Article

The nutritional value of invertebrate aquatic foods

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Most of the global population has inadequate micronutrient intake[1], leading to cascading adverse effects on economies and human health[2]. Aquatic invertebrates are a diverse, productive and socioecologically important food[3,4], yet their contribution to human nutrition is frequently overlooked[5]. Here, combining aquaculture production, capture fisheries and nutrient composition data, we quantify the contribution of aquatic invertebrates to global nutrient supplies. Furthermore, as nutrient information for invertebrates is sparse, using species-specific trait data, we develop a predictive model to estimate the nutrient content of over 50,000 invertebrate species registered in SeaLifeBase, a global database focused on marine non-fish species. We show aquatic invertebrates are exceptionally nutrient dense, with current aquatic invertebrate production supplying the equivalent annual requirement for over 5 billion people in terms of vitamin B_{12} and selenium; over 1 billion people for copper, omega 3 fatty acids, iodine and zinc; and over 100 million people for nutrients such as vitamins B_2 and B_3, iron, manganese and magnesium. Nutrient composition differs among taxonomic groups, consumption patterns (for example, body parts and processing form), and environmental and life-history factors such as the habitat or thermal regime the species lives in. Overall, provided that ecological sustainability is attained and socioeconomic and food-system barriers (such as food safety, access, affordability, cultural acceptance and bioavailability) do not prevent invertebrate consumption and nutrient uptake, our study highlights the potential benefits of integrating aquatic invertebrates into dietary portfolios across global societies, mainstreaming their nutritional importance in development projects, sustainability assessments and food policy.

The majority of the global population has inadequate micronutrient intake[1], leading to cascading adverse effects on economies and human health[2]. Meanwhile, increasing anthropogenic pressures are expected to drive micronutrient declines in major food sources[6,7], highlighting the need to better understand and account for the nutrient delivery from typically under-appreciated foods. Invertebrates account for most of the animal biomass and diversity on earth[8]. Aquatic invertebrates, more specifically, are diverse (over 1 million estimated species[9]), culturally and socially important[4], ecologically important[10], economically valuable (invertebrate ex-vessel prices can reach over US$10,000 per t)[11] and highly nutritious[12]. For example, aquatic invertebrates such as mollusks have higher nutrient concentrations per 100 g than other aquatic foods, such as ray-finned fishes (including vitamin B_{12}, iron, iodine, manganese, magnesium or zinc[13]). Furthermore, access to their diversity can help buffer current and future diet-related non-communicable diseases and nutritional deficiencies[12,14], especially in the context of environmental change[3,7].

Yet, despite their established importance, most aquatic invertebrates are grossly under-represented in fishery[15,16], conservation[17–19] and nutritional assessments[5,20–22]. Key advancements in ray-finned fish research have enabled the discernment of ecological, environmental[5] and phylogenetic traits[20] associated with nutrient content, making the prediction of nutrient composition for finfishes lacking such data possible[5]. Among others, these advancements have enabled estimation

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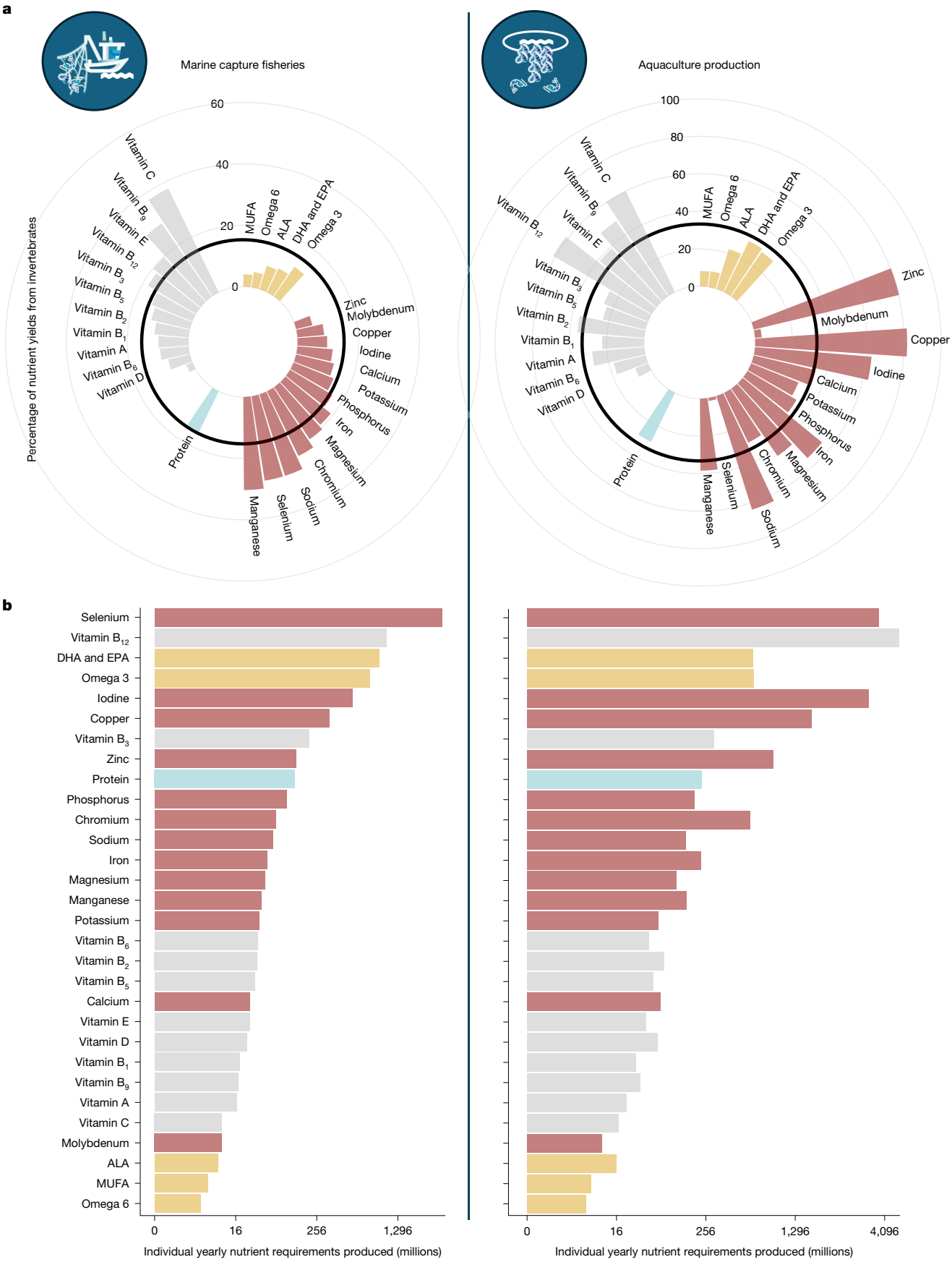

Fig. 1 | See next page for caption.

Fig. 1 | Nutrient contribution of aquatic invertebrates. a, The percentage of nutrient yields coming from invertebrates for global marine capture fisheries (left) and aquaculture production (right) in 2019. Inland reported fisheries estimates are shown in Extended Data Fig. 1. The black circles indicate the percentage contribution of invertebrates in terms of marine capture or aquaculture production volumes (that is, live weight). Cases in which bars surpass the black line indicate that invertebrates contributed disproportionately more nutrients relative to catch or production volumes. The figure using edible weights is shown in Extended Data Fig. 2. **b**, The number (in millions) of yearly nutritional requirements produced from aquatic invertebrates in marine capture fisheries or aquaculture production for 2019. For each nutrient, we use the average requirements across demographic groups (Supplementary Table 3). For clarity, the *x* axis was fourth-root-transformed and the reported values are shown on an arithmetic scale. Bars in **a** and **b** are colour coded by nutrient type: minerals in red, fatty acids in yellow, protein in blue, and vitamins in grey. The sample sizes used to derive the figure are described in the Methods. Year-, country-, sector- and phylum-specific variability in invertebrate contributions is shown in Extended Data Figs. 3–7.

of the potential contribution of fish-based food strategies to global nutrition security[5]. Yet similar research for invertebrates has lagged, despite their diversity[9], their increasing production levels relative to finfish[15], and their strong potential as a productive and low environmental footprint food[23,24]. Understanding the contribution of aquatic invertebrates to nutrient supplies, and their ability to meet nutritional adequacy targets, is crucial to (1) provide empirical evidence of current and potential nutritional contributions of aquatic invertebrates; and (2) understand the nutritional and public health implications of effective invertebrate monitoring, assessment, management and policy to meet multiple sustainability targets (for example, Sustainable Development Goal (SDG) of zero hunger, life below water or gender equality).

Here we integrated the Aquatic Food Composition Database (AFCD)[12] with capture fisheries[25,26], aquaculture production[26] and species-level environmental and ecological trait data[27] to estimate the contribution of aquatic invertebrates to global nutrient supplies (that is, available pool of nutrients produced or captured). First, we quantified the relative contribution of invertebrates to nutrient supplies of global capture fisheries and aquaculture production, identifying the sectors, species groups and countries that provide most aquatic invertebrate nutrients to human populations. In our analyses, we estimate global fisheries and aquaculture production of 30 nutrients essential for human health[13] (Methods). Second, we developed a series of Bayesian hierarchical models to determine the variability and potential drivers of nutrient content in aquatic invertebrates. For this, we combined species-level environmental and ecological trait data[27] with an updated invertebrate species-specific nutrient composition database[12] that includes 13,888 samples from 465 invertebrate species. Finally, we leveraged model predictions to estimate the nutrient composition of 50,807 macroinvertebrate species registered in SeaLifeBase[27], a global database focused on marine non-fish species, showcasing their potential contributions to public health and regional food security.

Nutrients from aquatic invertebrates

First, combining global statistics on capture fisheries and total aquaculture production with the nutrient content of aquatic foods, we estimated the contribution of aquatic invertebrates to global aquatic animal source nutrient supplies. We found that several nutrients were more concentrated in aquatic invertebrates than in other taxonomic groups, such as finfish. As a result, invertebrates contributed disproportionately to the supply of key essential nutrients, relative to their production volume. For marine capture fisheries, invertebrate aquatic foods contributed relatively more nutrient supply than biomass supply for 11 of the 30 nutrients examined (Fig. 1a). More specifically, while invertebrates contributed around 15% of total marine capture volumes, they comprised >30% of vitamin C and manganese; >25% of vitamin B_9 (folate), selenium and sodium; and >16% of chromium, magnesium, vitamin E, iron, vitamin B_{12} (cobalamin) and phosphorus supplies (that is, relatively more nutrient supply than biomass supply). For inland reported fisheries, invertebrates contributed around 5.8% in terms of inland fisheries volume but, relative to volumes, disproportionately contributed to the production of nutrients such as iodine (around 8.7%), copper (about 7.3%) or vitamin B_9 (approximately 8.4%) (Extended Data Fig. 1).

Within aquaculture production, relative to production volumes, invertebrates disproportionately contributed to the supplies of 13 nutrients (Fig. 1a). While invertebrates contributed about 33% of total aquaculture production volumes in 2019, they contributed >70% of aquaculture copper and zinc; >50% of sodium, iodine, vitamin B_{12}, vitamin C and iron; and >34% of vitamin B_9, magnesium, vitamin E, manganese, vitamin B_2 (riboflavin) and calcium. Note that, owing to the differences in species composition, aquaculture invertebrates contributed more nutrients (relative to production volumes) than marine captured invertebrates, with a different ranking and composition of nutrient contribution (Fig. 1a). In both marine capture fisheries and aquaculture production, we found that the relative importance of nutrient supply was robust to whether we accounted for live weight or edible weight (Methods and Extended Data Fig. 2). Other nutrients, such as potassium and molybdenum, vitamins B_1 (thiamin), B_3 (niacin), B_5 (pantothenic acid), B_6, A and D, protein, and total omega 3 and omega 6 fatty acids, including alpha-linolenic acid (ALA), eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), were supplied mainly by non-invertebrate aquatic foods (that is, invertebrates contributed less to these nutrient supplies than their contributions in terms of volumes; Fig. 1a). This emphasizes the role that a diverse portfolio of aquatic foods can have in tackling nutrition insecurity more broadly[12].

Second, to determine the public health implications of aquatic invertebrate nutrient supplies, we calculated the number of yearly recommended nutrient intakes (RNIs; recommended dietary allowance or adequate intake; Methods) potentially met from aquatic invertebrate production. We found that invertebrates met the highest number of RNIs for selenium, vitamin B_{12}, iodine, copper, omega 3 fatty acids (including DHA and EPA), zinc, chromium, vitamin B_3, protein, phosphorus, iron, sodium, manganese, magnesium, vitamin B_2, potassium, calcium and vitamin B_5 (in order of overall importance) (Fig. 1b). Specifically, we found that invertebrate production from aquaculture and marine capture fisheries in 2019 supplied the equivalent annual requirements of over 5 billion people for selenium and vitamin B_{12}; over 1 billion people for copper, omega 3 fatty acids (including DHA and EPA), iodine and zinc; over 300 million people for vitamin B_3, protein, chromium and phosphorus; over 100 million people for iron, manganese, sodium, magnesium, vitamin B_2, potassium, calcium and vitamin B_5; over 50 million people for vitamins E, B_6, B_9 and B_1; over 20 million people for vitamins A and C and ALA; and over 1 million people for molybdenum, monounsaturated fatty acids and omega 6 fatty acids (Fig. 1b). Dietary contributions varied by production method, with marine capture fisheries producing more DHA and EPA (around 937 million yearly requirements), and aquaculture producing more vitamin B_{12} (4.8 billion), selenium (3.8 billion), iodine (3.4 billion), copper (1.6 billion) and zinc (>900 million). Adding inland reported fisheries, acknowledging that they are probably underestimated[28], increased supplies by over 40 million people for nutrients such as iodine, vitamin B_{12} and omega 3 fatty acids (Extended Data Fig. 1). Overall, our study demonstrates that aquatic invertebrates are probably providing substantial health benefits to society, provided that their nutrient supplies are sustainable, well distributed and accessible to those who most need them.

Third, disaggregating capture and production by sector (that is, industrial, artisanal, subsistence or recreational fishing for marine

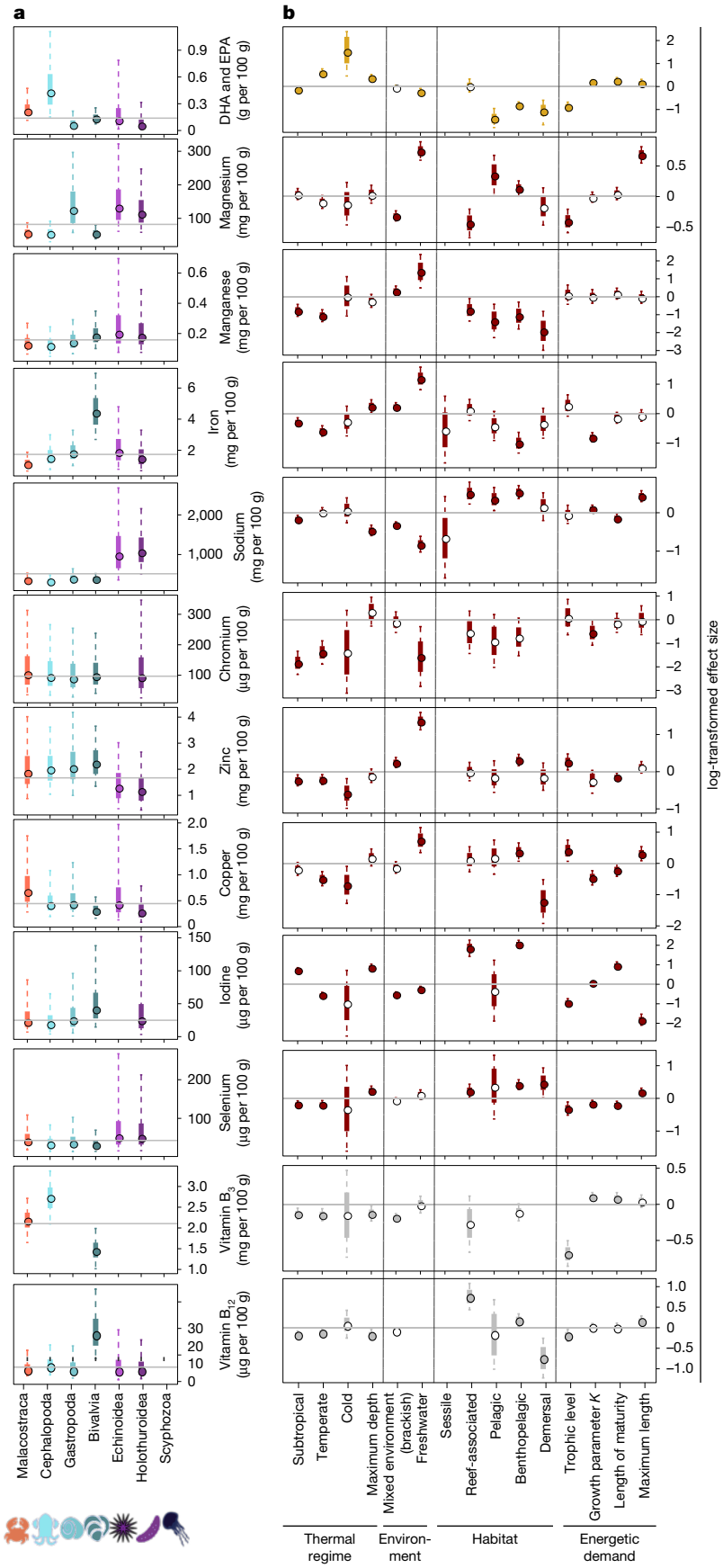

Fig. 2 | See next page for caption.

Fig. 2 | Variability and potential drivers of nutrient content in aquatic invertebrates. a, The estimated nutrient concentration per taxonomic class. Points are the median estimated nutrient concentration for that class (that is, global intercept plus relevant phylum and class intercept offsets), and the solid and dashed lines represent the 50% and 90% uncertainty intervals, respectively. The horizontal lines represent the median estimated global intercept for each nutrient across all invertebrates. Symbols are colour coded by class group. **b**, Effect sizes of different ecological and environmental factors (Supplementary Table 1) on average nutrient concentrations (on a log scale). Points are median values, and the solid and dashed lines represent the 50% and 90% uncertainty intervals, respectively. The horizontal lines are set at 0 (that is, the baseline category). Nutrients are colour coded by nutrient type: minerals in red, fatty acids in yellow, protein in blue and vitamins in grey. If the parameter's 90% uncertainty intervals overlapped zero, the point is not filled. Estimates in **a** and **b** are baselined for raw muscle tissue at average environmental and ecological continuous conditions (average depth, maximum length, length of maturity, growth parameter *K* and trophic level) and most common separate reference categories (tropical, marine and benthic). Missing estimates (for example, Scyphozoa in **a** or Sessile in **b**) indicate a lack of species-specific nutrient composition data under that category. Note that while we developed models for all nutrients with sufficient species-specific invertebrate data (that is, all but molybdenum, vitamin D and E; Methods), this figure highlights nutrients that were either (1) disproportionately contributed by invertebrates or (2) contributed the most to meeting human nutritional adequacy (Fig. 1). See Supplementary Table 2 for the exact sample sizes used in the models that derived these estimates, Extended Data Fig. 9 for the remaining nutrients, and Extended Data Fig. 10 for nuisance parameter results (that is, how nutrient concentrations vary with food part or processing form sampled).

capture fisheries; and marine or freshwater for aquaculture production), taxa and location (for example, country) revealed high variability in invertebrate contributions to nutrient supplies. In marine capture fisheries, the industrial sector supplied most of aquatic invertebrates in terms of total capture volumes (64%), followed by the artisanal and subsistence sectors (33% and 3%, respectively). Owing to the high volumes captured, the industrial sector produced the highest amount of nutritional requirements (except for selenium; Extended Data Fig. 4). However, relative to sector-specific catch volumes (for example, including fish), invertebrate catches and nutrients had the highest contributions to artisanal and subsistence sectors (Extended Data Fig. 5). Subsistence invertebrate fisheries contributed disproportionately more nutrients than catch volume (that is, 13 of the 30 nutrients; Extended Data Fig. 5), and artisanal invertebrate fisheries provided the highest yearly requirements of selenium in 2019 (over 1.2 billion yearly requirements; Extended Data Fig. 4). From the six phyla recorded (that is, mollusca, arthropoda, echinodermata, cnidaria, porifera and annelida), mollusks and arthropods dominated invertebrate catches and nutrient supplies, with captured mollusks supplying (in 2019) the equivalent annual requirements for over 1.5 billion people for selenium and over 400 million people for vitamin B_{12} and DHA and EPA (Extended Data Fig. 4), and disproportionately contributing to 16 of the 30 nutrients, relative to their phyla-specific catch volume (Extended Data Fig. 6).

Invertebrate contributions in marine capture fisheries also differed by country. Exclusive economic zones (EEZs) of China, Japan and Peru caught the highest invertebrate volumes, with China alone producing 32% and 23% of the total yearly requirements of selenium and vitamin B_{12} caught globally (821 and 241 million, respectively). Other EEZs with lower total invertebrate catch, such the Caribbean EEZ of Honduras (that is, 0.39% of China's catch), had higher prevalence of invertebrates in their catches (>85%), for example, capturing the equivalent annual selenium requirements for over 92 million people. Several island EEZs were notable in having high invertebrate contributions to nutrient supply, with Prince Edward Island, Heard and McDonald Islands, Fiji and American Samoa providing more nutrients than expected from catch volume for at least 20 out of 30 nutrients (Extended Data Fig. 7)

In aquaculture production, most of the invertebrates were supplied by the marine sector (84% in terms of live weight). Invertebrate mariculture in 2019 provided 76% of total mariculture supply, and over 85% of marine cultured zinc, copper, chromium, manganese, sodium, vitamin B_{12}, vitamin B_9 and iron supplies (Extended Data Fig. 5). This sector alone produced over 4 billion yearly requirements of vitamin B_{12} (Extended Data Fig. 4). Inland invertebrate aquaculture accounted for a small portion of inland aquaculture (8.3%) but was nutrient rich, disproportionately contributing to 13 of 30 nutrients (that is, higher nutrient yields than expected from inland production volumes; Extended Data Fig. 5). Similar to marine capture fisheries, cultured mollusks and arthropods also contributed most invertebrate nutrients, with cultured mollusks (1) dominating nutrient supplies in comparison to production volumes (22 out of the 30 nutrients examined; Extended Data Fig. 6), and (2) supplying the equivalent annual requirements for over 4 billion people for vitamin B_{12} and over 1 billion people for selenium, copper and iodine (Extended Data Fig. 4).

China, Vietnam and Indonesia produced most invertebrate aquaculture, with China producing 86%, 90% and 93% of the total yearly requirements of vitamin B_{12}, selenium and iodine cultured from invertebrates globally (that is, 4.1, 3.5 and 3.1 billion yearly requirements, respectively). In other countries, such as Ecuador, despite relatively low production volumes in comparison to China, invertebrates accounted for over 95% of cultivated aquatic foods, producing over 10 million requirements of selenium, copper and vitamins B_{12} and B_3. Relative to country-specific production volumes, French Polynesia, Barbados and New Caledonia ranked as the countries with greater nutrient contributions from cultured invertebrates, with at least 20 nutrients out of 30 being disproportionately contributed by invertebrates in comparison to other aquatic foods (Extended Data Fig. 7). Combined, all of these sector-, phyla- and country-specific results highlight that nutrient-sensitive approaches to invertebrate and aquatic food management in different geographies need to consider specific fishery and aquaculture contexts (for example, account for the variability in species composition profiles and quantities being caught or produced).

Aquatic invertebrate nutrient variability

Given the nutritional importance of invertebrates (Fig. 1), and building on predictive frameworks developed for finfishes[5], we estimated the variability and potential drivers of invertebrate nutrient content using species-specific invertebrate nutrient composition data, ecological and environmental trait data, and a series of Bayesian hierarchical models (Methods and Supplementary Table 1). First, we found that some nutrients vary considerably more than others among samples and taxonomic groupings (Extended Data Fig. 8). For example, variance decomposition results from our Bayesian hierarchical models show that iodine, chromium and selenium (for minerals) and vitamins B_{12} and A (for vitamins) had the highest variability. Similarly, for macronutrients (that is, fatty acids and protein), ALAs within invertebrates varied substantially more than others, such as protein or omega 6 fatty acids. These variability differences highlight the nutrients that may be best prioritized in future studies, for example, to model and quantify spatiotemporal variability in the nutrient content of aquatic foods.

Second, we show that when controlling for environmental and ecological traits, some taxonomic groups have higher nutrient concentration than others, but not consistently across all nutrients (Fig. 2a and Extended Data Fig. 9). For example, compared with average invertebrate values (Fig. 2a), bivalves had the highest concentrations of iron, iodine, zinc and vitamin B_{12}, whereas other groups, such as echinoderms (such as sea urchins and sea cucumbers), had the highest concentrations of selenium, magnesium, manganese and sodium (Fig. 2). These group-specific differences in nutrient content could help to inform public health programs and policies aimed at harnessing invertebrate foods to

improve undernourishment, particularly in locations in which policies may target specific nutrient deficiencies and vulnerable populations.

Third, similar to finfish[5], we found that several ecological and environmental predictors had strong associations with nutrient concentrations in aquatic invertebrates (Fig. 2b and Extended Data Fig. 9). Demersal invertebrate species, which live and feed in the water column near the seafloor, exhibited lower nutrient concentrations compared with reef-associated species, which had relatively higher concentrations across key nutrients examined (zinc, potassium, selenium, manganese, protein and vitamins B_2 and B_6, over two times the effect size; Fig. 2b and Extended Data Fig. 9). Similarly, invertebrate species sampled from freshwater environments showed higher copper, zinc, manganese and magnesium concentrations and lower sodium and chromium concentrations compared with species sampled from marine or mixed (brackish) environments (for example, median and 90% uncertainty effect sizes did not overlap zero; Fig. 2b). We also found nutrient concentration patterns with the latitudinal environment (thermal regime) occupied by the species, with (1) cold species having higher DHA and EPA fatty acids; and (2) cold and tropical species sometimes having similar nutrient concentrations but subtropical and temperate aquatic invertebrates showing relatively lower nutrient concentrations (for example, manganese, iron, and vitamins B_3 and B_{12}) per 100 g of raw muscle tissue (Fig. 2b). Species that inhabit deeper waters were also richer in DHA and EPA, iron, iodine and selenium and had lower concentrations of sodium than species that reach lower maximum depths. While some reported associations may reflect coupled ecological and life-history patterns rather than isolated effects of individual traits, these trends may also provide insights into potential nutrient sources and how specific environmental factors could shape species nutrient profiles. For example, freshwater streams typically have higher anthropogenic minerals that could be absorbed by organisms[29]. Similarly, our study suggests that the accumulation of nutrients in the muscle tissue of invertebrates is likely influenced by the thermal regime the species is exposed to, with some nutrients potentially having temperature-specific optima[30].

Fourth, we show that different scenarios of consumption patterns, for example, food processing forms and body parts potentially consumed, can shape the nutrient concentration of aquatic foods. Part of our approach aimed to control for factors (such as food processing and body parts) in our data that could impact the nutrient composition of aquatic invertebrates[31] (Methods and Supplementary Table 1). We found that these factors had strong associations with the nutrient content in aquatic invertebrates, often of higher magnitude than individual ecological and environmental traits (Extended Data Fig. 10). For example, whole or dried invertebrates tended to have higher nutrient concentrations (including iron, calcium, zinc, sodium, potassium, phosphorus or magnesium) than raw muscle tissue (Extended Data Fig. 10). Moreover, when performing variable selection, we found that these factors were often ranked as the best predictors of invertebrate nutrient concentration (Supplementary Fig. 1). These results highlight the need to consider what (that is, edible portion)[32] and how (that is, processing and preparation) aquatic foods are eaten in different dietary cultural contexts[33]. Furthermore, these results could indicate opportunities for value-added processing where highly nutritious body parts are not generally consumed (for example, fish crispy crackers from blue swimming crab shell waste[34]).

Nutrient estimates for data-poor invertebrates

Most aquatic foods produced by aquaculture and capture fisheries lack empirical species-specific nutrient composition data (66–97% dependent on nutrient; Supplementary Fig. 2). Thus, to advance research on the nutrient potential of aquatic invertebrates, we used model outputs to provide nutrient composition estimates for a total of 50,807 potentially edible macroinvertebrate species registered in SeaLifeBase[27] with available taxonomic, environmental and/or life-history traits (Methods). This revealed four key findings. First, on the basis of mean values across all aquatic macroinvertebrate species, 100 g of raw muscle tissue can provide over 85% of selenium, chromium and vitamin B_{12} daily requirements, over 50% of copper and iodine, more than 45% of niacin and DHA and EPA fatty acids, over 20% of protein, magnesium, iron, total omega 3 fatty acids and sodium, and around 17% of zinc daily requirements (Fig. 3a). Second, for some nutrients (such as copper, niacin or magnesium), our models predicted high variation among invertebrate species in the human requirements provided per 100 g of muscle tissue, whereas, for others (such as vitamin B_6 or B_9), there was less species-to-species estimated variability (Fig. 3a). Third, by focusing only on species that have a defined fisheries importance category (Methods and Supplementary Fig. 3), we showed that on the basis of mean values, invertebrate species typically used for subsistence are estimated to be relatively richer in vitamin B_{12} and iron, whereas highly commercial species are relatively richer in copper and zinc, and bycatch species are relatively richer in iodine and vitamin B_3 (Supplementary Fig. 3).

Finally, by matching estimated nutritional values to marine species occurrence data[35] (Methods) as an example, we show the geographical distribution of nutrient content among potentially occurring aquatic invertebrates (nutrient requirements per 100 g of muscle tissue, averaged across all nutrients that we developed models for; Fig. 3b). While limited in scope (for example, marine occurrence data do not include freshwater invertebrates), this revealed that present aquatic invertebrates have great potential for many regions with high inadequate intake of nutrients[1]. For example, the prevalence of inadequate iron intake is high in South Asia and Africa (over 50% of the population[1]) but the invertebrate species that occur in such regions have relatively high iron concentrations (Supplementary Fig. 4), with 100 g of invertebrate muscle tissue potentially providing about 50% of daily iron intake requirements (that is, 11.97 mg, which is the average daily iron requirements across demographic groups; Methods). Overall, these model-based aquatic invertebrate nutrient predictions can inform current and future developmental projects, aquatic food management and policy, and also increase our understanding on the potential trade-offs that may exist between nutrient supplies and the risk of toxins and contaminants[36].

Aquatic invertebrates within global targets

Our study quantified the potential contribution of aquatic invertebrates to human nutrition and estimated the variability and potential drivers of invertebrate nutrient content. In the process, we developed predictive models to estimate nutrient concentrations of aquatic invertebrates when analytical data are not available. This section highlights three future research avenues that can build on our work to further advance aquatic invertebrate accounting, facilitating the acceleration of theory and practice to improve nutrition security and achieve multiple global targets, such as the SDGs.

The first research avenue is the need for better empirical aquatic invertebrate nutrient composition and trait data. Models that predict the nutrient composition of aquatic foods using phylogenetic, taxonomic and environmental and ecological trait information[5,20] (Fig. 2) are useful tools to fill in data availability gaps, develop understanding of how environmental changes are likely to affect the nutrients available[7] and help to steer aquatic food systems towards greater sustainability[22], equity[37] and nutrition security[5]. For example, available predictions from our work (Fig. 3) can be used to inform targeted location-based research to aid nutrition interventions (such as incorporating invertebrates in diets to address specific nutritional adequacies[38]), nutrition-sensitive approaches to fisheries management[22] or research exploring the sustainability and climate-resilience of aquatic food systems[37]. However, models, while useful, are only as good as the data that inform them. For example, our study analysed species-specific nutrient composition

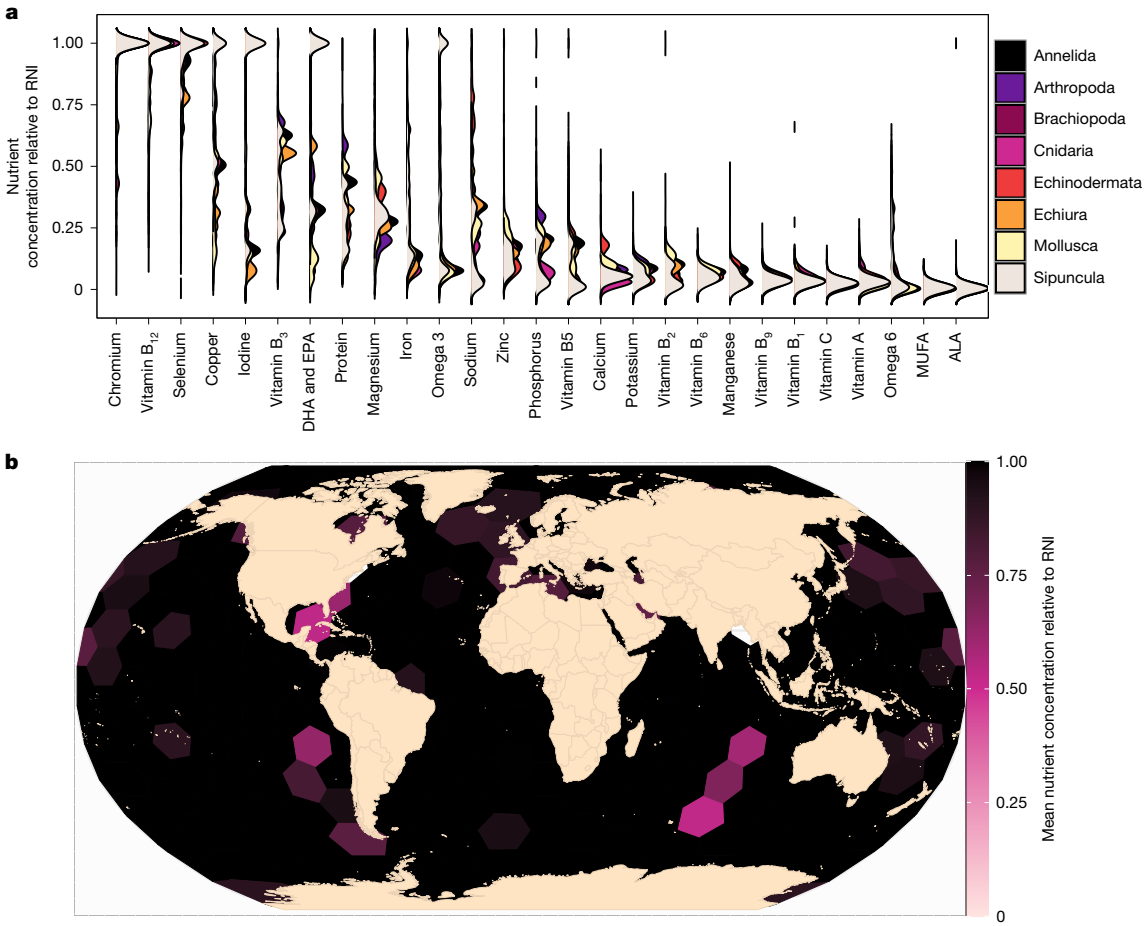

Fig. 3 | Estimated nutrient concentrations relative to RNIs for potentially edible macroinvertebrates. a, Median nutrient concentration predictions per 100 g of raw muscle tissue relative to recommended dietary intakes for a total of 50,807 potentially edible macroinvertebrate species available in SeaLifeBase[27]. Densities are colour coded by phylum groups as classified in SeaLifeBase[27]. **b**, The geographical distribution of potentially edible aquatic macroinvertebrates based on marine species occurrence data. Hexagons are bins of equal area that represent the mean nutrient concentration per 100 g of muscle tissue relative to daily RNI (across nutrients). See Supplementary Fig. 4 for individual nutrients. In cases in which values in **a** and **b** were greater than 1, we restricted them to 1.

data for 465 invertebrate species, yet the number of species varied by nutrient (Supplementary Table 2). As a consequence, some edible macroinvertebrate groups, such as jellyfish (Cnidaria), were scarce (that is, low sample size, informed mainly by estimated intercepts and ecological trait patterns of other groups) in our global models of nutrient concentration (Figs. 2 and 3). Similarly, some nutrients that are essential in diets and potentially rich sources in aquatic foods, either had limited sample size (for example, total omega 3 fatty acids; Supplementary Table 2), were not included due data inconsistencies (such as essential amino acids) or for not having established RNI reference values (such as arachidonic acid), or lacked sufficient species-specific invertebrate nutrient composition data to perform model predictions (for example, vitamins E and D; Supplementary Table 2). Future work that samples aquatic invertebrates for their nutrient content, and consistently reports it (for example, relative weight; Supporting Table 1), could target specific nutrients (such as vitamins D and E), selected aquatic invertebrate groups (such as edible sea worms or jellyfish) and invertebrates with specific ecological and environmental trait data (for example, freshwater mollusks). Such targeted sampling would increase aquatic invertebrate representation in model predictions, eliminate potential data structures in currently available data (for example, allow covariate balance in predictive tools[39]) and improve overall understanding of aquatic invertebrate nutrients. This also applies to the environmental and life-history traits used for nutrient predictions, as data-poor species without trait information are assigned to dominant ecological patterns, thereby reducing the potential variation in predicted nutrient concentrations (Fig. 3). Furthermore, as evidence on public health requirements accumulates (such as adequate intake or recommended daily allowance), additional nutrients, such as arachidonic acid, could also be incorporated.

The second, and related, research avenue is that which accounts for intraspecific and interspecific spatiotemporal variability in aquatic invertebrates, and aquatic foods more broadly. We used an updated version of the AFCD[12] to assign nutrient composition estimates to individual species and matched this to species-specific ecological and environmental traits in SeaLifeBase[27]. While these are the largest empirical compilations available of aquatic food nutrient composition and ecological information, spatiotemporal nutrient composition data (for example, how nutrients vary spatially and temporally within species or temporally across species) were limited (Supplementary Table 1). However, our results show which nutrients (such as iodine or vitamin A) vary the most (Extended Data Fig. 8) and which nutrients show patterns with spatiotemporal variables (such as selenium residuals and year of sampling; Supplementary Fig. 5), and could therefore be used to prioritize research that evaluates the drivers of nutrient content in aquatic foods. This could include studying the environmental drivers of nutrient content (how nutrient composition is likely to vary with temperature and ongoing climate change[40]) or how ontogenetic shifts (changes in habitat)[41] or biogeochemical cycles[29] influence the nutrient pool available from aquatic foods under different contexts. Moreover,

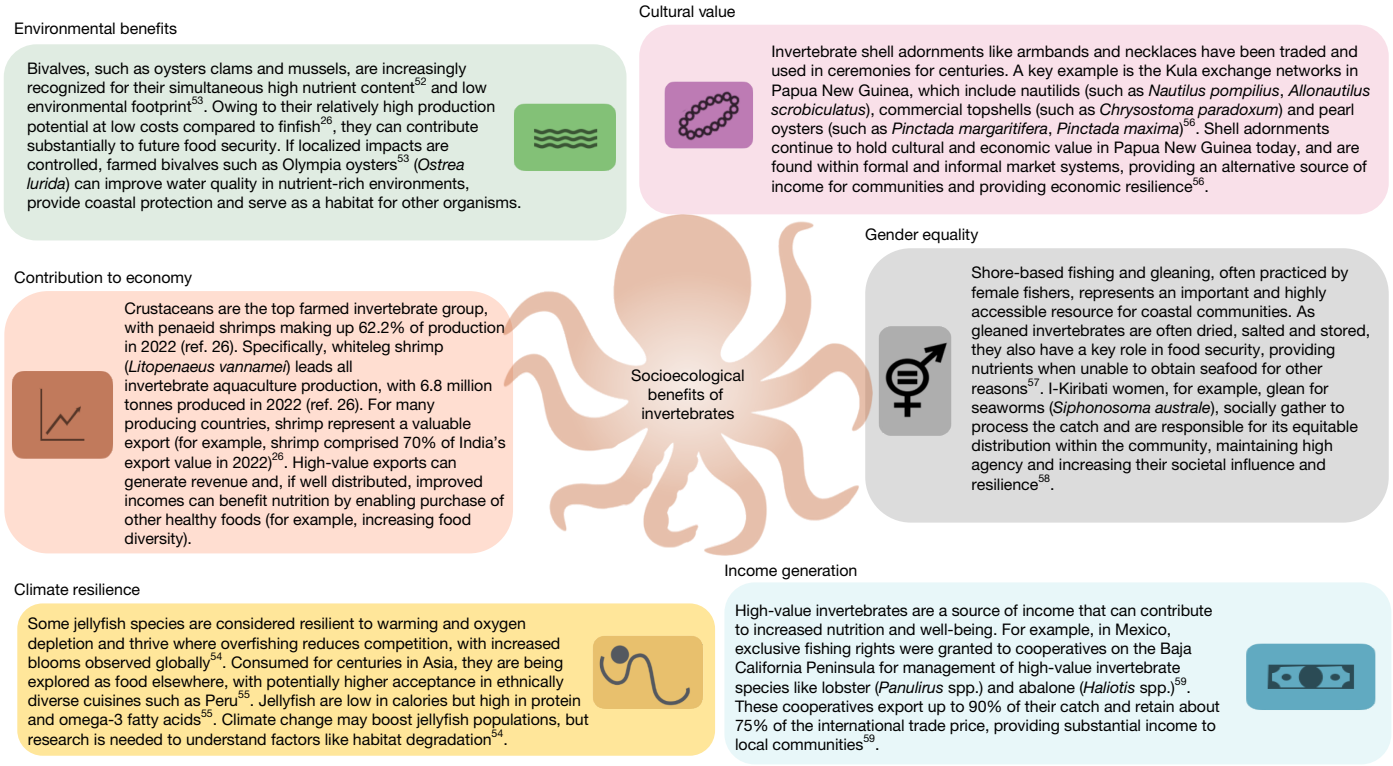

Fig. 4 | Additional socioecological benefits of aquatic invertebrates and their indirect contribution to nutrition. Conceptual diagram illustrating the multifaceted roles of aquatic invertebrates, such as bivalves, crustaceans, jellyfish and sea worms, in providing environmental, economic, cultural and equality-related benefits, in addition to income generation and promoting resilience to climate change[26,52–59].

aquatic foods are consumed in many forms, and what is considered edible can vary substantially across cultural and ecological contexts. Using live weight can overestimate nutrient availability when substantial portions of invertebrates are not consumed, whereas using muscle tissue samples or edible weights may underestimate specific nutrients consumed[32]. While our study shows the value of accounting for nutrient variability among body parts and processing forms, future research that specifically looks at consumption (not potential availability based on reported or reconstructed production estimates) and incorporates culturally explicit consumption patterns (for example, edible portions) could improve understanding of how potential invertebrate contributions estimated here can translate into realized consumption benefits.

Finally, given the food and nutrition-security relevance of aquatic invertebrates (Fig. 1), the diversity in their nutrient content (Fig. 2), as well as their social, economic and ecological importance[16], it is critical to enhance their effective monitoring, assessment and sustainable management to steer aquatic food systems towards meeting global, regional and local policy targets. Many aquatic invertebrates remain poorly assessed from a conservation and fisheries perspective, despite growing evidence of widespread invertebrate global declines. The potential nutritional benefits highlighted here depend on sustainable invertebrate supplies, halting current invertebrate declines, and maintaining invertebrate biodiversity and the integrity of the ecosystems that support invertebrate resources. The nutritional contributions documented here should not be interpreted as justification for increased exploitation, but rather as an additional argument for conserving and sustainably managing aquatic invertebrates, their diversity and the ecosystems that underpin their production. Aquatic invertebrates not only represent an important and diverse source of nutrients, but they also have diverse environmental, social and economic dimensions that also contribute to nutrition security (Fig. 4). They are a nutrient-rich food that is culturally appropriate and accessible in many locations[42], with high production potential at relatively low cost[3]. Policies that enhance their sustainable production and access can tackle multiple environmental and socioeconomic targets simultaneously (for example, zero hunger, gender equality, and responsible consumption and production; https://sdgs.un.org/goals).

However, overall, their sustainability and climate resilience is poorly understood[19]. For example, in terms of catches, we cannot determine whether nutrient supplies from invertebrates estimated here (Fig. 1) are sustainable because most of the increasingly exploited taxa are unassessed (that is, we do not know if they are sustainable or not[15]), and those invertebrates that are reported in catches are often grouped into broader taxonomic categories in comparison to vertebrates[26] (Supplementary Fig. 6). Even reported catches do not capture the reality of what is captured and consumed[29]. Innovative sampling technologies (environmental DNA[43] and automated monitoring[44]) in combination with remotely sensed products (for example, to predict recruitment)[45], better accounting of gleaning practices in catch monitoring programs[46], coupled with traditional field surveys that work under different contexts, such as underwater visual surveys[47], mark recapture[48] and community-based mapping methods[49], could help to increase the resolution and speed of invertebrate data collection, and therefore enhance their monitoring, assessment and sustainable management. Invertebrate monitoring is particularly relevant in the context of environmental change[50] and increased invertebrate overfishing[15] because it is critical to understand changes that invertebrate aquatic foods are undergoing[19] and ensure invertebrate nutrient supplies (Fig. 1) are sustainable and climate-resilient[51] as they change.

Online content

Any methods, additional references, Nature Portfolio 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/s41586-026-10908-7.

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Methods

Contribution of aquatic invertebrates to global nutrient supplies

Global capture and aquaculture statistics. To estimate the contribution of invertebrates to global animal capture fisheries and aquaculture production, we used 2019 reconstructed marine fisheries landings data from the Sea Around Us website[25] and reported inland fisheries and aquaculture production from the Food and Agriculture Organization[26]. Reported inland fisheries, which are probably an underestimate of true inland fisheries production[28], were analysed separately from marine capture fisheries throughout the Article, owing to the absence of globally standardized reconstruction datasets for freshwater systems. We used 2019 data in the main text because it is the latest year available with catch reconstructions. However, as a sensitivity analysis, invertebrate contributions were also estimated for other years (2014–2019). We found our invertebrate contribution results were consistent across years (Extended Data Fig. 3). The Sea Around Us uses officially reported landings from international and national fisheries statistics authorities as a baseline. Reconstructions are then performed by adding estimated unreported catches (such as landed illegal catches) using various literature sources. FishStatJ inland fisheries and aquaculture production[26] data of territories and land areas were reported at the country level. Aquaculture and inland fisheries production species, reported using the Aquatic Sciences and Fisheries Information System (ASFIS) taxonomic reference system in FishStatJ, were converted to scientific species and species groups names (for example, rainbow trout to *Oncorhynchus mykiss*)[60]. Aquatic invertebrates in production data included mollusks (such as clams, mussels, oysters, scallops, cockles, snails, abalone, whelks, conchs, octopus, squid and cuttlefish), crustaceans (such as shrimp, prawns, crabs, lobsters and crayfish), sea cucumbers, sea urchins, sea worms, sponges and jellyfish (Supplementary Table 4). Marine capture fisheries and aquaculture production estimates shown throughout this Article (Fig. 1a and Extended Data Fig. 2) are global estimates derived from a total of 208,728 and 2,507 observations, encompassing 2,304 and 492 unique species (not only invertebrates) and 282 and 206 unique countries, respectively. Similarly, invertebrate-specific estimates for marine capture fisheries and aquaculture production shown throughout the Article (Fig. 1b and Extended Data Fig. 4) are global estimates derived from a total of 28,358 and 624 observations, encompassing 552 and 150 unique species and 252 and 124 unique countries, respectively.

Assigning nutrient composition data to aquatic foods. Nutrient concentration estimates per 100 g and edible proportions for each individual entry in global data (for example, fish and invertebrates) were assigned using raw muscle tissue samples within the AFCD[12]. We selected 30 nutrients that are important for public health[13]: 13 minerals (calcium, chromium, copper, iodine, iron, magnesium, manganese, molybdenum. phosphorous, potassium, selenium, sodium and zinc), 11 vitamins (A, C, D, E, B_1 (thiamin), B_2 (riboflavin), B_3 (niacin), B_5 (pantothenic acid), B_6, B_9 (folate) and B_{12} (cobalamin)), 5 versions of essential fatty acids (total monounsaturated fatty acids (MUFAs), total omega 3 fatty acids, total omega 6 fatty acids, DHA and EPA, and ALA), and protein. We included total protein and not specific essential amino acids because the dataset that we are using is currently being updated for those nutrients (for example, validating units and conversions). Moreover, we did not include other nutrients, such as cobalt and arachidonic acid, because they lacked established RNI reference values. Mean nutrient composition estimates and edible proportions were assigned hierarchically on the basis of the closest taxonomic resolution (Supplementary Fig. 2). In other words, for any given nutrient, if a species had species-specific nutrient composition observations in AFCD, we assigned that value. However, if no observed nutrient concentrations were available at the species level, we assigned the mean of the next taxonomic level (such as genus). To obtain nutrient supplies or yields, nutrient concentrations per 100 g were multiplied by equivalent units in live weight. Note that we used live weights for our main analyses (that is, extrapolating the nutrient content from muscle tissue to live weight volumes), but also performed a sensitivity analysis using edible weight (for example, multiplying live weights by edible proportions; Extended Data Fig. 2). We grouped nutrient supplies and total catch or production volumes separately for invertebrates and fish, and calculated the percentage of nutrient supplies coming specifically from invertebrates. We separately did this for different sectors, taxa, years and countries or EEZs. Note that, similar to finfish[5], country- or EEZ-specific nutrient yields are not strongly correlated with the average nutrient concentration of their catches (Supplementary Figs. 7 and 8), indicating, for example, that a country or EEZ with high nutrient yields does not necessarily target the species with most nutrient concentrations.

Estimating public health relevance of aquatic foods. Nutrient supplies were converted to the number of yearly requirements met by dividing nutrient-specific nutrient supplies from aquatic invertebrates by their estimated RNI, averaged across available demographic groups (gender and age; Supplementary Table 3). When available, we used the recommended dietary allowance[61]. However, when such data were not available, we used adequate intake[61] estimates or values reported in the literature: 433 mg per day for DHA and EPA (that is, average between different studies reviewed)[62] and 48.8 g per day for MUFAs (that is, 20% of total energy recommended intake assuming that a gram of MUFA represents 9 kcal)[63,64]. Note that for total omega 6 fatty acids, we used recommended intakes reported for linolenic acids; and for total omega 3 fatty acids, we used the sum of ALA and DHA and EPA recommended intakes (that is, 1,633 mg per day). Yearly nutrient supplies were divided by yearly requirements, ensuring that units were the same and assuming 365 days (for example, yearly requirements in tonnes = daily requirements in tonnes × 365). Our approach estimates the number of nutrient requirements met exclusively from the nutrients available from aquatic invertebrates. While we acknowledge that people eat other foods and do not meet their nutritional adequacy exclusively from aquatic invertebrates, this enabled us to compare the importance of aquatic invertebrates across nutrients with a standardized unit relevant for public health.

Predictive model of invertebrate nutrient concentrations

To estimate the variability and potential drivers of nutrient content in aquatic invertebrates, we first updated and validated species-specific invertebrate nutrient concentration samples within AFCD. A total of 13,888 samples from 465 invertebrate species were compiled, updated and validated (for example, reviewing source studies or food composition tables for accuracy, and adding extra information (for example, sample preparation, relative weight)). Specifically, food part (that is, the body part that was sampled for nutrient concentration) and food processing (that is, mechanical or chemical processes that transform the animal to the form before consumption) were validated (for example, examining categorizations for accuracy and disaggregating processing from sample preparation; Supplementary Table 1). Sample sizes and species varied by nutrient (Supplementary Table 2).

We next merged species-specific nutrient data with ecological and environmental trait information available from SeaLifeBase[27]. Traits were assigned hierarchically, using species-specific data when available or the mean or most common category of the closest taxonomic group (for example, genus). Taxonomic level assignment of traits is shown in Supplementary Fig. 9. We included available traits related to energetic demand, thermal regime, habitat and environment that are likely to influence the nutrient composition of aquatic invertebrates (Supplementary Table 1).

Similar to work done on ray-finned fishes[5], we developed a series of Bayesian hierarchical models to predict the nutrient concentration of aquatic invertebrate species on the basis of their taxonomy and ecological and environmental traits, while controlling for other factors thought to impact the nutrient concentration of samples (for example, food part or processing form; Supplementary Table 1). Note that owing to limited

species-specific invertebrate sample sizes (Supplementary Table 2), from the nutrients highlighted, molybdenum, vitamin C and D were not included in this modelling section. Given the structure of our data and the importance of taxonomic identity in explaining the variability in nutrient content[65], taxonomy was included in our model hierarchically (that is, nested random effects of samples within genus, within families, within orders, within class and within phyla). All other factors (Supplementary Table 1) were included in the model as fixed effects, with (1) maximum depth log-transformed to normalize the spread of a highly skewed distribution (to increase model efficiency); (2) all continuous variables standardized by subtracting the mean and dividing by two times the standard deviation (s.d.); and (3) maximum length and length at maturity standardized within the taxonomic level of class because for invertebrates, different length types are recorded depending on the taxonomic group. Dividing by two times the s.d. facilitates a more direct comparison of regression coefficients between continuous and binary predictors within the same model[66]. Some variables were slightly correlated (all Pearsons's correlation coefficients < 0.6). For example, length of maturity was positively correlated to maximum length (Pearson's correlation coefficient = 0.43) and trophic level was positively correlated with maximum depth (Pearson's correlation coefficient = 0.57), indicating that (1) invertebrates that reach larger maximum lengths tend to mature at larger lengths; and (2) invertebrates that have higher trophic level tend to reach greater depths. While these correlations influence how marginal posteriors were interpreted, they did not cause problems to model fits.

Nutrients were modelled independently, owing to different sample sizes (Supplementary Table 2). For each nutrient, we tested three alternative model structures through cross validation[67]: a null model that includes only the intercept; a hierarchical model that includes only the intercepts reflecting the taxonomic nested structure of our data; and a full model that includes taxonomy hierarchically and ecological and environmental traits as covariates. First, we performed leave-out-one cross validation using pareto smoothed importance sampling (PSIS-LOO). However, as this process yielded some high Pareto k diagnostic values, we also performed k-fold cross validation[67]. To be able to perform k-fold cross validation, for some nutrients, covariate groups with limited sample sizes (for example, exoskeleton for body parts) were merged into another category (for example, whole/mix). Our k-fold cross validation results reinforced those obtained from leave-out-one cross validation: for a minority of nutrients examined (for example, vitamin B_{12}), the inclusion of the taxonomic hierarchy alone predicted the out-of-sample data as well as the full model that includes trait data (Supplementary Tables 5 and 6). However, across nutrients (that is, sum of leave-out-one or k-fold cross validation information criteria assuming response variables are conditional independent), the full model was significantly preferred in terms of predictive accuracy (Supplementary Tables 5 and 6), supporting the inclusion of both taxonomic hierarchy and ecological and environmental traits in predicting nutrient concentration for aquatic invertebrates. Thus, for each nutrient, the best linear model structure was:

$$\begin{aligned}
\mu = {} & \beta_{0,\mathrm{GEN}} + \beta_1 \times \mathrm{ENVTEMP}_{\mathrm{subtropical}} + \beta_2 \times \mathrm{ENVTEMP}_{\mathrm{temperate}} + \beta_3 \\
& \times \mathrm{ENVTEMP}_{\mathrm{cold}} + \beta_4 \times \mathrm{TL} + \beta_5 \times \mathrm{DEPTH} + \beta_6 \times \mathrm{LMAX} + \beta_7 \times \mathrm{LM} \\
& + \beta_8 \times \mathrm{K} + \beta_9 \times \mathrm{ENV}_{\mathrm{freshwater}} + \beta_{10} \times \mathrm{ENV}_{\mathrm{mixed}} + \beta_{11} \times \mathrm{DEMERSPELAG}_{\mathrm{benthopelagic}} \\
& + \beta_{12} \times \mathrm{DEMERSPELAG}_{\mathrm{pelagic}} + \beta_{13} \times \mathrm{DEMERSPELAG}_{\mathrm{demersal}} \\
& + \beta_{14} \times \mathrm{DEMERSPELAG}_{\mathrm{reef}} + \beta_{15} \times \mathrm{DEMERSPELAG}_{\mathrm{sessile}} \\
& + \gamma_1 \times \mathrm{PART}_{\mathrm{gills}} + \gamma_2 \times \mathrm{PART}_{\mathrm{skin}} + \gamma_3 \times \mathrm{PART}_{\mathrm{whole}} + \gamma_4 \times \mathrm{PART}_{\mathrm{viscera}} \\
& + \gamma_5 \times \mathrm{PART}_{\mathrm{reptissue}} + \gamma_6 \times \mathrm{PART}_{\mathrm{exoskeleton}} + \gamma_7 \times \mathrm{PROC}_{\mathrm{frozen}} + \gamma_8 \times \mathrm{PROC}_{\mathrm{dried}} \\
& + \gamma_9 \times \mathrm{PROC}_{\mathrm{canned}} + \gamma_{10} \times \mathrm{PROC}_{\mathrm{boiled}} + \gamma_{11} \times \mathrm{PROC}_{\mathrm{baked}} + \gamma_{12} \\
& \times \mathrm{PROC}_{\mathrm{cooked}} + \gamma_{13} \times \mathrm{PROC}_{\mathrm{unknown}} \\
\beta_{0,\mathrm{GEN}} & \sim N(\beta_{0,\mathrm{FAM}}, \sigma_{\mathrm{GEN}}) \\
\beta_{0,\mathrm{FAM}} & \sim N(\beta_{0,\mathrm{ORD}}, \sigma_{\mathrm{FAM}}) \\
\beta_{0,\mathrm{ORD}} & \sim N(\beta_{0,\mathrm{CLASS}}, \sigma_{\mathrm{ORD}}) \\
\beta_{0,\mathrm{CLASS}} & \sim N(\beta_{0,\mathrm{PHY}}, \sigma_{\mathrm{CLASS}}) \\
\beta_{0,\mathrm{PHY}} & \sim N(\beta_0, \sigma_{\mathrm{PHY}})
\end{aligned}$$

where $\beta_{0,\ldots}$ represents the estimated intercepts at different taxonomic hierarchical levels (GEN, genus; FAM, family; ORD, order; CLASS, class; and PHY, phylum) for average continuous and most common (that is, tropical, benthic and marine) covariate categories that are separate categorical predictors, β_0, is the global estimated intercept, β_{1-15} represents the estimated parameters for different covariates: thermal regime (ENVTEMP, subtropical, temperate or cold), trophic level (TL), maximum depth (DEPTH), maximum length (LMAX), length at maturity (LM), von Bertalanffy growth parameter (K), environment (ENV, freshwater or mixed) and preferred habitat (DEMERSPELAG, benthopelagic, pelagic, reef-associated, sessile or demersal), γ_{1-13} represent the estimated parameters for different nuisance variables: food part (PART, gills, skin, whole or multiple parts, viscera, reproductive tissue or exoskeleton) and food processing (PROC, frozen, dried, canned, boiled or steamed, baked, grilled or smoked, cooked other or unknown food preparation); and $\sigma_{\ldots}$ represent the estimated s.d. for the hierarchical taxonomic intercepts.

For nutrients with a limited number of zeroes (<2%; Supplementary Table 2) we only used positive data and used a Student's t family distribution on the variable's natural logarithm:

$$\log(N_i) \sim \mathrm{Student} - t(\nu, \mu, \tau),$$

whereas for nutrients with a higher number of zeroes (Supplementary Table 2), we used a hurdle log-normal data likelihood distribution:

$$\begin{aligned}
&\mathrm{if} N_i = 0,\ N_i \sim \mathrm{bernouilli_logit}\,(\delta) \\
&\mathrm{if} N_i > 0,\ N_i \sim \mathrm{lognormal}\,(\mu,\ \sigma)
\end{aligned}$$

where N_i is the nutrient concentration of sample i, μ is the mean nutrient concentration informed by the linear model structure above (in log scale), ν and τ are the degrees of freedom and scale parameters for the Student' t distribution, δ is the estimated probability of observing a zero for a given nutrient if it had >2% of zeroes, and σ is the s.d. of the variable's natural logarithm.

Models were run in Rstan[68] through the brms package[69] and using the following priors:

$$\begin{aligned}
\beta_0 &\sim N(0, 10) \\
\beta.. &\sim N(0, 2) \\
\gamma.. &\sim N(0, 2) \\
\nu &\sim \mathrm{gamma}(2, 0.1) \\
\delta &\sim \mathrm{beta}(1, 1) \\
\sigma.. &\sim N^{+}(0, 1) \\
\tau &\sim N^{+}(0, 1)
\end{aligned}$$

Four chains were run for each scenario using 10,000 iterations (5,000 warmup and a thinning of 5), leaving 4,000 samples in the posterior distribution of each parameter. Convergence was monitored by running four chains from different starting points, examining posterior chains and distribution for stability, checking that the potential scale reduction factor (also termed R hat) was close to 1 (below 1.01) and examining the effective sample sizes (>400). Some parameters (such as the s.d. of hierarchical structures) were informed by limited sample sizes; we therefore used a large number of iterations to ensure parameters informed by limited sample sizes exceeded the recommended effective sample sizes. Bayesian learning was examined by inspecting posteriors vs. prior distributions and by calculating posterior contraction values[70]. We examined posterior predictive distributions to check for model fit. Moreover, we checked model residual patterns against variables not included in our model, owing to high missingness (Supplementary Figs. 5 and 10). All final models reported converged, fit the data relatively well, had high posterior contraction for key parameters and had relatively well performing

probability integral transformations (PIT) plots (Supplementary Figs. 11–14).

Furthermore, to test whether (1) models of less complexity (for example, with less fixed effects) had better predictive accuracy than the full model; and (2) there were a minimal set of variables which could provide similar predictions to the full model, we performed projection predictive variable selection assuming positive data followed a log-normal distribution[71]. This revealed that (1) subsets of the full model did not provide better predictive accuracy than the full model (that is, the expected log-predictive density of the full model was always better or the same as simpler models); (2) the ranking of covariates being selected as most important to predict nutrient concentrations for invertebrates differed across nutrients; and (3) for some nutrients excluding some covariates could provide similar predictive performance to the full model, but the covariates to exclude varied by nutrient (Supplementary Fig. 1). Combined, these analyses supported the use of our full model to predict concentrations in invertebrates across nutrients.

Predicting nutrient composition of invertebrates in SeaLifeBase

Finally, we used model parameters estimated in the above section to predict nutrient composition of all macroinvertebrates available in SeaLifeBase[27]. While SeaLifeBase probably underestimates all invertebrate species (for example, freshwater invertebrate species), it is the most comprehensive life-history trait database available for non-fish species. The initial database contained a total of 71,591 species. From these, in total, 55,864 species were identified as macroinvertebrates on the basis of taxonomic groupings: 281 were confirmed as edible based on literature[72–77] and 50,807 were identified as potentially edible (excluding 834 non-edible species because of known toxicity and 4,223 species from the phyla *Bryozoa, Platyhelminthes, Porifera* and *Priapulida*, which we assumed were not edible, owing to the absence of documented human consumption and/or biological constraints, such as chemical defences, toxicity or parasitic lifestyles, that limit their suitability for consumption (for example, antipredatory metabolites in bryozoans and sponges or tetrodotoxin in some flatworms)). This designation does not imply cultural acceptance, safe consumption or practical harvestability across contexts. On the basis of available literature[25,27,72,73], some potentially edible macroinvertebrate species (1,083) were also categorized on the basis of their fisheries importance into the following groups: industrial, highly commercial, commercial, minor commercial, subsistence fisheries and bycatch. We provide nutrient composition estimates for all invertebrate species; but, in our analyses, we filtered the database to include only species classified as potentially edible macroinvertebrates (Fig. 3). Note that the database also included ascidians (phylum *Chordata*), which are not invertebrates. However, they were included in model predictions given (1) similarities in some ecological and environmental traits with invertebrates, and (2) that some are edible[78].

Some species had missing information. However, to perform predictions for all available species we took some assumptions. For example, if a specific group (such as Cnidaria) did not have a group-specific estimated intercept (that is, we did not have that group for that nutrient when building the Bayesian hierarchical models), we used the upper-level intercept (for example, global intercept) in combination with ecological and trait information. Similarly, if a species was missing some ecological or environmental trait information, we assumed the baseline category (for example, mean for continuous variables and most common separate categories: benthic, marine and tropical). To represent the data visually, we divided predicted nutrient concentrations by per capita daily RNIs (see above), restricting values to one when they were above such value (that is, if 100 g of muscle tissue provided over 100% of RNIs).

Ultimately, we used matched predictive nutrient concentrations in terms of RNIs of all potentially edible macroinvertebrate species to species-specific marine occurrence data[35] to show the geographical public health potential of macroinvertebrates (that is, what nutrient concentrations from invertebrates may be available in different geographical contexts).

Case studies

We developed six case studies representing a diverse array of geographies, target species, spatial scales and management contexts to highlight the multiple social and ecological benefits of aquatic invertebrates, including their environmental, economic, cultural and equity related benefits (Fig. 4). These case studies highlight the indirect contribution of aquatic invertebrates to nutrition by linking ecological functions and production systems to social outcomes such as income generation, gender equality and climate resilience.

Reporting summary

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

Data availability

Raw nutrient composition for aquatic foods[12] (https://dataverse.harvard.edu/dataverse/afcd), marine capture fisheries (Sea Around Us[25]; https://www.seaaroundus.org/), invertebrate traits (SeaLifeBase[27]; https://sealifebase.org/) and aquaculture production (FishStatJ[26]; https://www.fao.org/fishery/en/topic/166235/en) data used for this study are available through online repositories. Updated species-specific invertebrate nutrient composition data used for the predictive models and required clean data to perform the main analyses are available at Zenodo[79] (https://doi.org/10.5281/zenodo.20257513).

Code availability

Code to replicate the analyses is available on Zenodo[79] (https://doi.org/10.5281/zenodo.20257513). A report of the R packages used is provided in the Supplementary Information.

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Author contributions J.Z.-M. developed and implemented the project with support from C.D.G., C.C.H. and J.P.W.R.; J.G.M., K.M.K., M.L.D.P. and J.A.G. were actively involved in project development discussions. N.M. and S.-H.Y. cleaned and updated invertebrate specific nutrient composition data with support from J.Z.-M.; L.R.A. and V.A.P. cleaned and updated ecological and environmental trait data for invertebrate species with support from M.L.D.P.; J.Z.-M. performed the main analyses and wrote the first draft of the manuscript. J.G.E., L.G.E., J.A.G., W.R.F. and D.F.V. wrote individual case studies for Fig. 4 with support from J.Z.-M. All of the authors made substantial contributions to the text.

Competing interests J.A.G., C.C.H. and C.D.G. are members of the Oceana Science Advisor Board, and C.C.H. is also on the board of directors.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41586-026-10908-7.

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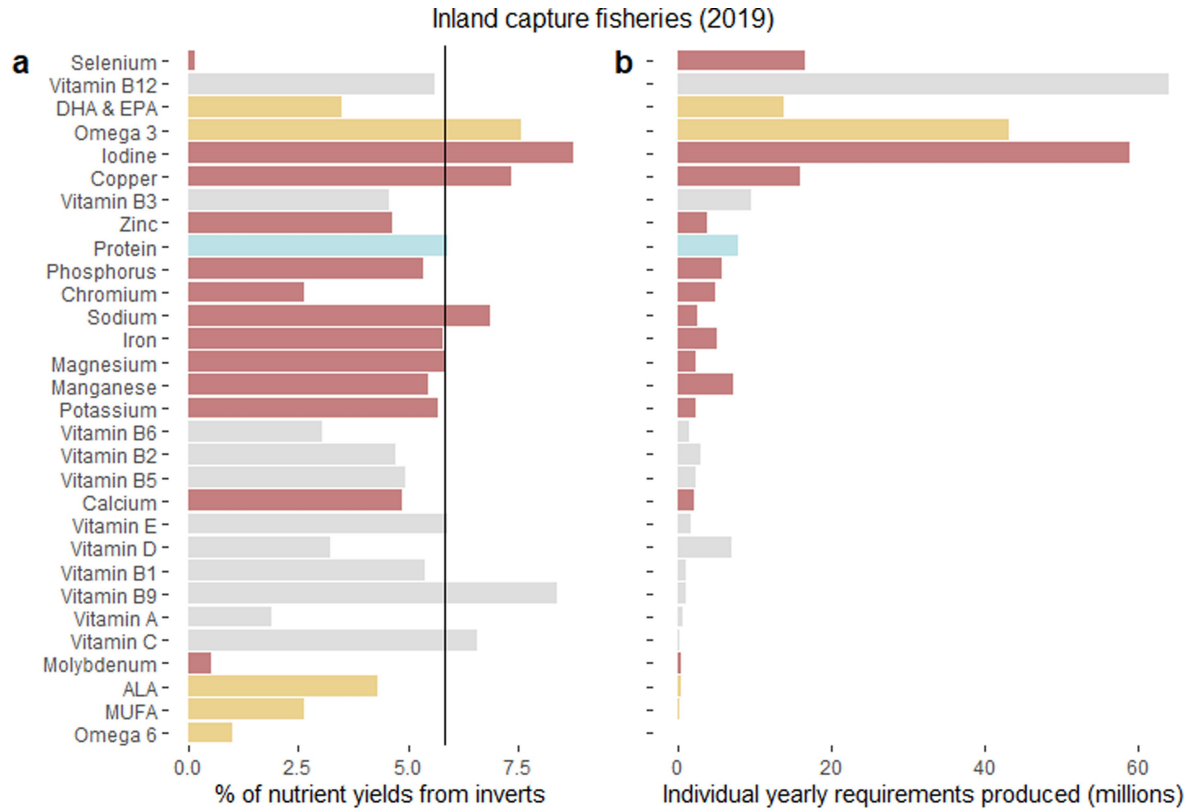
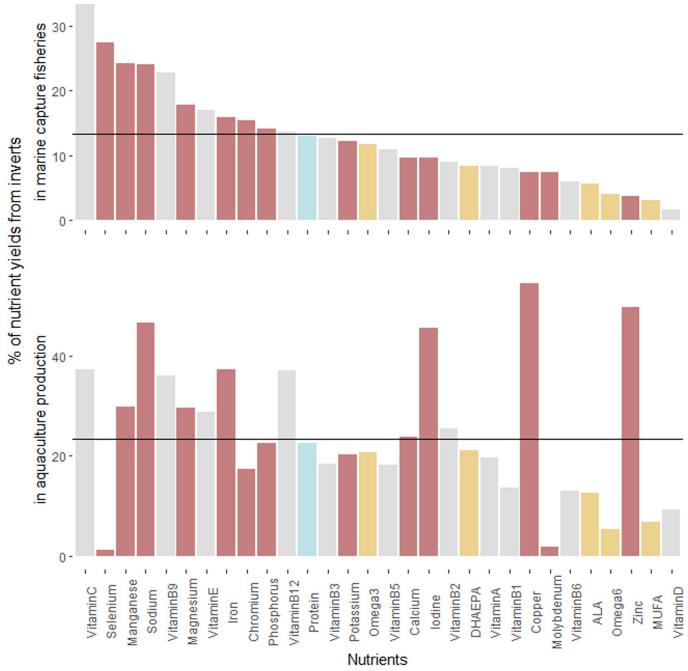
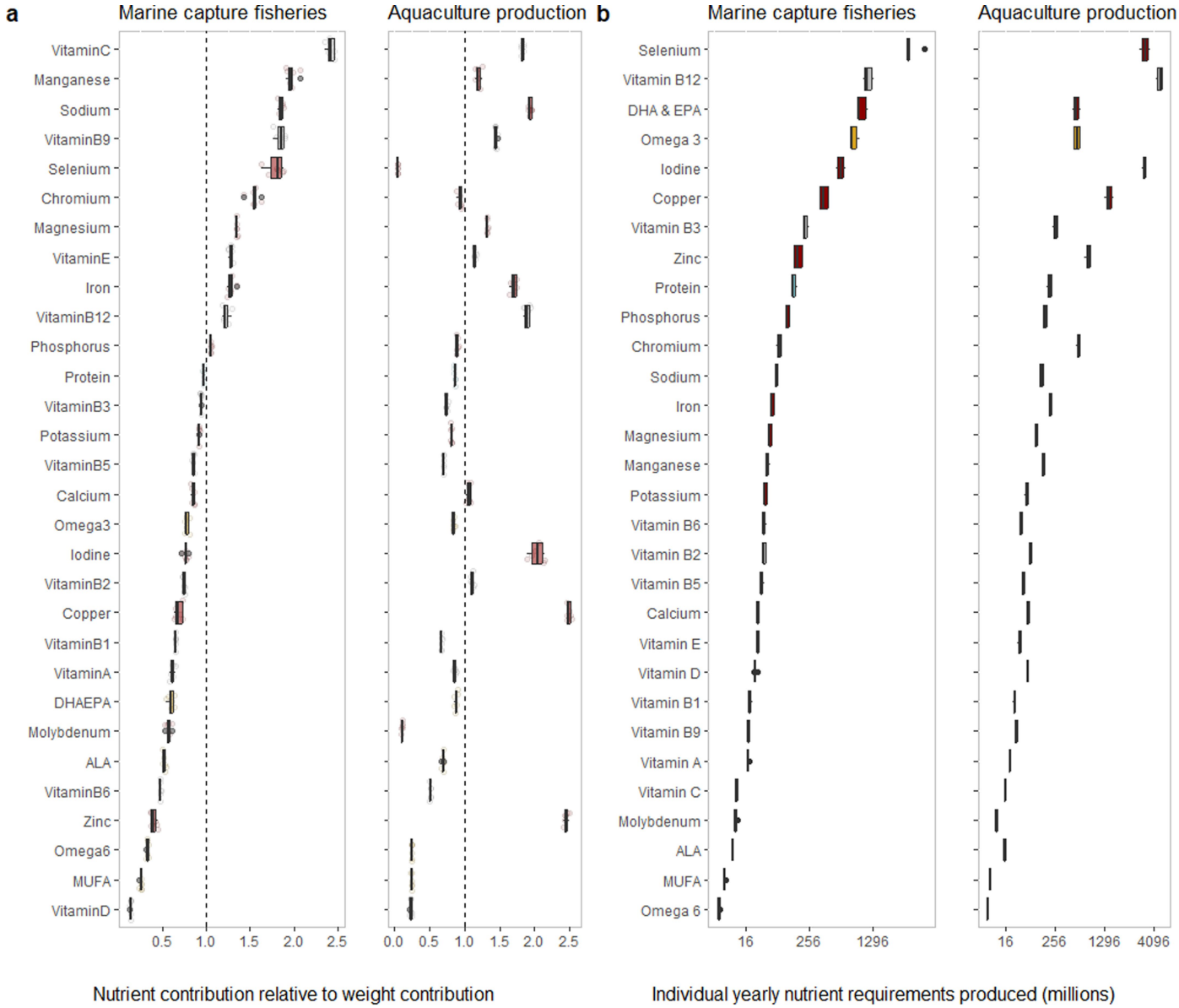


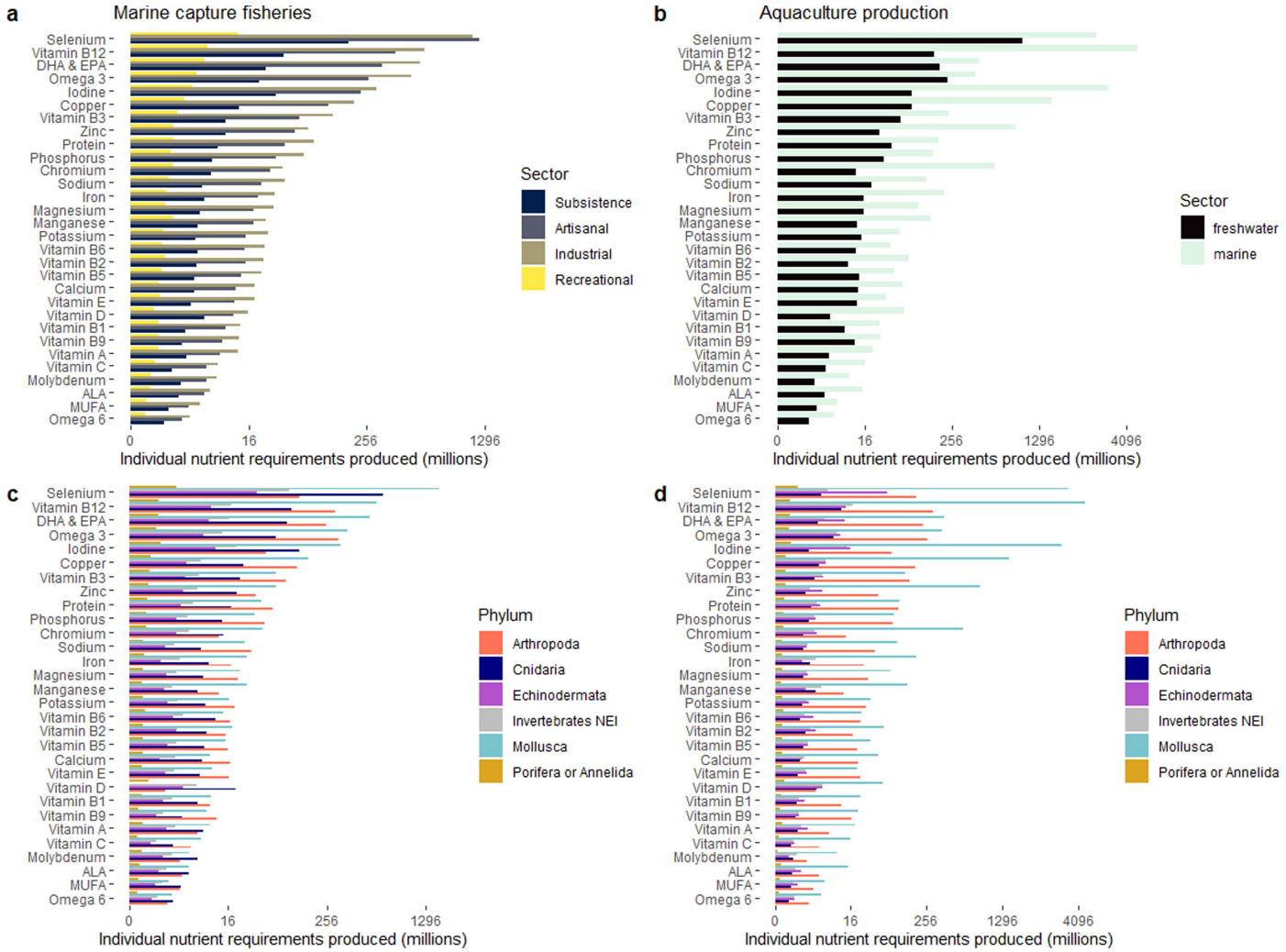
Extended Data Fig. 1 | Nutrient contribution of inland capture fisheries invertebrates based on reported data. (**a**) Percent of nutrient yields coming from invertebrates for reported inland capture fisheries in 2019. The bars represent a global estimate derived from 1,641 observations representing 437 unique species (not only invertebrates) and 155 unique countries. Black vertical line indicates the percent contribution of invertebrates in terms of inland capture volumes (i.e., live weight). Bars surpassing the black line means that invertebrates contributed disproportionately more nutrients relative to catch volumes. (**b**) Number (in millions) of yearly nutritional requirements produced from aquatic invertebrates in reported inland capture fisheries for 2019. The bars represent a global estimate derived from 105 invertebrate observations representing 34 unique species and 45 unique countries. For each nutrient, we use the average requirements across demographic groups (Supplementary Information Table 2). Bars in **a**-**b** are colour-coded by nutrient type: minerals in red, fatty acids in yellow, protein in blue, and vitamins in grey. Abbreviations represent MUFA (Monounsaturated fatty acids), DHA & EPA (eicosapentaenoic acid and docosahexaenoic acid), and ALA (alpha-linolenic acid).



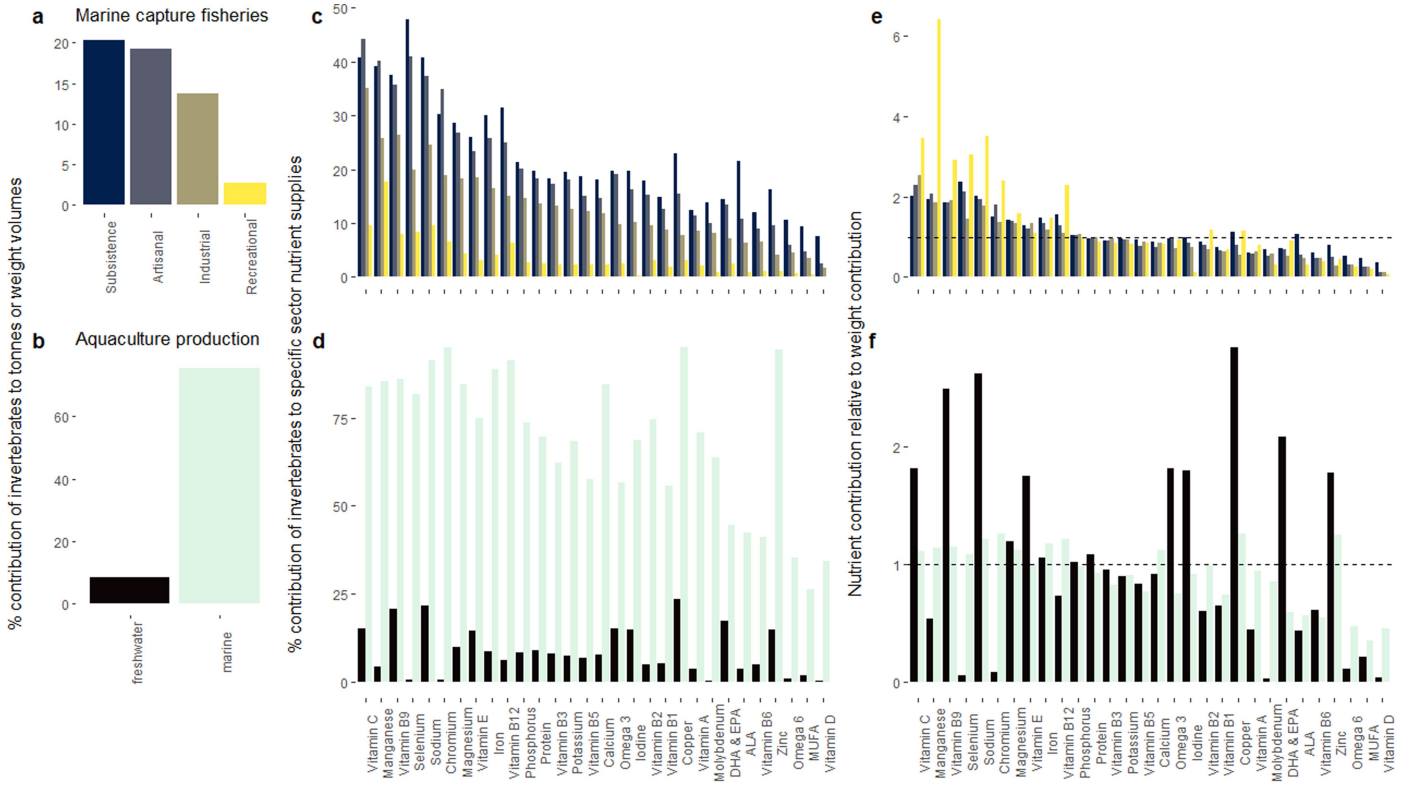
Extended Data Fig. 2 | Nutrient contribution of aquatic invertebrates to 2019 marine capture fisheries and aquaculture production using edible weights instead of live weights (i.e., Fig. 1). Bars are colour-coded by nutrient type (i.e., minerals, vitamins, protein or fatty acids). Horizontal line indicates the contribution of invertebrates to total catch and aquaculture production volumes, respectively. Abbreviations represent MUFA (Monounsaturated fatty acids), DHAEPA (eicosapentaenoic acid and docosahexaenoic acid), and ALA (alpha-linolenic acid).



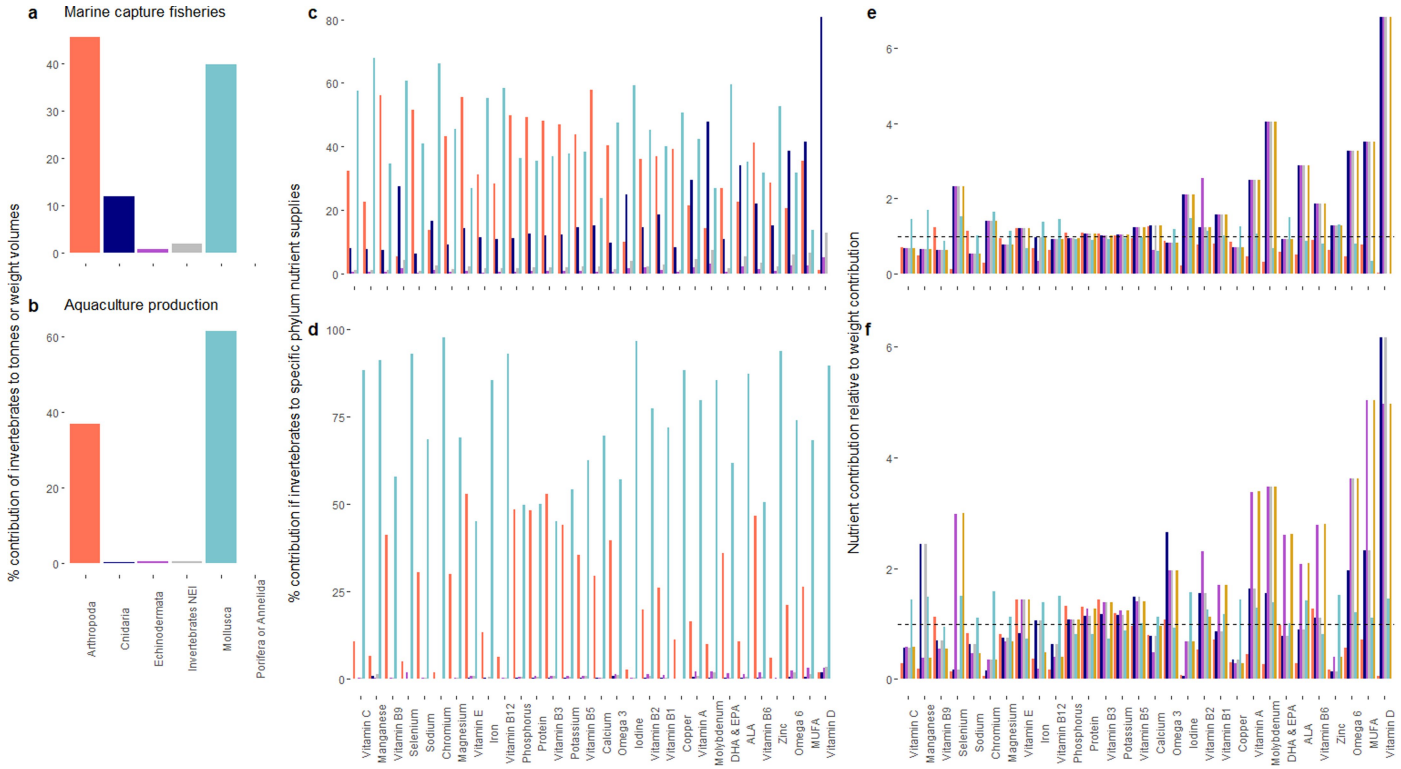
Extended Data Fig. 3 | Year-to-year variability in the nutrient contribution of aquatic invertebrates (n = 6 years). (**a**) Nutrient contribution relative to weight contribution. Vertical lines at one indicate when the nutritional contribution of invertebrates equals to the contribution of invertebrates to total weight, with values greater than one indicating invertebrates contributed disproportionally to the production of such nutrient. (**b**) Number (in millions) of yearly nutritional requirements produced from aquatic invertebrates in marine capture fisheries or aquaculture production. Boxes in **a**-**b** are colour-coded by nutrient type (i.e., minerals, vitamins, protein or fatty acids). Each point is a year. Boxplots show the median (centre line), interquartile range (box), and values within 1.5 × the interquartile range (whiskers), with points beyond this range plotted as outliers. Abbreviations represent MUFA (Monounsaturated fatty acids), DHA & EPA (eicosapentaenoic acid and docosahexaenoic acid), and ALA (alpha-linolenic acid).



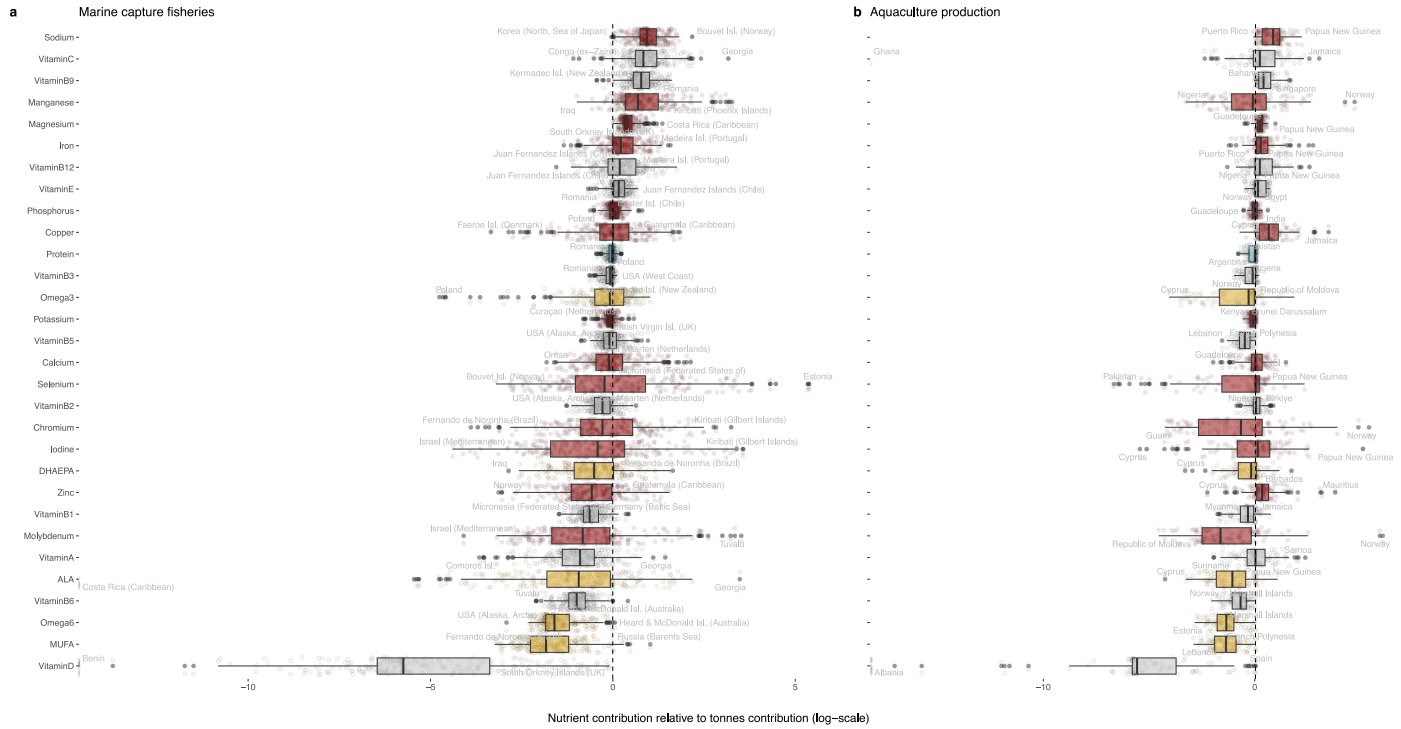
Extended Data Fig. 4 | Nutrient contribution of aquatic invertebrates separated by sector and phyla. Number (in millions) of yearly nutritional requirements produced from aquatic invertebrates in marine capture fisheries (**a**, **c**) or aquaculture production (**b**, **d**) for 2019. For each nutrient, we use the average requirements across demographic groups (Supplementary Information Table 3). To aid clarity the x axes were fourth-root transformed and reported values are on an arithmetic scale. Abbreviations represent MUFA (Monounsaturated fatty acids), DHA & EPA (eicosapentaenoic acid and docosahexaenoic acid), and ALA (alpha-linolenic acid).



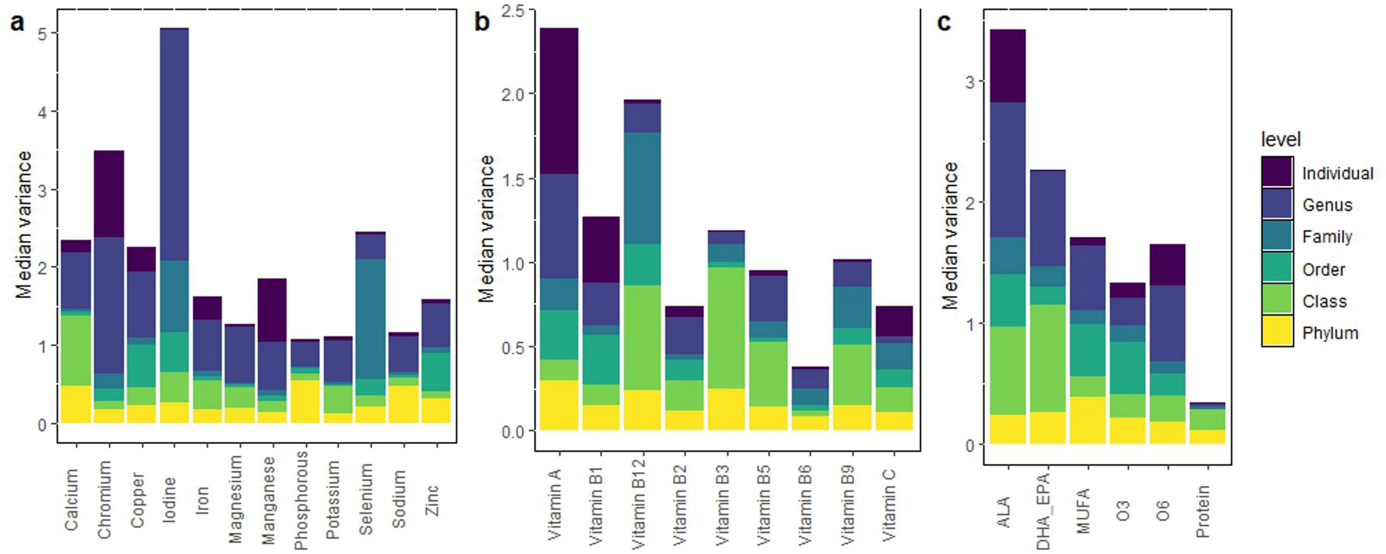
Extended Data Fig. 5 | Nutrient contribution of aquatic invertebrates to marine capture fisheries and aquaculture production in 2019 separated by sectors. Bars are colour-coded by sector. (**a**-**b**) % contribution of invertebrates to marine catch (**a**) or aquaculture production (**b**) volumes (i.e., weight). (**c**-**d**) % contribution of invertebrates to nutrient supplies in marine capture fisheries (**c**) and aquaculture production (**d**). (**e**-**f**) Nutrient contribution relative to catch or weight contribution for marine capture fisheries (**e**) or aquaculture production (**f**). Horizontal lines in **e**-**f** indicate when weight contributions are equal to nutrient contributions (i.e., bars above the line indicate invertebrates contribute disproportionately to that nutrient for that sector). Colours represent different sectors (e.g., Extended Data Fig. 4). Abbreviations represent MUFA (Monounsaturated fatty acids), DHA_EPA (eicosapentaenoic acid and docosahexaenoic acid), and ALA (alpha-linolenic acid).



Extended Data Fig. 6 | Nutrient contribution of aquatic invertebrates to marine capture fisheries and aquaculture production in 2019 separated by phylum. Bars are colour-coded by phylum. (**a**-**b**) % contribution of invertebrates to marine catch (**a**) or aquaculture production (**b**) volumes (i.e., weight). (**c**-**d**) % contribution of invertebrates to nutrient supplies in marine capture fisheries (**c**) and aquaculture production (**d**). (**e**-**f**) Nutrient contribution relative to catch or weight contribution for marine capture fisheries (**e**) or aquaculture production (**f**). Horizontal lines in **e**-**f** indicate when weight contributions are equal to nutrient contributions (i.e., bars above the line indicate invertebrates contribute disproportionately to that nutrient for that phylum). Colours represent different phyla (e.g., Extended Data Fig. 4). Abbreviations represent MUFA (Monounsaturated fatty acids), DHA_EPA (eicosapentaenoic acid and docosahexaenoic acid), and ALA (alpha-linolenic acid).



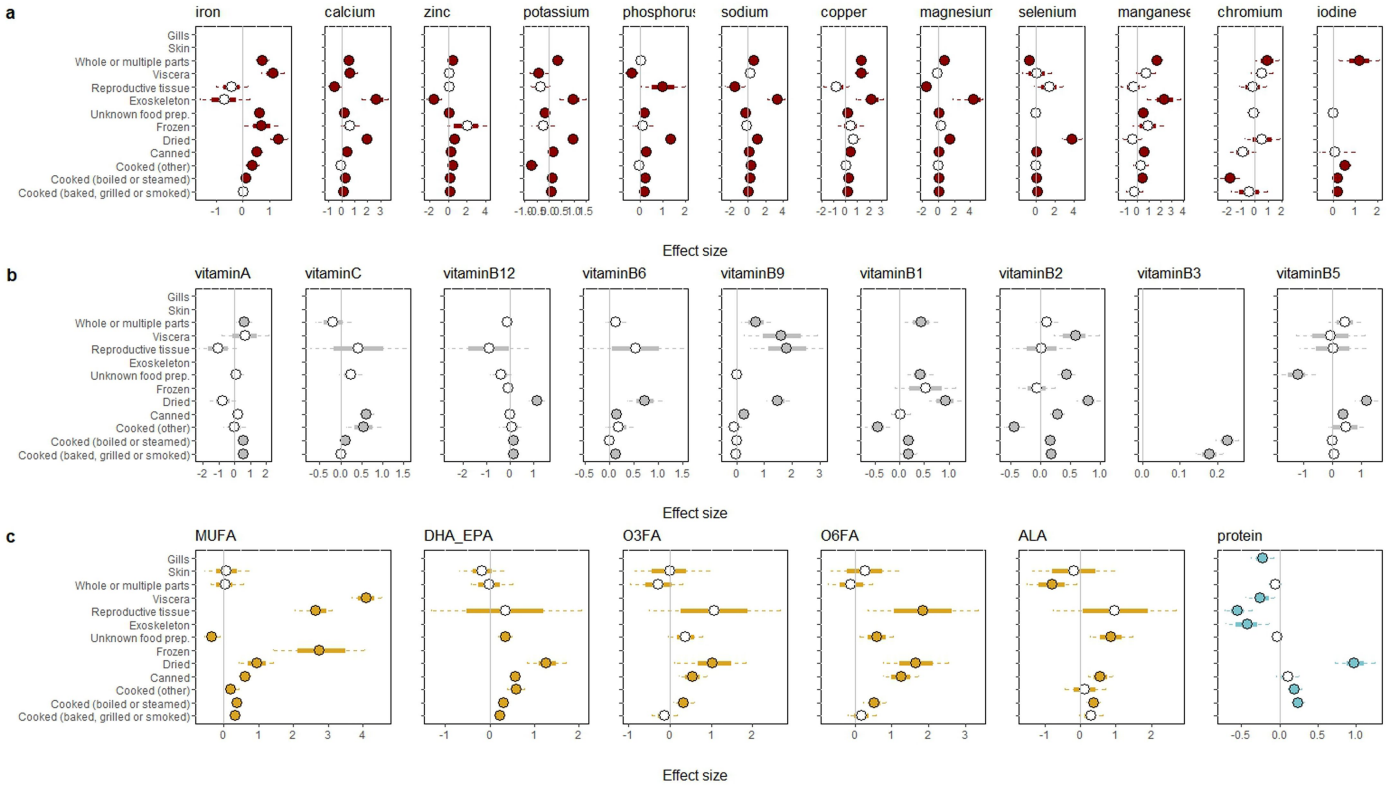
Extended Data Fig. 7 | Country specific variability in nutrient contribution of aquatic invertebrates relative to country-specific volume contributions for (a) marine capture fisheries and (b) aquaculture production (e.g., log (% contribution of invertebrates to copper supplies/ % contribution of invertebrates to catch volumes)). Each point is an EEZ (**a**) or country (**b**), n = 282 or 206, respectively; and grey labels are the EEZ or countries that ranked first or last (i.e., highest or lowest) in terms of overall nutrient contributions from invertebrates relative to weight volumes. The vertical line indicates when nutrient contribution and catch contribution of invertebrates is the same (i.e., points to the right of the line indicate invertebrates contribute disproportionately to that nutrient for those countries). Boxplots and points are colour-coded by nutrient type (i.e., minerals, vitamins, protein or fatty acids). Boxplots show the median (centre line), interquartile range (box), and values within 1.5 × the interquartile range (whiskers), with points beyond this range plotted as outliers. Abbreviations represent MUFA (Monounsaturated fatty acids), DHA_EPA (eicosapentaenoic acid and docosahexaenoic acid), and ALA (alpha-linolenic acid).



Extended Data Fig. 8 | Median estimated variance decomposition of our Bayesian Hierarchical models predicting nutrient content in aquatic invertebrates. Each column is a nutrient for which models were performed: (**a**) minerals, (**b**) vitamins, and (**c**) macronutrients (i.e., fatty acids and protein). Estimated variance for each group (nested) is stacked and colour-coded by the hierarchical level . Abbreviations represent MUFA (Monounsaturated fatty acids), DHA_EPA (eicosapentaenoic acid and docosahexaenoic acid), O3FA (omega 3 fatty acids), O6FA (omega 6 fatty acids) and ALA (alpha-linolenic acid).

Extended Data Fig. 9 | See next page for caption.

Extended Data Fig. 9 | Variability and potential drivers of nutrient content in aquatic invertebrates for nutrients not highlighted in Fig. 2. (**a**) minerals, (**b**) vitamins and (**c**) macronutrients: abbreviations represent MUFA (Monounsaturated fatty acids), and ALA (alpha-linolenic acid). As in Fig. 2, top rows are the estimated nutrient concentration per taxonomic class. Points are the median estimated nutrient concentration for that class (i.e., global intercept plus relevant phylum and class intercept offsets), solid and dashed lines represent 50 and 90% uncertainty intervals, respectively. Vertical line represents the median estimated global intercept. Results are colour-coded by class. Bottom rows are the effect sizes of different ecological and environmental factors on average nutrient concentrations (in log scale). Points are medians, solid and dashed lines represent 50 and 90 % uncertainty intervals, respectively. Vertical lines are set at 0 (i.e., the baseline category). Nutrients are colour-coded by nutrient type. Estimates are baselined for raw muscle tissue at average environmental and ecological continuous conditions (e.g., depth, maximum length, length of maturity, growth parameter K and trophic level) and most common categories (e.g., tropical, marine, and benthic). See Supplementary Information Table 2 for exact sample sizes used in the models that derived these estimates.



Extended Data Fig. 10 | Effect size of nuisance covariates accounted for in our model. Each plot is a nutrient colour-coded by nutrient type, separated by (**a**) minerals, (**b**) vitamins and (**c**) macronutrients: abbreviations represent MUFA (Monounsaturated fatty acids), DHA_EPA (eicosapentaenoic acid and docosahexaenoic acid), O3FA (omega 3 fatty acids), O6FA (omega 6 fatty acids) and ALA (alpha-linolenic acid). Points are medians, thick lines represent 50% uncertainty intervals and dashed lines represent 90% uncertainty intervals. If the parameter 90% uncertainty intervals overlapped zero, the point is not filled. Estimates are baselined for raw muscle tissue at average environmental and ecological continuous conditions (e.g., depth, Lmax, Lm, K, TL) and most common categories (e.g., tropical, marine, and benthic). See Supplementary Information Table 2 for exact sample sizes used in the models that derived these estimates.

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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	No software was used for data collection
Data analysis	Code used for this paper is available on Zenodo (DOI: 10.5281/zenodo.20257513). For the main analyses we used the brms package. Additional packages were used to re-arrange the data and for plotting purposes. All analyses were implemented in R (v. 4.5.2). Specific R packages used were: arrow v. 24.0.0, bayesplot v. 1.15.0, brms v. 2.23.0, broom.mixed v. 0.2.9.7, coda v. 0.19.4.1, data.table v. 1.18.2.1, dggridR v. 3.1.1, DHARMa v. 0.4.7, doParallel v. 1.0.17, GGally v. 2.4.0, ggpubr v. 0.6.3, ggrepel v. 0.9.8, ggridges v. 0.5.7, grid v. 4.5.2, janitor v. 2.2.1, lme4 v. 2.0.1, loo v. 2.9.0, matrixStats v. 1.5.0, parallel v. 4.5.2, plyr v. 1.8.9, projpred v. 2.10.0, R.utils v. 2.13.0, reshape2 v. 1.4.5, rnaturalearth v. 1.2.0, rnaturalearthdata v. 1.0.0, rstan v. 2.32.7, scales v. 1.4.0, sf v. 1.1.1, tidyverse v. 2.0.0, VIM v. 7.0.0, viridis v. 0.6.5

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Raw nutrient composition for aquatic foods12 (https://dataverse.harvard.edu/dataverse/afcd), marine capture fisheries (Sea Around Us25; https://www.seaaroundus.org/), invertebrate traits (SeaLifeBase27; https://sealifebase.org/) and aquaculture production (FishStatJ26; https://www.fao.org/fishery/en/topic/166235/en) data used for this study are available through online repositories. Updated species-specific invertebrate nutrient composition data used for the predictive models and required clean data to perform the main analyses is available on Zenodo (DOI: 10.5281/zenodo.20257513).

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Reporting on sex and gender	NA
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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	This study integrated the Aquatic Food Composition Database12 with marine capture fisheries25, aquaculture production26 and species-level environmental and ecological trait data27 to estimate the contribution of aquatic invertebrates to global nutrient supplies (i.e., available pool of nutrients produced or captured). First, we quantified the relative contribution of invertebrates to nutrient supplies of global marine capture fisheries and aquaculture production, identifying the sectors, species groups, and countries that provide most aquatic invertebrate nutrients to human populations. In our analyses, we estimate global fisheries and aquaculture production of 30 nutrients essential for human health (Methods13). Second, we developed a series of Bayesian hierarchical models to determine the variability and potential drivers of nutrient content in aquatic invertebrates. For this, we combined species-level environmental and ecological trait data27 with an updated invertebrate species-specific nutrient composition database(e.g., 12) that includes 13,888 samples from 465 invertebrate species. Finally, we leveraged model predictions to estimate the nutrient composition of 50,807 macroinvertebrate species registered globally27, showcasing their potential contributions to public health and regional food security.
Research sample	Nutrient composition for aquatic foods (Aquatic Food Composition Database; AFCD), marine capture fisheries (Sea Around Us, invertebrate traits (SeaLifeBase) and aquaculture production (FAO; FishStatJ) data used for this study were extracted from online repositories. Updated species-specific invertebrate nutrient composition data used for the predictive models were updated and validated from the AFCD.
Sampling strategy	All available samples were used. Sample size varied by nutrient. For model predictions, posterior contraction values were used to assess whether sample size was sufficient.
Data collection	No original data was collected for this study.

Timing and spatial scale	Nutrient supply analyses were done using 2019 global production data. A sensitivity analyses was performed covering 2014-2019 data.
Data exclusions	For nutrient composition model predictions, we excluded species-specific invertebrate food samples (6%) that included other ingredients because of the impact added ingredients could have on nutrient composition. These data exclusions are specified in the text.
Reproducibility	All attempts to reproduce the analyses were successfull
Randomization	Randomization was not relevant for this study
Blinding	Blinding was not relevant for this study

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
☒	☐ Clinical data
☒	☐ Dual use research of concern
☒	☐ Plants

Methods

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

Plants

Seed stocks	NA
Novel plant genotypes	NA
Authentication	NA