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Small pelagic fish supply abundant and affordable micronutrients to low- and middle-income countries

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Wild-caught fish provide an irreplaceable source of essential nutrients in food-insecure places. Fishers catch thousands of species, yet the diversity of aquatic foods is often categorized homogeneously as 'fish', obscuring an understanding of which species supply affordable, nutritious and abundant food. Here, we use catch, economic and nutrient data on 2,348 species to identify the most affordable and nutritious fish in 39 low- and middle-income countries. We find that a 100 g portion of fish cost between 10 and 30% of the cheapest daily diet, with small pelagic fish (herring, sardine, anchovy) being the cheapest nutritious fish in 72% of countries. In sub-Saharan Africa, where nutrient deficiencies are rising, <20% of small pelagic catch would meet recommended dietary fish intakes for all children (6 months to 4 years old) living near to water bodies. Nutrition-sensitive policies that ensure local supplies and promote consumption of wild-caught fish could help address nutrient deficiencies in vulnerable populations.

A nutrient-adequate diet is unaffordable for almost three billion people, particularly in Southern Asia and sub-Saharan Africa, contributing to growing global malnutrition and food insecurity[1,2]. In these regions, fish is a key component of the food system that is often produced by small-scale sectors[3]. Critically, in these settings fish provide a local source of highly bioavailable micronutrients such as iron and zinc[4] that are often lacking in diets[5]. In populations that have access to and consume relatively high amounts of fish, studies have demonstrated improved pregnancy and birth outcomes[6,7] and faster child growth[8].

Fish is expected to contribute to healthy diets where it is affordable and accessible but the cost and availability of nutrient-rich foods, including fish, is highly variable across and within countries[9–11]. In the Global South, lower household income[9] and proximity to markets[12] and fisheries[13] can restrict access to fish and thus limit its potential to contribute to people's health. Yet scarcity of data on fish prices at the species level mean that large-scale analyses of fish affordability typically combine aggregate products by ecosystem category (for example, pelagic or demersal fish[14]) or simply as 'fish'[10]. These data simplifications limit understanding of how the affordability of fish

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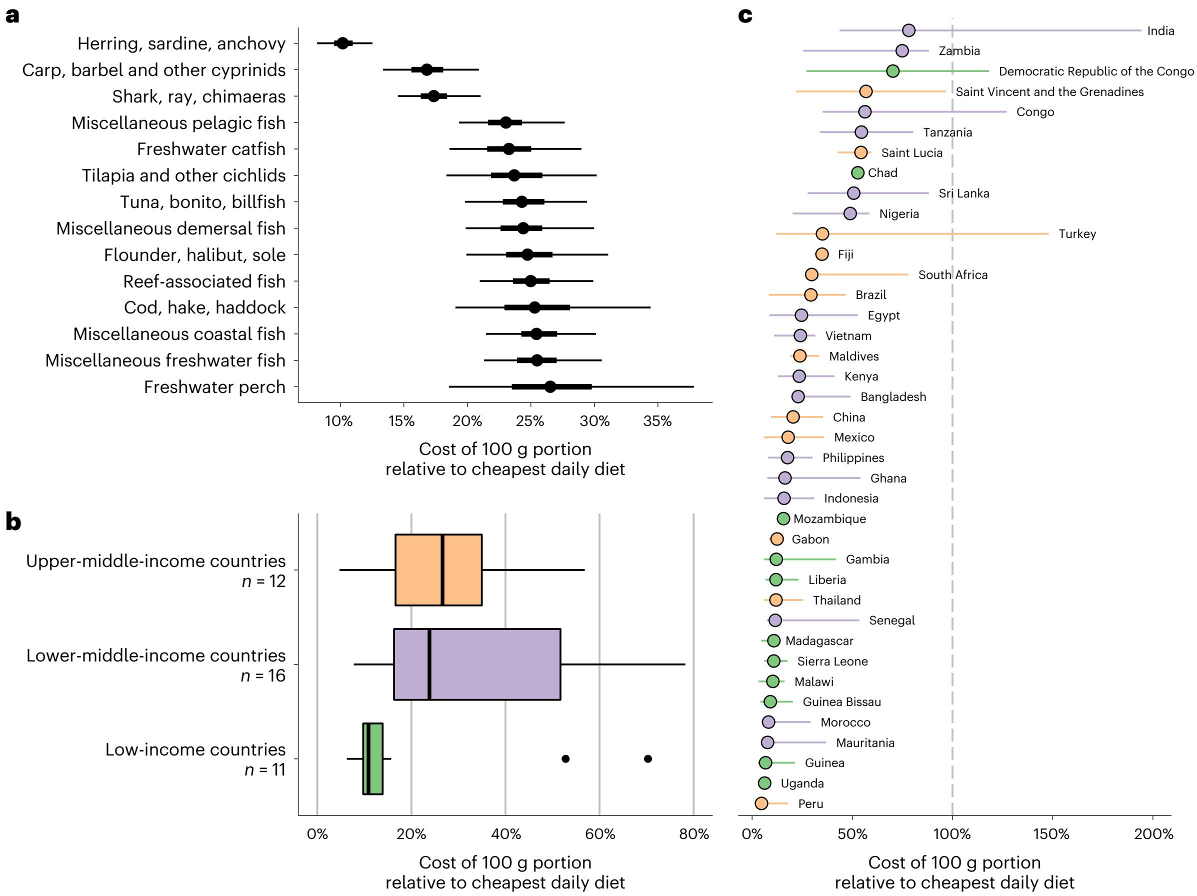

Fig. 1 | Affordability of a 100 g portion of fish (cost relative to a low-cost diet of caloric adequacy from starchy staples). a, Predicted affordability of each species group, where the points are median posterior values with 95% and 50% certainty intervals. **b**, Affordability by country income status. **c**, Affordability for each of the 39 countries. The box plots show the median and 75% interquartile range (IQR) across countries (lines are 1.5 times the IQR). Points are the catch-weighted mean with error bars representing the minimum and maximum affordability across species. See Extended Data Fig. 2 for equivalent country-level values in US$. Model fitted to catch dataset for 39 countries (*n* = 2,290).

varies among species, production methods and locations. Furthermore, the productivity and nutrient content of wild-caught fish vary greatly[4], such that micronutrient-rich fish may not be available (that is, produced or traded) and affordable in every country. Three key questions remain unanswered: (1) where are wild, micronutrient-rich fish affordable?; (2) which wild-caught species are the cheapest, most micronutrient-rich fish?; and (3) where do fisheries provide an abundant supply of nutritious food?

In this study, we examine the affordability and supply of wild-caught fish in 39 low- and middle-income countries. We compile information on catch weight, price (at the point of landing, 'ex-vessel') and nutrient content of species landed by marine and inland fisheries. We use these data to quantify the affordability (cost relative to staple foods) and apparent supply (landed catch) of fish-derived nutrients in each country. We identify fish species that provide the most affordable nutritious portion in each country and examine the potential for catches of these species to meet recommended aquatic food intakes in sub-Saharan Africa, where inadequate micronutrient intakes are prevalent.

Results

Affordability of fish

We collated catch and price data for wild fisheries in 39 low- and middle-income countries to quantify the affordability of fish. Affordability was the cost of a 100 g portion of fish relative to the cheapest daily diet, defined as the total food cost required to meet daily energy needs from starchy staples (caloric adequacy or 2,109 kcal day^{-1})[10]. Our affordability metric measures the expense of adding a daily portion of fish to the cheapest diets, based on the staple foods available in each country, allowing comparison of fish affordability across countries with different food systems (for example, production, trade) and income status.

Across 2,438 species representing almost 34 million tonnes of annual landed catch, a 100 g portion of fish was equivalent to approximately 10–30% of the cost of the cheapest daily diet that fulfilled caloric (although not necessarily micronutrient) needs (Fig. 1a). Fisheries spanned biogeographical realms (for example, tropical, temperate, freshwater, marine) so to facilitate comparisons of catch affordability among countries, species were aggregated into 14 groups (Methods). Ten groups represented species that were targeted in specific fisheries (for example, lakes, coral reefs), aggregated species with similar biological characteristics and phylogenetic histories (for example, demersal Gadiformes: cod, hake, haddock) or contained 'miscellaneous' species from specific ecosystems (four groups). Small pelagic species such as herring, sardine and anchovy were most affordable and were up to twice as affordable as other fish groups, whereas temperate demersal species, such as cod and flounder, were the least affordable. The equivalent cost of fish increased as species body size increased (Extended Data Fig. 1). Small-bodied species (<50 cm length at maturity) were equivalent to 15% of the cheapest daily diet, rising to 25–35% for large-bodied species over 100 cm.

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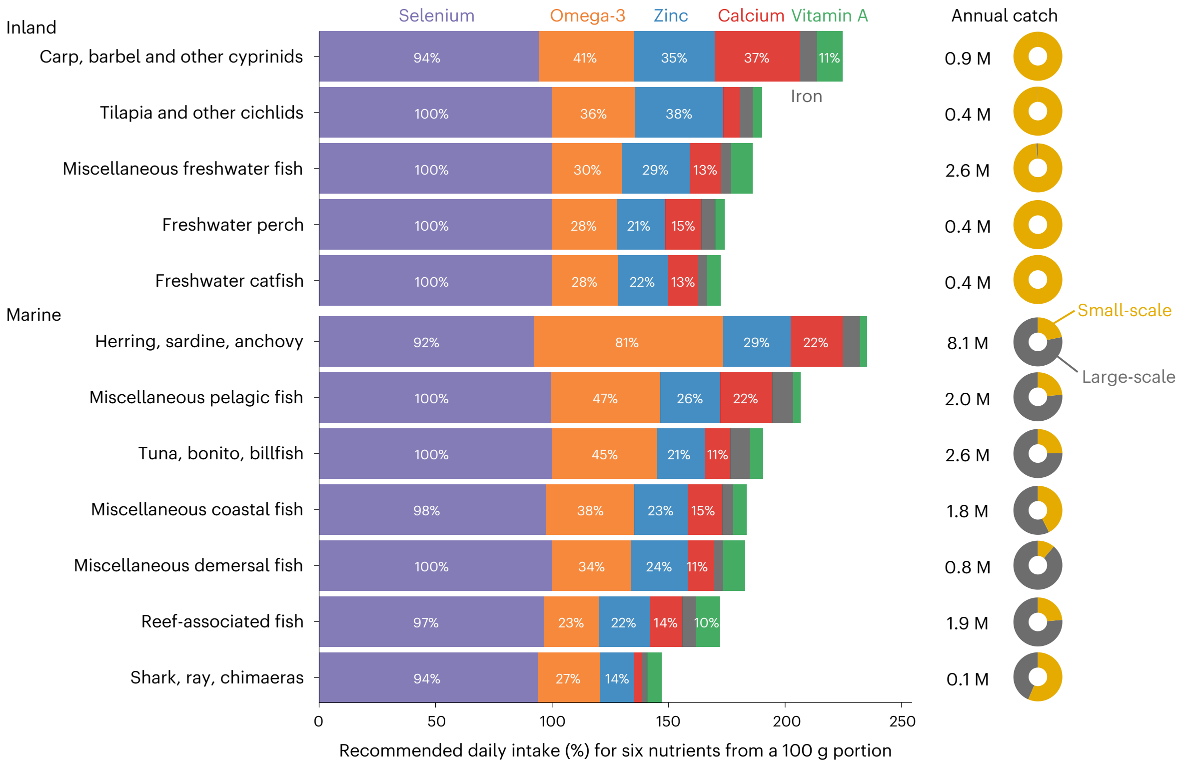

Fig. 2 | Nutrient density of fish caught in 39 low- and middle-income countries. The bars show the contribution of freshwater and marine fish groups to the recommended nutrient intake (%) of six nutrients (calcium, iron, selenium, zinc, omega-3 fatty acids, vitamin A) for adult women, for a 100 g portion of raw muscle tissue. Each bar is the mean nutrient contribution across all species within a group (values > 10% are annotated), weighted by their total catch contributions, with groups categorized as primarily caught by inland or marine fisheries. Adjacent text indicates the mean annual catch (tonnes) of each fish group (total from 39 countries), with the donuts showing relative catch proportions from small- (yellow) and large-scale (grey) sectors. Species groups were identified as marine/inland and small/large-scale according to each country's reporting of catches (Methods).

Next, we modelled variation in fish affordability by country and region to account for compositional differences in landed catch. In all low-income countries (except Chad and the Democratic Republic of the Congo), a 100 g portion of fish cost less than 20% of the cheapest energy-sufficient diet (Fig. 1b). Fish were most affordable in sub-Saharan African countries including Madagascar (11%), Sierra Leone (8%) and Uganda (8%) (Fig. 1c) and were 50% less affordable in lower-middle- and upper-middle-income countries than low-income countries (Fig. 1b and Extended Data Fig. 2). Fish affordability also varied across species within the same country (on average, the cheapest species was one-third the cost of the most expensive species), particularly in middle-income countries such as India, Congo and Turkey (Fig. 1c).

Least-cost nutritious fish

Fish vary in their nutrient content, owing to differences in growth rate, feeding strategies and ecosystem type[4]. We estimated the nutrient content of each species group, based on predicted species-level concentrations of six nutrients important to human health[15,16]. For inland fisheries, freshwater carp and other cyprinids had the highest nutrient density, a combined measure of the contribution of a 100 g portion to daily recommended intakes of calcium, iron, selenium, zinc, omega-3 fatty acids and vitamin A (Fig. 2). A 100 g portion of a cyprinid fish provided over a third of the recommended intake of calcium (37%), zinc (35%) and omega-3 fatty acids (41%), as well as 11% of vitamin A (Fig. 2); these species were only caught by small-scale, freshwater fisheries. For marine fisheries, herring, sardine and anchovy had slightly higher nutrient density (235%) than cyprinids (225%) and had the highest total catch of all species groups, providing an average annual catch of 7.2 million tonnes, primarily from large-scale sectors (Fig. 2).

We next combined modelled fish affordability estimates with nutrient content data to identify species that were both affordable and nutritious in low- and middle-income countries. We calculated the cost of a portion of fish required to meet 33% nutrient adequacy[15,17] across six micronutrients (calcium, iron, selenium, zinc, omega-3 fatty acids and vitamin A), hereafter called a 'nutritious portion'. As with fish affordability (Fig. 1), the cost of a nutritious portion from each species was expressed relative to the cheapest daily diet in each country. The least-cost nutritious portion came from fish that were generally small (<30 cm length at maturity; Fig. 3a) and cost 12–20% of the cheapest daily diet. Nutrients from other species were up to eight times less affordable than the lowest-cost nutritious species (on average, three times less affordable) (Fig. 3b), reflecting both their higher market price and lower nutrient content. The lowest-cost nutritious species group accounted for an average 34% of the total catch, although catch contributions varied between 1% (Democratic Republic of the Congo, Madagascar, Nigeria, Uganda, Zambia) and almost 100% (Chad, Maldives) (Extended Data Fig. 3). Herring, sardine (Clupeidae) and anchovy (Engraulidae) were the least-cost nutritious fish in 28 countries (Fig. 3c and Extended Data Fig. 3), represented by over 49 species (Extended Data Fig. 4) that were primarily caught in marine fisheries and accounted for an average approximate 30% of the national catch (Fig. 3d).

Other least-cost nutritious species were freshwater fish (Cyprinidae and miscellaneous species) caught in countries (Kenya, Malawi, Mozambique, Tanzania, Uganda) within Africa's Great Lakes Region and landlocked Chad, and tuna and reef fish caught in three middle-income tropical countries (Fiji, Maldives, Saint Lucia) that have extensive coral reef and pelagic fishing areas (Extended Data Fig. 3). In contrast, 'most-cost' fish (that is, the most expensive source of nutrients in each

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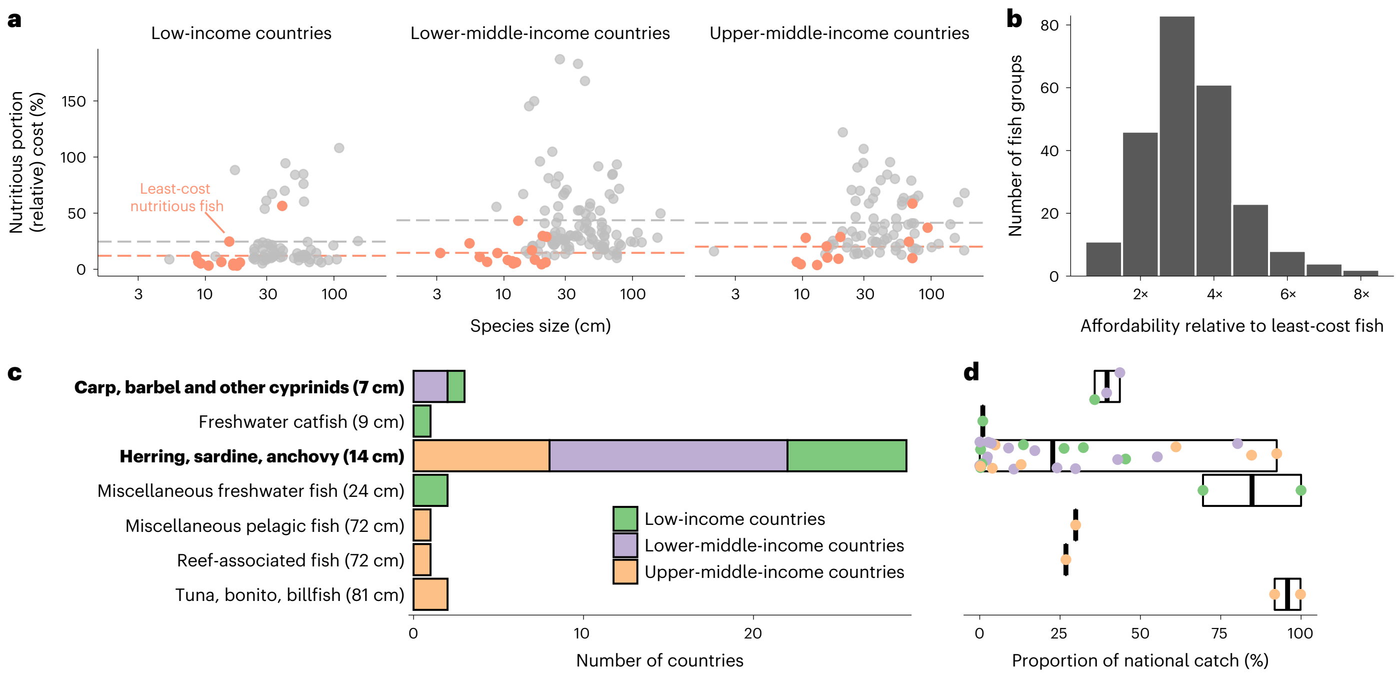

Fig. 3 | Catch and identity of least-cost nutritious fish. a, The points are the cost of a nutritious portion for each fish group by its body size (length at maturity, cm). The red points indicate the least-cost nutritious fish group in each country ($n = 39$) and the dashed lines indicate the average cost for each income status (red, least-cost; grey, not least-cost). The cost of nutrients and body size were the catch-weighted average for each group of related species in each country. **b**, Affordability of fish groups relative to the least-cost fish in each country, showing the relative affordability of 239 fish groups that were more expensive than the least-cost nutritious fish. **c**, Identity and body size (length at maturity, cm) of the least-cost nutritious fish group in each country. The bars indicate the number of countries with each least-cost fish group, filled by income status. Small pelagic groups are indicated in bold. **d**, Proportion of national catch for each fish group. The points are individual countries coloured by income status; the thick black lines are the median value; and the boxes are the minimum and maximum values (for groups caught in more than one country).

country) were represented by 11 species groups and contributed an average 10% of the national catch (Extended Data Fig. 5). Most-cost fish were often 'miscellaneous' species groups (41% of countries), suggesting that these groups consist of relatively infrequently caught species fetching a high ex-vessel price.

Food supply from small pelagic fish in sub-Saharan Africa

Small pelagic fish have particular potential to address malnutrition[18] due to their fast turnover rates and high productivity that can sustain large catches[19,20]. We next explored the potential for catches of these species to meet the recommended aquatic food intake for adults and children, focusing on sub-Saharan Africa where, in low-income countries such as Malawi, Senegal and Zambia, over one-third of people have an inadequate intake of essential micronutrients (Fig. 4a and Extended Data Fig. 6). Many of these countries also catch large volumes of small pelagic fish, which are affordable (Fig. 3) and have high nutrient densities (>200%) (Fig. 4b). In the 19 sub-Saharan African countries we analysed, low-cost fish caught by inland fisheries were freshwater cyprinids (for example, *Rastrineobola argentea*, *Engraulicypris sardella*) caught in the Great Lakes[19], whereas low-cost marine fish were primarily *Sardinella* species (*Sardinella aurita*, *Sardinella maderensis*), European anchovy (*Engraulis encrasicolus*) and Bonga shad (*Ethmalosa fimbriata*) caught along the coast of West Africa[21] (Extended Data Fig. 4).

In most countries, the catch of low-cost, nutritious, small pelagic fish (herring, sardine, anchovy, cyprinids) alone could provide all adults (aged 18–65 years) living within 20 km of a coastline or lakeshore with their annual recommended aquatic food intake of 10.6 kg[22] (Fig. 4c,d). In West Africa, catches of marine shads, sardine and anchovy could supply 18 kg per person (median value), ranging from 6 kg per person in Ghana to 262 kg per person in Mauritania (Fig. 4c). Small pelagic catch in East African countries was dominated by inland Great Lakes fisheries, with freshwater cyprinids landed at 20 kg per person, ranging from 7 kg per person in Mozambique to 27 kg per person in Zambia (Fig. 4d). Of the 19 sub-Saharan African countries we analysed, only Chad (inland) and Guinea-Bissau (marine) did not produce enough small pelagic fish to meet per capita annual recommended intakes, with relatively low catch reported (36 and 63 tonnes, respectively). Chad's catch was also only recorded as a mixed species group, which may have led us to overestimate the cost of fish (Fig. 1c and Extended Data Figs. 3 and 5).

Despite high apparent fish supply to coastal populations in sub-Saharan Africa, 10 million children suffered wasting and 55 million children were stunted in 2020 (ref. [2]). Children experience growth and developmental delays when their consumption of animal-source foods is inadequate[8], leading to deficiencies in essential micronutrients such as calcium, iron and zinc[23,24]. Small pelagic fish are concentrated, bioavailable sources of these micronutrients (Fig. 2) and fish consumption can improve nutritional outcomes in young children[25]. Children under 5 in sub-Saharan Africa consume just 38% of their recommended seafood intake[26] (Extended Data Fig. 6) and current prevalence of micronutrient deficiencies among this group is 62%[27]. Our results suggest that, in 17 of 19 countries, less than 20% of small pelagic fish catches could provide all children between 6 months and 4 years old living within 20 km of a coastline or lakeshore with a daily fish portion (40 g) (Fig. 4e). Targeting supplies and consumption of small pelagic fish towards young children could meet 9–41% of the recommended daily intake (average of calcium, iron and zinc) (Fig. 4e) and thus contribute to closing these dietary gaps. As for adults (above), Chad and Guinea-Bissau did not produce enough small pelagic fish to meet the recommended aquatic food intake (annual intake met for approximately 2% of children).

Discussion

Using extensive catch, price and nutrient content datasets representing 2,438 species caught in 39 countries, we showed that small pelagic species are the most affordable and nutritious wild-caught fish in most

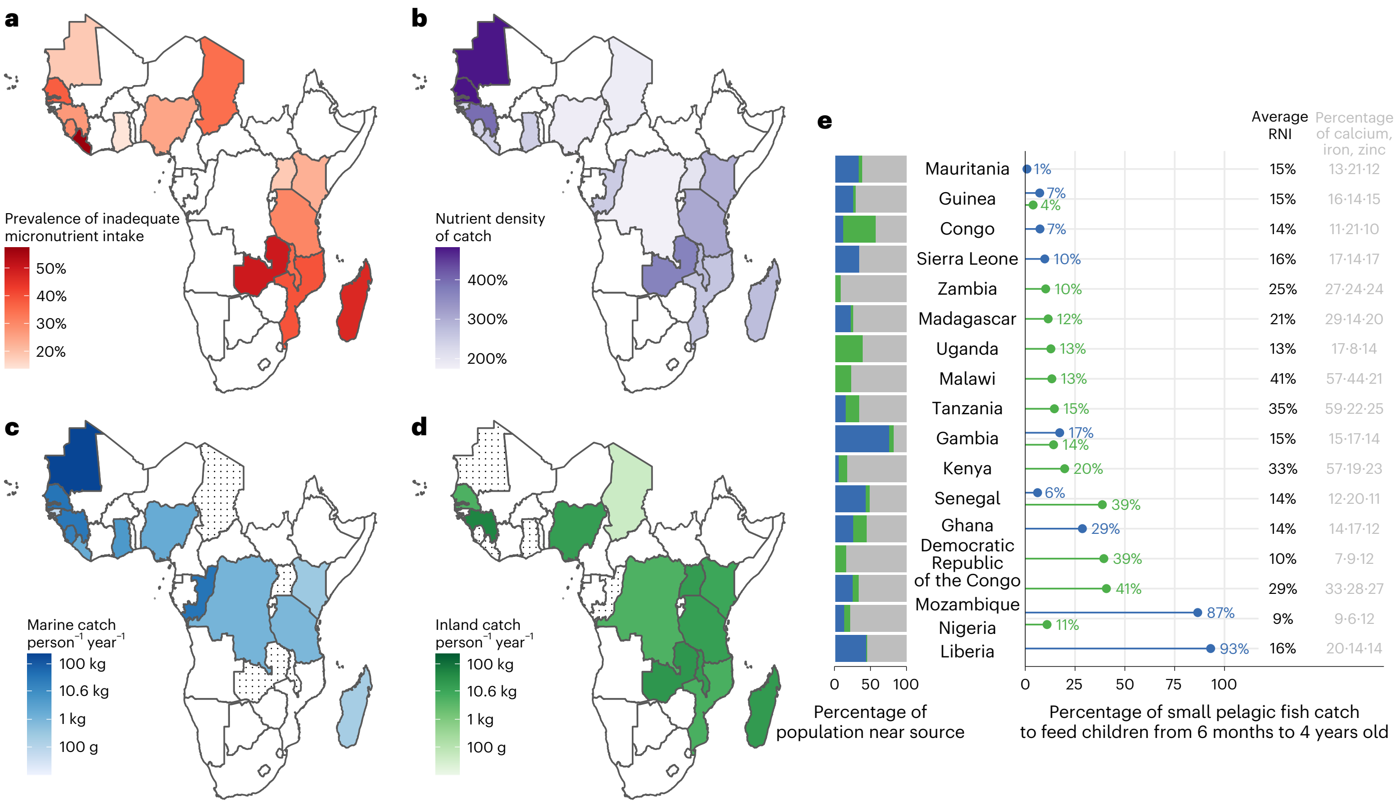

Fig. 4 | Potential food supply from small pelagic fish. a, Prevalence of inadequate micronutrient intake[24] **b**, Average nutrient density of fishery catches in 19 low- and lower-middle-income countries in sub-Saharan Africa. **c**,**d**, The annual food supply per person shown for marine (**c**) and inland (**d**) catches of least-cost, nutritious, small pelagic fish. Countries without micronutrient intake estimates and those not included in our catch database are coloured white and countries with small pelagic catch records from only one ecosystem are shaded with dots (**c**,**d**) (for example, Chad has no marine catch). **e**, The points are the proportion of small pelagic catch that could provide a daily fish portion (40 g) to all children (6 months to 4 years old) living within 20 km of a coastline or lake. The bars are the proportion of each country's adult population living within 20 km of inland (green) and marine (blue) water. RNI is the average recommended daily nutrient intake of calcium, iron and zinc in a 40 g portion of small pelagic fish for children aged 6 months to 4 years old based on each country's pelagic catch composition (Extended Data Fig. 4). The RNI for each nutrient is shown in grey. Population estimates are adults (**c**,**d**) or children (**e**) living within 20 km of a coastline or large water body; 10.6 kg per person is the recommended annual intake for adults[22]. Low-cost catches that were too small to feed all children (that is, >100% catch required) were excluded.

countries. These species were particularly affordable in low-income African countries, such as Uganda and Guinea, and remained affordable in middle-income countries (for example, India, Turkey) despite markedly higher prices of other, less nutritious fish. Small pelagic fish can sustain productive marine and freshwater fisheries because of their fast growth rates and high biomass turnover[19,28] and are typically consumed by poor households[29–32]. These species are often eaten whole and preserved by drying, salting or smoking, enhancing the concentrations of some nutrients[29] and enabling distribution to population centres and rural communities[30,33,34]. Low-cost fish that are processed and consumed whole are thus likely more nutritious than the estimates we used in this study (that is, model predictions for fish tissue; Methods), particularly in nutrients concentrated in organs and bones (for example calcium and vitamin A[35,36]) and in nutrients with sparse content data (for example, B_{12} (ref.[37])). Furthermore, catch of low-cost, small-bodied fish is often underestimated[32], suggesting that many small pelagic fisheries supply more nutrients than estimated in this study (for example, catches without species information, such as Ghana (24%) and Nigeria (54%)).

Improving access to nutritious and affordable small pelagic fish and fish-based products could help reduce existing nutrient deficiencies[38]. However, in marine systems, many of these species are already fished at or above sustainable limits[39]. In West Africa, marine pelagic stocks face growing demand for both domestic food supply[40] and global demand for fish, fish meal and fish oil[28,41], undermining local food security[42] and contributing to substantial catch declines since 1950 (refs. [21,43]). Overexploitation of small pelagic fish has caused deficits in West Africa's aquatic food supply, with countries such as Ghana transitioning from a net fish exporter to net importer[44], in part due to artisanal fleets transitioning to bigger and more powerful vessels, industrial and distant-water fleets targeting small pelagic stocks and growth in illegal, unregulated and unreported fishing[43,45,46]. Therefore, widespread prevalence of overfishing of small pelagic stocks limits the availability of marine fish for local consumption. Climate-driven shifts in species distributions are also expected to further decrease catch potential[47] and lead to regional governance conflicts[48]. In contrast, many of East Africa's inland fisheries exhibit long-term stability or increases in total catches[49], which may signal that inland small pelagic fish stocks are currently fished below sustainable limits[19].

Despite high apparent supply of nutritious catches, small pelagic fish may not always contribute to human health. High and increasing rates of nutrient deficiencies across sub-Saharan Africa[2] suggest that the diets of many women, men and children, or their ability to use the nutrients in their diets, are inadequate. Such gaps between supply, consumption and health may arise for many reasons, including conflict, climate shocks, poor sanitation, illness and supply chain inefficiencies that reduce the affordability and supply of healthy foods[2]. Poor access to, or utilization of, healthy diets compounds the effects of poverty and income inequality on human health, contributing to rising malnutrition[2]. For aquatic foods, low household

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incomes can limit access to fish, even within fishing communities[50,51]. Emerging markets for animal feed ingredients increase demand for small pelagic fish, making catches less accessible and affordable to local consumers[28,41]. Although farmed freshwater fish have boosted aquatic food supplies across the Global South[52], expansion of some forms of aquaculture has led to substitution of wild-caught species with nutrient-poor farmed fish, reducing nutrient intake in diets[53,54]. Small-fish catch is also prone to post-harvest waste[55], while processing methods may increase health risks by introducing microbial contaminants, carcinogens and heavy metals[33]. In addition to affordability, different sectors of society exert different food choices based on the beliefs and preferences associated with culture, ethnicity and geography[56,57]. Social influences on fish consumption can result in women, men and children experiencing different access to fish, independently of their nutritional need (for example, higher nutrient requirements for pregnant women)[57].

Therefore, widening access to and utilization of healthy diets through sustainable increases in pelagic fish production will require coordinated fisheries, trade and health interventions that together protect the supply of small pelagic catch for consumption by nutritionally vulnerable populations[58]. Development of nutrition-sensitive aquatic food systems could help to achieve these objectives[59]. For example, capture fisheries can be managed to maximize sustainable catch of nutritious species[60] and supported with trade agreements that allocate low-cost species for domestic food consumption[61] (and most-cost species for international trade), while ensuring that local dietary needs are not negatively impacted by growth in other food sectors (for example, aquaculture, animal feeds)[34,62]. Post-harvest interventions that support supply chain actors to improve safety standards for processed fish and reduce loss and waste would improve the shelf life and nutritional quality of processed aquatic foods[55,63,64]. These approaches can be supported with public health policies that work to improve sanitary conditions and food safety[2], promote the use of small pelagic fish during pregnancy and complementary feeding[51,65] and use fish to address specific nutrient deficiencies in vulnerable populations[37,38]. These policies and investments should be guided by research that distinguishes between populations and places where fish already make essential contributions to healthy diets and those where improving access to fish could improve public health outcomes[13,57].

High cost and low affordability of nutritious animal-source foods is a critical barrier to reducing all forms of hunger, particularly in low- and middle-income countries. Diets that meet nutritional needs can cost five times as much as energy-sufficient diets, with protein-rich foods accounting for almost one-quarter of the cost of a healthy diet[1]. Indeed, consumption of aquatic foods can be associated with wealth[66], whereas in other contexts, fish is considered food of the poor[67]. Our results reveal that small pelagic species are among the least-cost nutritious species in many low- and middle-income countries across the world, caught in large amounts from both marine and freshwater habitats. Such low-cost, nutritious, animal-source foods are likely to be key contributors to healthy diets in places with access to fish markets or where households practise subsistence fishing, particularly in low-income countries. In sub-Saharan Africa, many countries support highly productive pelagic fisheries yet populations have high rates of deficiencies in nutrients that are concentrated in small pelagic fish, suggesting that fish supply is not fulfilling local nutritional needs. Policies that prioritize the sustainability of fisheries that catch cheap, abundant and nutritious fish, and social interventions that promote and protect their use for human consumption[4,15,59], could significantly enhance the contribution of affordable small pelagic fish to global food and nutrition security.

Methods

Catch, price and nutrient data

Catch and price data for wild capture fisheries were compiled through country-level case studies as part of the Illuminating Hidden Harvests project, a collaborative study by the Food and Agriculture Organization of the United Nations (FAO), Duke University and WorldFish[68]. This project assessed the global contributions of small-scale fisheries to the economic, social and environmental dimensions of sustainable development. Countries were selected through a ranking process that quantified the importance of fisheries using indicators including production, employment, fish protein intake, and estimated small-scale fisheries production at the global and national levels. Rankings were developed using existing data, separately for marine and inland sectors (Supplementary Methods and Supplementary Table 1). This expert-led procedure produced a set of 58 countries and territories spanning a range of economic statuses and geographical locations, representing 70% of global marine catch and 65% of global inland catch[69]. In this study, we focus on 39 low- and middle-income countries in this dataset, spanning Africa ($n = 23$), Central and South America ($n = 5$), South-East Asia ($n = 10$) and Oceania ($n = 1$).

For each country, catch and price data were disaggregated by marine and inland and small- and large-scale fisheries, according to official or commonly used definitions for fishery sectors in each country. A consistent protocol was used in all countries to compile catch data aggregated by fishery and/or species, from both official governmental fisheries agencies (80% of the total catch) and unofficial data sources, including peer-reviewed and grey literature. We extracted estimates of the nominal annual total fish catch (metric tonnes of live weight equivalent) over 2013–2018 from both marine and inland environments. All non-fish (that is, plants, invertebrates, marine mammals) catches were excluded due to lack of species-level data on nutrient content, although some of these aquatic foods are also nutritious and contribute to micronutrient intake globally[70]. Catches were identified to the lowest taxonomic resolution available, with species information available for 95.7% of total landed weight (average 87% of country-level landings). To facilitate comparison of catches across regions with different species compositions, we grouped species with similar biological and functional characteristics according to FAO International Standard Statistical Classification of Aquatic Animals and Plants (ISSCAAP) categories[71]. We added two new categories of freshwater fish for catfish and *Latidae* perch since both are 'miscellaneous' in ISSCAAP but had large catch quantities in the catch database. Catches without species-level information were excluded. The country case studies also provided ex-vessel price (that is, price received at the point of landing) estimates for catch records, where available. These were compiled from official sources (56% of records, 73% of catch weight), historic data (23 and 16%) and estimates provided by recognized fishery experts and key stakeholders in each country (11 and 6%). A gap-filling protocol was used to fill missing price estimates, using a four-tiered imputation process that estimated price (1) according to each country's observed price data, (2) within the most similar and best available data from neighbouring countries, (3) within countries sharing the same income level and (4) from price estimates from all remaining countries. Price estimates were available for 39% of catch records (71% catch weight) and mostly provided in US$. Any local currency records were converted to US$ using bilateral exchange rates for each catch record year. For each species in each country, we estimated the average total annual catch in tonnes and average price per tonne in US$. We extracted each species' length at maturity (cm), or the average length at maturity for mixed species catches, from FishBase[16].

Next, we estimated the concentration of calcium, iron, selenium, zinc, vitamin A and omega-3 fatty acids of each catch record, using Bayesian model estimates from FishBase[16] and accessed from https://github.com/mamacneil/NutrientFishbase. Nutrient concentrations from a meta-analysis of 3,558 nutrient samples from 539 species were fitted to a trait-based Bayesian model, as described in Hicks et al.[4]. We extracted traits for all 2,438 species in the catch database and predicted species-level concentrations of each of the 6 nutrients (per 100 g of raw white muscle tissue). Catches of mixed species groups were assigned

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the average nutrient concentration of all species recorded in the catch; higher-order catches were assigned family- or order-level nutrient concentrations. We estimated the nutrient density (%) of each species, defined as the combined reference nutrient intake (RNI) of six nutrients (calcium, iron, selenium, zinc, omega-3 fatty acids, vitamin A) for adult women, for a 100 g portion[72,73].

Fish affordability

We standardized the US$ price of each catch record by the relative cost of caloric adequacy (the lowest-cost set of starchy staples required to meet daily energy needs; 2,109 kcal per day (refs. [9,10])). This metric facilitates comparison of foods between countries of varying economic status and food consumption patterns. Therefore, we defined the price of 100 g of fish relative to the cost of starchy staples in each country (that is, the cost of adding a 100 g fish portion to an energy-sufficient diet), accounting for differences in both the type and cost of staple food in each country (for example, rice, maize, tubers).

We used a Bayesian mixed-effects model to predict fish affordability (that is, fish price relative to starchy staples) for each species and ISSCAAP species group. The affordability of each catch record *i* was drawn from a log-normal distribution ($logN(\mu,\sigma)$) and fitted to varying intercepts for each species *a* and ISSCAAP species group *b*.

$$y_i = \text{species}_a + \text{species group}_b + \beta_1 \text{length at maturity}_i + \beta_2 \text{ catch}_i + \text{country}_j + \text{subregion}_k + \text{region}_l \quad (1)$$

Nested intercepts modelled variance in affordability among countries (*j*), subregions (*k*) and regions (*l*); total catch (tonnes) and species body size (length at maturity, cm) were scaled to a mean of zero and fitted as continuous effects. Intercept and continuous covariates had weakly informative priors ($logN(0,1)$) and variance priors were *exponential*(1) or $U(0,10)$. We then extracted posterior draws for each species group, conditioned on country, subregion, region and body size. These posterior samples provided country-specific affordability estimates for all species groups with catch records. Models were fitted using the 'Rethinking' package in R[74] and implemented using a Metropolis–Hastings sampler in Stan[75] for 5,000 iterations (warm-up for 1,500) across 3 chains. We inspected trace plots and ensured that Rhat values were less than 1.01, indicating that chains were well mixed.

Least-cost nutritious fish

Next, we identified catches that were both cheap and nutritious by integrating affordability estimates for each catch record with its estimated nutrient concentration. For each catch, we estimated the cost of reaching 33% nutrient adequacy[15,17] from a 100 g portion of unprocessed muscle tissue, defined as the portion size of a species or species group that provides an average 33% of recommended daily intakes for adult females (18–50 years of age) across 6 nutrients (calcium, iron, selenium, zinc, vitamin A, omega-3 fatty acids). This metric represents the potential contribution of a single portion of fish towards the recommended intake of multiple essential nutrients that are concentrated in fish. Note that nutrient adequacy is different from the cost of nutrient adequacy[10], which is the lowest-cost combination of all available food items to achieve the total recommended daily intake (adequate intake or recommended dietary allowance) of energy, carbohydrates, protein, lipids and 20 nutrients. Although our metric of nutrient adequacy can skew towards individual nutrients with concentrations exceeding the recommended intake (for example, selenium in fish; Fig. 2), it was also positively correlated with the number of nutrient targets (1 target = ≥10% of recommended nutrient intake[76]), showing that species with high nutrient adequacy also contribute to the recommended intake of multiple nutrients (Extended Data Fig. 7).

We used these estimates to identify the lowest-cost nutritious fish in each country, defined as the species group that reached 33% nutrient adequacy at the lowest cost (relative to starchy staples). Therefore, lowest-cost species were likely locally consumed and thus could contribute to healthy diets if caught in sufficient quantities and distributed to local markets. We also estimated the highest-cost nutritious fish in each country (species group that reached 33% nutrient adequacy at the highest cost), as a contrast to least-cost species, revealing catches that are least likely to contribute to affordable diets.

Pelagic fish supply in sub-Saharan Africa

We estimated the potential food supply from low-cost nutritious fish catches in sub-Saharan Africa, where fish consumption is high[34] but people suffer some of the highest rates of inadequate nutrient intake in the world[24]. For each of the 19 low- and lower-middle-income countries, we extracted the total annual catch of the 3 lowest-cost nutritious fish groups in this region (herring, sardine, anchovy; carp and other cyprinids; miscellaneous freshwater fish). Miscellaneous freshwater fish were lowest-cost species in Chad and Mozambique, where miscellaneous species were small (average size ≤54 cm; Fig. 3b). Therefore, we assumed that only small species were the lowest-cost nutritious fish in this group and excluded the catches of large-bodied species (>54 cm).

Fisheries catch is more accessible to people living near the coastline and water bodies[77]. We used the United Nations World Population Prospects adjusted population count for 2015 (ref. [78]) to estimate the population of adults (18–65 years old) and children (0.5–4 years old) living within 20 km of a coastline or large inland water body. Marine coastlines were extracted from Natural Earth[79] and large, inland water bodies (lakes with area ≥50 km^2 and reservoirs with capacity >0.5 km^3) were extracted from Lehner & Döll[80]. Spatial buffers were applied using simple features (version 1.0-7)[81] in R (version 4.2.0)[82]. We then combined population counts with average national fish catch estimates to measure the potential pelagic fish supply per person, assuming an edible portion of fish of 87%[62]. We assumed that marine catch was only available for coastal populations and inland catch for lakeshore populations and thus combined population and catch estimates separately for marine and inland fisheries. For children, we also estimated the average contribution to the RNI of calcium, iron and zinc from a 40 g portion of raw muscle tissue because these nutrients are particularly concentrated in small tropical fish and essential for child development[4].

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

Modelled catch, price and nutrient data are available at https://github.com/jpwrobinson/small-pelagic-fish. Source data are provided with this paper.

Code availability

The analysis was performed using R v.4.2.0 and the code is available at https://github.com/jpwrobinson/small-pelagic-fish.

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Author contributions

J.P.W.R., D.J.M., N.A.J.G. and C.C.H. conceptualized and designed the study. D.J.M., G.A.A., K.B., M.M.M.C., P.J.C., G.N. and F.S. were involved in data collection. J.P.W.R. conducted the analyses and drafted the manuscript. All authors interpreted the data, contributed to manuscript writing and approved its submission.

Competing interests

The authors declare no competing interests.

Additional information

Extended data is available for this paper at https://doi.org/10.1038/s43016-022-00643-3.

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s43016-022-00643-3.

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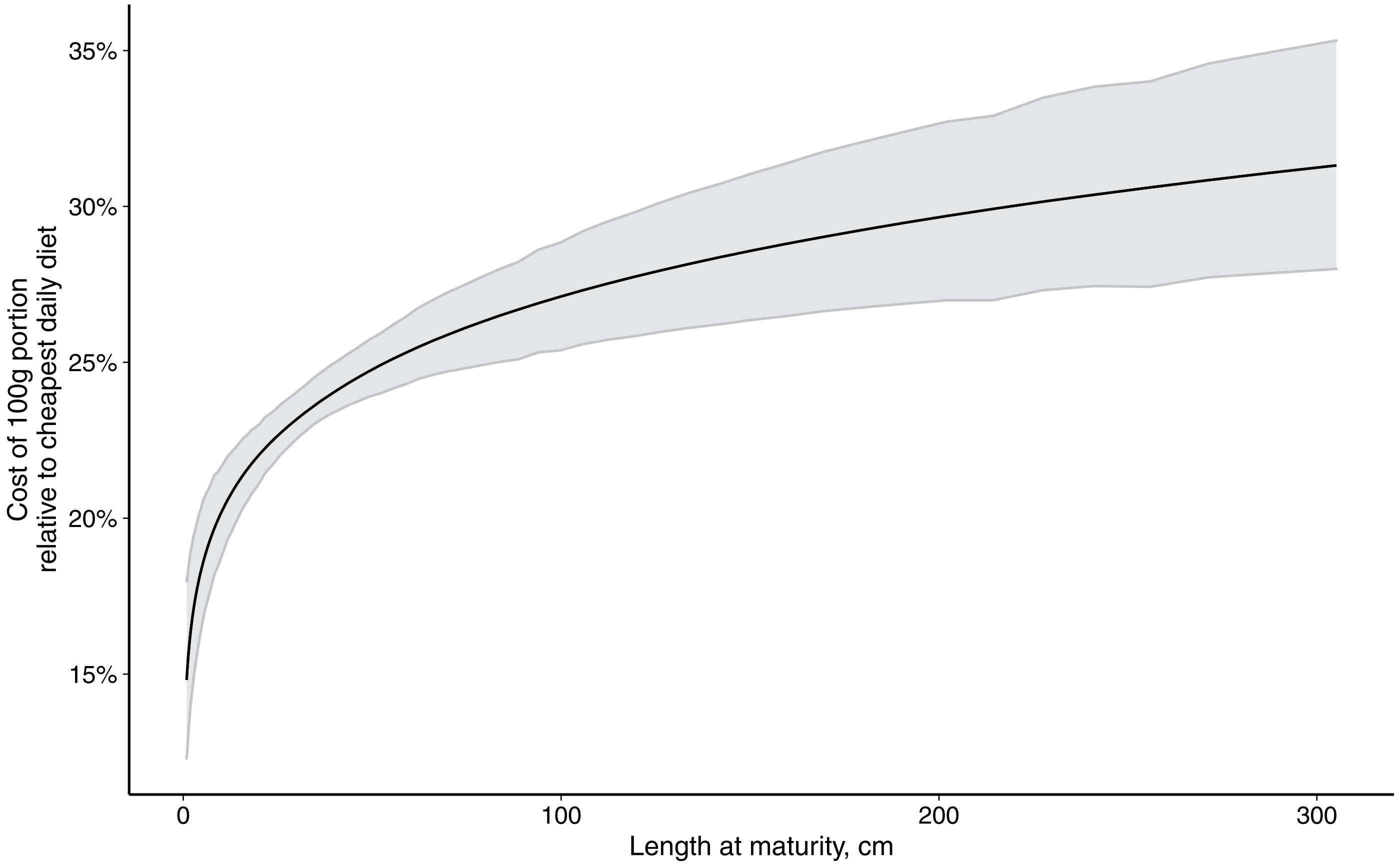

Extended Data Fig. 1 | The affordability of a 100 g portion of fish by species' body size (length at maturity, cm). Line is the median posterior predicted value, shaded with 95% certainty intervals.

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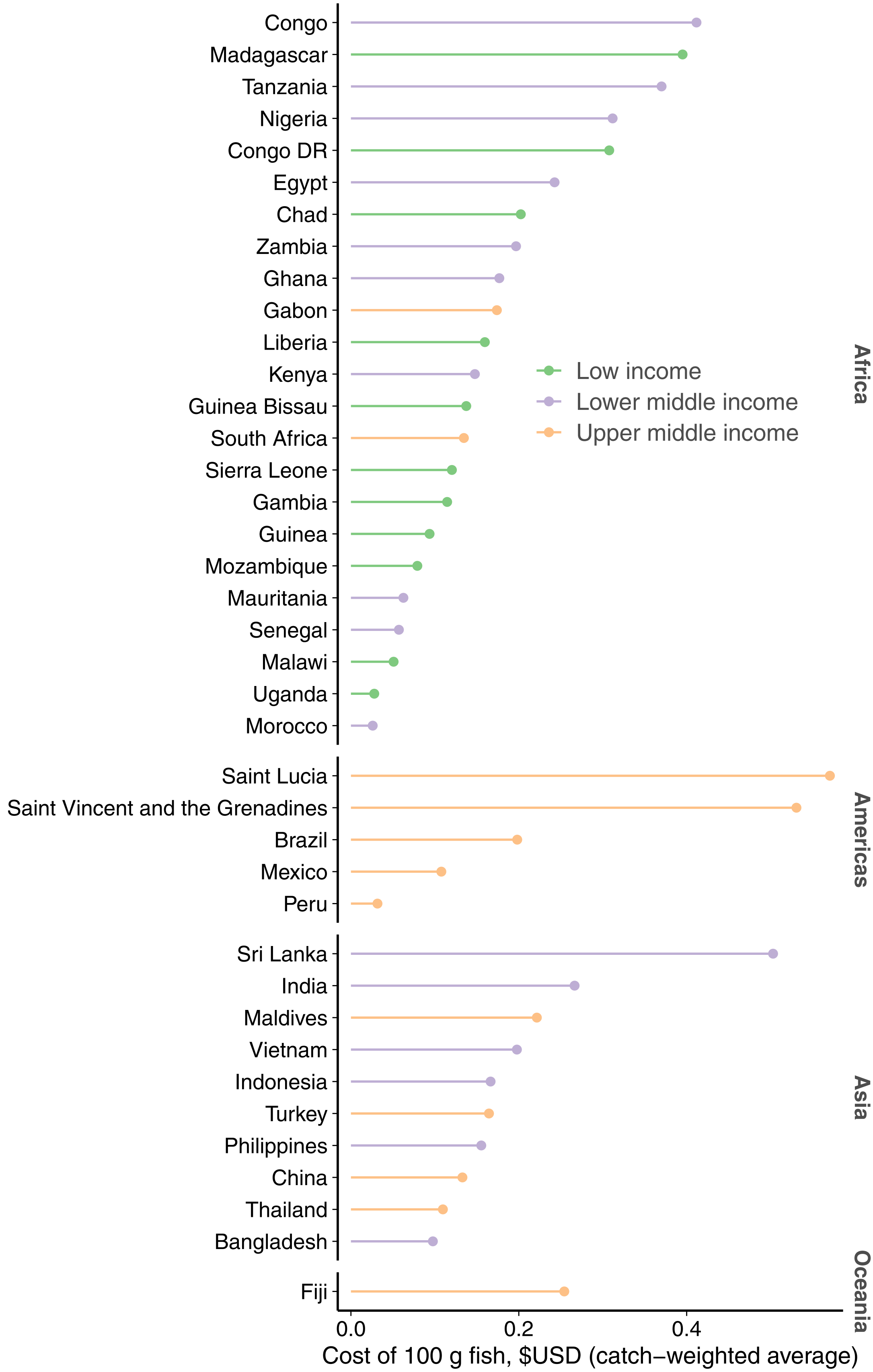

Extended Data Fig. 2 | The cost of a 100 g portion of fish in USD. Points are the median posterior predicted USD price of fish in each country.

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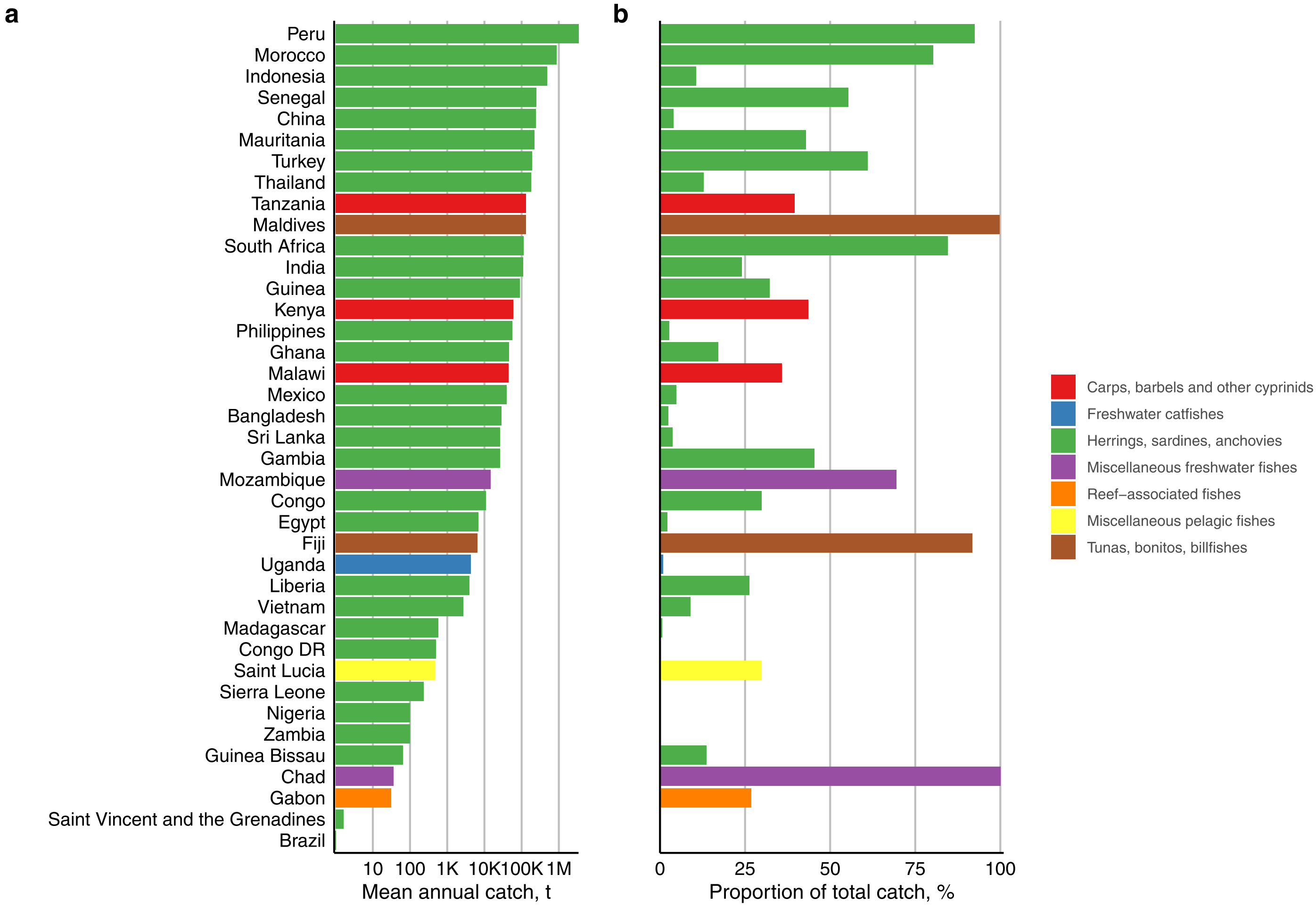

Extended Data Fig. 3 | Identity of the least-cost nutritious fish group in each country, showing the mean annual catch (a) and proportion of total annual catch (b). Bars are coloured by fish ISSCAAP group.

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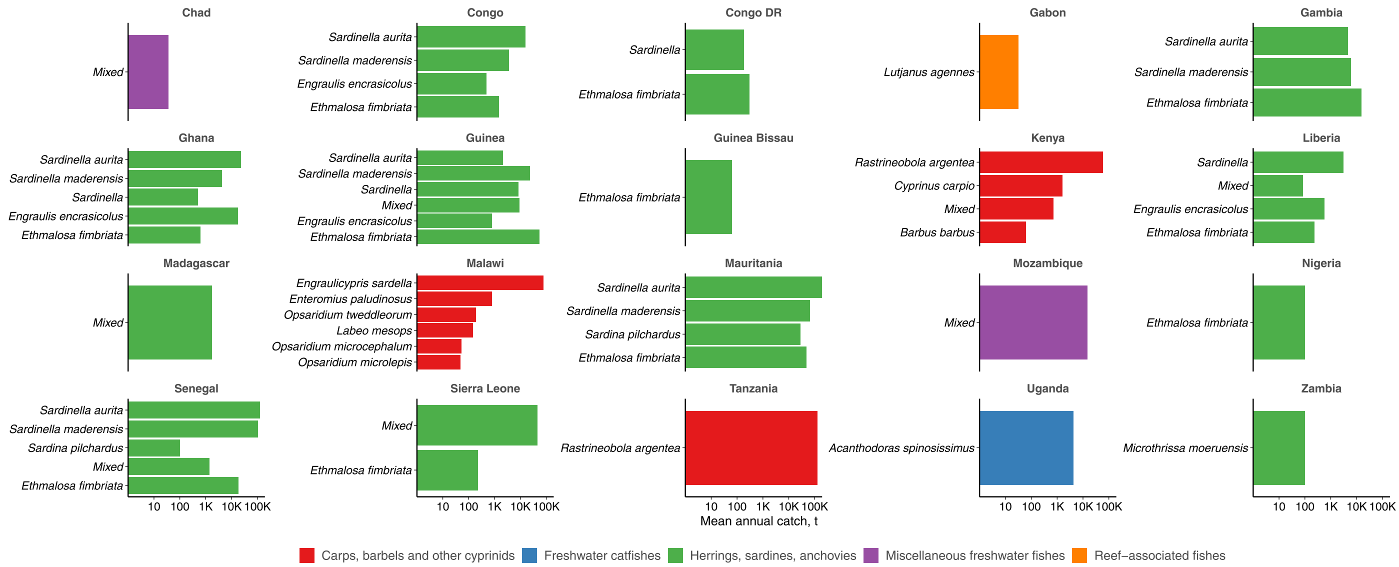
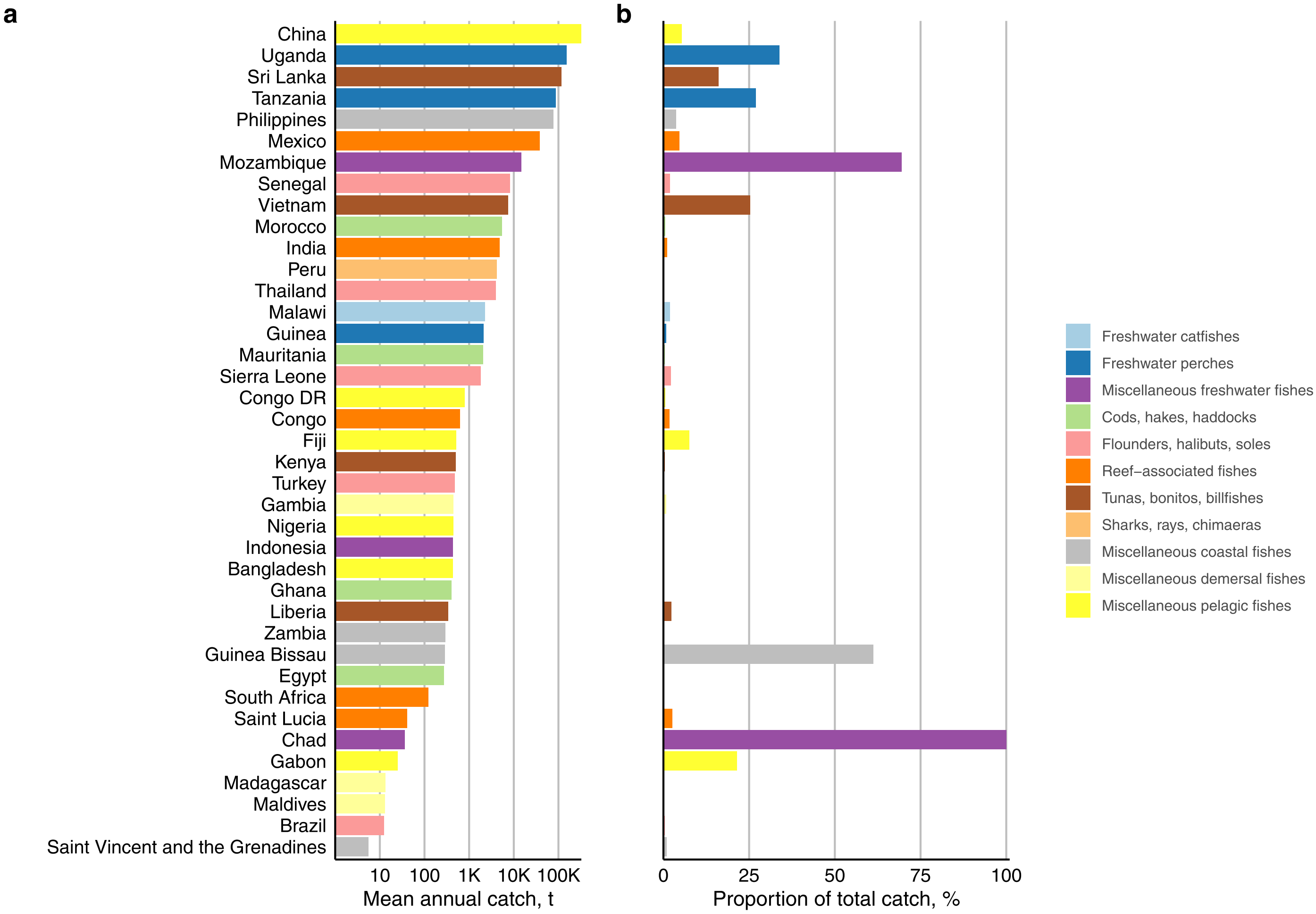


Extended Data Fig. 4 | Species in each country's least-cost nutritious fish groups in each country. Bars are the mean annual catch, coloured by fish ISSCAAP group.



Extended Data Fig. 5 | Identity of the most-cost nutritious fish group in each country, showing the mean annual catch (a) and proportion of total annual catch (b). Bars are coloured by fish ISSCAAP group.

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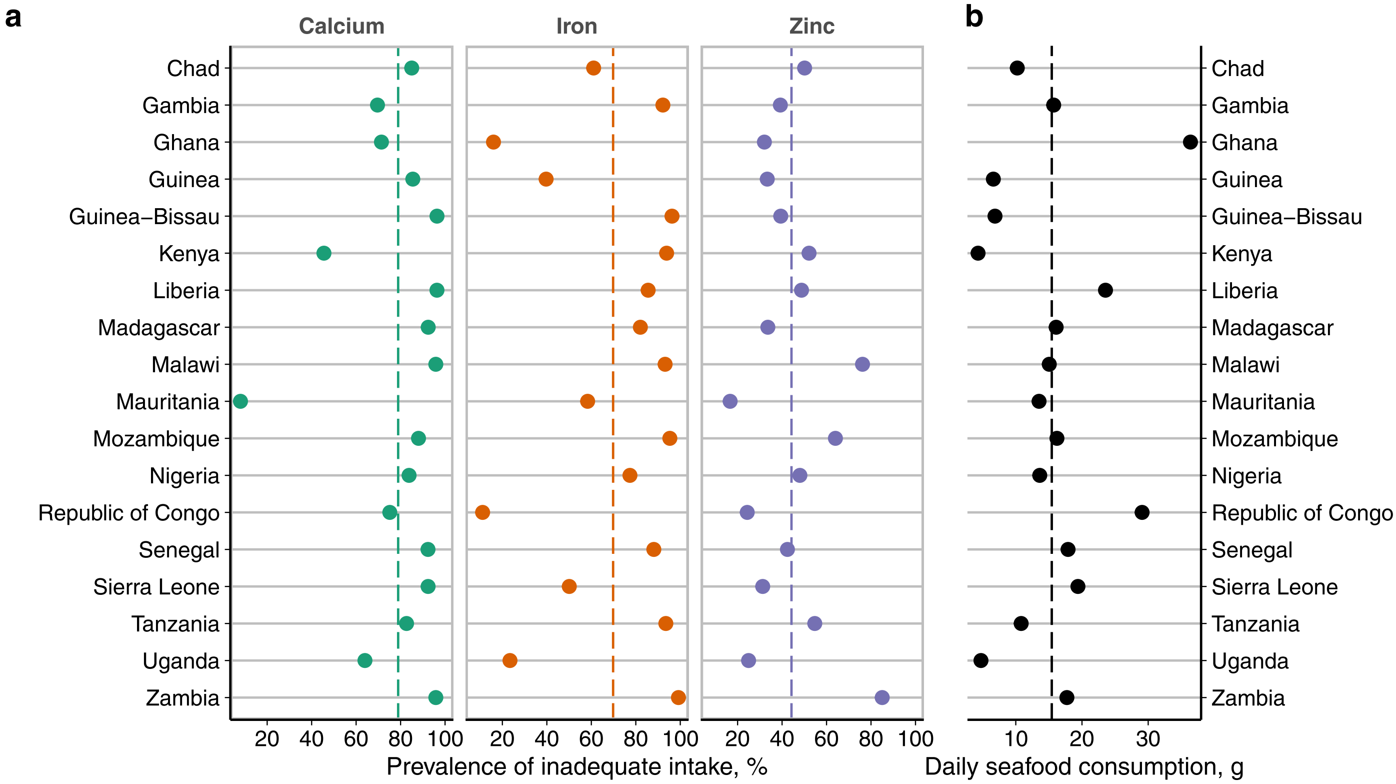

Extended Data Fig. 6 | Nutrient intakes and seafood consumption in sub-Saharan Africa. (a) Estimated prevalence of inadequate intakes of calcium, iron and zinc, for total population in each country by Beal et al. 2017 (ref. [24]). **(b)** Daily seafood consumption in children 2–5 years old, estimated by Global Dietary Database (ref. [26]). Dashed lines indicate average values across all 18 countries. Data for Democratic Republic of Congo were unavailable.

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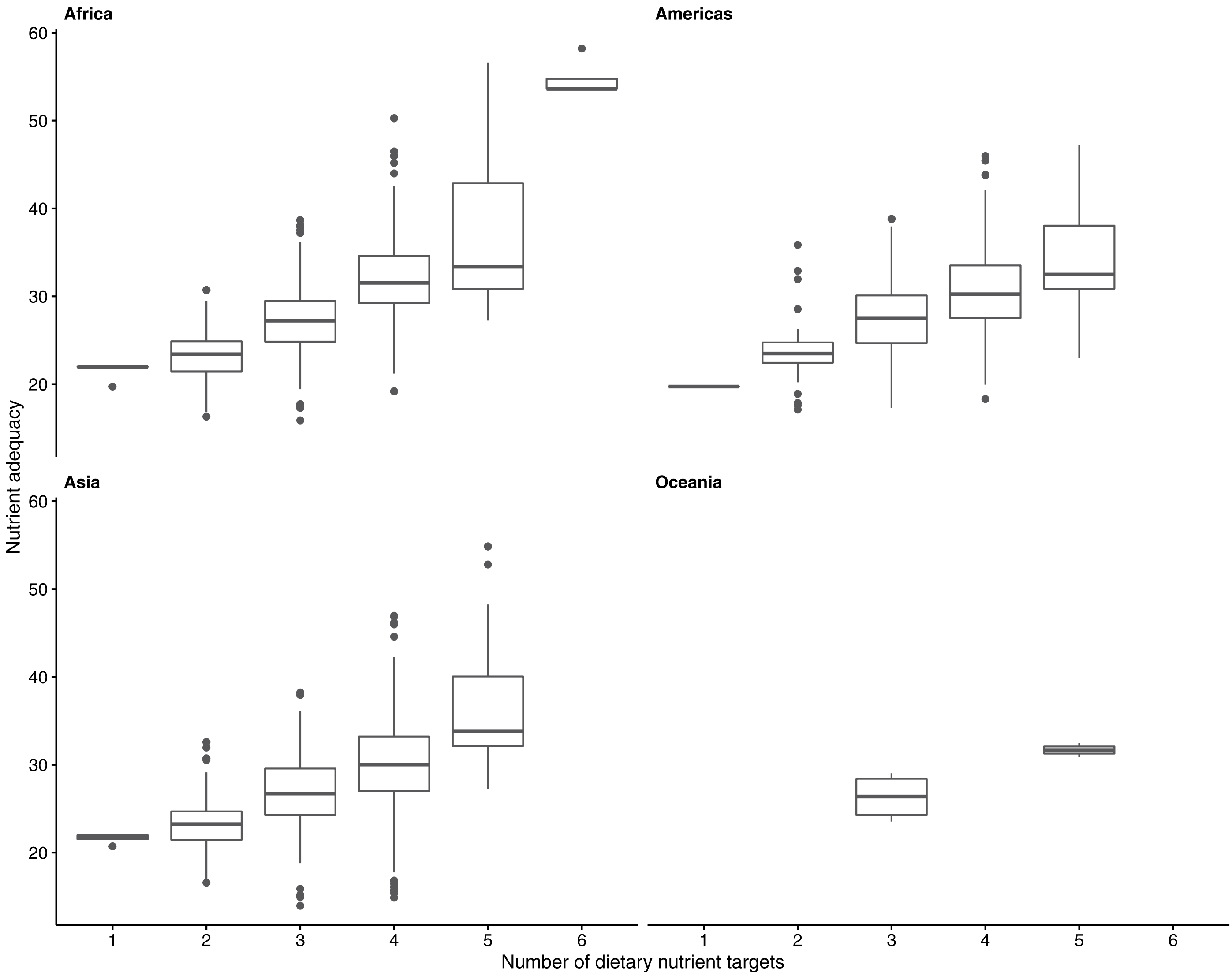

Extended Data Fig. 7 | Nutrient adequacy and the number of dietary targets (over 10% recommended intake per nutrient) contained in one portion. Data are species groups per country in the 39-country dataset, with boxplots showing median and 25th and 75th quantiles (±1.5*interquantile range).

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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	All data was collected and cleaned using Microsoft Excel.
Data analysis	All data was analyzed in R.

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 and 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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Modelled catch, price and nutrient data are available at https://github.com/jpwrobinson/small-pelagic-fish

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☐ Life sciences ☐ Behavioural & social sciences ☒ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

Ecological, evolutionary & environmental sciences study design

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

Study description	Data were collected from fisheries catch databases and combined with a publicly available nutrient content database.
Research sample	Fisheries catch data collected in 39 countries and representing 2,348 species.
Sampling strategy	Samples were collected for 2013-2018 from published fishery catch databases.
Data collection	Data were collated by the Illuminating Hidden Harvests project.
Timing and spatial scale	Data are annual catches from 2013-2018 for 39 countries.
Data exclusions	Data without species-level information were excluded.
Reproducibility	Analyses can be reproduced using the R code.
Randomization	No random allocation.
Blinding	No blinding.

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 and archaeology
☒	☐	Animals and other organisms
☒	☐	Human research participants
☒	☐	Clinical data
☒	☐	Dual use research of concern

Methods

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