ARTICLES
https://doi.org/10.1038/s43016-021-00242-8
nature food

Check for updates

Substitution of inland fisheries with aquaculture and chicken undermines human nutrition in the Peruvian Amazon

Sebastian A. Heilpern[1,2] ✉, Kathryn Fiorella[3], Carlos Cañas[4], Alexander S. Flecker[5], Luis Moya[6], Shahid Naeem[1], Suresh A. Sethi[7], Maria Uriarte[1] and Ruth DeFries[1]

With declining capture fisheries production, maintaining nutrient supplies largely hinges on substituting wild fish with economically comparable farmed animals. Although such transitions are increasingly commonplace across global inland and coastal communities, their nutritional consequences are unknown. Here, using human demographic and health information, and fish nutrient composition data from the Peruvian Amazon, we show that substituting wild inland fisheries with chicken and aquaculture has the potential to exacerbate iron deficiencies and limit essential fatty acid supplies in a region already experiencing high prevalence of anaemia and malnutrition. Substituting wild fish with chicken, however, can increase zinc and protein supplies. Chicken and aquaculture production also increase greenhouse gas emissions, agricultural land use and eutrophication. Thus, policies that enable access to wild fisheries and their sustainable management while improving the quality, diversity and environmental impacts of farmed species will be instrumental in ensuring healthy and sustainable food systems.

Increasing food security while minimizing environmental degradation is one of the greatest sustainability challenges facing humanity[1]. Fisheries are at the centre of this challenge for their role in both transforming aquatic ecosystems and in providing millions of people across the world with a major source of key macro- and micronutrients[2]. Yet fish catch is stagnating and many of the world's fisheries are exploited beyond sustainable levels[3]. Strategies to supplement the contribution of fisheries to population nutrition partially hinge on finding substitutes for wild fish, particularly with economically comparable animal foods, such as farm-raised fish and chicken[4,5]. Animal production farming, however, is most often characterized by low species diversity cultivated for their economic rather than their nutritional potential[6]. Furthermore, farmed species contribute to greenhouse gas emissions, eutrophication of waterways and land conversion[7]. Although the environmental costs of farmed foods are well established[1,8], the nutritional implications of substituting wild fisheries with farmed species, such as chicken and aquaculture, have not been widely quantified.

Here we analyse the nutritional consequences of substituting wild inland fish with chicken and aquaculture in Loreto, in the Peruvian Amazon. As in many other inland and coastal regions, Loreto's population is heavily dependent on diverse capture fisheries but is rapidly transitioning to a less diverse set of farmed animal foods. This transition is concentrated on chicken and aquaculture species, which are considered less financially and environmentally costly than other farmed animals such as livestock[7]. Wild fish harvests in Loreto have remained relatively constant but are showing signs of overexploitation[9]. In contrast, between 2010 and 2016, chicken production increased from 19,628 to 32,671 t, and aquaculture from 642 to 1,136 t[10,11]. These patterns reflect global trends, where growth in chicken and aquaculture production has outpaced that of capture fisheries, particularly in developing countries[12]. Further mirroring these global patterns, aquaculture production in Loreto is low diversity, with four species (*Prochilodus nigricans*, *Brycon* sp., *Colossoma macropomum* and *Arapaima gigas*) accounting for over 98% of regional farmed fish production. Although expanding chicken and aquaculture production is driven by myriad factors, including human population growth, shifting dietary preferences and stagnating wild fish production, governmental policies in particular, typically supported by multilateral institutions, such as the World Bank, are incentivizing dietary shifts from wild fish to chicken and aquaculture[13]. Although these policies are often designed to mitigate food insecurity, whether these alternatives to wild fish undermine or support nutrition has yet to be determined.

Using human demographic and health information, and animal nutrient composition data from Loreto (Supplementary Data 1), we examined the nutritional overlap between wild and common farm species, and employed simulation models to estimate how substituting wild fish with chicken and aquaculture affects the supply of animal-derived nutrients to Loreto's urban population (that is, protein, iron, zinc, calcium and omega-3 fatty acids—α-linolenic acid (ALA), eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA)). Nutrient supplies were estimated as the number of people, scaled to Loreto's population age structure, meeting their annual reference nutrient intakes (RNIs), or the amount required to ensure nutritional needs are met for a given nutrient as established by the World Health Organization[14]. In Loreto, 43.3% of children under 5 yr are iron deficient and 25.3% are chronically malnourished, or stunted; and 22.4% of women of reproductive age are iron deficient[15]. Thus, beyond considering how adjustments to food supply might exacerbate existing nutritional gaps, we further discuss our results in the context of other environmental and food security

[1]Ecology, Evolution and Environmental Biology, Columbia University, New York, NY, USA. [2]Department of Natural Resources and the Environment, Cornell University, Ithaca, NY, USA. [3]Population Medicine and Diagnostic Sciences, Cornell University, Ithaca, NY, USA. [4]Independent researcher, Florahome, FL, USA. [5]Ecology and Evolutionary Biology, Cornell University, Ithaca, NY, USA. [6]Wildlife Conservation Society, Iquitos, Peru. [7]US Geological Survey, New York Cooperative Fish and Wildlife Research Unit, Department of Natural Resources and the Environment, Cornell University, Ithaca, NY, USA. ✉e-mail: s.heilpern@cornell.edu

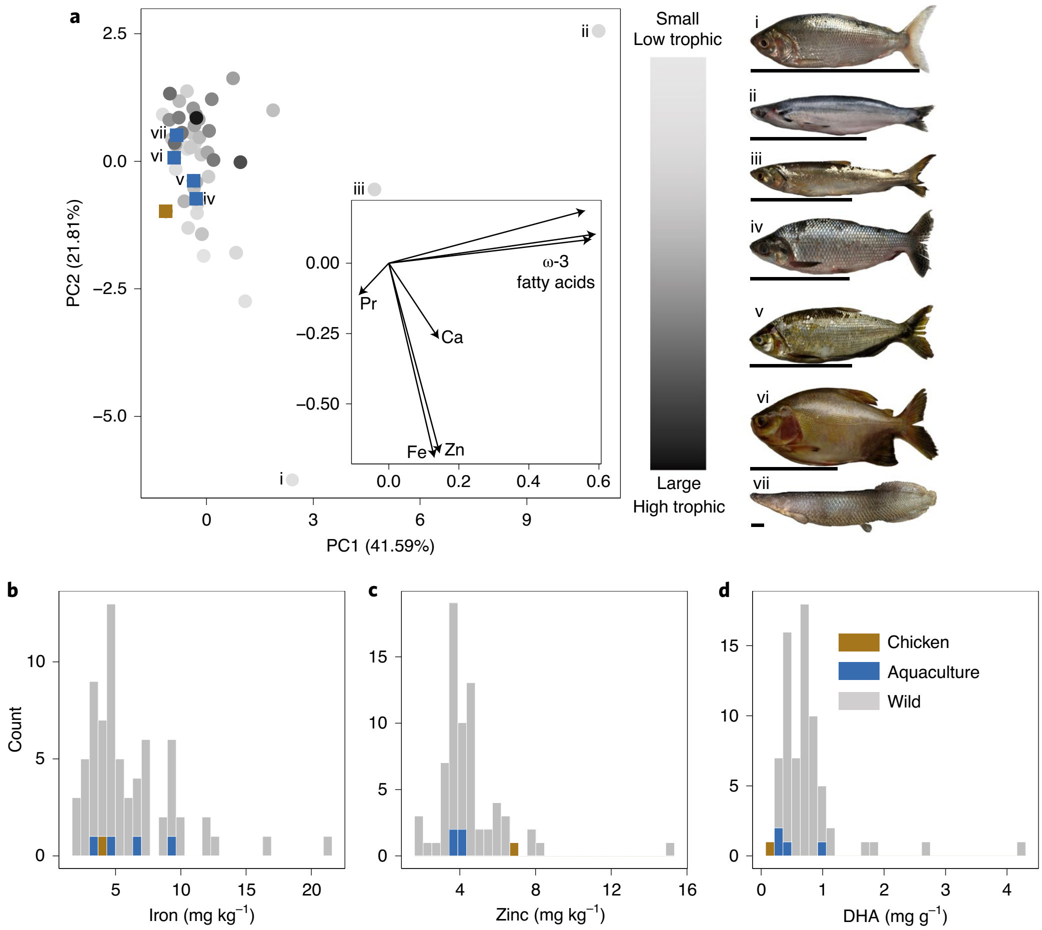

Fig. 1 | Variation in nutritional composition of wild fish, chicken and aquaculture species from Loreto, Peru. **a**, Constituent nutrient factor loadings (inset) indicate that animal food species separate primarily by omega-3 fatty acids (associated with PC1) and minerals (that is, iron, zinc; associated with PC2). Example fish species (inset photographs) are ordered by body size and trophic level (smaller, lower trophic-level species in light grey, to larger and higher trophic-level species in dark grey): *Psectrogaster amazonica* (i), *Ageneiosus* sp. (ii), *Potamorhina altamazonica* (iii), *Prochilodus nigricans* (iv), *Brycon* sp. (v), *Colossoma macropomum* (vi) and *Arapaima gigas* (vii). The scale bar below each species represents 15 cm. **b–d**, Poultry (tan) has above-average zinc, but low iron and DHA compared to wild (grey) and aquaculture (blue) fish options. Aquaculture production focuses on a small set of species whereas wild species span high diversity in nutrient profiles. Coloured bars indicate nutrient values for poultry and aquaculture species (from low to high values): **b**, vi, vii, v, iv; **c**, iv, vii, v, vi; **d**, iv, vi, vii, v. For farmed *P. nigricans* and *A. gigas*, nutrient values for their wild counterparts were used.

dimensions. The study underscores the substantial, although often underappreciated, role that inland fisheries play in providing people with a diversity of nutrients[16,17].

Results and discussion

Fish substitutions, diversity and nutrient supplies. To understand how nutritionally substitutable wild fish are, we examined nutrient diversity across all species under consideration here (wild fish, chicken and aquaculture) using principal-component analysis. Farmed animals were found typically to have lower nutritional quality and variation than wild fish (Fig. 1). The first two principal components combine to explain 63.4% of the variation in nutritional composition, with omega-3 fatty acids (PC1), and iron and zinc (PC2) dominating the loadings for these axes. Wild fish species, and particularly small and low trophic species, are notably rich in both minerals and fatty acids (Fig. 1b–d and Supplementary Fig. 1). Chicken is rich in protein and offers moderate quantities of zinc, but otherwise has relatively lower nutrient content. Aquaculture species fall near the centroid of nutritional principal-component space and thus are not distinguished in any particular nutrient.

Current annual capture fisheries harvests could feed many of Loreto's approximately 600,000 urban residents. Annually, capture fisheries in the region provided enough protein for 275,000 people, essential omega-3 fatty acids for 230,000 people, zinc for 45,000, iron for 30,000 and calcium for 5,000 (Supplementary Fig. 2). However, substituting wild fish with chicken or aquaculture affected nutrient supplies. For each wild fish species replaced by chicken, the mean $\pm$ s.e. number of people potentially meeting annual protein and zinc requirements increased by 924 ± 213 and 382 ± 115, respectively (Fig. 2). With each wild fish replaced, however, there were declines in the number of people meeting annual iron (272 ± 91) and fatty acid requirements (ALA, 397 ± 106; EPA, 470 ± 147; DHA, $2{,}332 \pm 434$). The reduction in supply of critical nutrients was largest for children under 5 yr and women of reproductive age, particularly for iron and omega-3 fatty acids, which are most in demand for those groups (Fig. 3 and Supplementary Figs. 3 and 4).

Positive and negative changes induced by replacing capture fisheries production with aquaculture were similar in direction but less pronounced than with chicken because aquaculture species are nutritionally more like average wild fish species (Fig. 2). For each wild fish species replaced by aquaculture species, the number of people potentially meeting annual protein increased by 101 ± 42, whereas for zinc, changes were negligible (3 ± 65). Calcium, iron,

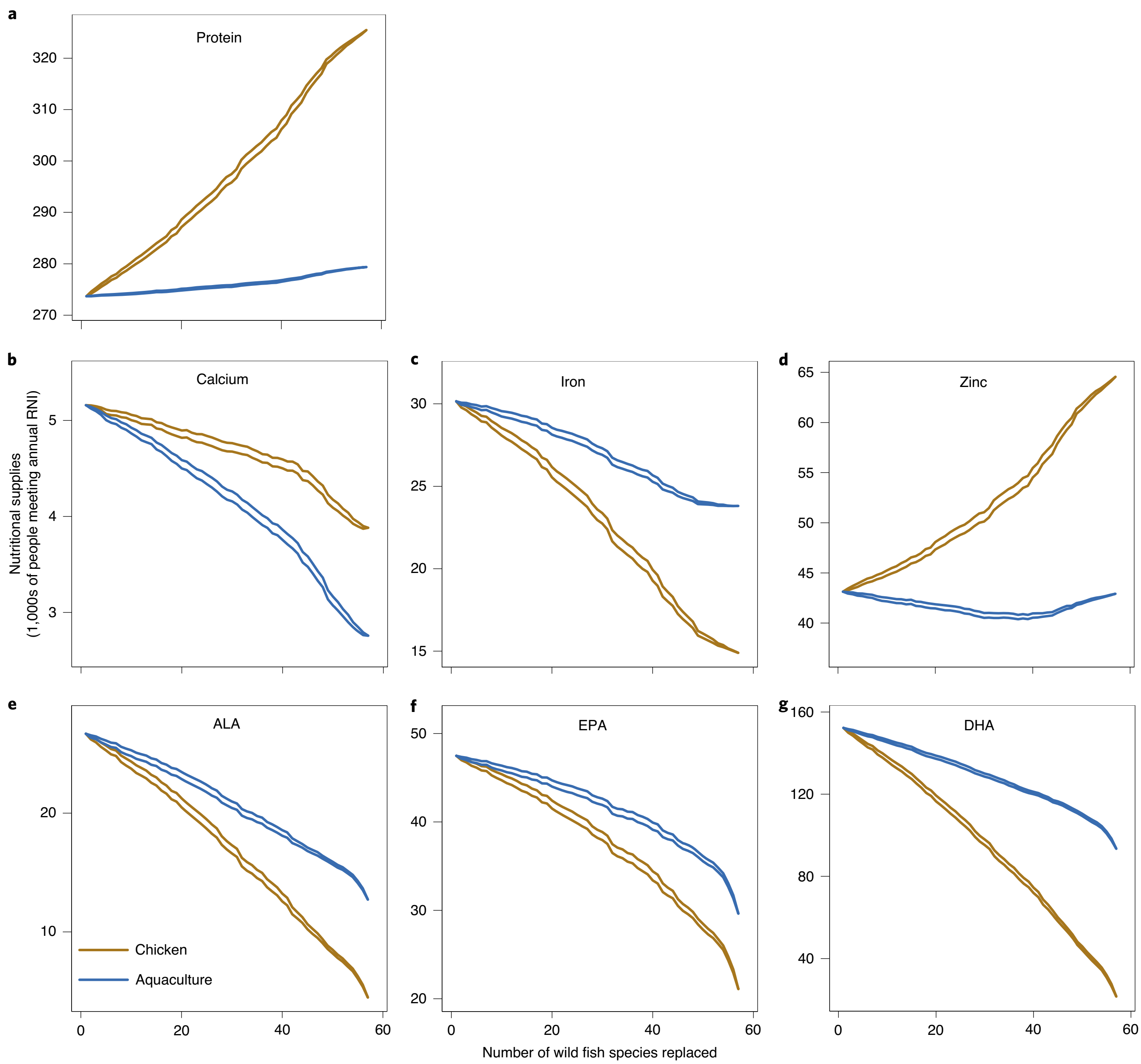

Fig. 2 | Wild fish substitutions and nutritional supplies. a–g, Changes in the number of adults (in 1,000s) meeting their annual RNIs for macronutrients (**a**), minerals (**b**,**c**) and omega-3 fatty acids (**e**–**g**) when substituting wild fish species with chicken or aquaculture. While protein (**a**) and zinc (**d**) supplies increase by substituting wild fish with farmed species, declines of other nutrients, such as iron and omega-3 fatty acids (**c**,**e**–**g**), exacerbate nutritional deficiencies. Lines represent 95% confidence intervals.

ALA, EPA and DHA all declined, but less dramatically than when replacing wild fish with chicken. As with chicken, these results were more dramatic for children or women of reproductive age (Fig. 3). Substituting wild fish randomly versus based on size and trophic level resulted in few qualitative differences (Supplementary Figs. 3–5).

Beyond changing nutrient supplies, substituting wild fish with aquaculture or chicken reduced overall species diversity in the food supply, a change that has strong implications for ensuring adequate dietary intakes. Because no single species can offer all key nutrients, a diversity of species is needed to sustain nutritionally adequate diets. The influence of small fish, which lay at the edges of nutritional principal-component space, in increasing nutrient diversity stands in contrast to that of chicken or aquaculture, which fall near the centre (Fig. 1a). Additionally, unlike larger fish, smaller fish are often consumed whole, and the contribution of organs and bones is probably underestimated because our nutrient values are based on muscle[18]. More generally, smaller fish are consistently more nutritious than larger fish in inland[19] and marine ecosystems[2,20], and declining species diversity associated with the replacement of wild fish with larger aquaculture species could have similar impacts in other regions where food security is strongly tied to fisheries.

Shifting diets, sustainability and food security. The transition from wild to farmed species in the Amazon is mirrored by food system shifts across the globe and contributes to growing obesity

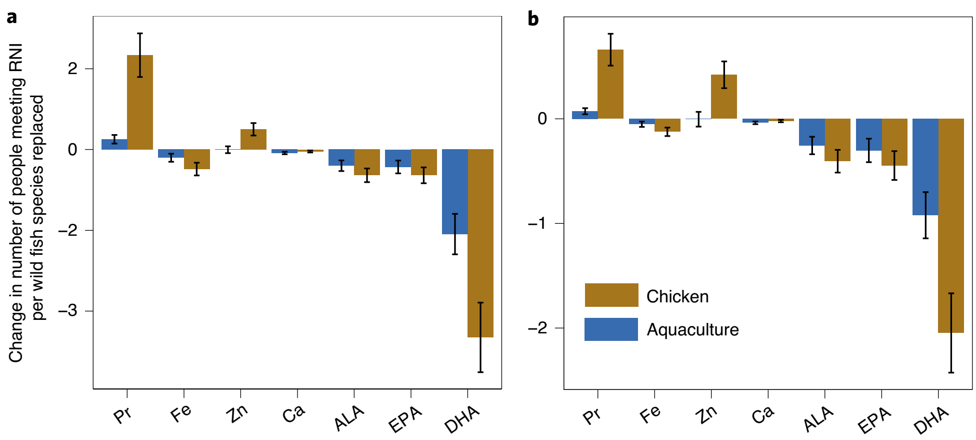

Fig. 3 | Nutritional impacts of wild fish substitutions for vulnerable subgroups. a,**b**, The change (mean ± s.e.) in the number of children under 5 yr (**a**) and women of reproductive age (**b**) meeting their annual RNIs per wild fish species replaced with chicken or aquaculture. For each wild species replaced by chicken, the number of children and women meeting their RNI per tonne of animal food increases for zinc and protein, but declines for other nutrients. For these vulnerable populations, substituting wild fish with chicken induces larger changes in the number of people meeting their RNI than substituting wild fish with aquaculture.

and malnutrition rates[21]. In Bangladesh, for example, higher consumption of aquaculture relative to wild species has increased fat and protein intakes, but decreased iron and zinc intakes[22], while in Madagascar, restrictions on bushmeat access have the potential to increase anaemia rates[23]. Despite these trends, farmed animal systems could also offer several benefits over wild foods. For example, farmed animal production systems can be more stable than wild fisheries and their nutritional content more amenable to improvements, such as through DHA-fortified feed. More generally, without further improvements to the nutritional quality of farmed species, substituting a diverse portfolio of wild fish with chicken or aquaculture will further complicate the nutritional impacts of ongoing dietary transitions.

Compounding the nutritional consequences of substituting wild fish are the potential environmental impacts associated with chicken and aquaculture production[1,7,24]. Although it is difficult to compare inputs and output impacts from wild capture fishing against farmed alternatives, and region-specific lifecycle assessments for chicken or aquaculture are unavailable, evidence from other systems indicates that the environmental footprint of the artisanal inland fisheries in the Amazon is probably lower than those of chicken or aquaculture[1,7,25]. Wild capture fisheries impact aquatic ecosystems by removing fish biomass, and if left unmanaged, could lead to fish population collapses[3,9]; however, energy use and pollution outputs are generally low for tropical capture inland fisheries such as in the Amazon[25–27]. In contrast, although poultry production systems are typically more efficient than the semi-intense aquaculture systems prevalent in much of the developing world[7,8,27–29], both systems rely on feed inputs, contributing to greenouse gas emissions, land conversion and eutrophication[1,7,24]. Although increasing production efficiency will reduce the environmental costs of chicken and aquaculture[28], evaluating the full impact of shifting diets on broader sustainability goals requires further consideration of the nutritional and environmental tradeoffs of different production systems[30,31].

Our analysis examined changes in nutrient supplies, but food security is multidimensional, and utilization of and access to different food items could also shape the nutritional consequences of substituting wild fish with farmed species. Culturally, the Westernization of diets is associated with changing food preferences, a phenomena documented in the Amazon[32], and potentially accelerating shifts from wild to farmed species[21,33,34]. Chicken production and projected growth is larger than that of aquaculture, and could reflect shifting preferences from fish to land-based species. Furthermore, although we assumed mass-balanced substitutions, differences in how species are utilized, including in preparation methods and serving size, could also influence the nutritional consequences of wild fish substitutions.

In addition to utilization, access is often determined by differences in price among species. Although we did not analyse the economic viability of substituting wild fish, it should be noted that chicken and aquaculture species are currently more expensive than many of the most nutritious wild fish species (wild fish, US\$1.25 kg^{-1}; aquaculture, US\$2.19 kg^{-1}; chicken, US\$4.50 kg^{-1} (mean prices)). This renders chicken and aquaculture as less economically accessible than wild fish species, which could limit the ability for poorer segments of the population to substitute wild with farmed species[23]. Changes in species supplies and production efficiency affect prices, however, and knowledge of these dynamics may help better demonstrate which groups may be most impacted by changes associated with ongoing food supply substitutions. For example, substantial declines of wild fish production associated with unsustainable harvests could drive up prices for wild fish and magnify nutrition access issues for some population segments[35].

Conclusions

Our results show that maintaining a diverse portfolio of food species is paramount for providing adequate nutrition, while also ensuring sustainable food supplies. Importantly, although substituting capture fisheries production with chicken and aquaculture could meet some nutritional needs (for example, protein and zinc), because wild fish are rich in iron and omega-3 fatty acids, shifts to these alternatives threaten to undermine nutrition in a region with persistently high malnutrition rates. Although chicken continues to play a central role in food security development assistance efforts in low- and middle-income countries[32,36], promoting consumption of small fish can be particularly effective in combating food insecurity because of their high nutritional value, lower price and lower environmental impact[2]. Rather than solely focusing on expanding farmed species production, policies that invest in managing capture fisheries, such as through protection of key habitats and harvest monitoring, can work towards increasing food security while also abating the impacts of overfishing on aquatic ecosystems. Finally, as a complement for wild fish, aquaculture may benefit from prioritizing nutrition in addition to economics by developing systems where nutritious species are interspersed with economically valuable species, possibly improved with fortified feed[6]. Ultimately, as policy-makers try to balance the ecosystem impacts of food production with food security under uncertain climatic conditions, integrating diversity into fisheries and food security policy holds potential for delivering on multiple global sustainability initiatives.

Methods

The department of Loreto, Peru, is home to 883,510 people, 606,743 of whom live in the region's urban centres[15]. Most transport is by river or air, and the vast majority of animal-sourced foods are produced within the department. Demographic and health information (that is, age-structured population, anaemia and malnutrition prevalence) was obtained from the Instituto Nacional de Estadística e Informática, which conducted its last census in 2017. Fishery information was obtained from the Dirección Regional de la Producción-Loreto (DIREPRO-Lor), which has the mandate to collect daily landings information, including price, volume and taxonomic information, at ports of the largest urban centres (that is, Iquitos, Nauta, Requena, Contamana, Caballo Cocha, San Lorenzo and Yurimaguas). Following the landings data resolution available from DIREPRO-Lor which sometimes aggregates morphologically similar, but taxonomically different, species into groups, we combined a number of fish taxa into common groups (for example, piranas, palometas, anostomids; Supplementary Data 1). Species mean annual biomass harvested were estimated from landings data for 2000–2016. Information on aquaculture production and price was also obtained from DIREPRO-Lor[11], whereas chicken production and price information was obtained from the Ministerio de Desarrollo Agrario y Riego-Loreto[10].

Nutritional composition data. To obtain information on the nutritional content of fish species, we collected between 6 and 20 individual fish specimens for 51 of the 59 taxa included in the DIREPRO-Lor database at the Belén market in Iquitos, Loreto, between February and June 2019. Fish were placed on ice and taken to a laboratory at the Universidad de la Amazonía Peruana, where each specimen was weighed, measured and photographed. Fish were then frozen at −20 °C and sent whole to Lima to be analysed at the Instituto Tecnológico Pesquero, an accredited governmental institute. If an individual fish was too large (approximately over 50 cm), a portion, rather than the whole specimen, was sent for analysis. Although some fish species are consumed whole, we decided to standardize the analysis for all species by only using muscle from the left upper portion of a specimen's body. Given differences in preparation methods, where small species are preferentially consumed whole, this could lead to underestimates in nutrient values.

Protein content was obtained by the Kjeldahl method; calcium, iron and zinc were obtained by atomic absorption spectroscopy (flame atomizer); fats were first extracted using a Soxhlet extractor and then omega fatty acid content was analysed by gas chromatography with flame ionization detection. For aggregate landings taxa, we assigned the averaged nutrient content for constituent taxa. For species for which we were able to obtain six or more individuals, samples were pooled into three groups based on their source of origin, and the average nutritional value was used. For species for which we were unable to obtain samples for nutritional analysis, we used family-level nutrient averages because phylogeny is often a strong predictor for nutritional content[20]. Chicken nutritional composition data were obtained from the Brazilian table of food composition[37], since for Peru the current data available are not complete for all nutrients. Data for aquaculture species were obtained from analysing samples (as above) for *C. macropomum* and *Brycon* sp. We were not able to obtain farmed *A. gigas* or *P. nigricans* specimens, and therefore used nutritional composition data from wild samples instead. Although comparisons between the nutritional quality of farmed and wild individuals are not available for these species, evidence from other regions suggests that farmed individuals can be fattier than wild individuals[19,38], which could potentially lead to smaller changes in omega-3 fatty acids induced by substitutions of wild for aquaculture species.

Supply. Nutrient supplies (Y_N) were estimated as the total number of people able to obtain 100% of their annual RNI for each nutrient N by dividing the total pool of nutrients available across species by a per-person annual nutritional requirement. Rather than assuming a homogeneous population, RNI values were obtained by stratifying the population into segments: children under 5 yr; children 5–10 yr; females 11–14 yr; males 11–14 yr; women of reproductive age (15–49 yr); adult males (15–64 yr); menopausal women (50–64 yr); elderly females (≥65 yr); and elderly males (≥65 yr). Thus, Y_N was estimated as:

$$Y_N = \sum_{j=1}^{P} \frac{p_j \sum_{i=1}^{S} \text{Biomass}_i N}{\text{RNI}_{N,j}}$$

where S is the number of species and p_j is the proportion of the people in population segment j. Initial Biomass_i values for each species were parametrized using the species i mean annual harvest in kilogrammes from the annual landings data. RNI values for protein and ALA were obtained from the Food and Nutrition Board of the Institute of Medicine, US National Academy of Sciences[39], while RNIs for Fe, Zn, Ca, EPA and DHA were obtained from the World Health Organization[40].

Nutritional variation. To examine the variation in nutritional quality among the wild species and farmed species we performed principal-component analysis using the seven nutrients for the 59 wild taxa, four aquaculture species and chicken (total of 64 species). Before analysis we standardized nutritional values (z-transformed), which is considered appropriate for data with different measurement scales.

Species replacement. A detailed description of our modelling approach is provided in ref. [41]. Briefly, we first estimated Y_N for each nutrient as above. Then, we ran two replacement scenarios: random replacement (that is, any wild fish species is selected at random for replacement by farmed animals); trait-based replacement (that is, the largest and highest trophic position have a higher replacement probability, reflecting higher potential vulnerability to overexploitation and collapse). At each step, one wild fish species was replaced by allocating its biomass to either chicken or aquaculture species and Y_N was estimated, until all wild species were replaced. For aquaculture, wild fish biomass was allocated based on the average ratio of production from 2009 to 2015 of each aquaculture species. In addition to estimating the Y_N for the total population at each step, we estimated the number of children under 5 yr and of women of reproductive age able to meet 100% of their annual RNI with 1 t of animal-sourced foods. One hundred simulations were run per replacement scenario. All analysis were conducted with R[42].

Data availability

Data used are available in the main text and Supplementary Data 1.

Code availability

All code is available upon request from the corresponding author.

Received: 16 July 2020; Accepted: 16 February 2021;
Published online: 19 March 2021

References

1. Tilman, D. & Clark, M. Global diets link environmental sustainability and human health. *Nature* **515**, 518–522 (2014).
2. Hicks, C. C. et al. Harnessing global fisheries to tackle micronutrient deficiencies. *Nature* **574**, 95–98 (2019).
3. *SOFIA 2020—State of Fisheries and Aquaculture in the World 2020* (FAO, 2020).
4. Godfray, H. C. J. et al. Food security: the challenge of feeding 9 billion people. *Science* **327**, 812–818 (2010).
5. Kawarazuka, N. & Béné, C. The potential role of small fish species in improving micronutrient deficiencies in developing countries: building evidence. *Public Health Nutr.* **14**, 1927–1938 (2011).
6. Belton, B. & Thilsted, S. H. Fisheries in transition: food and nutrition security implications for the global South. *Glob. Food Sec.* **3**, 59–66 (2014).
7. Hilborn, R., Banobi, J., Hall, S. J., Pucylowski, T. & Walsworth, T. E. The environmental cost of animal source foods. *Front. Ecol. Environ.* **16**, 329–335 (2018).
8. Froehlich, H. E., Runge, C. A., Gentry, R. R., Gaines, S. D. & Halpern, B. S. Comparative terrestrial feed and land use of an aquaculture-dominant world. *Proc. Natl Acad. Sci. USA* **115**, 5295–5300 (2018).
9. Heilpern, S. *Integrating Food Webs and Food Security to Understand the Impact of Biodiversity Loss on Ecosystem Functions and Services.* PhD thesis, Columbia Univ. (2020).
10. Ministerio de Desarrollo Agrario y Riego (Midagri); https://www.gob.pe/midagri
11. Ministerio de la Producción (Produce); https://www.gob.pe/produce
12. *OECD-FAO Agricultural Outlook*, 2019 edn (OECD/FAO, 2020).
13. *Peru—National Program for Innovation in Fisheries and Aquaculture Project* (World Bank, 2017).
14. DeFries, R. et al. Metrics for land-scarce agriculture. *Science* **349**, 238–240 (2015).
15. *Loreto: Resultados Definitivos de la Población Economicamnte Activa 2017* (Instituto Nacional de Estadistica e Informática, 2018).
16. McIntyre, P. B., Liermann, C. A. R. & Revenga, C. Linking freshwater fishery management to global food security and biodiversity conservation. *Proc. Natl Acad. Sci. USA* **113**, 12880–12885 (2016).
17. Youn, S.-J. et al. Inland capture fishery contributions to global food security and threats to their future. *Glob. Food Sec.* **3**, 142–148 (2014).
18. Kawarazuka, N. & Béné, C. The potential role of small fish species in improving micronutrient deficiencies in developing countries: building evidence. *Public Health Nutr.* **14**, 1927–1938 (2011).
19. Bogard, J. R. et al. Nutrient composition of important fish species in Bangladesh and potential contribution to recommended nutrient intakes. *J. Food Compos. Anal.* **42**, 120–133 (2015).

20. Vaitla, B. et al. Predicting nutrient content of ray-finned fishes using phylogenetic information. *Nat. Commun.* **9**, 1–10 (2018).
21. Popkin, B. M. Nutrition, agriculture and the global food system in low and middle income countries. *Food Policy* **47**, 91–96 (2014).
22. Bogard, J. R. et al. Higher fish but lower micronutrient intakes: temporal changes in fish consumption from capture fisheries and aquaculture in Bangladesh. *PLoS ONE* **12**, e0175098 (2017).
23. Golden, C. D., Fernald, L. C. H., Brashares, J. S., Rasolofoniaina, B. J. R. & Kremen, C. Benefits of wildlife consumption to child nutrition in a biodiversity hotspot. *Proc. Natl Acad. Sci. USA* **108**, 19653–19656 (2011).
24. Davis, K. F. et al. Meeting future food demand with current agricultural resources. *Global Environ. Change* **39**, 125–132 (2016).
25. Parker, R. W. R. & Tyedmers, P. H. Fuel consumption of global fishing fleets: current understanding and knowledge gaps. *Fish Fish.* **16**, 684–696 (2015).
26. Parker, R. W. R. et al. Fuel use and greenhouse gas emissions of world fisheries. *Nat. Clim. Change* **8**, 333–337 (2018).
27. Avadí, A. et al. Comparative environmental performance of artisanal and commercial feed use in Peruvian freshwater aquaculture. *Aquaculture* **435**, 52–66 (2015).
28. Fry, J. P., Mailloux, N. A., Love, D. C., Milli, M. C. & Cao, L. Feed conversion efficiency in aquaculture: do we measure it correctly? *Environ. Res. Lett.* **13**, 024017 (2018).
29. Prudêncio da Silva, V., van der Werf, H. M. G., Soares, S. R. & Corson, M. S. Environmental impacts of French and Brazilian broiler chicken production scenarios: an LCA approach. *J. Environ. Manage.* **133**, 222–231 (2014).
30. Seto, K. & Fiorella, K. J. From sea to plate: the role of fish in a sustainable diet. *Front. Mar. Sci.* **4**, 74 (2017).
31. Lynch, A. J. et al. Inland fish and fisheries integral to achieving the Sustainable Development Goals. *Nature Sustain.* **3**, 579–587 (2020).
32. Nardoto, G. B. et al. Frozen chicken for wild fish: nutritional transition in the Brazilian Amazon region determined by carbon and nitrogen stable isotope ratios in fingernails. *Am. J. Hum. Biol.* **23**, 642–650 (2011).
33. Khoury, C. K. et al. Increasing homogeneity in global food supplies and the implications for food security. *Proc. Natl Acad. Sci. USA* **111**, 4001–4006 (2014).
34. Kearney, J. Food consumption trends and drivers. *Philos. Trans. R. Soc. Lond B Biol. Sci.* **365**, 2793–2807 (2010).
35. Pinnegar, J. K., Hutton, T. P. & Placenti, V. What relative seafood prices can tell us about the status of stocks. *Fish Fish.* **7**, 219–226 (2006).
36. Wong, J. T. et al. Small-scale poultry and food security in resource-poor settings: a review. *Global Food Sec.* **15**, 43–52 (2017).
37. *Tabela Brasileira de Composição de Alimentos—TACO* (Núcleo de Estudos e Pesquisas em Alimentação—NEPA/UNICAMP, 2011).
38. Cahu, C., Salen, P. & de Lorgeril, M. Farmed and wild fish in the prevention of cardiovascular diseases: assessing possible differences in lipid nutritional values. *Nutr. Metab. Cardiovasc. Dis.* **14**, 34–41 (2004).
39. *Vitamin and Mineral Requirements in Human Nutrition* (WHO/FAO, 2004).
40. *Fats and Fatty Acids in Human Nutrition: Report of an Expert Consultation* (FAO, 2010).
41. Heilpern, S. A., Weeks, B. C. & Naeem, S. Predicting ecosystem vulnerability to biodiversity loss from community composition. *Ecology* **99**, 1099–1107 (2018).
42. R Core Team. *R: A Language and Environment for Statistical Computing* (R Foundation for Statistical Computing, 2020).

Acknowledgements

We thank M. Montoya for supporting field logistics and R. Arbildes-Tello, G. Alvarez and M. Cueva for help with collecting and processing samples. This work was supported through grants to S.A.H. by the NYC Community Trust and the Conservation, Food and Health Foundation. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the US Government.

Author contributions

S.A.H. initially conceptualized the research with substantial input from R.D.F. and S.N. All authors subsequently refined the research goals. S.A.H. led the data analysis and wrote the first draft with all authors subsequently providing input.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s43016-021-00242-8.

Correspondence and requests for materials should be addressed to S.A.H.

Peer review information *Nature Food* thanks K. Seto and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

Reprints and permissions information is available at www.nature.com/reprints.