Report

Current Biology

Micronutrient supply from global marine fisheries under climate change and overfishing

Highlights

- Micronutrient-dense catches are more vulnerable to climate change than fishing
- Climate change threatens micronutrient fisheries yields in 40% of countries
- Catches are nutrient dense but vulnerable where dietary intakes are most inadequate
- Fisheries management can be optimized toward resilient and nutrient-dense species

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In brief

Maire et al. investigate how climate change and overfishing jeopardize the current capacity for marine fisheries to support the food and nutrition security of individual nations. Climate change is the most pervasive threat to the continued supply of micronutrients, but opportunities may exist to move toward nutrient-sensitive fisheries management.

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Report

Micronutrient supply from global marine fisheries under climate change and overfishing

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SUMMARY

Fish are rich in bioavailable micronutrients, such as zinc and iron, deficiencies of which are a global food security concern.[1,2] Global marine fisheries yields are threatened by climate change and overfishing,[3,4] yet understanding of how these stressors affect the nutrients available from fisheries is lacking.[5,6] Here, using global assessments of micronutrient content[2] and fisheries catch data,[7] we investigate how the vulnerability status of marine fish species[8,9] may translate into vulnerability of micronutrient availability at scales of both individual species and entire fishery assemblages for 157 countries. We further quantify the micronutrient evenness of catches to identify countries where interventions can optimize micronutrient supply. Our global analysis, including >800 marine fish species, reveals that, at a species level, micronutrient availability and vulnerability to both climate change and overfishing varies greatly, with tropical species displaying a positive co-tolerance, indicating greater persistence to both stressors at a community level.[10] Global fisheries catches had relatively low nutritional vulnerability to fishing. Catches with higher species richness tend to be nutrient dense and evenly distributed but are more vulnerable to climate change, with 40% of countries displaying high vulnerability. Countries with high prevalence of inadequate micronutrient intake tend to have the most nutrient-dense catches, but these same fisheries are highly vulnerable to climate change, with relatively lower capacity to adapt.[11] Our analysis highlights the need to consolidate fisheries, climate, and food policies to secure the sustainable contribution of fish-derived micronutrients to food and nutrition security.

RESULTS AND DISCUSSION

Fish provide an accessible source of critical micronutrients, such as iron, zinc, vitamin A, and omega-3, to billions of people, highlighting the potential for fisheries to contribute to alleviating malnutrition.[1,2,12] However, climate change and overfishing threaten global fisheries.[3–5] The combined influence of climate change and overfishing on the nutritional contribution of global fisheries has not been assessed yet is critical to understanding patterns of vulnerability in nutrient supplies from global fisheries.

Fish species micronutrient density is weakly associated with both fishing and climate change

To determine how species-specific vulnerability to climate change and fishing relate to micronutrient content, we first established species-specific (1) vulnerabilities to fishing,[8] (2) vulnerabilities to climate change,[9] and (3) micronutrient densities,[13] based on 5 key micronutrients (calcium, iron, zinc, selenium, and vitamin A) that are rich in fish and essential for human health but for which inadequate intakes are particularly prevalent globally. Micronutrient density captures the percent contribution of a 100-g portion (wet weight) to a dietary reference value (e.g., recommended dietary allowance [RDA]) summed across five micronutrients (500% maximum; STAR Methods). We established these for all marine finfish species recorded in the Sea Around Us (SAU) catch reconstruction database for each maritime exclusive economic zone (EEZ) in the period 2010–2014 (discards were excluded).

We used a co-tolerance framework to investigate the sign and the strength of the correlation, ρ, between species' vulnerability to fishing and climate change.[10] A positive co-tolerance, where species responses to both stressors are positively correlated, would result in reduced species loss at a community scale in doubly stressed ecosystems, because although vulnerable species will be lost to both stressors, other species, with low vulnerability to both stressors, will survive. In contrast, a negative co-tolerance relationship would result in additive impacts and higher species loss, as species that survive a climate stress will be impacted by a fishing stress and vice versa.[10] We find that marine fish species exhibit random co-tolerance (ρ = 0.11), with 25% of species facing double jeopardy from both stressors (Figure 1A). Only tropical species exhibit weak positive co-tolerance

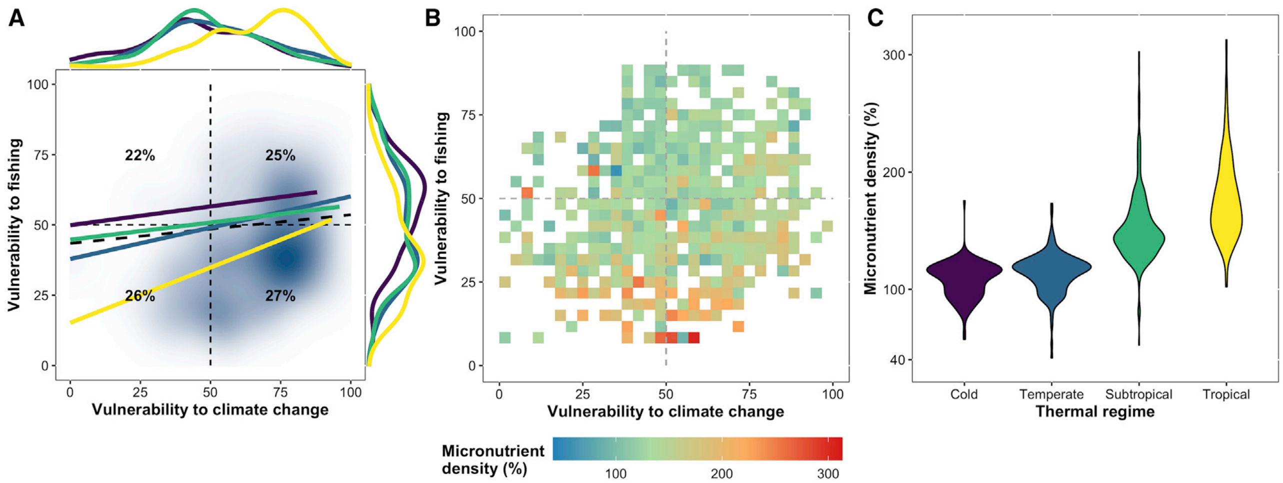

Figure 1. Relationships among global marine fish species' vulnerability to fishing, climate change, and micronutrient density

(A) Relationship between species-level vulnerability to fishing and climate change. Globally, fish species exhibit random co-tolerance (black dashed line, $\rho = 0.11$), with 25% of species facing double jeopardy from both stressors. Tropical (yellow, $\rho = 0.38$) species exhibit positive co-tolerances (weak) to both stressors, suggesting a great proportion of the community persisting in the face of both stressors than their cold-water (purple, $\rho = 0.16$), temperate (blue, $\rho = 0.12$), and subtropical (green, $\rho = 0.23$) counterparts. Species density is represented from low (white) to high (dark blue). Numbers show the percentage of species that fall into the quadrant among the 821 species. Marginal plots represent density distributions of vulnerability to fishing and climate change across four thermal regimes.
(B) Association between micronutrient density and vulnerability to fishing and climate change. Micronutrient density is highly variable (mean = 142; range: 41%–313%) among species and is only weakly associated with both stressors. Species density is represented from low (blue) to high (red) micronutrient density.
(C) Species micronutrient density among thermal regimes. Subtropical and tropical species are more likely to cover a higher proportion of the nutritional needs in five key micronutrients (calcium, iron, zinc, selenium, and vitamin A). Thermal regime was extracted from FishBase.[17]
See also Figures S1 and S2.

($\rho = 0.38$) that may imply a greater proportion of the community persists in the face of both climate change and fishing (Figure 1A). Overall, the framework demonstrates the severity of the combined effects of overfishing and climate change on fish communities, which together are known to affect the size, distribution, and abundance of fish species globally.[4,14–16]

Micronutrient density varies considerably among globally targeted fish species (mean = 142; range: 41%–313% of RDA; Figure 1B). In general, fish species are relatively rich in selenium (averaged contributions >85% of RDA; Figure S1), indicating a key role for fisheries to play in combating selenium deficiencies that impact up to 1 billion people and are projected to increase.[18] Changes in micronutrient density among species are most sensitive to variation in other micronutrient (calcium, iron, zinc, and vitamin A) concentrations, and temperate and cold-water species have consistently lower micronutrient concentrations (Figure S1). This indicates that fisheries targeting multiple species are more likely to supply the diversity of micronutrients needed for human health.[19] At the species level, micronutrient density is only weakly associated with fishing and climate change stressors (Figures 1B and S2). This suggests species exist that are nutrient dense and not very vulnerable to the impacts of climate change and overfishing. In the short term, there may be opportunities for some fisheries to adapt their target species away from those vulnerable to overfishing or climate change and thus safeguard micronutrient availability under climate and overfishing pressures. Tropical species exhibit higher micronutrient densities (Figure 1C) and are associated with higher concentrations of calcium, zinc, and vitamin A[2], suggesting tropical fisheries have the potential to supply a higher proportion of the nutrients needed in regions where food and nutrition security is of concern and highly dependent on fisheries.[20]

Micronutrient-dense catches are more vulnerable to climate change than fishing

The full implications of species-level patterns in micronutrient density, and vulnerability to fishing and climate change, will depend on the species and abundances targeted within each country's EEZs. We therefore investigated the relationship between micronutrient density and vulnerability status for reported and unreported marine finfish catches within 157 countries' EEZs between 2010 and 2014.[7,21] For each country's EEZ catches, we calculated the biomass-weighted micronutrient density, vulnerability to fishing, and vulnerability to climate change.[22] We also quantified the evenness[23] of micronutrient density for national fish catches over the same period to evaluate the extent to which micronutrient contributions are distributed evenly across species or dominated by few species, which would exacerbate the vulnerability of a fishery to the loss of a species.

Where biomass-weighted micronutrient densities are lower (bottom quartile), catches tend to be less vulnerable to climate change but can be more vulnerable to fishing (Figures 2A and S3). Conversely, where micronutrient densities are greater, catches tend to be less vulnerable to fishing but more vulnerable to climate change (Figures 2B and S3). Most (88% or 139) countries are located in the bottom two quadrants, suggesting overall low vulnerability to fishing, and very few (4% or 6) countries face double jeopardy from both stressors (Figure S3). Critically, many countries (41% or 65) are located in the two right-hand

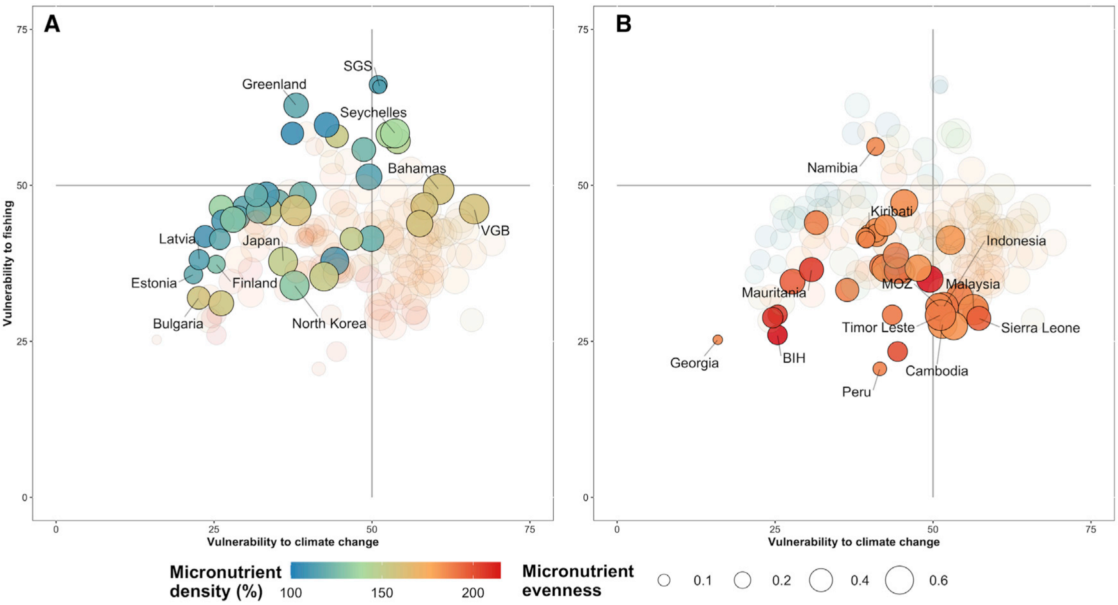

Figure 2. Relationships between micronutrient density and vulnerability status of fish catches at the country scale

Relationship for countries having (A) less nutritious (bottom quartile, n = 40) and (B) more nutritious (top quartile, n = 39) catches. Micronutrient density (mean = 166; range: 106%–215%) is represented from low (blue) to high (red). The size of the circles indicates micronutrient evenness, a richness-independent standardized metric (mean = 0.52; range: 0.06–0.78) that increases as nutrient provision is evenly distributed through species within national catches. Other countries (intermediate quartiles, n = 78) are shaded. BIH, Bosnia and Herzegovina; MOZ, Mozambique; SGS, South Georgia and Sandwich Islands; VGB, British Virgin Islands. See also Figures S3 and S4.

quadrants, indicating micronutrient supplies from their fisheries are highly vulnerable to climate change (Figure S3).

The extent to which fisheries can continue to generate nutrient-dense catches is of particular importance to sustaining nutrient provisions to vulnerable populations. Low micronutrient evenness, which indicates a small proportion of the target species contributes a large proportion of micronutrient density, suggests catches may be more affected by potential stressors,[24] representing an additional aspect of vulnerability to climate change and fishing. Although countries access different micronutrients according to catch composition and habitat, micronutrient provisioning tends to be more evenly distributed among species when micronutrient density of fish catches is moderate to high (Figure S4). Micronutrient evenness is a richness-independent standardized metric (range: 0 to 1); however, we observe that low evenness values are dominated by countries with lower species richness in catches, while micronutrient density is weakly associated with species richness in catches (Figure S4). For countries having low micronutrient evenness, few or one species contribute disproportionately to catches, such that micronutrient density of catches is largely driven by the micronutrient density of dominant nutrient-poor (*Clupea harengus* for Finland or *Sprattus sprattus* for Estonia and Latvia) or nutrient-dense (*Sardina pilchardus* for Montenegro and Croatia) species (Figure S4; Table S1). This suggests that some countries have high micronutrient density catches (top quartile, such as Indonesia, Timor-Leste, and Malaysia) spread among a high number and diversity of nutrient-rich species (high evenness and micronutrient density), conferring a greater resilience to stressors. In contrast, some countries have less nutritious catches (bottom quartile, such as Finland and Bulgaria), which tend to be composed of a reduced number of nutrient-poor species (low evenness and micronutrient density; Figures 2 and S4). Exceptions exist, such as Georgia and Peru, that have micronutrient-dense catches (top quartile) but have low micronutrient evenness (<0.2; Figure 2). In contrast, Japan, Seychelles, and Bahamas have low micronutrient density in their catches, despite high nutrient evenness (>0.6; Figure 2), indicating low potential to manage these fisheries toward higher nutrient yields. Conversely, low evenness can highlight opportunities for fisheries management to prioritize high(er)-nutrient species that are underrepresented in catches.

Countries in the tropics are more likely to have species with higher micronutrient concentrations[2] compared to countries in Europe and North America (Figures 1C and 3). However, other factors, such as measures of human development and fishery-dependent drivers of national fish catches, together influence micronutrient densities of national catches (Figure 3). For example, species richness is associated with higher micronutrient densities, and there are negative relationships between micronutrient density of catches, fishery yields, and fishing area, highlighting that the increased nutrient quality of a fishery is determined by its species composition (Figure 3). More importantly, fisheries with higher species richness may not only provide greater micronutrient densities, but they are also likely to be more stable over time, with lower rates of collapse for commercially important fish.[6] Finally, although fishing capacity is heavily dependent on national development status,[25] fisheries in countries with a low human development index (HDI) are associated with greater micronutrient density

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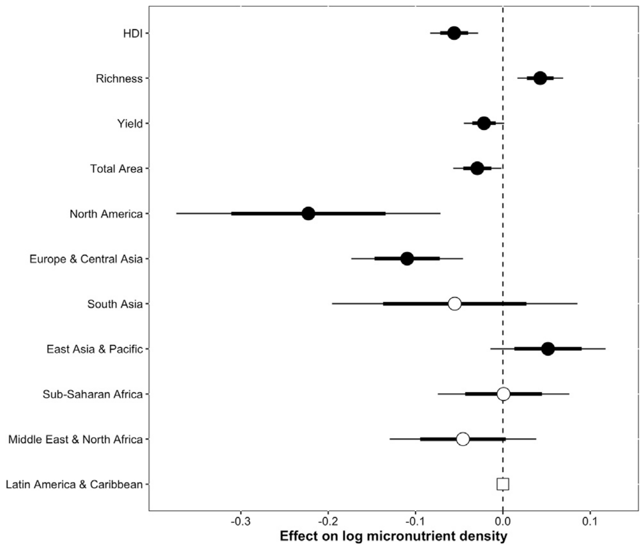

Figure 3. Relationships between the nutritional quality and associated ecological, development status, and fishery-dependent drivers of national fish catches

The model integrated species richness in fish catches (richness), total fishery yield and area, the fishing region, and HDI of the country. Points represent estimates from a linear model testing for an effect of each explanatory variable on log micronutrient density at the country level. Thick lines represent 75% confidence intervals (CIs), and thin lines represent 95% CIs. All estimates and CIs are scaled (mean-centered and scaled by one standard deviation) to facilitate comparisons of effect sizes among the explanatory variables. Black dots indicate that the 75% CIs do not overlap zero, whereas white circles indicate that the 75% CIs overlap zero. Open squares indicate the baseline region in the statistical model.

(Figure 3), and most are associated with strong dependence on marine resources.[2,26]

Micronutrient densities greatest where inadequate micronutrient intake is highest

To explore the food and nutrition security implications of the patterns of vulnerability and micronutrient density, we examined how micronutrient supply from fish catches correlate with prevalence of inadequate micronutrient intake at the country scale. We calculated the prevalence of inadequate intake, averaged across four key micronutrients, calcium, iron, vitamin A, and zinc, selected because they have the lowest levels of adequate estimated intake globally[27] and often co-occur in the same population (Figure S5). We found that in countries where the estimated prevalence of inadequate intake is higher, micronutrient density of fish catches is also higher (Figure 4), suggesting unmet potential for fisheries to help reduce micronutrient deficiencies, especially among coastal communities,[2] although some of these fisheries, with high micronutrient densities, tend to be less vulnerable to fishing but more vulnerable to climate change (Figures 2 and S3), making effective climate mitigation a high priority. However, opportunities may exist to preferentially target fish species among the pool of species locally available that support adaptation to secure nutrient provisions from fisheries through time. For example, fisheries with low micronutrient evenness could be managed to maintain or increase nutrient yields by preferentially targeting nutrient-rich species, with low vulnerabilities to climate change that are locally available but currently underrepresented in catches. This would be possible if such species can be preferentially targeted with certain gears or in specific habitats.

Nutritional dependence on marine ecosystems, a composite index that integrates the importance of seafood in protein intake, diet diversity, and the proportion of underweight children,[26] weakly correlates ($r = 0.35$; $p < 0.005$) with high prevalence of inadequate micronutrient intake (Figure 4). For example, inadequate intake is low (28%) in Malaysia and high (57%) in Georgia, where nutritional dependence on marine systems is very high and medium, respectively. This suggests that nutritional dependence on marine resources does not reflect the prevalence of inadequate micronutrient intake globally, highlighting the likely interdependence of marine-and terrestrial-based food systems (Figures 4 and S5) and issues around distribution and access to fish.[5] Most food security indices only consider energy availability or certain nutrients, such as protein or fats.[26] However, accounting for both the bioavailability and the estimated intake of micronutrients, from marine and terrestrial sources, remains essential to tackling hidden hunger,[2,27] especially as global individual-level dietary intake data become increasingly available.[28]

Countries such as Japan, Bulgaria, and North Korea have moderate to high (30%, 34%, and 82%, respectively) prevalence of inadequate micronutrient intake (Figure 4), but their catches have very low micronutrient densities (Figures 2 and 4), suggesting limited potential for domestic fisheries to help close nutrient gaps. Moreover, high variability in micronutrient density (associated with low evenness) may jeopardize the stability of nutritional contribution from fish catches over time because a small number of species, which are not caught in every year, make a disproportionate contribution, especially for countries where prevalence of inadequate micronutrient intake is moderate to high, such as Georgia, Bulgaria, and Mauritania (Figure 4). Such instability of micronutrient supply may be further exacerbated in countries threatened by climate change, such as Mozambique and Sierra Leone (Figures 2 and 4). Conversely, countries such as Indonesia, Cambodia, and Timor Leste have high (63%, 70%, and 84%, respectively) prevalence of inadequate micronutrient intake (Figure 4), but their catches are particularly nutrient rich and evenly distributed (Figures 2 and 4), highlighting great potential for fisheries to contribute to solving micronutrient deficiencies. The potential of fisheries to contribute to nutritional security needs to consider multiple dimensions, including density and distribution of nutrients across catches, vulnerability to climate change and fishing, and access to fish by the most vulnerable in society.

Caveats and future research

Although the SAU data cover vertebrate and invertebrate species, we limited the scope of our study to marine finfish. The mechanisms predicting nutrient concentrations in invertebrates are poorly understood, making it difficult to assess the nutritional contribution of invertebrates to human nutrition.[2,29] Furthermore, inland fisheries and aquaculture make a critical contribution to food security but remain widely underreported and thus undervalued, especially in low-income countries.[30,31] Overall, the future of all capture fisheries (e.g., non-fed aquatic animals)

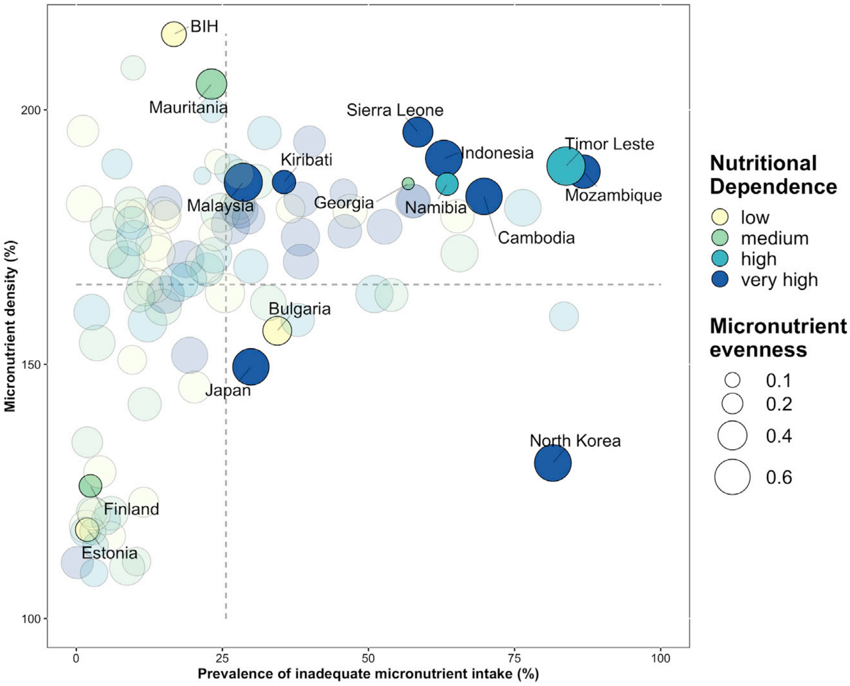

Figure 4. Dietary micronutrient dependence on fish, prevalence of inadequate intake, and micronutrient density in fishery-dependent countries

Prevalence of inadequate micronutrient intake averaged across 4 key micronutrients: calcium; vitamin A; zinc; and iron.[27] The color denotes the nutritional dependence on marine systems at the country scale.[26] The size of the circles indicates the nutrient evenness, a richness-independent standardized metric (range: 0 to 1) that increases as nutrient provision is evenly distributed through species within national fish catches. Dashed horizontal and vertical lines represent mean values of each metric across 103 countries. For more clarity, countries that are not named are shaded. BIH, Bosnia and Herzegovina. See also Figure S5.

under climate change is expected to decrease in production,[4,32–34] and although there is scope for compensation through aquaculture,[35] associated changes in micronutrient concentrations remain poorly understood. Integrating micronutrient content of fish with bioclimate models of global fisheries[32] and aquaculture[36] production may help to identify regions that will face sharp declines in micronutrient supply in the future due to climate change.

Seafood is among the most globally traded food commodities. Thus, countries' nutrient availability and their sensitivity to the vulnerabilities of fish stocks to fishing and climate change are expected to be affected by seafood imports and exports. We consider reported and unreported fish catches because they are potentially available for local consumption. However, patterns of foreign fishing and regional and international trade mean catches may not reach local populations, especially for countries such as Namibia and Kiribati, where estimates of inadequate nutrient intake are moderate to high (Figure 4), yet only a small fraction of fish caught (<13%) in their EEZs are retained for domestic markets.[2] Our study provides a framework to examine how seafood trade may modify our conclusions in future research.

Conclusions

Our analysis considers how climate change and overfishing are likely to affect micronutrient supply from marine fish species to assess the potential future contribution of global fisheries to food and nutrition security under contemporary ocean threats. We show that global fisheries have relatively low nutritional vulnerability to fishing. Fisheries with higher species richness tend to be nutrient dense and evenly distributed but are more vulnerable to climate change. More specifically, climate change is the most pervasive threat to the continued supply of micronutrients from marine fisheries for 40% of all coastal countries globally, adding to expected changes in potential catches[32] and national incomes.[37]

We also find that micronutrient densities of fish catches are higher where the prevalence of inadequate intake is moderate to high, reinforcing the considerable contribution marine fish can make to food and nutrition security. Countries with the highest prevalence of inadequate micronutrient intake tend to have the most nutrient-dense catches, but these same fisheries are highly vulnerable to climate change, with relatively lower capacity to adapt,[11] making effective climate mitigation a high priority.

Human impacts on marine resources are accelerating,[38] and climate change is also expected to impair nutrient availability from agriculture production,[39] suggesting that policies connecting terrestrial and aquatic (both marine and freshwater) food systems can make a decisive difference in successfully achieving the challenge of "ending all forms of hunger and malnutrition" (SDG 2). Our results highlight opportunities may exist to move toward nutrient-sensitive fisheries management, which identifies and targets suites of species that are available and nutrient dense,[40] particularly those that have low vulnerabilities to both fishing and climate change.

STAR★METHODS

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SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.cub.2021.06.067.

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AUTHOR CONTRIBUTIONS

E.M. conceived the study with C.C.H. and N.A.J.G.; E.M. and M.A.M. developed and implemented the analyses. E.M. led the manuscript with input from all authors.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
Vulnerabilities of marine fishes to fishing	Cheung et al.[8]	https://doi.org/10.1016/j.biocon.2005.01.017
Vulnerabilities of marine fishes to climate change	Jones and Cheung[9]	https://doi.org/10.1111/gcb.13869
Prevalence of inadequate micronutrient intake	Beal et al.[27]	https://doi.org/10.1371/journal.pone.0175554
Dataset and R code for running the analyses and figures	This paper; GitHub repository	https://github.com/EvaMaire/NutrientGlobalFisheries
Software and algorithms		
R 4.0.3 binary for macOS 10.13 and higher	The R Project for Statistical Computing	https://cran.r-project.org

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the Lead Contact, Eva Maire, Lancaster Environment Centre, Lancaster University, LA1 4YQ United Kingdom (e.maire@lancaster.ac.uk).

Materials availability

This study did not generate new unique reagents.

Data and code availability

Data and R code used to estimate the nutritional and vulnerability status of global marine fisheries can be found at https://github.com/EvaMaire/NutrientGlobalFisheries. Data and code for FishBase micronutrient estimation are available at https://github.com/mamacneil/NutrientFishbase.

METHOD DETAILS

Nutrient content of marine fish species

Using the concentration of 5 key micronutrients (calcium, iron, zinc, selenium and vitamin A) in more than 350 species of marine fish from FishBase,[17] which uses Bayesian hierarchical models to estimate how diet (feeding pathway and trophic level), energetic demand (maximum length, age at maturity, K and maximum size) and thermal regime (maximum depth and geographical zone) predict nutrient content of marine finfish species, based on an update of the model developed in Hicks et al.[2] This included estimated nutrient content of all marine fish species recorded in the SAU database.

Fishing and climate change vulnerability of marine fish species

We considered the intrinsic vulnerability of marine finfishes relative to fishing and climate change, using two established and tested indices of fish species vulnerability to fishing[8] and climate change.[9] Both indicators use a fuzzy logic expert system to take account of key life history and ecological characteristics that are known to influence species vulnerability to the specific threat. Variables included in the fishing vulnerability index were maximum length, age at first maturity, K, natural mortality, maximum age, geographic range, fecundity and spatial behavior.[8] Variables included in the climate change index were an exposure to climate hazards value, temperature tolerance range, maximum body length, latitudinal range, depth range, fecundity, and habitat specificity.[9]

Micronutrient density score

We focused on five micronutrients (calcium, iron, zinc, selenium, and vitamin A) that are essential for human health.[27,41] The lack of available data precluded inclusion of other essential micronutrients in our analysis, such as amino acids and vitamin B.[42,43] We applied the concept of nutrient density[13] to micronutrients of fish, defining micronutrient density as the sum of percentage dietary references for the five key micronutrients calculated per raw portion of 100 g of fish (wet weight). Higher micronutrient density scores represent higher nutrient densities, up to a maximum potential value of 500%, where all 5 nutrients are fulfilling needs. Percentage contribution to dietary references were capped at 100% to avoid extreme values dominating patterns of variation in density score (e.g., fish species or nutrients with especially high values). We use recommended dietary allowance (RDA), which represents the daily intake level at which the dietary needs of nearly all (97% to 98%) of the population are met, for each of the five micronutrients as dietary reference. We calculated the average RDA for children under 5 years of age.[19] To calculate average RDA for children under 5 years of age, we assumed infants between birth and 6 months of age were exclusively breastfed, and would thus not consume fishery-derived nutrients directly. We then calculated the average RDA for children between 6 months and 4 years (that is, children < 5 years), assuming the population of each country was evenly distributed across the first 5 years of life.[19] While we focused on children under 5 years of age, recommended dietary allowance between population groups (e.g., children under 5 years of age and the rest of the population) are strongly correlated,[19] suggesting our results apply across age groups.

QUANTIFICATION AND STATISTICAL ANALYSIS

Applying micronutrient density and vulnerability indexes to catch data

Using the SAU catch reconstruction database,[21] we extracted catches from the EEZ of each country in tonnes and by species for the period 2010–2014. Reported and unreported catches are generally available for human consumption, but discards are not. Thus, we extracted data on reported and unreported catches from the EEZ of each country and we excluded discards from these data. We limited the scope of our study to marine fisheries. Thus, we only considered landed marine finfish and all invertebrates and freshwater species were removed from the database. For each species recorded in the SAU dataset, we calculated the micronutrient density and we extracted the vulnerability to fishing[8] and the vulnerability to climate change[9] when available. In total, 821 marine fish species had values for the 3 indexes and were considered in the co-tolerance analysis.

Micronutrient density and vulnerability status of fish catches

For the fish catches data, where SAU data were reported at family or genus level, we used the average index values (fishing and climate vulnerability) and averaged nutrient concentrations (for 5 key nutrients) for that family or genus. For each country,[44] we computed the biomass-weighted micronutrient density and vulnerability to fishing and climate change as the weighted mean of each index (I) using the relative abundance of each species in annual catch data following the formula:

$$I_k = \frac{\sum_{i,k} w_{i,k} \cdot I_i}{\sum_{i,k} w_{i,k}}$$

where I_k is the biomass-weighted index value (micronutrient density or vulnerability) for the year k, I_i is the intrinsic index value (independent of the year) of species i and $w_{i,k}$ is the weight of species i in annual catches of year k. We then averaged each biomass-weighted index over the period 2010-2014.

For each country,[44] we applied Pielou's evenness,[23] J, to micronutrient density to measure the evenness of nutrient provision of fish catches following the formula:

$$J = \frac{H'}{H\prime_{max}}$$

$$H' = -\sum_{i=1}^{N} p_i l_n p_i$$

Where H' is the Shannon's diversity index with p_i the proportion of the species i in fish catches and H'_{max} is the maximum possible value of H' which is equal to ln N, with N being the total number of species in fish catches of a given country. We then averaged annual evenness over the period 2010-2014 for each country. For each country, we checked correlation between evenness of the micronutrient density score and evenness of each micronutrient. We found strong correlation (Pearson correlation > 0.8; p value < 0.05) suggesting that our micronutrient density score accurately represents differences in micronutrient balance.

All higher-level groupings above family (for example, order and mixed categories) were removed for the purpose of calculating nutrient value, evenness, and vulnerability status of fish catches. We only considered countries for which marine fish catches were described for at least 60% of the fish catches. This resulted in 157 countries remaining in our analysis (see details in Table S1).

Predictive model of the micronutrient density of national fish catches

To understand drivers of micronutrient density from global fisheries, we developed a linear model to predict the biomass-weighted micronutrient density of each country based on ecological, development status and fishery-dependent drivers of their national fish catches. We built models considering species richness in catches, total fishery yield and area, the fishing region, and Human Development Index (HDI) of the country. The region was assigned following the regional classification as defined in the World Bank Development Indicators[45] which considered 7 major regions: Europe & Central Asia, Middle East & North Africa, East Asia & Pacific, Sub-Saharan Africa, Latin America & Caribbean, South Asia, North America. Each EEZ was attributed to the country it belonged to as fishing zones of some countries are split in different EEZs and total fishery area was estimated as the cumulative area (in km^2) of all EEZs of each sovereign country.[21] Total fishery yield was determined as the averaged catches (in tons) of all EEZs of each country over the period 2010-2014. Species richness was computed as the average number of taxa recorded in fish catches of all EEZs of each country over the period 2010-2014. We used HDI 2018 values from the 2019 Human Development Report published by the

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UNDP.[46] If HDI was not available we manually assigned the HDI value of its sovereign state. Because HDI 2018 was missing for 7 countries (Greenland, Nauru, North Korea, Somalia, Taiwan, Tuvalu and US Virgin Islands), we considered 150 countries in our model.

Prior to modeling, micronutrient density (response variable) was log-transformed and all continuous covariates were standardized (mean-centered and scaled by one standard deviation) to facilitate comparisons of effect sizes among the covariates. None of the covariates were sufficiently collinear to be problematic for the model (VIF < 2). Our model explained up to 41% of the variability observed in log micronutrient density. To check the fit of the linear model, we checked for the representation of actual versus predicted values and we calculated the accuracy of the models, which came to 65%. To examine homoscedasticity, we checked residuals against fitted values and we checked that the residuals were normally distributed.

Nutritional dependence and prevalence of inadequate intake of countries

We extracted the nutritional dependence on marine ecosystems from a previously published study which designed a conceptual model to map human dependence on marine ecosystems through nutritional, economic and coastal protection benefits.[26] Nutritional dependence integrated food consumption and availability, such as the importance of marine protein in diet, protein and fat diversity, and the proportion of underweight children.[26] Dietary micronutrient supply was not explicitly measured.

We extracted data on the prevalence of inadequate intake of 4 key micronutrients: calcium, iron, vitamin A and zinc for each country in 2011, which was estimated from the bioavailability and the estimated intakes and requirements of each nutrient.[27] To echo our micronutrient density which integrated multiple micronutrients, we averaged the prevalence of inadequate intake across these 4 key micronutrients: calcium, iron, vitamin A and zinc. Individual prevalence indexes are strongly correlated globally (> 0.78, Figure S5) suggesting that deficiency risks likely co-occurred, and our averaged metric accurately represented deficiency risk of each nutrient. For this analysis, 103 countries had values for both the nutritional dependence and prevalence of inadequate micronutrient intake.

All data was processed and visualized in R 4.0.3.