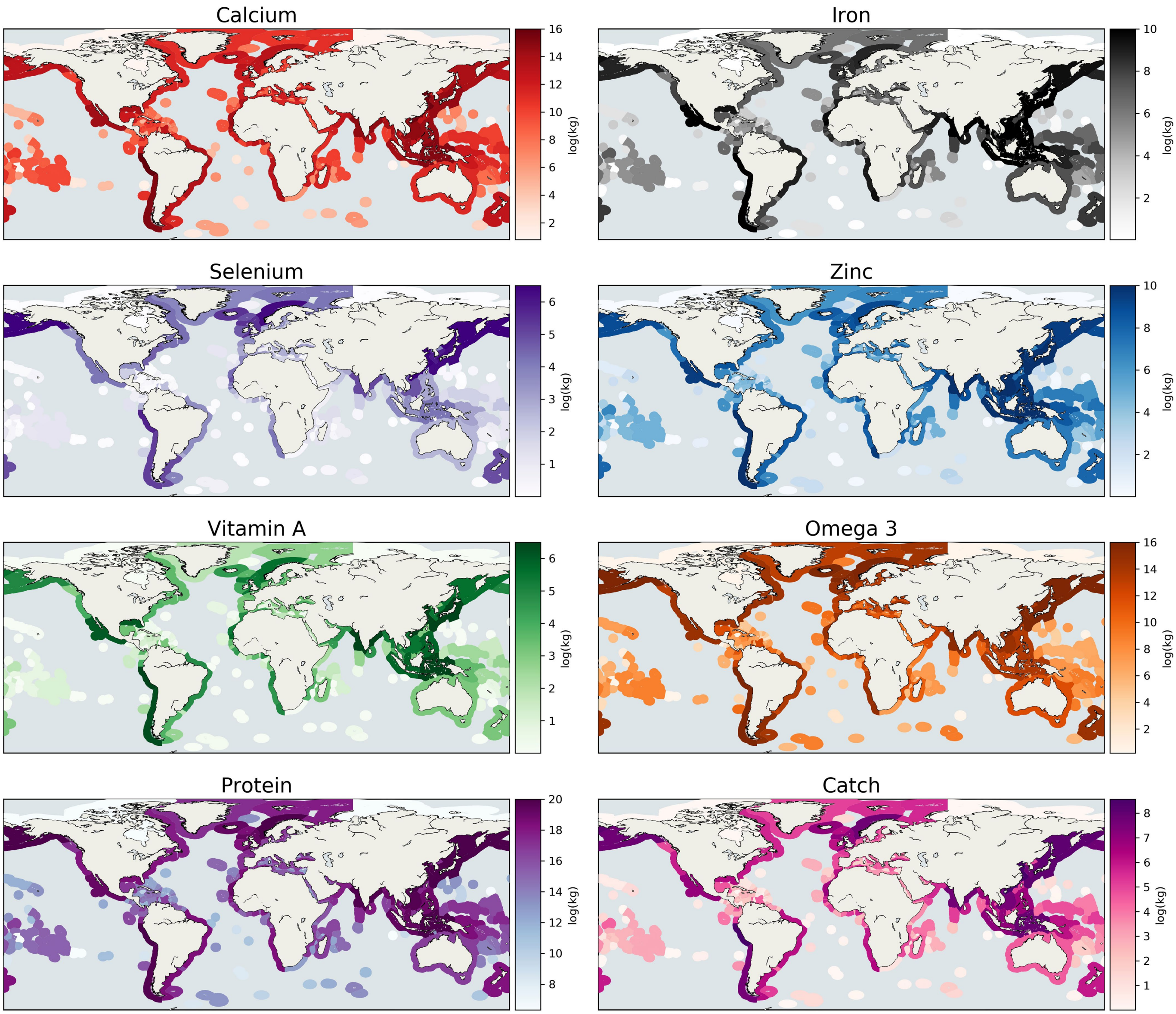


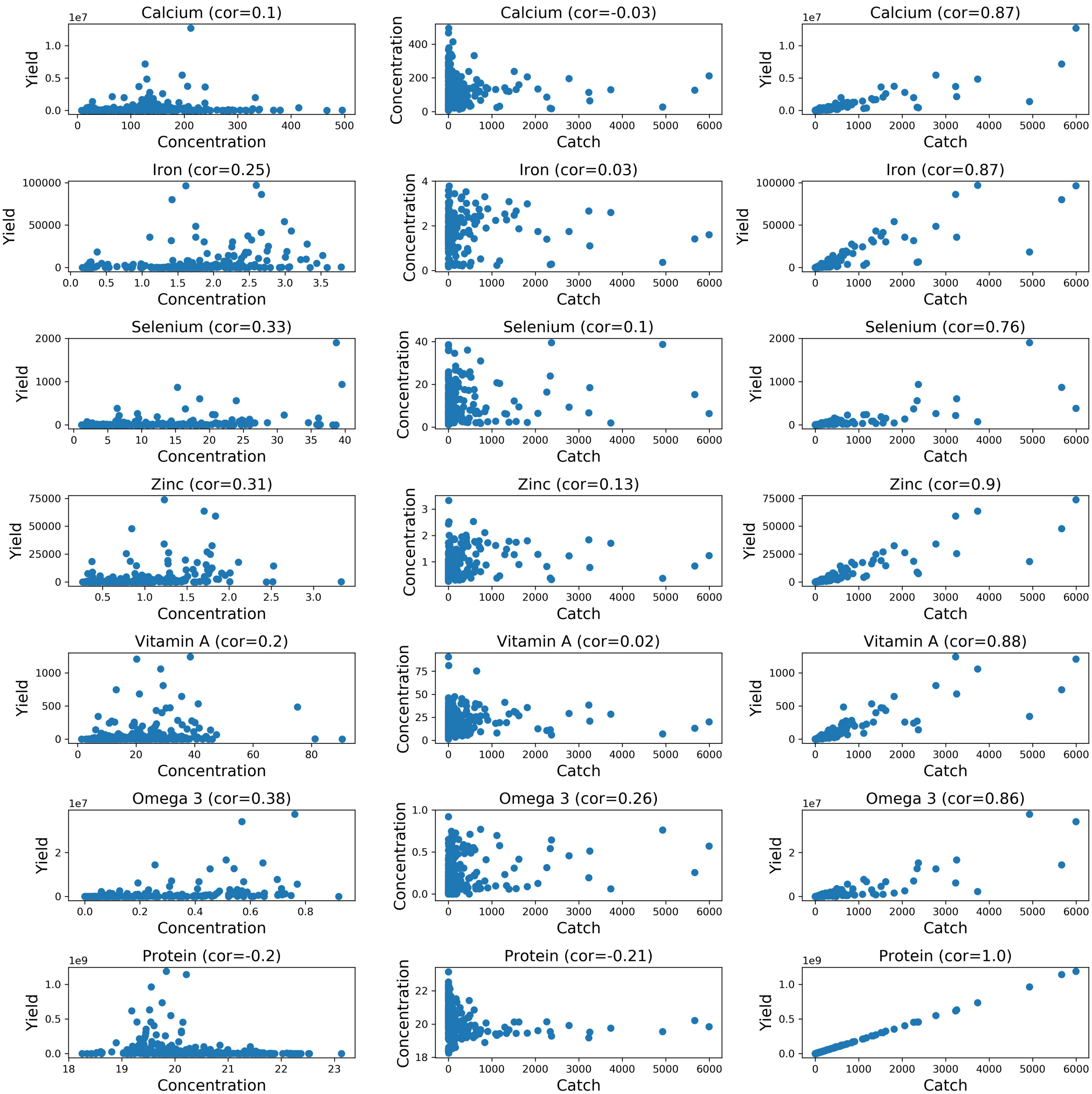
Extended Data Fig. 1 | Bayesian diagnostic plots I. Forest plots for each nutrient, given their respective model, including highest posterior densities (filled cicles), 50% (thick line) and 95% (thin line) uncertainty intervals for each parameter (left). Also included are R-hat (Gelman–Rubin) statistics (right), showing evidence of model convergence from four independent model runs (chains). R-hat values close to one show a consistent, stable relationship between the within-chain and among-chain variances, suggesting no evidence of non-convergence.



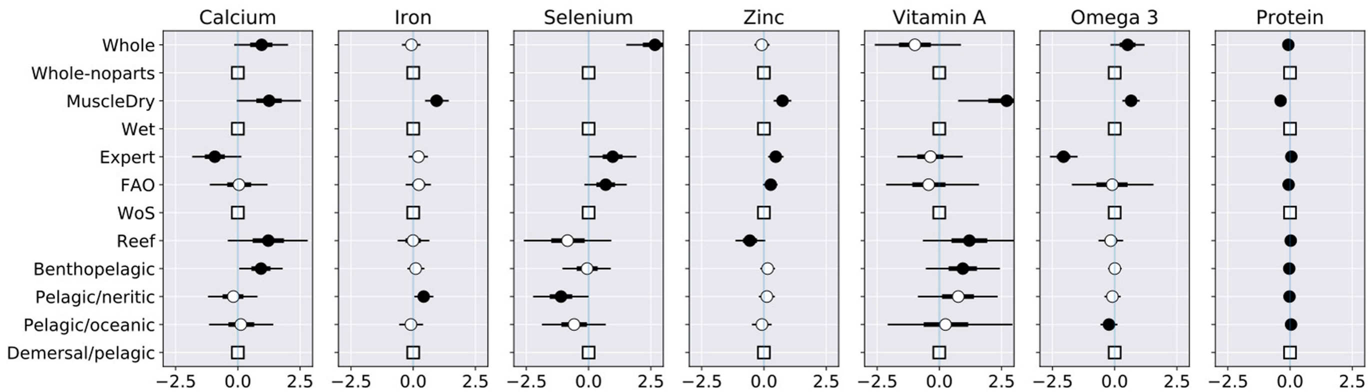
Extended Data Fig. 2 | Bayesian diagnostic plots II. The 25 randomly chosen posterior predictive distributions (small blue histograms; left) for observed values (red vertical lines) of individual nutrients under each nutrient-specific model. Red lines on top of the blue distribution indicate evidence of model fit; whereas red lines beyond the posterior suggest observations that are not consistent with the underlying model. Posterior predictive distributions (large blue histograms; right) for the observed overall mean (blue vertical lines) under each nutrient-specific model. Blue lines on top of the histogram indicate evidence of model fit, with a posterior predictive mean consistent with the observed data.



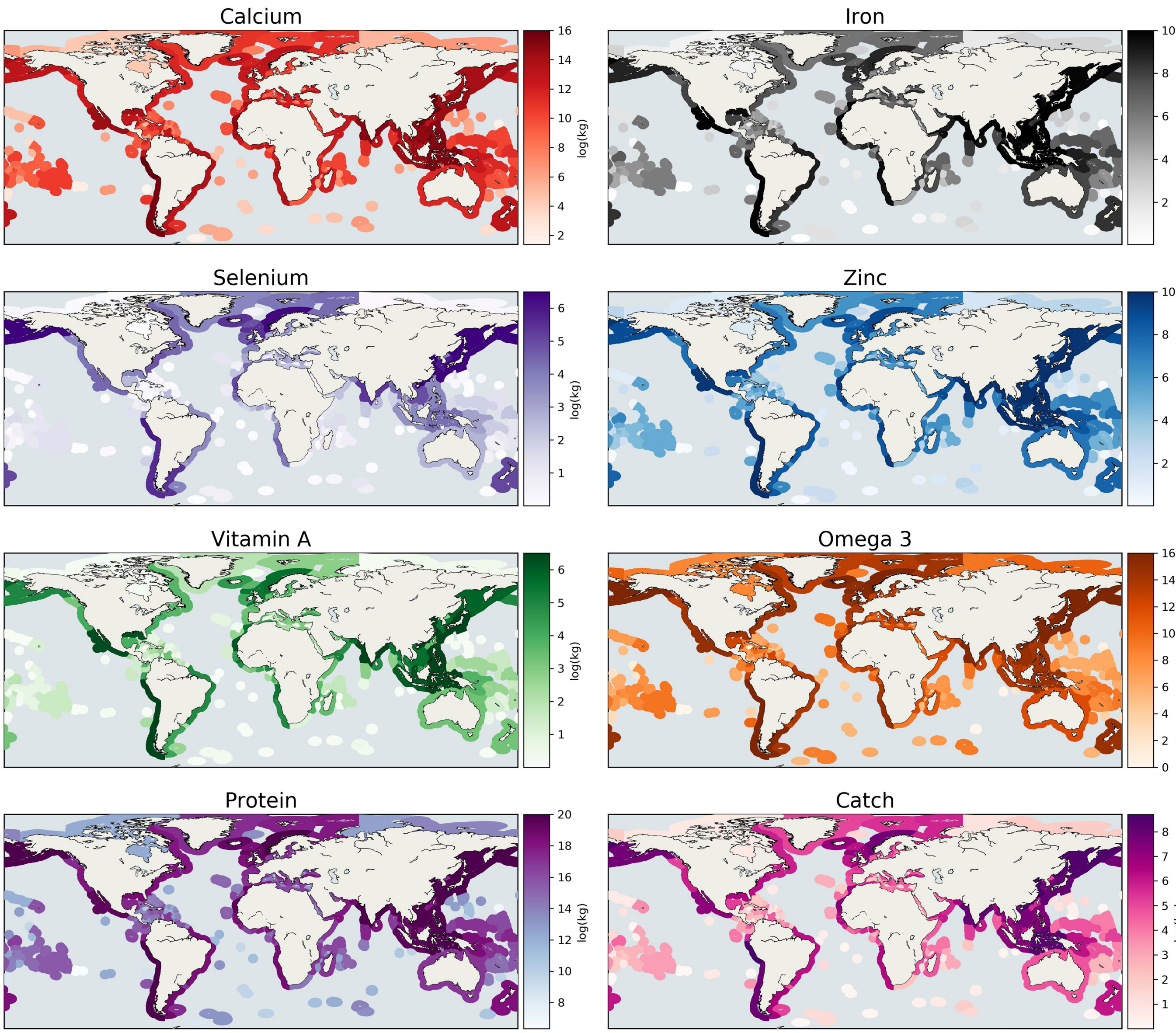
Extended Data Fig. 3 | Reported nutrient yield of fisheries and total fishery yield by EEZ. Data based on average taxon composition of annual reported catches[19] from 2010 to 2014, showing calculated yields of calcium, iron, selenium, zinc, vitamin A, omega-3 fatty acids and protein and the total catch. Data are plotted at the scale of EEZ areas as previously defined[19]. Base maps were generated using the matplotlib library[31] (https://matplotlib.org) in Python.



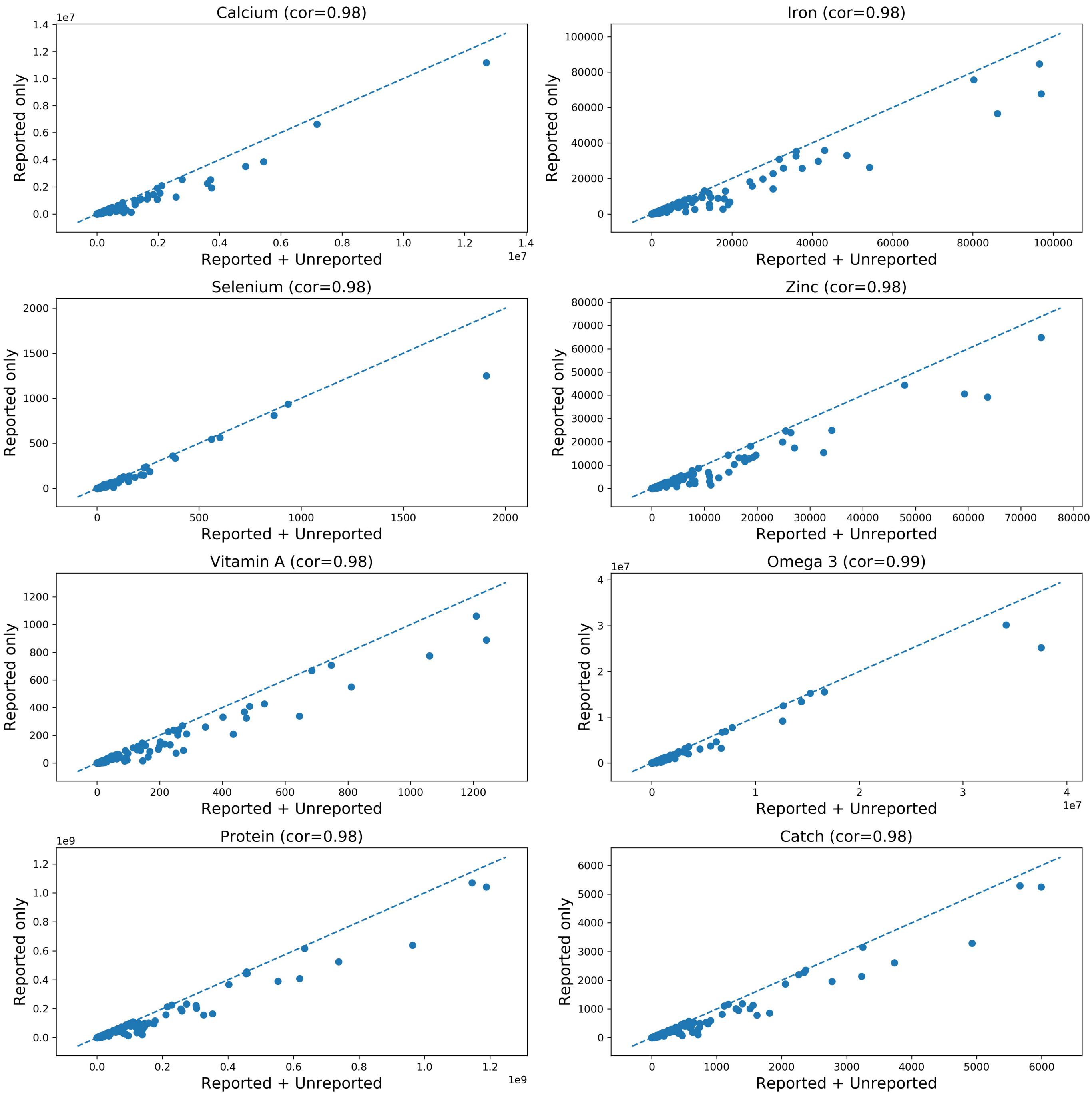
Extended Data Fig. 4 | Relationships between nutrient yield, nutrient concentration and total catch. Relationships are shown for calcium, iron, selinium, zinc, vitamin A, omega-3 fatty acids and protein, showing Pearson product–moment correlation coefficients, calculated using the corrcoef function in the 'numpy' library of Python ($n = 280$ EEZ areas, as previously defined[19]).



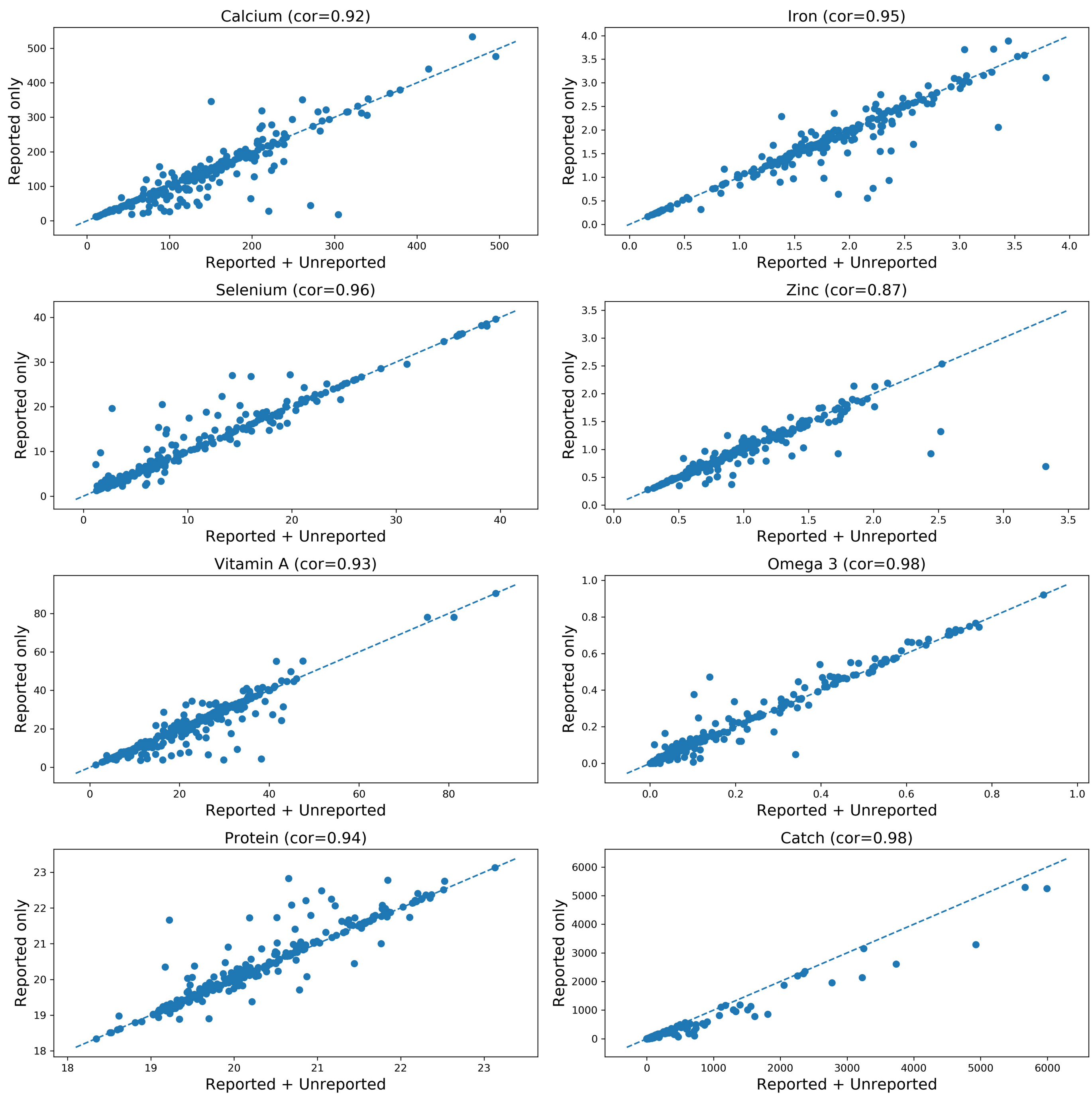
Extended Data Fig. 5 | Nuisance parameters for Bayesian hierarchical predictive model of nutrient concentrations. Standardized effect sizes for known factors that may influence results but that are not of interest to the study (nuisance parameters) are shown. These factors were included in the overall model, meaning their influence was accounted for in the predictions. Parameter estimates are Bayesian posterior median values, 95% highest posterior density uncertainty intervals (thin lines) and 50% uncertainty intervals (thick lines). Black dots indicate that the 50% uncertainty intervals do not overlap zero, indicating that more than 75% of the posterior density was either positive or negative; and open squares indicate the baseline category in the statistical model. Underlying sample sizes are as follows: calcium, $n = 170$ biologically independent samples; iron, $n = 173$; selenium, $n = 134$; zinc, $n = 196$; vitamin A, $n = 69$; omega-3 fatty acids, $n = 176$; and protein, $n = 627$.



Extended Data Fig. 6 | Reported and unreported nutrient yield of fisheries and total fishery yield by EEZ. Data based on average taxon composition of annual reported and unreported catches[19] from 2010 to 2014, showing calculated yields of calcium, iron, selenium, zinc, vitamin A, omega-3 fatty acids and protein and the total catch. Data are plotted at the scale of EEZ areas as previously defined[19]. Base maps were generated using the matplotlib library[31] (https://matplotlib.org) in Python.



Extended Data Fig. 7 | Relationships between reported only and reported and unreported catch nutrient yields per EEZ. Pearson product–moment correlation coefficients were calculated using the corrcoef function in the numpy library of Python ($n = 280$ EEZ areas, as previously defined[19]).



Extended Data Fig. 8 | Relationships between reported only and reported and unreported catch nutrient concentration per EEZ. Pearson product–moment correlation coefficients were calculated using the corrcoef function in the numpy library of Python ($n = 280$ EEZ areas, as previously defined[19]).

Extended Data Table 1 | Top 20 countries by nutrient concentration

	Calcium mg/100g		Iron mg/100g		Selenium µg/100g		Zinc mg/100g		Vitamin A µg/100g		Omega-3 g/100g		Protein %
Venezuela	410	Brunei[4]	3.8	N. Korea	35.9	Bosnia[5]	2.4	Sudan	60.3	Argentina	0.8	A. Samoa[8]	22
Belize	380	Cameroon	3.5	Argentina	31.5	Bangladesh	2.1	Angola	53.8	Estonia	0.8	C. Islands[9]	22
Honduras	356	Bangladesh	3.4	Greenland	26.8	Guatemala	2.1	Bosnia[5]	50.5	Finland	0.7	Brazil	22
Libya	340	Bosnia[5]	3.3	Ireland	25.0	Brunei	2.0	Oman	49.5	N. Korea	0.7	Dominica	22
Haiti	339	Sierra Leone	3.3	Norway	24.2	Sierra Leone	2.0	Pakistan	49.5	Iceland	0.7	F. Polynesia[10]	22
Senegal	335	Jordan	3.1	Denmark	21.9	Sri Lanka	1.9	Haiti	49.4	Latvia	0.7	Vanuatu	22
Congo, R.	325	Yemen	3.1	Finland	21.8	Cameroon	1.9	Nigeria	48.8	Russia	0.6	Kiribati	22
Antigua[1]	314	Sri Lanka	3.1	Uruguay	21.7	Mozambique	1.9	Dominican[2]	48.0	Bulgaria	0.6	Grenada	22
Cuba	289	Guinea	3.1	Iceland	21.2	Philippines	1.8	UAE	47.2	Lithuania	0.6	Cape Verde	22
Dominican[2]	282	Oman	3.0	Canada	21.1	Pakistan	1.8	Bulgaria	46.4	Sweden	0.6	Seychelles	22
Sudan	274	Trinidad[6]	3.0	N. Zealand	20.8	Angola	1.8	Equatorial G[7]	46.2	Peru	0.6	Malta	22
Jamaica	262	Philippines	3.0	S. Africa	20.8	Nigeria	1.8	Sierra Leone	45.3	Ireland	0.6	N. Zealand	22
Cyprus	252	Timor-Leste	3.0	Sweden	19.5	Guinea	1.8	Ukraine	45.1	Denmark	0.6	Nauru	22
Gaza Strip	249	St. Lucia	2.9	Poland	19.2	Equatorial G[7]	1.7	Brunei	45.1	Namibia	0.5	Marshall	22
Tunisia	242	Israel	2.8	Greece	18.4	Indonesia	1.7	Philippines	44.8	Georgia	0.5	Palau	22
Guinea-B[3]	242	Pakistan	2.8	Germany	18.2	Montenegro	1.7	Antigua[1]	44.6	Poland	0.5	Sao Tome[11]	22
Togo	240	Indonesia	2.8	Italy	18.2	China	1.7	Honduras	43.9	Germany	0.5	Tuvalu	22
Mauritania	238	UAE	2.7	Gaza Strip	17.9	Yemen	1.7	Yemen	43.8	Ukraine	0.5	Vincent[12]	22
Georgia	229	India	2.7	Malta	17.5	Eritrea	1.6	Mozambique	43.8	Canada	0.5	Micronesia	21
Qatar	226	Nigeria	2.7	Senegal	17.4	Cambodia	1.6	Iraq	43.3	Croatia	0.4	Bahamas	21
EEZ Av	**128**	**EEZ Av**	**1.7**	**EEZ Av**	**10.9**	**EEZ Av**	**0.9**	**EEZ Av**	**24.9**	**EEZ Av**	**0.2**	**EEZ Av**	**20**

[1]Antigua and Barbuda.
[2]Dominican Republic.
[3]Guinea-Bissau.
[4]Brunei Darussalam.
[5]Bosnia and Herzegovina.
[6]Trinidad and Tobago.
[7]Equatorial Guinea.
[8]American Samoa.
[9]Cook Islands.
[10]French Polynesia.
[11]Sao Tome and Principe.
[12]Saint Vincent and the Grenadines.

Extended Data Table 2 | Foreign fishing and trade (2010–2014)

Catch (tonnes)	Fishing vessels		Trade	
	Foreign	Domestic	Export	Import
Iceland	66785	1046397	694161	77725
Kiribati	242467	32885	53808	454
Maldives	21536	172582	42224	1279
Mauritania	1038985	472035	275689	3439
Namibia	130332	477092	434007	19367

Volumes (tonnage) of fishing within the EEZ of a country, by foreign and domestic vesssels[19] and fish trade[54] for countries for which nutrient yields exceed the RDA for their coastal population. The fishing vessel and trade data are estimates and from different sources; therefore, although they are indicative of proportions of catches retained or not in countries, they should not be seen as exact balances.

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☐	☒	For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
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☐	☒	Estimates of effect sizes (e.g. Cohen's d, Pearson's r), indicating how they were calculated

Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	No software was used for data collection
Data analysis	Python 3.7.1, PyMC3 3.3.6, and R 3.5.3

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors/reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Research guidelines for submitting code & software for further information.

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Data used for all figures in this paper will be made available through the GitHub links in the Methods upon acceptance. Some of the data (e.g. Sea Around Us catch data) are already in the public domain.

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Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	The study aimed to determine the nutritional quality of marine fish species, use this to estimate the nutritional yields from fisheries, and finally contrast nutritional yields to country level nutrient deficiency data. Nutrient content data were collated from existing databases and from the literature. Environmental and ecological traits were collected on fish species from FishBase, and used to determine which factors best predicted the 7 nutrients examined. Fisheries landing data were downloaded from the Sea Around Us catch reconstruction database, and the Bayesian model of nutrient predictions used to determine estimated nutritional yields per Exclusive Economic Zone. Country level nutrient yields were compared to nutrient deficiency data taken from the published literature. FAO data were used to examine trade for key countries.
Research sample	The underlying research samples are nutrient concentrations from marine finfish species. All data are from the FOA INFOODS database, the published literature, or key informant recommended grey literature. Fisheries landings data,mostly as species level, was downloaded from the Sea Around Us Catch Reconstruction Database, for the period 2010-2014. Country level nutrient deficiency data was downloaded from Beal et al. 2017. Recommended dietary allowance of the nutrients of interest for different groups of people was extracted from the Dietary Reference Intakes Tables and Application, published by the National Academies of Sciences, Engineering, and Medicine. Coastal human population data was calculated using the Global Administrative Areas Database and the Socioeconomic Data and Application Centre's gridded population of the world database.
Sampling strategy	The fish nutrient database was constrcuted using the following 3 approaches: 1) Thomson Reuters Web of Science search of the scientific literature published between the years 1980 and 2015. 2) FAO/INFOODS food composition for biodiversity database produced by the Food and Agriculture Organisation (FAO) of the United Nations. 3) Key informant grey literature sources of finfish nutrient composition databases identified through snowballing of nutrition experts. All other data was pre-determined by the database and published studies utilized.
Data collection	Data collection was performed by Coralie D'Lima and Matthew Roscher, and overseen by Christina Hicks and Philippa Cohen.
Timing and spatial scale	Fish nutrient content data span 1980-2015. Fishery landings and select country trade data are for a five year period - 2010-2014. The nutrient deficiency data is from the period 1961-2011. All data used are global.
Data exclusions	No data were excluded
Reproducibility	No experiments were undertaken. Analyses were run multiple times to ensure the models converged on the same findings. A full description of the methodologies used is provided in the Methods, and the data and full code necessary to reproduce the findings will be provided through the GitHub links in the Methods.
Randomization	Randomization was not relevant as we are making global estimates, rather that contrasting samples in different treatments.
Blinding	Strict protocols were used for the nutrient database building, including pre-defined search. Other data was already available and produced by external groups to the authors here. The statistical modeler had no involvement in data collation.

Did the study involve field work? ☐ Yes ☒ No

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology
☒	☐ Animals and other organisms
☒	☐ Human research participants
☒	☐ Clinical data

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging