Unlocking the potential of forage fish to reduce the global burden of disease

Shujuan Xia ,[1] Jun'ya Takakura,[1] Kazuaki Tsuchiya,[1] Chaeyeon Park,[1,2] Ryan F Heneghan,[3,4] Kiyoshi Takahashi[1]

[1]National Institute for Environmental Studies, Tsukuba, Japan
[2]National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, Japan
[3]Queensland University of Technology, Brisbane, Queensland, Australia
[4]Technology and Engineering, University of the Sunshine Coast, Sippy Downs, Queensland, Australia

Correspondence to
Dr Shujuan Xia;
xia.shujuan@nies.go.jp

ABSTRACT

Red meat consumption is associated with an elevated risk of mortality from non-communicable diseases (NCDs). In contrast, forage fish, as highly nutritious, environmentally friendly, affordable, and the most abundant fish species in the ocean, are receiving increasing interest from a global food system perspective. However, little research has examined the impact of replacing red meat with forage fish in the global diet on diet-related NCDs.

Methods We based our study on datasets of red meat projections in 2050 for 137 countries and forage fish catches. We replaced the red meat consumption in each country with forage fish (from marine habitats), without exceeding the potential supply of forage fish. We used a comparative risk assessment framework to investigate how such substitutions could reduce the global burden of diet-related NCDs in adults.

Results The results of our study show that forage fish may replace only a fraction (approximately 8%) of the world's red meat due to its limited supply, but it may increase global daily per capita fish consumption close to the recommended level. Such a substitution could avoid 0.5–0.75 million deaths and 8–15 million disability-adjusted life years, concentrated in low- and middle-income countries. Forage fish as an alternative to red meat could double (or more) the number of deaths that could be avoided by simply reducing red meat consumption.

Conclusions Our analysis suggests that forage fish is a promising alternative to red meat. Policies targeting the allocation of forage fish to regions where they are needed, such as the Global South, could be more effective in maximising the potential of forage fish to reduce the global burden of disease.

INTRODUCTION

Considerable evidence has shown that red meat, especially processed red meat, is associated with increased risks of non-communicable diseases (NCDs) in humans.[1–5] NCDs accounted for approximately 70% of all deaths globally in 2019.[6] Of these, four diseases — ischaemic heart disease (IHD), stroke, diabetes, and colorectal cancer — account for 44% of deaths, with IHD being the leading cause of global mortality.[6] To reduce the burden of diet-related NCDs without sacrificing environmental health, by

---

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ To improve human health and the health of the planet we should limit the consumption of red meat and move towards foods that are both healthy and environmentally friendly.

⇒ Compared with red meat, seafood not only provides a higher concentration of essential nutrients, but also prevents diet related non-communicable diseases (NCDs).

WHAT THIS STUDY ADDS

⇒ In the seafood category, forage fish as the most nutritious fish species with the lowest carbon footprint, could be a highly promising alternative to red meat.

⇒ Our study demonstrates that the adoption of forage fish as a red meat alternative would potentially offer substantial public health benefits (with the avoidance globally of 0.5–0.75 million deaths from diet related NCDs), particularly in terms of reducing ischaemic heart disease.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ This study could inform all decision-makers about the health consequences of policy options on forage fish consumption and trade.

⇒ This study points to the need for fish-based food policy guidelines and nutrition-sensitive policies to pay more attention to the composition of future fish intake and to promote forage fish consumption.

2050 we need to limit the consumption of greenhouse gas emission-intensive red meat and shift to foods that are both healthy and environment-friendly.[7]

Seafood not only provides higher concentrations of essential nutrients than terrestrial animal-source foods (ASFs)[8] but also prevents diet-related NCDs,[9 10] as it is rich in two main omega-3 long-chain polyunsaturated fatty acids: docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA), the intake of which may prevent IHD.[11] The incidence of cardiovascular disease could be reduced by moderate consumption of seafood in many global North countries.[12] Forage fish (ie, small pelagic fish of marine habitats, such

as anchovies, herrings, and sardines, but excluding lake and other inland species) and salmon are recognised as excellent sources of DHA and EPA and are rich in essential micronutrients such as calcium and vitamin B12.[10] However, the higher price of salmon compared with other seafood leads to less consumption in lower-income groups.[13] Forage fish, on the other hand, account for almost 30% of global marine capture fisheries,[14] and are rated highest in terms of nutrient richness among ASFs,[10] and are also the cheapest and most abundant fish in low- and middle-income countries (LMICs).[15 16] A dietary shift from red meat to forage fish may slightly reduce zinc intake (less than 2%) but can greatly increase the intake of other essential nutrients, especially DHA and EPA.[17] Additionally, forage fish have the lowest carbon footprint of any ASF that meets nutritional requirements.[8]

However, only approximately 26% of the caught forage fish are currently consumed by humans.[18] The remaining 74%, including a significant amount caught off the coasts of countries suffering from food insecurity and malnutrition in the Global South,[19] are ground into fishmeal and fish oil.[18] These products are mostly used for feeding farmed seafood, such as salmon and trout,[20] which is aimed at higher income consumers.[21] Using forage fish to raise cultured species is inefficient because fewer nutrients are retained; for example, less than 50% of DHA and EPA are retained in Scottish farmed salmon.[22] A recent study revealed that only a small fraction (< 20%) of current forage fish landings in sub-Saharan Africa would meet daily nutritional requirements for local children under 5 years of age.[15] These findings suggest that forage fish could be a promising alternative to red meat.

Although numerous studies have revealed the potential nutritional and environmental contributions of forage fish,[8 10 17] it is not clear to what extent they may reduce the global burden of disease if consumed directly by humans as a substitute for red meat. We aimed to contribute to filling this knowledge gap by quantifying the impact of replacing red meat with all forage fish currently used for non-food purposes on the global disease burden in 2050 under different meat substitution scenarios. This study did not explore the feasibility of red meat replacement with forage fish, but rather the extent to which forage fish consumption would provide national and global health benefits if used for direct human consumption in each meat substitution scenario.

METHODS

We used red meat and fish consumption under the middle-of-the-road shared socioeconomic pathway (SSP2) scenario (business as usual),[23] which features a continuation of current trends, as our reference scenario (REF scenario). The availability of forage fish as a substitute for red meat by 2050 was estimated using historical forage fish catch data. To explore the potential of forage fish as a red meat alternative to reduce the global burden of disease, we created four red meat substitution scenarios, each representing a different pattern of forage fish allocation globally. Each component and scenario is described in detail below.

Red meat and fish consumption before substitution

We obtained the country-level red meat and fish supply estimates for the year 2050 from the study 'Alternative pathways to 2050' published by the Food and Agriculture Organization of the United Nations (FAO).[24] This dataset provides projections of the supply of 50 food items until the year 2050 in five- or ten-year intervals under three scenarios ('Business as usual', BAU; 'Towards sustainability', TSS; and 'Stratified societies', SSS). We extracted the data on the daily energy supply (kcal/person/day) of red meat (consisting of three of the 50 food items: beef and veal, sheep and goat, and pig meat) and fish in 2050 under the BAU scenario, as red meat, and fish supply under our REF scenario. The data are available for 137 countries. For a more targeted replacement of red meat, we grouped red meat into two categories: ruminants (beef and veal, sheep and goat) and non-ruminants (pig meat) based on the magnitude of their environmental impact.

For the diet-related health impact analyses below, we first multiplied the daily energy supply of red meat and fish (including forage fish and other fish species) by the waste percentages at the consumption level and the conversion factors that represent the proportion of edible amount to obtain the daily energy consumption of red meat and fish respectively[25] (online supplemental table 1). The daily energy supply of red meat and fish was then converted into the amount of consumption (g/person/day) using the food quantity-food energy supply ratio provided by FAOSTAT[26] for each country, respectively.

Availability of forage fish as a red meat alternative in 2050

To estimate the availability of forage fish, we first used the catch of forage fish in the past decades as the potential supply of forage fish by 2050. We sourced historical catch data (live weight) (1980–2018) from the FAO capture database[27] for the top 40 forage fish species that represented approximately 85% of the global average forage fish catch during this period (online supplemental figure 1). The live weight was converted to edible weight by multiplying by a conversion factor[28] of 0.87. The edible weight was then converted into energy (kcal) for meat substitution using raw fish energy data from the United States Department of Agriculture (USDA) Food Data Central[29] for each forage fish species (online supplemental table 2). When energy data for a species were not available, we used data from species belonging to the same family. Finally, we subtracted the current direct human consumption use (26%)[18] from the edible energy supply obtained in the previous step. To explore the maximum potential benefits of forage fish as food, we assumed that no forage fish food waste occurred at the consumption stage. We also assumed that alternative feedstuffs are available for

Table 1 Four red meat substitution scenarios were used to evaluate the health benefits of forage fish as a red meat alternative

Substitution scenario	Identification	Description
I	Domestic supply prioritised	Forage fish were caught for national consumption or red meat substitution.
II	Minimised meat intake	Substitution was prioritised in countries with ruminant meat consumption above the recommended level of 15 kcal,[31] as ruminants have a greater environmental impact than non-ruminants,[73] allowing for a win-win situation for human and environmental health.
III	Adequate fish intake	Priority was given to countries with fish consumption below the recommended level of 40 kcal[31] for substitution.
IV	Equal percentage replaced	All countries had the same percentage of red meat that was replaced and the percentage of replacement was determined by the availability of forage fish.

feeding cultured fish species and that consumer demand for cultured fish remains constant.

Red meat substitution scenarios

We assumed that consumers will gradually move away from red meat and adopt forage fish as a substitute by 2050, thus allowing a transition time for this dietary change. Countries (Afghanistan, Ethiopia, and Tajikistan) with zero fish consumption in the REF scenario due to cultural or data availability reasons were excluded from the analyses. For other countries, four red meat substitution scenarios were constructed in which red meat was replaced with equivalent caloric forage fish to reduce red meat consumption while increasing fish consumption. The four scenarios were: (1) Help to achieve a more equitable distribution of forage fish consumption to meet local health needs[15] (table 1, scenario I); (2) Reduce health risks in countries with higher ruminant meat consumption (table 1, scenario II); (3) Increase fish consumption in countries where fish consumption does not reach recommended levels while reducing diet-related deaths (table 1, scenario III); and (4) Allow countries with higher red meat consumption to be substituted more and countries with lower red meat consumption to be substituted less to avoid nutritional deficiencies associated with insufficient red meat intake (table 1, scenario IV).

To explore the potential contribution of forage fish to global health, we assumed that the forage fish trade system enables these scenarios to be realised. In scenario I, forage fish do not enter international trade, whereas in scenarios II to IV, the trade system allows forage fish to be allocated to countries with higher red meat consumption and/or lower fish consumption. In the first two scenarios, to avoid the concentration of substitution in one or a limited number of countries, we reduced ruminant meat consumption and increased fish consumption to the same level as in the countries where substitution occurred, respectively. We assumed that post-substitution red meat consumption would not be less than 10% of the pre-substitution level in all scenarios, a constraint typically used in diet optimisation studies.[30] For countries (eg, Namibia and Rwanda) with calorie intakes below the recommended value of 2500 kcal[31] in the REF scenario,[24] we did not replace red meat but only increased their forage fish consumption in all substitution scenarios, with a final calorie intake of no more than 2500 kcal.

Comparative risk assessment framework

The health impacts associated with changes in red meat and fish consumption were investigated using a comparative risk assessment[32] with four types of NCDs (IHD, stroke, diabetes, and colorectal cancer) and two dietary risk factors (diet high in red meat and diet low in seafood omega-3 fatty acids (DHA+EPA)). We estimated the avoided deaths attributable to these two risk factors by first calculating population-attributable fractions (PAFs) which are defined as the proportional reduction in death that results from a change in risk exposure from a baseline scenario (ie, red meat and DHA+EPA consumption in the REF scenario) to an alternative scenario (ie, scenarios I–IV). The formula for calculating PAFs is as follows.[32 33]

$$PAF_{d,r,f} = \frac{RR_{d,f}^{C_{REF,r}/S_f} - RR_{d,f}^{C_{alternative,r}/S_f}}{RR_{d,f}^{C_{REF,r}/S_f}}, \qquad (1)$$

where $PAF_{d,r,f}$ is the population attributable fraction for disease d and country r from risk factor f; $RR_{d,f}$ is the relative risk for disease d from risk factor f; $C_{REF,r}$ and $C_{alternative,r}$ are the daily per capita consumption of red meat or DHA+EPA in country r under the REF and alternative scenarios, respectively; and S_f is the standard serving size for each risk factor f.

The relative risk parameters $RR_{d,f}$ in equation (1) were obtained from the dose-response meta-analyses of prospective studies and cohort studies[1–4 11] (online supplemental table 3). We calculated the increase in DHA+EPA intake by multiplying the forage fish calorie intake by the average DHA+EPA concentration, which was sourced from FishBase[34] (online supplemental table 2). The serving sizes S_f used in this analysis were 100 g[33] for red meat and 0.1 g[35] for DHA+EPA. For the dietary risk factors, we assumed an increasing risk from zero consumption of red meat and a decreasing risk from zero consumption of DHA+EPA, both of which were

unbounded. Given that one disease can be attributable to multiple risk factors, for each disease, the combined disease burden attributable to each risk factor was expressed as follows:[36]

$$PAF_{d,r} = 1 - \prod_f \left(1 - PAF_{d,r,f}\right). \tag{2}$$

Impact of dietary change on disease outcomes

We estimated the number of avoided deaths under each substitution scenario by multiplying $PAF_{d,r}$ in equation (2) by disease-, country-, and age-specific population size and baseline mortality rate for the year 2050 under the SSP2 scenario. As the two risk factors in this study are primarily responsible for diet-related NCDs in adults and diet-related NCDs are extremely low in children,[37] we focused on people aged 20 years or older. Population data by country and 5 year age groups were obtained from the SSP database.[38] Disease-specific mortality data for each age group were adopted from Sellers,[39] which provides cause of death projections for all countries from 2020 to 2100, incorporating the effects of socioeconomic, environmental, and developmental outcomes in the future world. However, in Sellers'[39] projections, IHD, stroke, and colorectal cancer are not treated as individual cause categories, but are aggregated with other related diseases into different groups. Therefore, we separated the mortality due to IHD, stroke, and colorectal cancer from those groups by applying the Institute for Health Metrics and Evaluation (IHME) projections of deaths in 2040 for each specific cause, as data for 2050 were not available.[40] The proportions of these three diseases in the respective disease groups to which they belonged were assumed to remain approximately the same in 2040 and 2050.

The disability-adjusted life years (DALYs) were calculated using the IHME estimated country-, age-, and disease-specific DALY-death ratios for the year 2019.[37 41] According to the IHME estimates, the DALY-death ratio for each age group in each country has remained almost constant over the last 30 years; therefore, we assumed that the DALY-death ratios in 2050 would be the same as in 2019.

Patient and public involvement statement

Patients and/or the public were not involved in the design, or conduct, or reporting or dissemination plans of this research.

RESULTS

The availability of forage fish that could be used as a meat alternative in 2050 was approximately 3.0×10^{13} kcal, while the total meat consumption of the 137 countries projected by FAO[24] was 3.8×10^{14} kcal; therefore, forage fish could replace approximately 8% of red meat globally. Substitution occurred only in coastal countries where forage fish were caught (88 countries) in scenario I, using only 78% of the potential supply of forage fish,

while in the other three scenarios, the entire supply was used for substitution. Countries with intensive meat consumption under the REF scenario, such as Mongolia and Brazil (online supplemental figure 2), were given priority for substitution in scenario II (figure 1A), while many African countries with low fish intake were given priority for substitution in scenario III. In scenario IV, approximately 8% of the red meat consumption in each country was replaced by forage fish.

In scenario I, for almost 63% of coastal countries, the forage fish caught could replace 0.1–83% (with an average of 19%) of their red meat consumption (online supplemental figure 3). In contrast, for Estonia, Latvia, Norway, Morocco, Namibia, Chile, and Peru, the calories available in the forage fish caught exceeded their red meat consumption; therefore, 90% of the red meat was replaced in these countries, except for Namibia, where no red meat was replaced, and all forage fish caught were used for domestic consumption to alleviate the deficit in calorie intake. Consequently, Namibia's per capita calorie intake increased from 2252 kcal to 2402 kcal. Compared with scenario I, targeted substitution in countries with a high consumption of ruminant meat could substantially reduce meat consumption in meat-intensive countries such as Mongolia and Argentina (figure 1A, scenario II). In scenario III, daily per capita fish consumption could be increased to close to the recommended level of 40 kcal[31] in most countries, with less than 30 kcal of red meat replaced (figure 1B). In scenario IV, countries with a higher per capita red meat intake had higher calories of red meat being replaced, mainly outside Africa. Total fish consumption after substitution was higher in China and some European countries (eg, Norway) due to higher fish consumption than in other countries before substitution (online supplemental figure 2).

Compared with the REF scenario, the replacement of part of the red meat with forage fish mainly reduced deaths from IHD, while for the other three diseases (stroke, diabetes, and colorectal cancer), a lower percentage (<5%) of deaths could be avoided (figure 2). Countries with higher levels of meat substitution also had a higher percentage of deaths (figures 1A and 2). Forage fish caught in coastal countries may reduce mortality from IHD if consumed domestically. For example, more than 30% of deaths can be avoided in some countries, such as Norway and Namibia (scenario I). In scenario II, a higher percentage of avoidable deaths from IHD was found in Mongolia (75%), Central Asian countries (40–70%), South American countries such as Argentina (65%), Brazil (34%), and Oceanian countries (35–42%). Furthermore, higher levels of red meat substitution in Argentina, Mongolia, and Turkmenistan contributed to a higher percentage of deaths from colorectal cancer (16–21%) and diabetes (12–15%) than in other countries. In scenarios III and IV, less than 20% of the avoided deaths occurred in countries where substitution occurred.
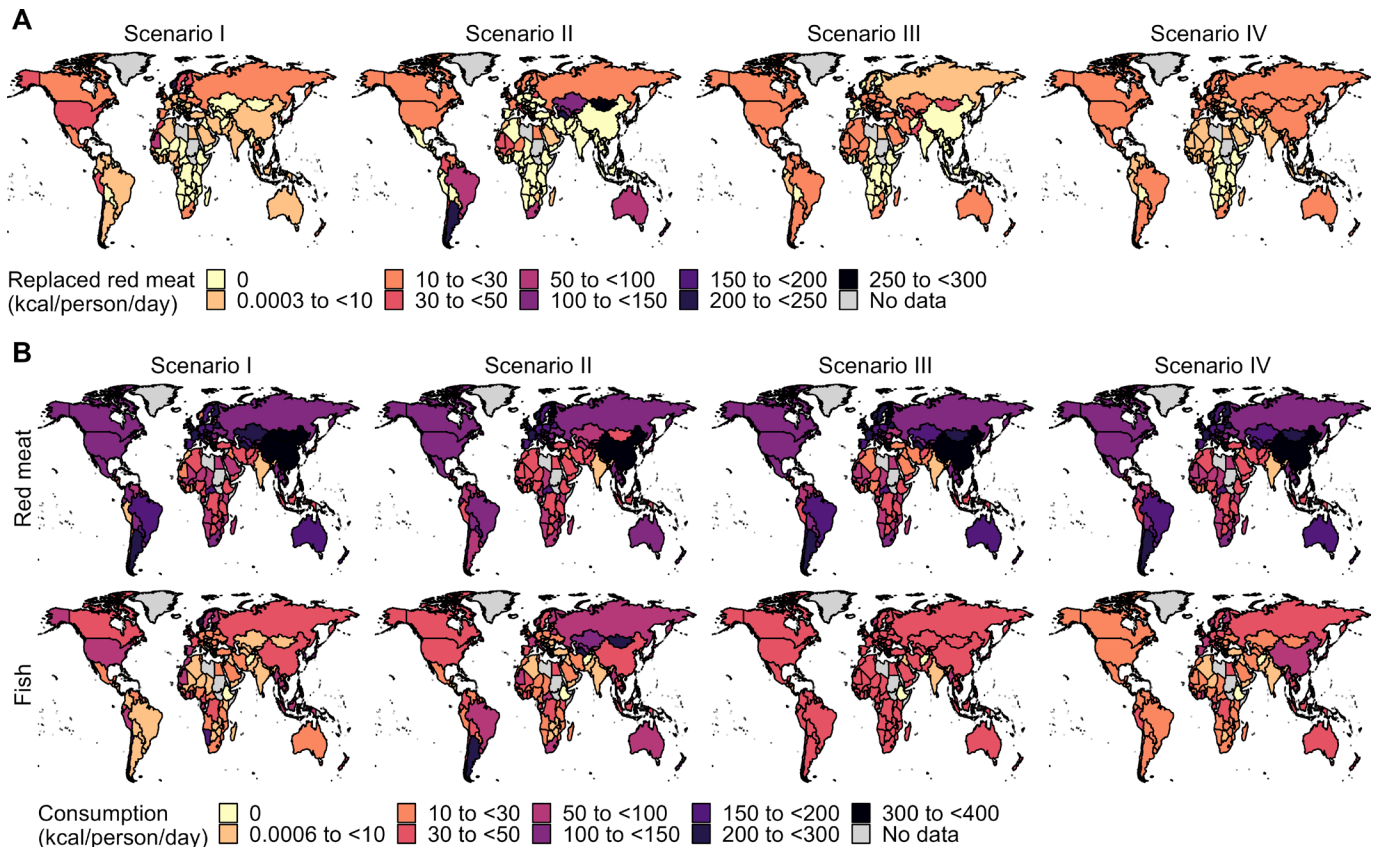
Figure 1 Changes in red meat and fish consumption in 2050: (A) Calories of red meat replaced by forage fish and (B) Consumption of red meat, and fish after substitution in each country under each meat substitution scenario (scenario I: Domestic supply prioritised; scenario II: Minimised meat intake; scenario III: Adequate fish intake; scenario IV: Equal percentage replaced).

The distribution of the rates of total avoidable deaths and DALYs of IHD, stroke, diabetes, and colorectal cancer was similar to that of the percentage of avoidable deaths (figure 3A and B). For some countries, such as Morocco and Mauritania, if the forage fish caught was for domestic consumption (scenario I), the avoided deaths per million of the population was >1.5 times higher than in other scenarios. In scenario II, Mongolia, Central Asia, and Argentina had higher rates of avoidable deaths and DALYs than the other countries. Russia, while having a lower percentage of avoided deaths than other regions, such as Oceania (figure 2), had a higher rate of avoidable deaths (figure 3A) due to its higher disease mortality in the REF scenario (online supplemental figure 4). In scenario III, higher avoidable mortality occurred in countries (eg, Ukraine and Belarus), which showed higher disease mortality in the REF scenario (figure 3A), while a higher rate of avoidable DALYs occurred in Pakistan and Turkmenistan due to the relatively high DALY-death ratios (figure 3B). When an equal percentage of red meat was replaced in each country (scenario IV), the rate of total avoidable deaths was <500 per million people in all countries.

In each scenario, approximately 90% of all avoided deaths or DALYs could be attributed to reduced IHD, 4% to stroke, 4% to diabetes, and 2% to colorectal cancer

(figure 4A). The total number of deaths averted by substitution scenarios ranged from 0.5 million (scenario I) to 0.75 million (scenario III), while DALYs ranged from 8 million to 15 million compared with the REF scenario, with large variability between regions. Overall, scenario I had the fewest avoided deaths, while scenario III had the most avoided deaths. On the regional scale, the highest number of avoided deaths and DALYs was found in Asia (avoided deaths, 0.45 million; reduced DALYs, 7 million) in scenario IV, with China making the largest contribution (figure 4B), while the lowest number of avoided deaths or DALYs was in Oceania in all scenarios. Russia (scenario I), Brazil (scenario II), and Pakistan (scenario III) contributed the most to the number of avoided deaths and DALYs (figure 4B), consistent with the total amount of red meat replaced (online supplemental figure 5). Although total red meat replacement in the US was higher than that in Russia in scenario I (online supplemental figure 5), the number of avoided deaths from fish intake was lower because forage fish caught in the US contained lower DHA+EPA than those caught in Russia. Importantly, using forage fish as an alternative to red meat could double (or more) the number of deaths that could be avoided by simply reducing red meat consumption (figure 4B).
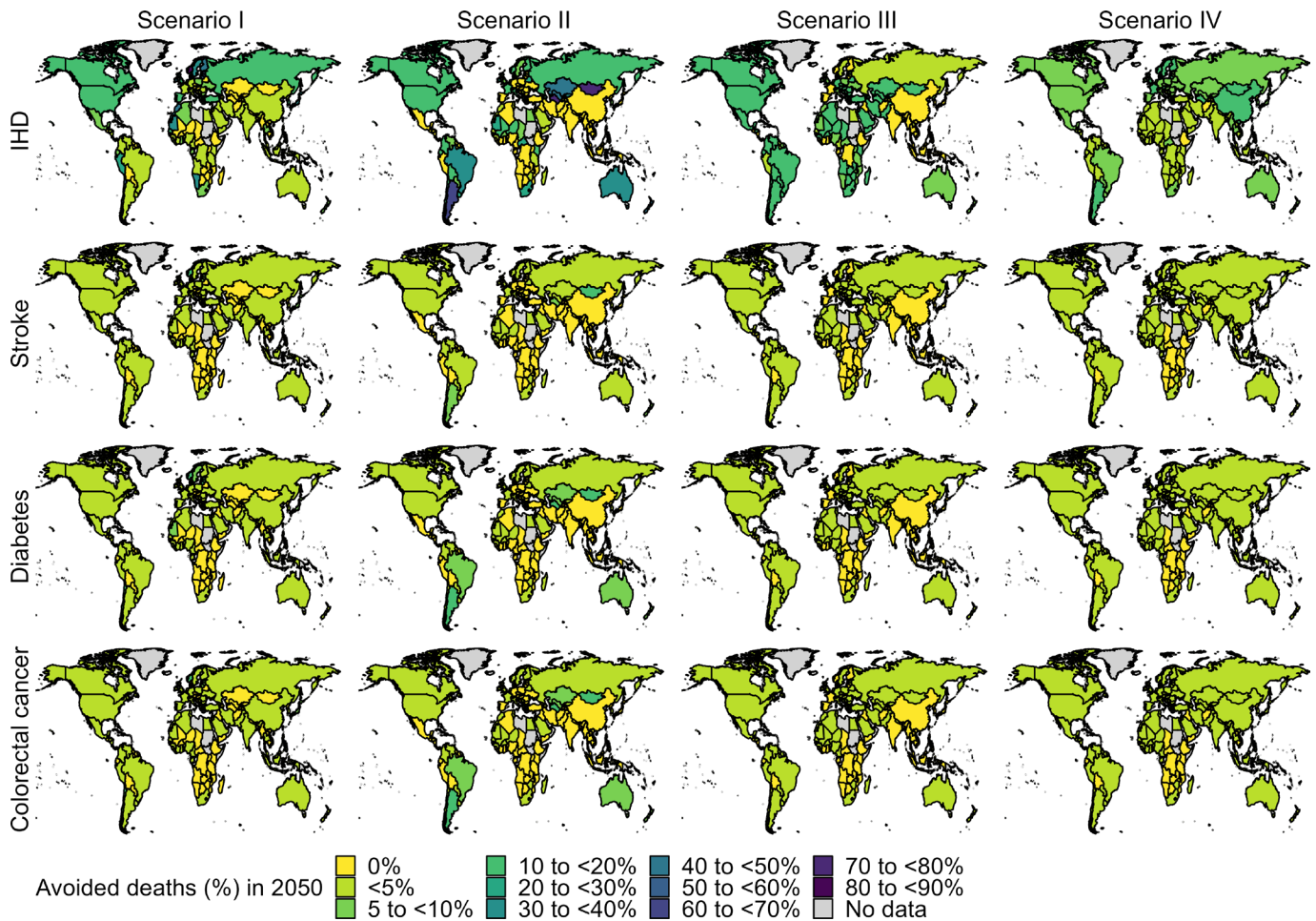
Figure 2 Percentage of avoided deaths by disease. Percentage of avoided deaths or disability-adjusted life years (DALYs) for ischaemic heart disease (IHD), stroke, diabetes, and colorectal cancer in each meat substitution scenario (scenario I: Domestic supply prioritised; scenario II: Minimised meat intake; scenario III: Adequate fish intake; scenario IV: Equal percentage replaced) compared with the reference (REF) scenario in 2050.

DISCUSSION

Our study demonstrates that forage fish, if widely adopted for direct human consumption, would potentially offer substantial public health benefits, particularly in terms of reducing the occurrence of IHD. Although forage fish are not sufficient to replace all red meat, forage fish alone may increase the daily per capita consumption of fish to close to the recommended level of 40 kcal[31] in most countries (figure 1B), as well as reduce total deaths from the four diseases by 2% by 2050. Of the four meat substitution scenarios, scenario I had the lowest number of avoided deaths, not only because the substitution occurred in different regions and to a different extent than the other three scenarios, but also because not all forage fish catches were consumed by these coastal countries. For example, in Chile, 46% of the forage fish caught was sufficient to replace 90% of the red meat in the diet, leaving 54% of the forage fish uncaught. Our results suggest that allocating all forage fish to regions where fish consumption is below the recommended value (mainly in LMICs) may reduce the global burden of disease more effectively.

The major burden (80%) of NCDs is concentrated in LMICs, particularly in Africa, which is currently experiencing an epidemic of NCDs on an alarming scale.[42] One response to this issue has been the call to move to a healthy diet, such as the Mediterranean diet, in which the preferred animal protein is fish.[43] However, lower incomes[44 45] and inefficient use of food resources,[46] among other reasons, contribute to the low per capita consumption of fish in LMICs (online supplemental figure 2). In this study, we showed that replacing red meat with affordable forage fish allows countries (mainly in LMICs) with the lowest fish consumption to have the greatest health (ie, scenario III) (figures 2 and 4), contributing substantially to reducing the burden of disease in LMICs. Therefore, to maximise the potential of forage fish, trade policies should be implemented to ensure that populations with higher NCD burdens and insufficient DHA+EPA intake have access to forage fish.[12] For coastal countries, an agenda for nutrition-sensitive governance of fisheries in the Global South based on prioritising domestic and local needs is proposed[46 47] to promote the consumption of forage fish, thus demonstrating the
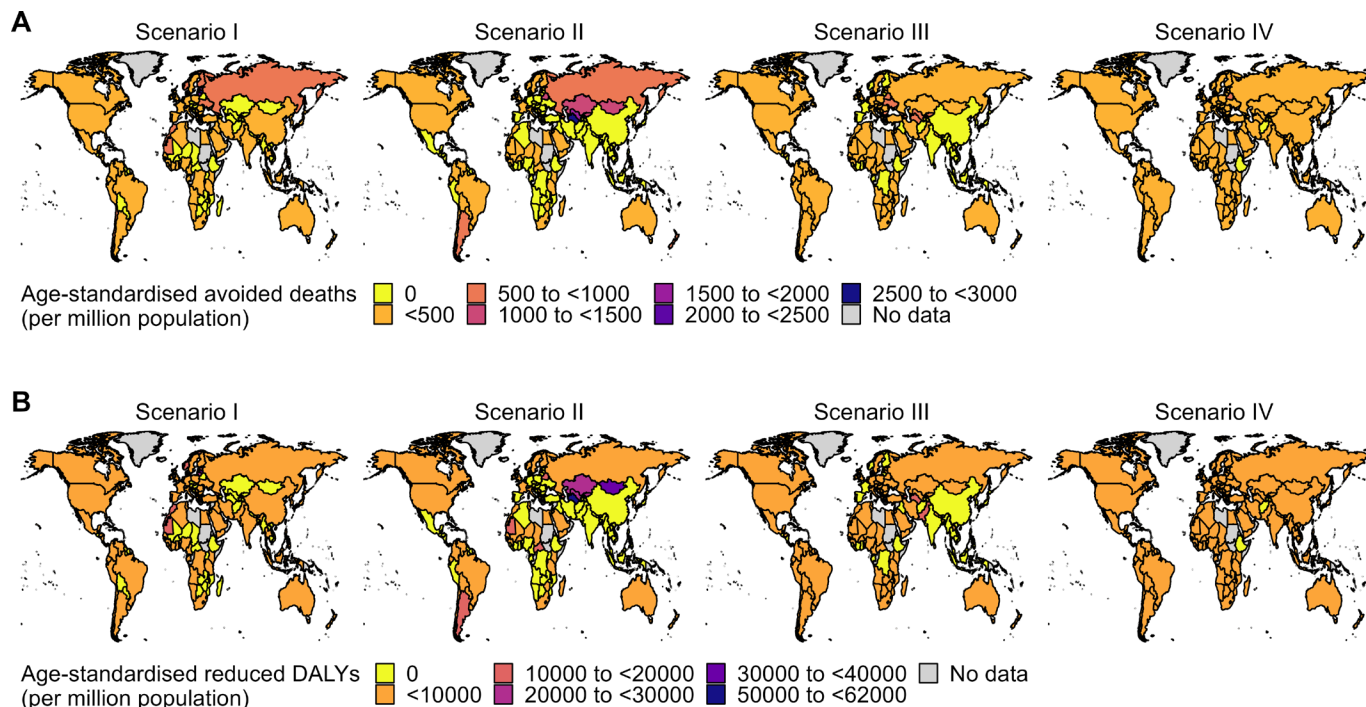
Figure 3 Avoided death and disability-adjusted life year (DALY) rate attributable to dietary substitution. (A) Avoided age-standardised deaths per million population and (B) DALYs per million population in 2050 compared with the reference (REF) scenario. Scenario I: Domestic supply prioritised; scenario II: Minimised meat intake; scenario III: Adequate fish intake; scenario IV: Equal percentage replaced.

contribution of forage fish to global health. For land-locked countries without direct access to seafood, such as Mongolia, Turkmenistan, and other African countries, global marketing and trade in forage fish need to be expanded.[14] In addition, freshwater forage fish, although not analysed in this study, is also of high nutritional value, and increasing children's and malnourished populations' access to it could contribute to improving global health.[48]

Our health assessment framework is in line with existing analyses, but for risk factors, we used DHA+EPA rather than fish. Many studies have used a nonlinear relationship (a restricted cubic spline model) between fish intake and IHD mortality[49] to calculate the relative risk of fish intake on IHD, with no further reduction in IHD mortality above 50 g/day of fish intake.[33] However, such an approach leaves the relationship between DHA+EPA intake and IHD unclear because of the diversity of fish species in terms of DHA+EPA concentrations[46] and, thereby, obscures the health contribution of fish with high DHA+EPA concentrations. By treating fish as a single food commodity without considering differences in DHA+EPA content between species, Springmann *et al.,*[50] estimated that increased fish intake would contribute less than 1% to premature mortality in 2030 with a pescatarian diet (two-thirds of meat is replaced by fish). Our study suggests that if fish that are high in DHA+EPA, such as forage fish, are consumed in larger proportions, then the contribution of fish might have been underestimated in previous studies.

Apart from the positive effects, there are also negative effects associated with fish consumption, as fish also contain harmful chemicals such as methylmercury (MeHg) and dioxin-like-polychlorinated biphenyls (dl-PCBs) that can cause health hazards (eg, chloracne and impaired neurological development).[51] The negative effects of forage fish consumption were not investigated in this study and are mainly attributed to two reasons. One reason is that there is a lack of studies exploring the possible relationship between MeHg exposure and the risk of the four diseases described here.[52] However, although MeHg concentrations in forage fish (2–110 µg/kg)[53 54] are higher than those in the same wet weight of red meat (0.6–5.6 µg/kg),[55] they are well below the recommended safe intake limit (500 µg/kg).[54] For example, based on a risk-benefit analysis, Thomsen *et al.,*[9] suggested that pregnant women should consume fewer large predatory fish with high mercury content, such as tuna and swordfish, but no less than 200–350 g of forage fish per week to gain greater health benefits. Another reason is that accurately estimating the concentration of dl-PCBs in forage fish is challenging because it is influenced by geographical origin; dl-PCB concentrations of the same species can vary several-fold based on geographical location.[51 56] Nevertheless, red meat, particularly ruminant meat, contains much higher levels of dl-PCBs than forage fish.[51 57] Therefore, in terms of the health hazards caused by dl-PCBs, replacing red meat with forage fish would at least offset the other's negative effects. Recent studies on the health effects of replacing red meat with forage fish in the Danish diet have shown that the negative effects of forage fish are almost negligible compared with the positive effects of such a substitution.[9] Fish-based food policy
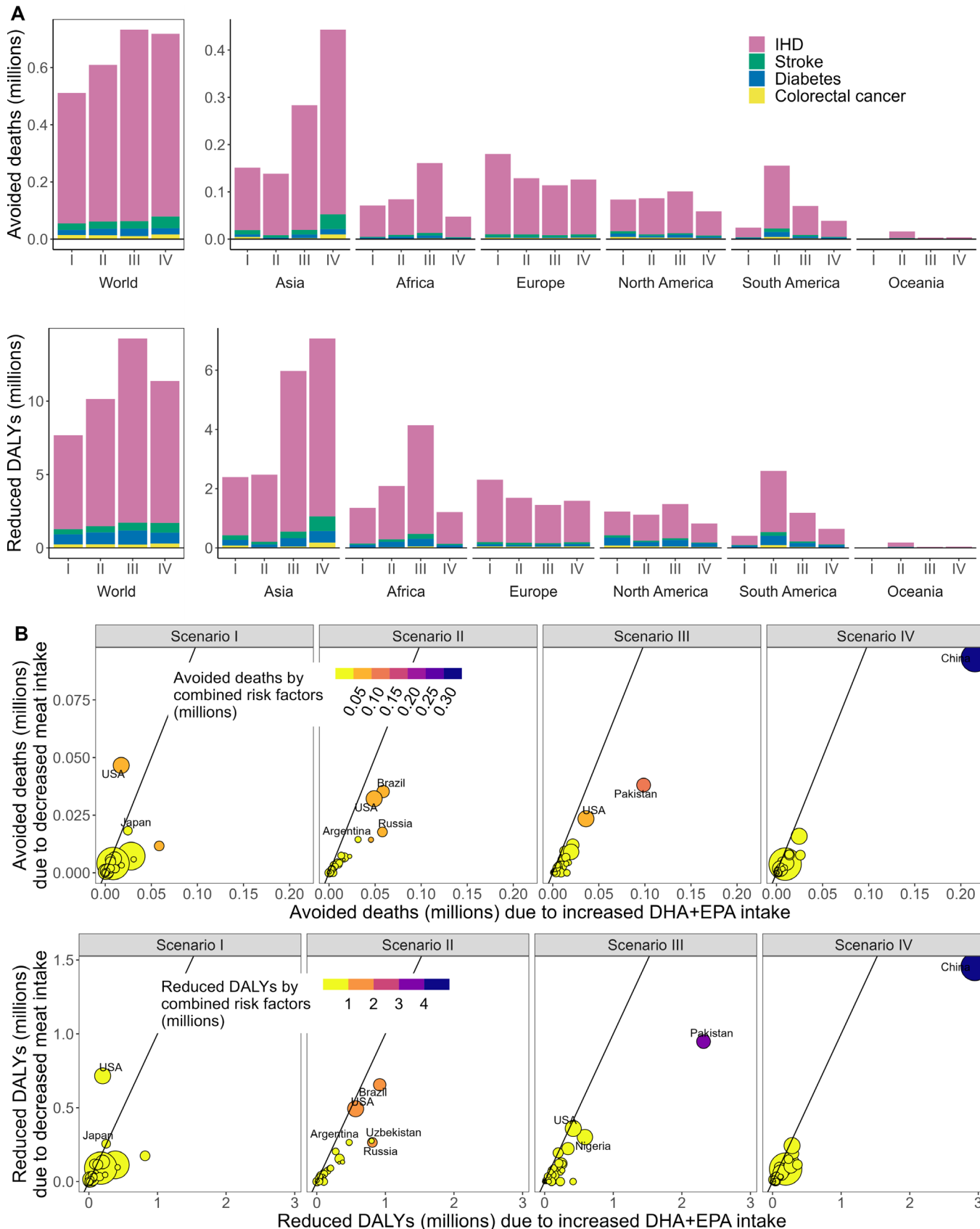
Figure 4 Changes in the number of deaths and disability-adjusted life years (DALYs) relative to the reference (REF) scenario: number of total avoided deaths and DALYs from ischaemic heart diseases (IHD), stroke, diabetes, and colorectal cancer (A) by region due to combined risk factors, and (B) by country due to individual risk factor. The bubble size in B is scaled to population in 2050 under the 'middle of the road' shared socioeconomic pathway (SSP2) scenario.[23] The solid lines in B indicate that Y=X. Abbreviations: DHA+EPA, Docosahexaenoic acid plus Eicosapentaenoic acid.

guidelines should focus on the composition of future fish intake and provide safe intake ranges for different fish species, especially for pregnant women and children. This study could inform decision makers regarding the health consequences of policy options on forage fish consumption and trade.

Despite the theoretical potential of forage fish, several barriers such as fish meal and oil processing, overfishing, climate change, and cultural acceptance may prevent the health benefits of forage fish from being realised. The conversion of forage fish to human food may reduce aquaculture production. However, recent research[18] suggests that other feedstuffs such as microalgae, soy, and insects have the potential to completely replace fishmeal and fish oil in feeding cultured species. Microalgae is one of the most promising alternative feeds, and not only does it not significantly reduce the nutrient content of the species being fed (eg, DHA and EPA concentrations), but also it does not change the flavour or colour, all of which may influence consumer demand.[18 58] Therefore, expanding the production of microalgae and other feedstuffs to replace fish oil and fishmeal from forage fish may compensate for the decline in aquaculture production due the reduced availability of forage fish, and may increase the contribution of forage fish to human health.

Forage fish dominate marine fish biomass in upwelling systems. For example, the Northwest African coast (Canary Current Upwelling System) is one of the four largest eastern boundary upwelling systems in the world, where nutrient-rich water sustains large fish populations.[59] In countries along this coastline, such as Senegal, forage fish accounts for over 70% of landings and 80% of fish consumption, playing a critical role in the health and well-being of the population.[60] However, overfishing caused by ineffective fisheries management policies,[61] rising temperatures,[62] increased export levels, and growing demand for fishmeal and oil have led to declining catches and threatened local food security.[60] The increase in temperature may also lead to a decrease in the quality of food for forage fish, which may contain more zooplankton with low carbon contents,[63] and therefore, may reduce the health contribution of forage fish in this study.

This study did not consider the impact of climate change on the future potential supply of forage fish, but a previous study predicted that forage fish yield in 2050 would change by less than 3% compared with that in 2020 under a severe emission scenario (representative concentration pathway 8.5),[64] implying that the supply of forage fish in 2050 would not be significantly lower than that depicted by this study's results. To support the sustainable production of forage fish, mitigation strategies could be adopted to reduce fishing pressure,[65] and to reallocate fisheries to areas where environmental conditions are more favourable for forage fish under climate change.[66] Multi-sectoral policy coordination and action[21] (eg, prioritising access to affordable fish such as forage fish for the poor and promoting the use of nutrient-rich microalgae[18] as fish feed) could help to address some of these barriers.

In addition to environmental influences, cultural acceptance and taste can prevent forage fish from realising its potential. The cultural context strongly influences the choice of food. Dietary recommendations and nutritional advice may conflict with the cultural beliefs of many populations. However, culturally tailored interventions that promote healthy lifestyles, increase family and community support, and increase patient awareness of the relationship between disease and diet can increase the success of behaviour and diet changes and, thus, disease prevention.[67 68] Other effective strategies, such as climate change impact menu labels on food items with high-climate impact (eg, red meat)[69] and consumer education on high nutritional value and fewer chemicals in forage fish,[70 71] have the potential to facilitate a change in consumer diets from red meat to forage fish. Additionally, approaches that include the development of new food products such as 'pulled herring'[71] and the establishment of 'Anchoveta Weeks' that provide dishes and sauces with anchoveta[72] have increased the consumption of forage fish in Finland and Peru.

terminology, drug names and drug dosages), and is not responsible for any error and/or omissions arising from translation and adaptation or otherwise.

ORCID iD
Shujuan Xia http://orcid.org/0000-0003-0525-4176

REFERENCES

1 Micha R, Wallace SK, Mozaffarian D. Red and processed meat consumption and risk of incident coronary heart disease, stroke, and diabetes mellitus: a systematic review and meta-analysis. *Circulation* 2010;121:2271–83.
2 Chan DSM, Lau R, Aune D, et al. Red and processed meat and colorectal cancer incidence: meta-analysis of prospective studies. *PLoS One* 2011;6:e20456.
3 Chen G-C, Lv D-B, Pang Z, et al. Red and processed meat consumption and risk of stroke: a meta-analysis of prospective cohort studies. *Eur J Clin Nutr* 2013;67:91–5.
4 Feskens EJM, Sluik D, van Woudenbergh GJ. Meat consumption, diabetes, and its complications. *Curr Diab Rep* 2013;13:298–306.
5 Bellavia A, Stilling F, Wolk A. High red meat intake and all-cause cardiovascular and cancer mortality: is the risk modified by fruit and vegetable intake? *Am J Clin Nutr* 2016;104:1137–43.
6 Murray CJL, Aravkin AY, Zheng P. Global burden of 87 risk factors in 204 countries and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019. *Lancet* 2020;396:1223–49.
7 Springmann M, Clark M, Mason-D'Croz D, et al. Options for keeping the food system within environmental limits. *Nature* 2018;562:519–25.
8 Koehn JZ, Allison EH, Golden CD, et al. The role of seafood in sustainable diets. *Environ Res Lett* 2022;17:035003.
9 Thomsen ST, Pires SM, Devleesschauwer B, et al. Investigating the risk-benefit balance of substituting red and processed meat with fish in a Danish diet. *Food Chem Toxicol* 2018;120:50–63.
10 Golden CD, Koehn JZ, Shepon A, et al. Aquatic foods to nourish nations. *Nature* 2021;598:315–20.
11 Khan SU, Lone AN, Khan MS, et al. Effect of omega-3 fatty acids on cardiovascular outcomes: a systematic review and meta-analysis. *EClinicalMedicine* 2021;38:100997.
12 Crona BI, Wassénius E, Jonell M, et al. Four ways blue food can help achieve food system ambitions across nations. *Nature* 2023;616:104–12.
13 Love DC, Thorne-Lyman AL, Conrad Z, et al. Affordability influences nutritional quality of seafood consumption among income and race/ethnicity groups in the United States. *Am J Clin Nutr* 2022;116:415–25.
14 FAO. *The State of World Fisheries and Aquaculture 2020: Sustainability in Action*. Rome: Food and Agriculture Organization of the United Nations, 2020.
15 Robinson JPW, Mills DJ, Asiedu GA, et al. Small pelagic fish supply abundant and affordable micronutrients to low- and middle-income countries. *Nat Food* 2022;3:1075–84.
16 Bank TW. World bank country and lending groups. World Bank Data Help Desk; 2021.
17 Xia S, Takakura J, Wu W, et al. Potential environmental and nutritional benefits of replacing ruminant meat with forage fish. *Sustain Prod Consum* 2023;40:265–76.
18 Cottrell RS, Blanchard JL, Halpern BS, et al. Global adoption of novel aquaculture feeds could substantially reduce forage fish demand by 2030. *Nat Food* 2020;1:301–8.
19 Konar M, Qiu S, Tougher B, et al. Illustrating the hidden economic, social and ecological values of global forage fish resources. *Resour Conserv Recycl* 2019;151:104456.
20 Froehlich HE, Jacobsen NS, Essington TE, et al. Avoiding the ecological limits of forage fish for fed aquaculture. *Nat Sustain* 2018;1:298–303.
21 Thilsted SH, Thorne-Lyman A, Webb P, et al. Sustaining healthy diets: the role of capture fisheries and aquaculture for improving nutrition in the post-2015 era. *Food Policy* 2016;61:126–31.
22 Willer DF, Robinson JPW, Patterson GT, et al. Maximising sustainable nutrient production from coupled fisheries-aquaculture systems. *PLOS Sustain Transform* 2022;1:e0000005.

23 O'Neill BC, Kriegler E, Ebi KL, et al. The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century. *Glob Environ Change* 2017;42:169–80.
24 FAO. The future of food and agriculture – Alternative pathways to 2050. Rome, Available: https://www.fao.org/global-perspectives-studies/food-agriculture-projections-to-2050/en/
25 FAO. Global food losses and food waste – Extent, causes and prevention. Rome.
26 FAO, FAOSTAT. Food balances (2010-). CC BY-NC-SA 3.0 IGO; 2019.
27 FAO Yearbook. Fishery and aquaculture statistics 2019; 2021. Available: https://www.fao.org/fishery/en/statistics/software/fishstatj
28 Naylor RL, Kishore A, Sumaila UR, et al. Blue food demand across geographic and temporal scales. *Nat Commun* 2021;12:5413.
29 U.S. Department of Agriculture, Agricultural Research Service. FoodData central; 2019. Available: fdc.nal.usda.gov
30 Chaudhary A, Krishna V. Country-specific sustainable diets using optimization algorithm. *Environ Sci Technol* 2019;53:7694–703.
31 Willett W, Rockström J, Loken B, et al. Food in the anthropocene: the eat–lancet commission on healthy diets from sustainable food systems. *Lancet* 2019;393:447–92.
32 Murray CJ, Ezzati M, Lopez AD, et al. Comparative quantification of health risks: conceptual framework and methodological issues. *Popul Health Metr* 2003;1:1–20.
33 Springmann M, Mason-D'Croz D, Robinson S, et al. Global and regional health effects of future food production under climate change: a modelling study. *Lancet* 2016;387:1937–46.
34 Froese R, Pauly D, eds. FishBase. World Wide Web electronic publication; 2022. Available: www.fishbase.org
35 Pertiwi K, Küpers LK, de Goede J, et al. Dietary and circulating long-chain omega-3 polyunsaturated fatty acids and mortality risk after myocardial infarction: a long-term follow-up of the alpha omega cohort. *J Am Heart Assoc* 2021;10:e022617.
36 Lim SS, Vos T, Flaxman AD, et al. A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: a systematic analysis for the Global Burden of Disease Study 2010. *Lancet* 2012;380:2224–60.
37 Institute for Health Metrics and Evaluation (IHME). GBD results. Seattle, WA IHME, University of Washington; 2020. Available: https://vizhub.healthdata.org/gbd-results
38 Kc S, Lutz W. The human core of the shared socioeconomic pathways: population scenarios by age, sex and level of education for all countries to 2100. *Glob Environ Change* 2017;42:181–92.
39 Sellers S. Data from: cause of death variation under the shared socioeconomic pathways. *Clim Change* 2020;163:559–77.
40 Foreman KJ, Marquez N, Dolgert A, et al. Forecasting life expectancy, years of life lost, and all-cause and cause-specific mortality for 250 causes of death: reference and alternative scenarios for 2016–40 for 195 countries and territories. *Lancet* 2018;392:2052–90.
41 Springmann M, Mason-D'Croz D, Robinson S, et al. Mitigation potential and global health impacts from emissions pricing of food commodities. *Nature Clim Change* 2017;7:69–74.
42 Ndubuisi NE. Noncommunicable diseases prevention in low- and middle-income countries: an overview of health in all policies (HiAP). *Inquiry* 2021;58:46958020927885.
43 Davis C, Bryan J, Hodgson J, et al. Definition of the mediterranean diet; a literature review. *Nutrients* 2015;7:9139–53.
44 Headey DD, Alderman HH. The relative caloric prices of healthy and unhealthy foods differ systematically across income levels and continents. *J Nutr* 2019;149:2020–33.
45 Onumah EE, Quaye EA, Ahwireng AK, et al. Fish consumption behaviour and perception of food security of low-income households in urban areas of Ghana. *Sustainability* 2020;12:7932.
46 Hicks CC, Cohen PJ, Graham NAJ, et al. Harnessing global fisheries to tackle micronutrient deficiencies. *Nature* 2019;574:95–8.
47 Allegretti A, Hicks CC. 'Getting the right nutrients to those who need them most': towards nutrition-sensitive governance of fisheries in the Global South. *Rev Fish Biol Fisheries* 2023;33:561–71.
48 O'Meara L, Cohen PJ, Simmance F, et al. Inland fisheries critical for the diet quality of young children in sub-Saharan Africa. *Glob Food Sec* 2021;28:100483.
49 Zheng J, Huang T, Yu Y, et al. Fish consumption and CHD mortality: an updated meta-analysis of seventeen cohort studies. *Public Health Nutr* 2012;15:725–37.
50 Springmann M, Wiebe K, Mason-D'Croz D, et al. Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: a global modelling analysis with country-level detail. *Lancet Planet Health* 2018;2:e451–61.

51 Nøstbakken OJ, Rasinger JD, Hannisdal R, *et al*. Levels ofomega 3 fatty acids, vitamin D, dioxins and dioxin-like PCBs in oily fish; a new perspective on the reporting ofnutrient and contaminant data for risk-benefit assessments of oily seafood. *Environ Int* 2021;147:106322.

52 Downer MK, Martínez-González MA, Gea A, *et al*. Mercury exposure and risk of cardiovascular disease: a nested case-control study in the PREDIMED (PREvention with MEDiterranean Diet) study. *BMC Cardiovasc Disord* 2017;17:9.

53 Hsi H-C, Hsu Y-W, Chang T-C, *et al*. Methylmercury concentration in fish and risk-benefit assessment of fish intake among pregnant versus infertile women in Taiwan. *PLoS One* 2016;11:e0155704.

54 Capodiferro M, Marco E, Grimalt JO. Wild fish and seafood species in the western Mediterranean Sea with low safe mercury concentrations. *Environ Pollut* 2022;314:120274.

55 Nawrocka A, Durkalec M, Szkoda J, *et al*. Total mercury levels in the muscle and liver of livestock and game animals in Poland, 2009–2018. *Chemosphere* 2020;258.

56 Fechner C, Frantzen S, Lindtner O, *et al*. Human dietary exposure to dioxins and dioxin-like PCBs through the consumption of Atlantic herring from fishing areas in the Norwegian Sea and Baltic Sea. *J Consum Prot Food Saf* 2023;18:19–25.

57 Hoogenboom R, Dam GT, van Leeuwen SPJ, *et al*. High levels of dioxins and PCBs in meat, fat and livers of free ranging pigs, goats, sheep and cows from the island of Curaçao. *Chemosphere* 2021;263.

58 Nagappan S, Das P, AbdulQuadir M, *et al*. Potential of microalgae as a sustainable feed ingredient for aquaculture. *J Biotechnol* 2021;341:1–20.

59 Cury P, Bakun A, Crawford RJ. Small pelagics in upwelling systems: patterns of interaction and structural changes in "wasp-waist" ecosystems. *ICES J Mar Sci* 2000;57:603–18.

60 Deme M, Failler P. Small pelagic fish in Senegal: a multi-usage resource. *Marine Policy* 2022;141:105083.

61 Belhabib D, Sumaila UR, Le Billon P. The fisheries of Africa: exploitation, policy, and maritime security trends. *Mar Policy* 2019;101:80–92.

62 Lam VWY, Cheung WWL, Swartz W, *et al*. Climate change impacts on fisheries in West Africa: implications for economic, food and nutritional security. *Afr J Mar Sci* 2012;34:103–17.

63 Heneghan RF, Everett JD, Blanchard JL, *et al*. Climate-driven zooplankton shifts could cause global declines in food quality for fish. *Nat Clim Chang* 2023;13:470–7.

64 Petrik CM, Stock CA, Andersen KH, *et al*. Large pelagic fish are most sensitive to climate change despite pelagification of ocean food webs. *Front Mar Sci* 2020;7.

65 Siple MC, Essington TE, Plagányi É. Forage fish fisheries management requires a tailored approach to balance trade-offs. *Fish Fish* 2019;20:110–24.

66 Ramírez F, Shannon LJ, van der Lingen CD, *et al*. Climate and fishing simultaneously impact small pelagic fish in the oceans around the southernmost tip of Africa. *Front Mar Sci* 2022;9:1031784.

67 Winham DM. Culturally tailored foods and CVD prevention. *Am J Lifestyle Med* 2009;3:64S–68S.

68 Joo JY, Liu MF. Culturally tailored interventions for ethnic minorities: a scoping review. *Nurs Open* 2021;8:2078–90.

69 Wolfson JA, Musicus AA, Leung CW, *et al*. Effect of climate change impact menu labels on fast food ordering choices among US adults: a randomized clinical trial. *JAMA Netw Open* 2022;5:e2248320.

70 Fréon P, Sueiro JC, Iriarte F, *et al*. Harvesting for food versus feed: a review of Peruvian fisheries in a global context. *Rev Fish Bio Fish* 2014;24:381–98.

71 Pihlajamäki M, AsikainenA, IgnatiusS, *et al*. Forage fish as food: consumer perceptions on Baltic herring. *Sustainability* 2019;11:4298.

72 Majluf P, De la Puente S, Christensen V. The little fish that can feed the world. *Fish Fish* 2017;18:772–7.

73 Tilman D, Clark M. Global diets link environmental sustainability and human health. *Nature* 2014;515:518–22.