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Reducing climate change impacts from the global food system through diet shifts

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How much and what we eat and where it is produced can create huge differences in GHG emissions. On the basis of detailed household-expenditure data, we evaluate the unequal distribution of dietary emissions from 140 food products in 139 countries or areas and further model changes in emissions of global diet shifts. Within countries, consumer groups with higher expenditures generally cause more dietary emissions due to higher red meat and dairy intake. Such inequality is more pronounced in low-income countries. The present global annual dietary emissions would fall by 17% with the worldwide adoption of the EAT-Lancet planetary health diet, primarily attributed to shifts from red meat to legumes and nuts as principal protein sources. More than half (56.9%) of the global population, which is presently overconsuming, would save 32.4% of global emissions through diet shifts, offsetting the 15.4% increase in global emissions from presently underconsuming populations moving towards healthier diets.

Food choices impact both our health and the environment[1,2]. The food system is responsible for about one-third of global anthropogenic GHG emissions[3,4] and climate goals become unattainable without efforts to reduce food-related emissions[5,6]. However, not everyone contributes the same way to food-related emissions because of disparities in lifestyle, food preferences and affordability within and across countries[7–9]. High levels of food consumption (especially animal-based diets), one of the leading causes of obesity and non-communicable diseases[10,11], lead to substantial emissions[9,12]. Simultaneously, >800 million people still suffer from hunger and almost 3.1 billion people cannot afford a healthy diet[13]. Ending hunger and malnutrition while feeding the growing population by extending food production will further exacerbate climate change[14,15]. Given the notable increase in emissions driven by food consumption despite efficiency gains[16], changing consumer lifestyles and choices are needed to mitigate climate change[17].

Research shows that widespread shifts towards healthier diets, aligned with the sustainable development goals (SDGs) of the United Nations[18], offer solutions to this complex problem by eradicating hunger (SDG 2), ensuring health (SDG 3) and mitigating emissions (SDG 13)[19–22]. Numerous dietary options have been proposed as guidelines for diet shifts[1,23,24]. The planetary health diet[12], proposed by the EAT-Lancet Commission, stands out as a prominent option. It aims to improve health while limiting the impacts of the food system within planetary boundaries by providing reference intake levels for different food categories[9,25]. It is flexibly compatible with diversities and preferences of regional and local diets[12]. Previous research has estimated changes in country-specific environmental impacts, including GHG emissions[26–28] and water consumption[25], resulting from adopting the planetary health diet. However, there is limited evidence on how different population groups will contribute differently in this process[7].

Food consumption and associated emissions differ as a result of disparities in consumer choices guided by social and cultural preferences, wealth and income[29]. Quantifying food-related emissions along the entire supply chain for different products and population

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groups provides information for emission mitigation through changing consumer choices[17]. With the improved availability of household consumption data, recent studies have revealed inequality in energy consumption[30,31] and carbon emissions[17,32–34]. Although there are several studies on income- or expenditure-specific food-related emissions within individual countries based on survey-based data[35–38], previous studies have not assessed global food-related emissions with a detailed breakdown into specific products and population groups. Furthermore, reducing the overconsumption of wealthy or otherwise overconsuming groups can increase the availability of resources for reducing hunger and malnutrition[7]. However, it remains unclear how emissions from different population groups would change in response to global diet shifts.

To fill these gaps, this study evaluates GHG emissions (CO_2, CH_4 and N_2O) throughout the global food supply chains (including agricultural land use and land-use change, agricultural production and beyond-farm processes)[16] induced by diets, termed 'dietary emissions', in 2019 and the potential emission changes of global diet shifts. Food loss and waste during household consumption[25,39,40] have been subtracted from the national food supply to obtain dietary intake. We quantify dietary emissions of 140 products[16] (classified into 13 food categories[12]) on the basis of the global consumption-based emissions inventory of detailed food products[16]. By linking detailed food intake amounts to the food consumption patterns of 201 global expenditure groups (grouped according to the per capita total expenditure of each group) from the household-expenditure dataset[41] based on the World Bank Global Consumption Database (WBGCD)[42], we analyse the unequal distribution of dietary emissions in 139 countries or areas, covering 95% of the global population. Despite limitations, the total expenditure of consumers, which effectively reflects patterns in household income, consumption and asset accumulation, is a useful approximation to represent levels of income and wealth[31,43]. Additionally, we build a scenario of shifting from diets in 2019 to the global planetary health diet to estimate emission changes (Methods). This study investigates differences in dietary emissions among regions, countries and population groups, identifying areas where efforts are needed to mitigate emissions during the global transition towards a healthier and more planet-friendly diet.

Present dietary emissions across countries

In this study, dietary emissions account for emissions along the entire global food production supply chains, which are allocated to final consumers of diets. We use the term 'GHG footprints' to specifically refer to the dietary emissions of an individual over 1 year[17,34]. The total dietary emissions and country-average per capita GHG footprints show different distributions across countries in 2019 (Fig. 1a; for detailed food categories see Supplementary Figs. 1–9). The present total global dietary emissions reach 11.4 $GtCO_2e$ (95% confidence interval 8.2–14.7 Gt) (details of uncertainty ranges in Supplementary Tables 1 and 2). China (contributing 13.5% of emissions) and India (8.9%), the world's most populous countries (Supplementary Table 3), are the largest contributors to global dietary emissions. Alongside Indonesia, Brazil, the United States, the Democratic Republic of Congo, Pakistan, Russia, Japan and Mexico, the top ten contributors represent 57.3% of global dietary emissions but with very unequal per capita emissions within and between countries. We find the highest country-average per capita footprints in Bolivia, with 6.1 tCO_2e, followed by Luxembourg, Slovakia, Mongolia, the Netherlands and Namibia, with >5.0 tCO_2e (Supplementary Discussion 2.1). Haiti (0.36 tCO_2e) and Yemen (0.38 tCO_2e) have the lowest country-average footprints, followed by Burundi, Ghana and Togo. Insufficient food intake of residents due to limited food affordability[44,45] is the root cause of low footprints in these low- and lower-middle-income countries[46].

While animal-based (52%) and plant-based (48%) products contribute nearly equally to global dietary emissions[4,16], the latter accounts for 87% of calories in global diets (Supplementary Table 4). The three main sources of emissions, namely red meat (beef, lamb and pork) (5% of calories), grains (51%) and dairy products (5%), contribute to 29%, 21% and 19% of global emissions, respectively. The substantial emissions from red meat and dairy products are attributed to their considerably higher emissions per unit of calories compared to other categories (Supplementary Table 4).

To highlight emission differences at a regional level, we further group the country-level results into 18 regions according to geographical locations and development levels (Fig. 1b and Supplementary Fig. 10). In most regions, animal-based products contribute fewer calories (less than a quarter) (Supplementary Data 21) but yield more emissions than plant-based products, especially in Australia (84% from animal-based products), the United States (71%) and the region Rest of East Asia (71%) where residents excessively consume both red meat and dairy products. However, the consumption of plant-based products in Indonesia (83% of total calories), Rest of Southeast Asia (92%) and Sub-Saharan Africa (77%) accounts for the most emissions, at 92%, 73% and 64%, respectively. Southeast Asia including Indonesia has a high-emission proportion from grains (42%) due to the prevalent meals dominated by rice. The typical food basket in Sub-Saharan Africa is broadly made up of grains, tubers, legumes and nuts[25,47], representing over half of the regional emissions.

Unequal distribution of dietary emissions within countries

We find substantial differences in per capita GHG footprints within countries and regions. To clearly present the distribution of footprints within each country and region, individuals are sorted in ascending order of their total expenditure levels and then sequentially allocated to ten expenditure deciles with equal population size (Supplementary Fig. 11 and Fig. 2a). As expenditures increase, individuals tend to have higher levels of footprints, with the largest increase attributed to red meat and dairy products. Richer populations usually have higher per capita footprints related to animal-based products than the poorer in most regions (Fig. 2b). However, there are differences in per capita footprints within expenditure deciles. For example, even in high-income countries such as Australia and Japan, the dietary intake of red meat for some people in the poorest deciles falls below the recommended levels (Supplementary Data 15). Rest of East Asia is one exception, with the poorest decile having high footprints due to a substantial intake of red meat, as seen in Mongolia where beef and mutton are the most common dish[48].

Footprints related to plant-based products in specific regions show a different trend from animal-based products as expenditures increase. The middle expenditure groups are responsible for the highest footprints associated with grains in Sub-Saharan Africa and Southeast Asia and the highest footprints of tubers, vegetables and fruits (mainly starchy tropical fruits[49]) in the Rest of Oceania. These locally produced, high-carbohydrate products are traditional staple foods. In poor countries, agricultural policy primarily targets improving the productivity of staple food, with little investment in the market and facilities for nutrient-rich products[50,51]. Consequently, the need for dietary diversity for middle- and low-income people is not adequately addressed[50], leading to increased consumption of these lower-cost products. However, wealthier consumers can afford more expensive products, such as red meat, reducing their reliance on these staple products.

We use the GHG footprint Gini (GF-Gini) coefficient, calculated on the basis of data from 201 expenditure groups, to measure the dietary emission inequality within a country (Fig. 3), with 0 indicating perfect equality and 1 indicating perfect inequality. The inequality of dietary emissions tends to decline with the increase of the per capita GDP of a country, especially for animal-based products. We find the highest inequality of dietary emissions of food products generally in low-income countries, most of which are located in Sub-Saharan

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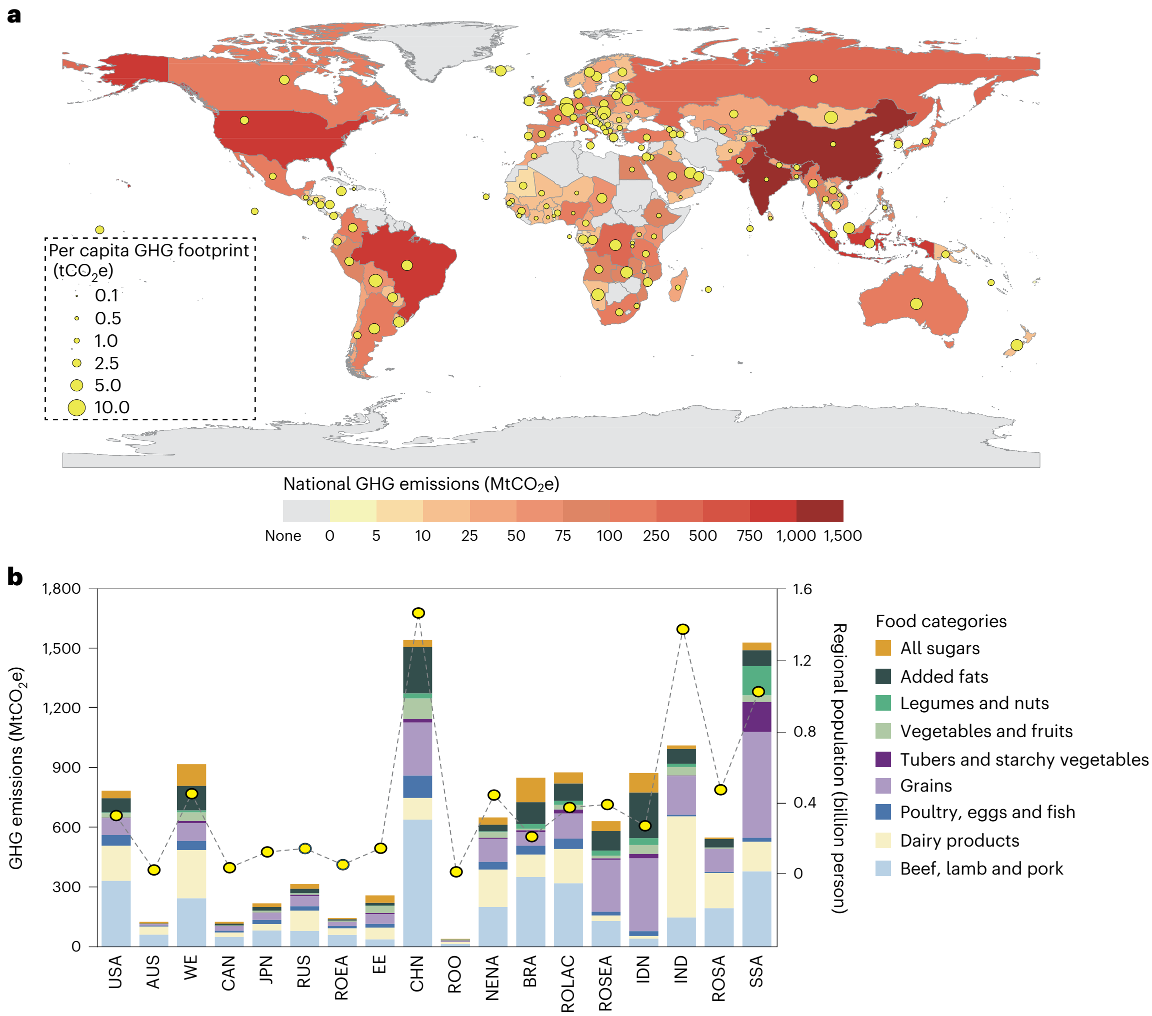

Fig. 1 | National and regional dietary GHG emissions in 2019. a, Total and per capita dietary emissions for 139 countries/areas. **b**, Regional dietary emissions from different food categories and populations. The bar chart (left primary axis) shows the regional emission amounts and the line chart (right secondary axis) shows the number of regional populations. Columns are ordered by the descending per capita GDP of regions (Supplementary Tables 5 and 6). USA, United States; AUS, Australia; WE, Western Europe; CAN, Canada; JPN, Japan; RUS, Russia; ROEA, Rest of East Asia; EE, East Europe; CHN, China; ROO, Rest of Oceania; NENA, Near East and North Africa; BRA, Brazil; ROLAC, Rest of Latin America and the Caribbean; ROSEA, Rest of Southeast Asia; IDN, Indonesia; IND, India; ROSA, Rest of South Asia; and SSA, Sub-Saharan Africa. Details for the division and scope of regions are shown in Supplementary Fig. 10 and Supplementary Tables 7 and 8. Country classification by income levels is based on the World Bank[46]. Credit: World Countries basemap, Esri (https://hub.arcgis.com/datasets/esri::world-countries/about).

Africa. In Sub-Saharan Africa, the highest spending 10% of the population contributes 40% of the regional emissions from red meat, 39% from poultry and 35% from dairy products. In contrast, high-income countries generally have relatively low inequality with high levels of emissions despite country-to-country variations. The GF-Gini coefficients for all types of products of most Western European countries are <0.20 (Supplementary Tables 9 and 10), which is lower than for other high-income countries such as the United States, Australia, Canada and Japan.

Dietary emission shares across consumer groups

There are notable differences in dietary emission shares associated with food categories across expenditure deciles between regions (Fig. 4). In high-income countries, expenditure groups have relatively similar patterns of dietary emissions, with large shares of red meat and dairy products contributing the largest amount of emissions. Even poor consumer groups in high-income countries tend to be more likely to be able to afford animal-based products as a result of relatively lower prices for dairy products, eggs, white meat and processed red meat. This contrasts with the high prices of animal-based products due to supply constraints in most low- and lower-middle-income countries[52,53]. Except in high-income countries, starchy staple foods (including grains and tubers), with low prices but high-carbohydrate content[44,54], constitute a large proportion of dietary emissions because of the high level of consumption, especially in Southeast Asia and Sub-Saharan Africa. As individuals' expenditures increase in these countries, emission shares from starchy staple foods in total emissions decrease substantially. These changes demonstrate that as the affordability of food increases, populations tend to adopt instead more diverse diets composed of fewer starchy staple foods and more meat, dairy products, vegetables and fruits. This trend generally aligns with Bennett's Law[25,55,56]. For example, research shows that with rapid economic growth, China's urban or high-income groups increase their intake of non-starchy foods to fulfil their requirements of dietary diversity[35], while poorer groups, often engaging in strenuous physical jobs, predominantly consume inexpensive starchy staple foods. One exception is Rest of Oceania, where poorer groups have higher percentages of emissions from not only tubers but also vegetables and fruits. Owing to relatively low

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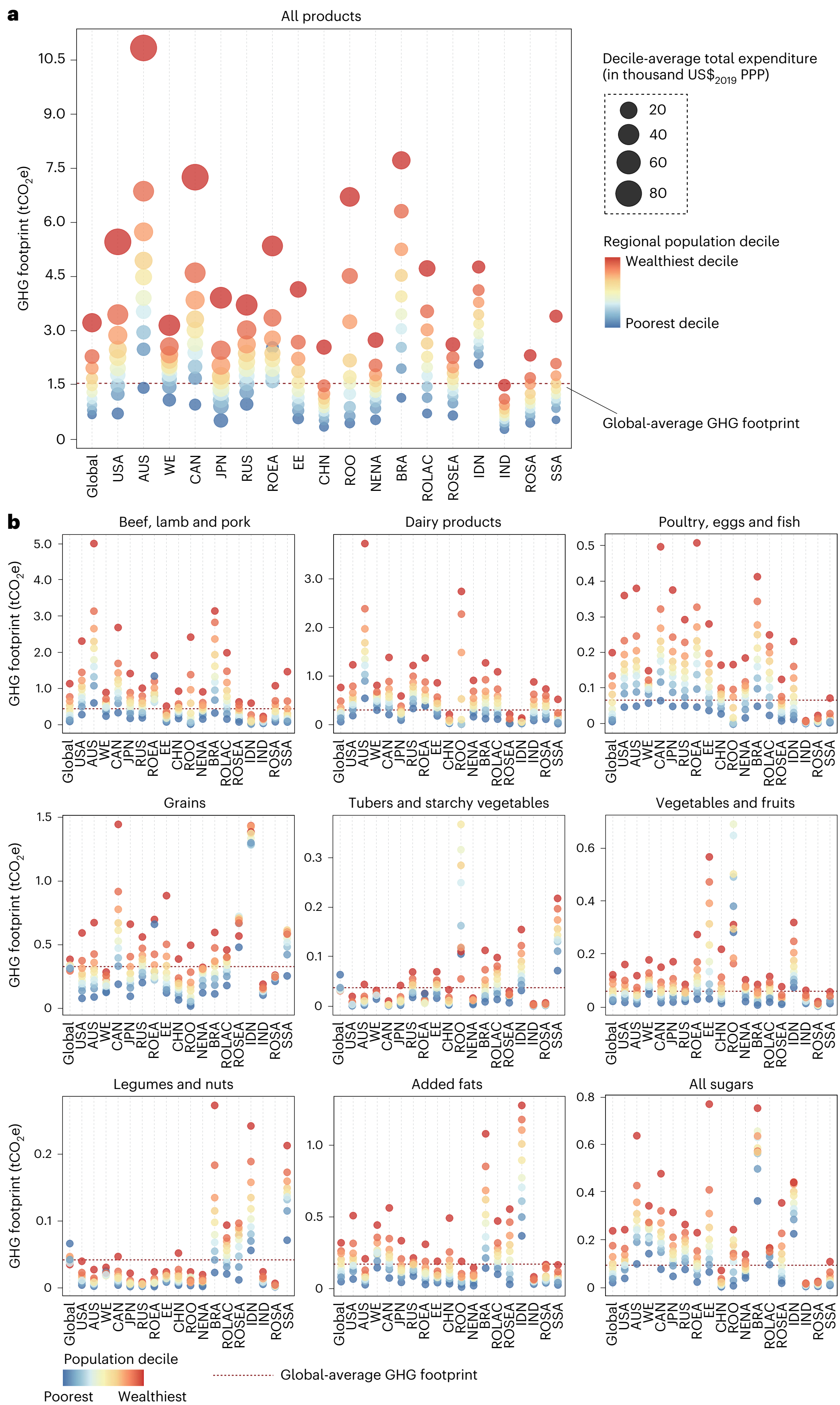

Fig. 2 | Per capita dietary GHG footprints for each decile of global and regional populations in 2019. a, GHG footprints from all types of food categories. The size of the bubble refers to the average total expenditure represented by the decile. **b**, GHG footprints from different food categories. The colours of bubbles in **a** and **b** indicate expenditure deciles ranging from the poorest in blue to the wealthiest in red and are comparable only within each region.

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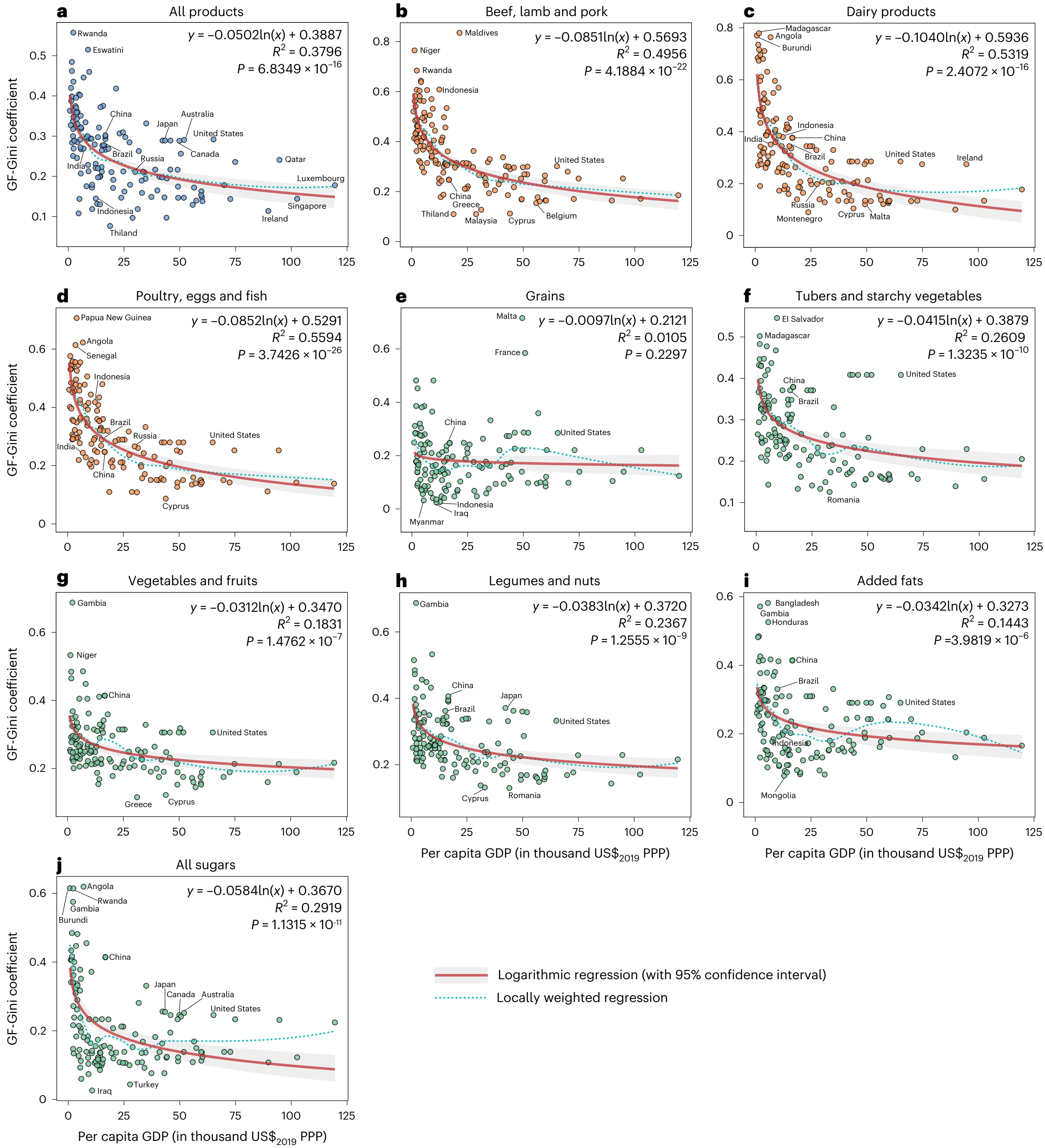

Fig. 3 | Scatterplot for GF-Gini coefficients as a function of per capita GDP in 139 countries/areas. **a**–**j**, The *x* axis represents the country-average per capita GDP, and the *y* axis represents the national GF-Gini coefficients of all types of (**a**) and different (**b**–**j**) food categories. **b**, Beef, lamb and pork. **c**, Dairy products. **d**, Poultry, eggs and fish. **e**, Grains. **f**, Tubers and starchy vegetables. **g**, Vegetables and fruits. **h**, Legumes and nuts. **i**, Added fats. **j**, All sugars. Logarithmic regression (red solid line) and locally weighted regression analysis (blue dotted line) are used to determine the relationship between the national GF-Gini coefficient (dependent variable) and the country-average per capita GDP (independent variable). The coefficients of determination (R^2) and the exact *P* values from the two-sided Student's *t*-test for the logarithmic regression are indicated in each subgraph. The error bands (grey shaded areas) represent 95% confidence intervals around the fitted logarithmic regression lines. Blue, orange and green dots represent all types of products, animal-based products and plant-based products, respectively.

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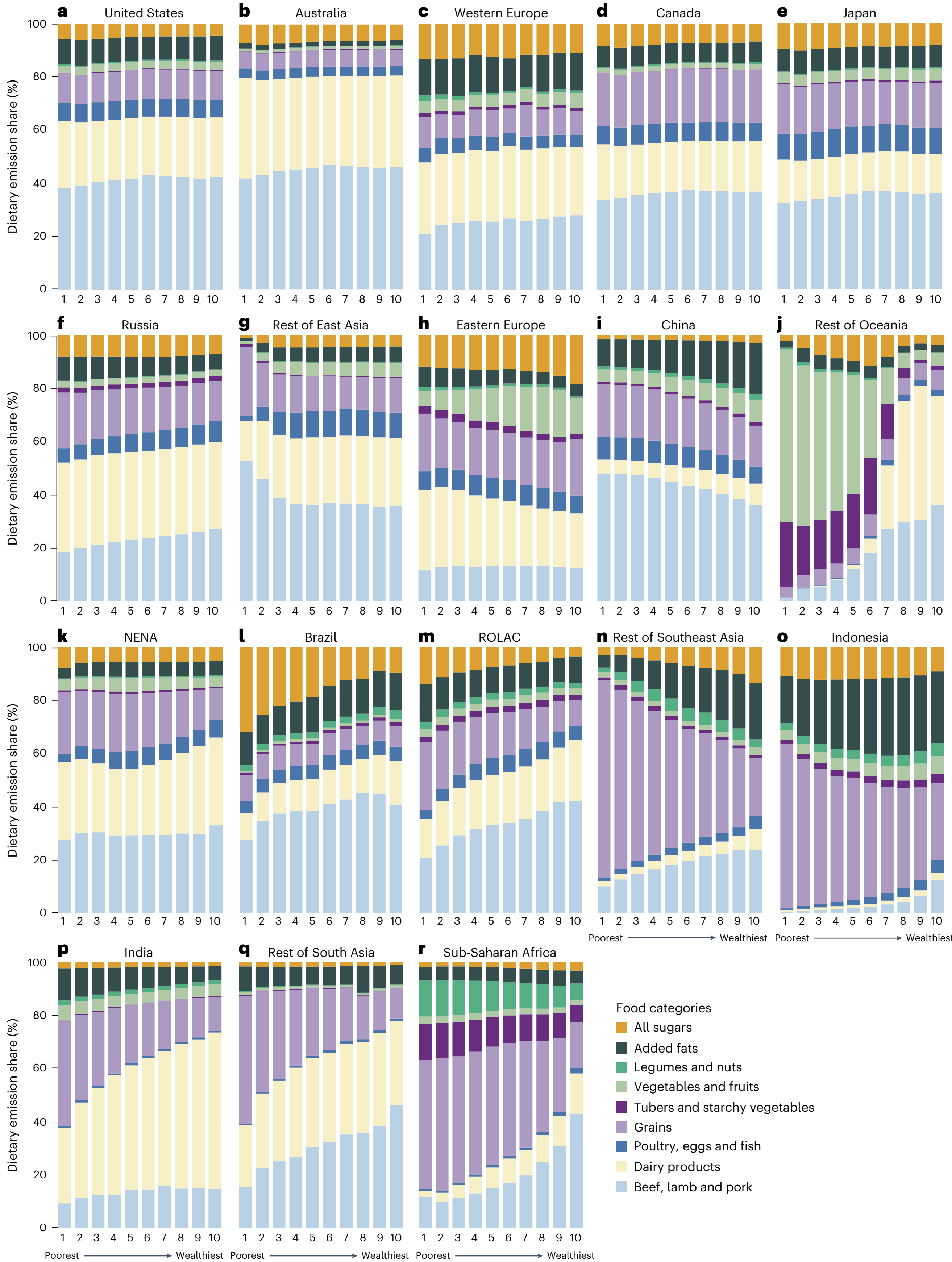

Fig. 4 | Relative contributions of per capita dietary GHG footprints for different food categories for regional expenditure deciles. The numbers at the bottom of each bar represent the expenditure levels of regional expenditure deciles, ranging from the poorest (1) to the wealthiest (10). Food categories are shown in the colour legend. **a**, United States. **b**, Australia. **c**, Western Europe. **d**, Canada. **e**, Japan. **f**, Russia. **g**, Rest of East Asia. **h**, Eastern Europe. **i**, China. **j**, Rest of Oceania. **k**, NENA. **l**, Brazil. **m**, ROLAC. **n**, Rest of Southeast Asia. **o**, Indonesia. **p**, India. **q**, Rest of South Asia. **r**, Sub-Saharan Africa.

expenditure on food, poor populations in this island region usually choose locally cultivated tubers and fruits (such as cassava, taro and bananas)[57,58] with high intensities of land-use emissions[59].

Emission changes from adopting the planetary health diet

To estimate the emission changes from a global diet shift, we build a hypothetical scenario by assuming that everyone in all countries adopts the planetary health diet (Methods). Results indicate that the global dietary emissions would decrease by 17% (1.94 (1.51–2.39) $GtCO_2e$) compared with the 2019 level (details of the uncertainty ranges can be found in Supplementary Tables 11 and 12). The presently overconsuming groups (56.9% of the global population) would save 32.4% of global emissions through diet shifts, more than offsetting the 15.4% increase in global emissions from the presently underconsuming groups (43.1% of the global population) as a result of adopting healthier diets (Supplementary Table 13). National dietary emissions in 100 countries would decline by 2.88 $GtCO_2e$, whereas the other 39 countries (mainly low- and lower-middle-income countries[46] in Sub-Saharan Africa and South Asia) would have an increase in emissions by 938 $MtCO_2e$ (Fig. 5a; for detailed food categories see Supplementary Figs. 12–20).

Countries would be affected differently regarding emission changes by adopting the planetary health diet, reflected in the percentage change in national emissions (Fig. 5a). Uzbekistan (−74%), Australia (−70%), Qatar (−67%), Turkey (−65%) and Tajikistan (−64%) would see the largest percentage decrease. In comparison, most of the countries with an estimated considerable percentage increase are located in Sub-Saharan Africa and the Middle East, with the largest percentage increase from Iraq (+155%). Notably, with the increase in per capita GDP, the percentage change in overall dietary emissions of countries shows a shift from a positive to a negative trend, primarily led by changes in animal-based emissions (Supplementary Fig. 21).

Global emission reduction would be dominantly driven by red meat and grains (Fig. 5b). The reduction in meat, eggs and fish would lead to 2.04 $GtCO_2e$ of emission reduction, of which 94% is driven by the decrease in red meat. China (22%), the United States (15%) and Brazil (14%) would be the largest contributors to emission reduction associated with a decrease in red meat consumption. A decline in grains would result in 914 $MtCO_2e$ of emission reduction, of which 56% would happen in Asia. A further 240 and 89 $MtCO_2e$ reduction in emissions would come from reduced sugars and tubers, respectively. However, increased proteins (legumes and nuts and dairy products), added fats and vegetables and fruits would partly offset the above-reduced emissions by 41%. Intake of legumes and nuts would increase in all regions, leading to a further 757 $MtCO_2e$ of emissions, whereas most of the emission increase related to added fats (largely vegetable oils) (279 Mt) and dairy products (143 Mt) would take place in Sub-Saharan Africa, China and other Asian countries. Global dietary emissions associated with vegetables and fruits would increase by 163 Mt, despite declines in China and Rest of Oceania.

The decline in per capita GHG footprints would be achieved primarily in wealthy consumer groups in high- and upper-middle-income countries, while increased footprints would occur mainly in poor groups in most countries (Fig. 6a). Results show that the shifts of chief protein sources from animal-based to plant-based proteins according to the planetary health diet[12] would contribute the most to changes in footprints globally (Fig. 6b). For example, in Australia, Brazil, Canada and the United States where diets are dominated by red meat and dairy products, the top and upper-middle expenditure groups would have notable reductions in footprints. However, most populations in South and Southeast Asia and Sub-Saharan Africa would have a considerable increase in footprints because of the present low levels of red meat intake. Meanwhile, the present intake of plant-based proteins in all countries is below the recommended level[25]. Footprints related to legumes and nuts would increase for most expenditure groups in all regions to meet nutrient demands. This increase is particularly substantial in Rest of Oceania, Brazil, Indonesia and Sub-Saharan Africa, where most of the consumed legumes and nuts are domestically produced with high land-use emission intensities[59,60], assuming the present production and trade patterns remain unchanged.

Discussion and conclusions

This study uncovers the extent of inequality of dietary emissions within countries based on detailed expenditure data[17,34] and underlines the dependence of dietary emissions on expenditure and income levels. Emissions aggregated at expenditure deciles may lose some fine-grained information from the 201 expenditure groups. For example, people from the lowest expenditure groups in affluent countries may experience malnutrition or even hunger, which is not adequately captured at a decile level. Nevertheless, the GF-Gini coefficient calculated from 201 groups provides an accurate reflection of emission inequality. Results show that affluent countries consume high-emission diets but show relatively lower levels of inequality, whereas many poor countries tend to have diets with lower emissions but higher levels of inequality.

The objective of the diet shift scenario is to assess the potential implications of emission mitigation of the food system resulting from changing consumer choices. Widespread diet shifts offer dual benefits by moving 43.1% of the global population out of underconsumption and mitigating 17% of global dietary emissions. The simulated changes in the volume of global emissions under the planetary health diet approximate the findings by ref. 26 (Supplementary Discussion 1). However, worldwide diet shifts require tailored policies targeted at regions, countries, expenditure groups and products instead of 'one-size-fits-all' policies.

We find that, compared to plant-based products, animal-based products, particularly red meat and dairy products, exhibit greater potential for reducing both emission volumes and emission disparities among different expenditure groups. Priorities lie in reducing the overconsumption of specific emission-intensive products in affluent countries (particularly the high-expenditure groups), such as beef in Australia and the United States, to achieve health[9,12] and climate benefits[25,26,28]. Incentives, such as implementing subsidies or taxation on environmental externalities through food or carbon pricing[61], ecolabelling[62] and expanding the availability of less emission-intensive products (for instance, menu design for diverse vegetarian foods[63]), can encourage consumers to make dietary changes. Moreover, a well-designed (primarily urban) food environment can reshape residents' dietary patterns[35] and the parallel development of urban planning and infrastructure can alleviate the time and financial burdens of shifts to healthier diets[64]. However, in countries such as Mongolia, where diets heavily rely on red meat and dairy products because of their traditional nomadic lifestyle and limited accessibility of diverse foods, especially in rural areas[48], diet shifts may not be feasible but there is a need to improve national nutritional education[48].

Low-income countries face more severe challenges in reaching healthier diets. On the one hand, diet shifts require increased food consumption in these countries. For example, in Sub-Saharan Africa, the planetary health diet requires a 3.4-fold increase in dairy consumption for the entire population and a 69-fold increase for the poorest decile (Supplementary Fig. 22). However, Sub-Saharan Africa and South and Southeast Asia, which have experienced stagnating agriculture production efficiency for decades[8], cannot produce domestically nor afford to import the food required for diet shifts[65]. It is crucial to enhance the production efficiency of feed and food crops through various measures such as crop and soil management techniques[8,66] and the introduction of high-yielding crop varieties and hybrids[67,68]. Moreover, increasing the proportions of nutrient-rich products in food imports[65] and reducing restrictive trade policies which tend to raise food prices[25,69] help to address this challenge. On the other hand, poor populations often opt for lower-cost, calorie-dense but less nutritionally beneficial foods. High cost and low affordability remain the largest barriers for these individuals to select healthier diets[44,54,70,71]. Others[44] found that

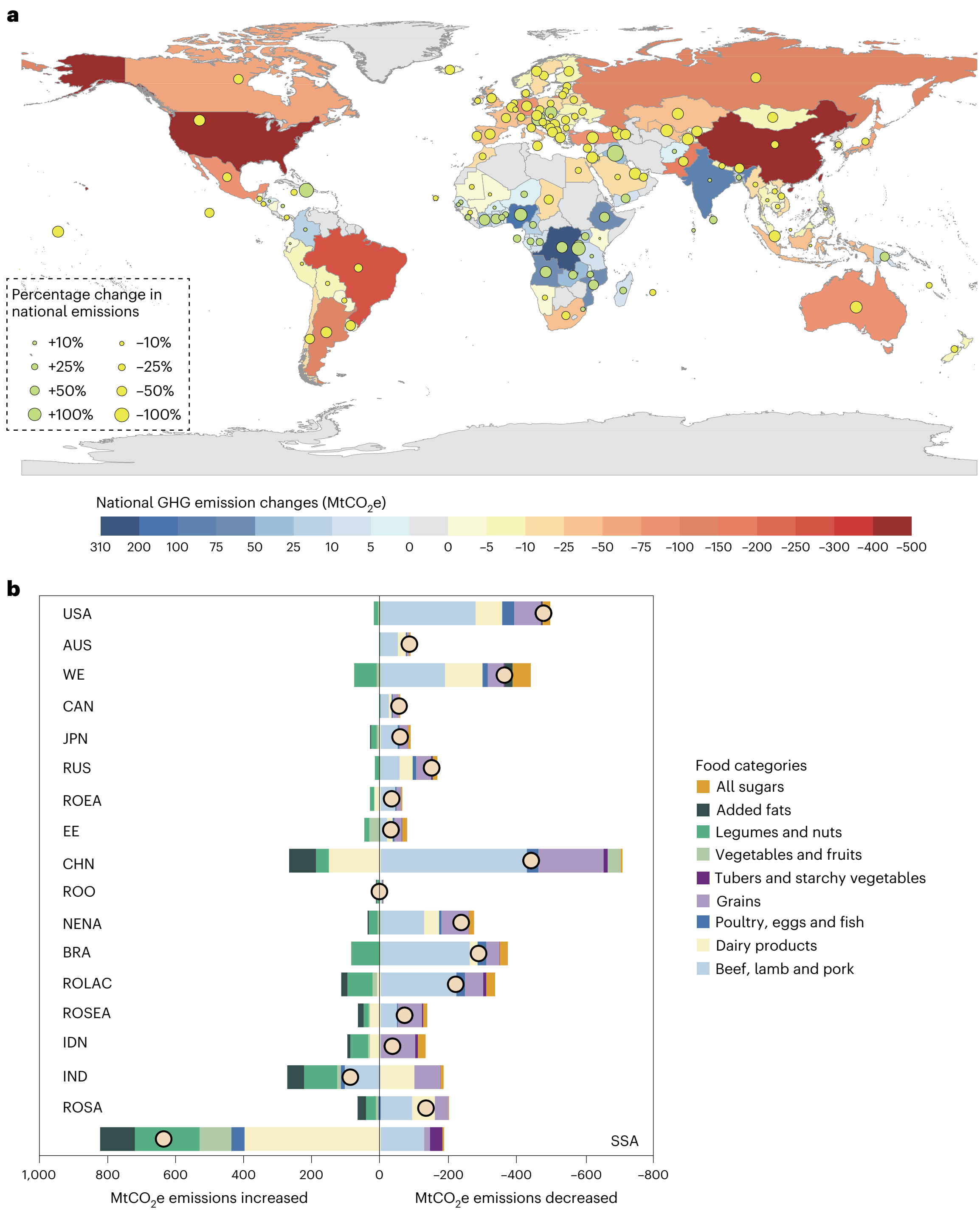

Fig. 5 | Changes in dietary emissions for adopting the planetary health diet in countries and regions. a, Volume changes and percentage changes of national emissions for 139 countries/areas. **b**, Regional emission changes from different food categories. Abbreviations of 18 regions and the source of the base map are listed in Fig. 1 caption.

>1.58 billion low-income populations worldwide cannot afford the cost of the planetary health diet. Therefore, policy efforts (for instance, pricing interventions[72], technical assistance to reduce food production costs[73] and so on) should focus on making food more affordable and accessible, especially for lower expenditure groups[37,74]. However, studies indicate that lower food prices may decrease the income of agricultural households[75,76], widen wealth gaps between individuals employed in food- and non-food sectors, especially in low-income agrarian countries and exacerbate rural poverty[1,77]. In this sense, policies aimed at promoting diet shifts should be deliberately and cautiously designed with vulnerable groups in mind to reduce inequality[37,61].

Lastly, altered food demand due to diet shifts can induce notable structural adjustments within the global agri-food system. Although this study does not assess the feasibility of countries supplying sufficient food if the planetary health diet was adopted, results indicate that the composition of global food production would change considerably to adapt to the substantial changes in demand[8,25,77]. The diet shifts would necessitate the global supply (in calorie content) of red meat decrease by 81%, all sugars by 72%, tubers by 76% and grains by 50%, while that of legumes and nuts increase by 438%, added fats by 62% and vegetables and fruits by 28% (Supplementary Data 16). Research[77,78] confirms that changed food demand could cause fluctuating prices of

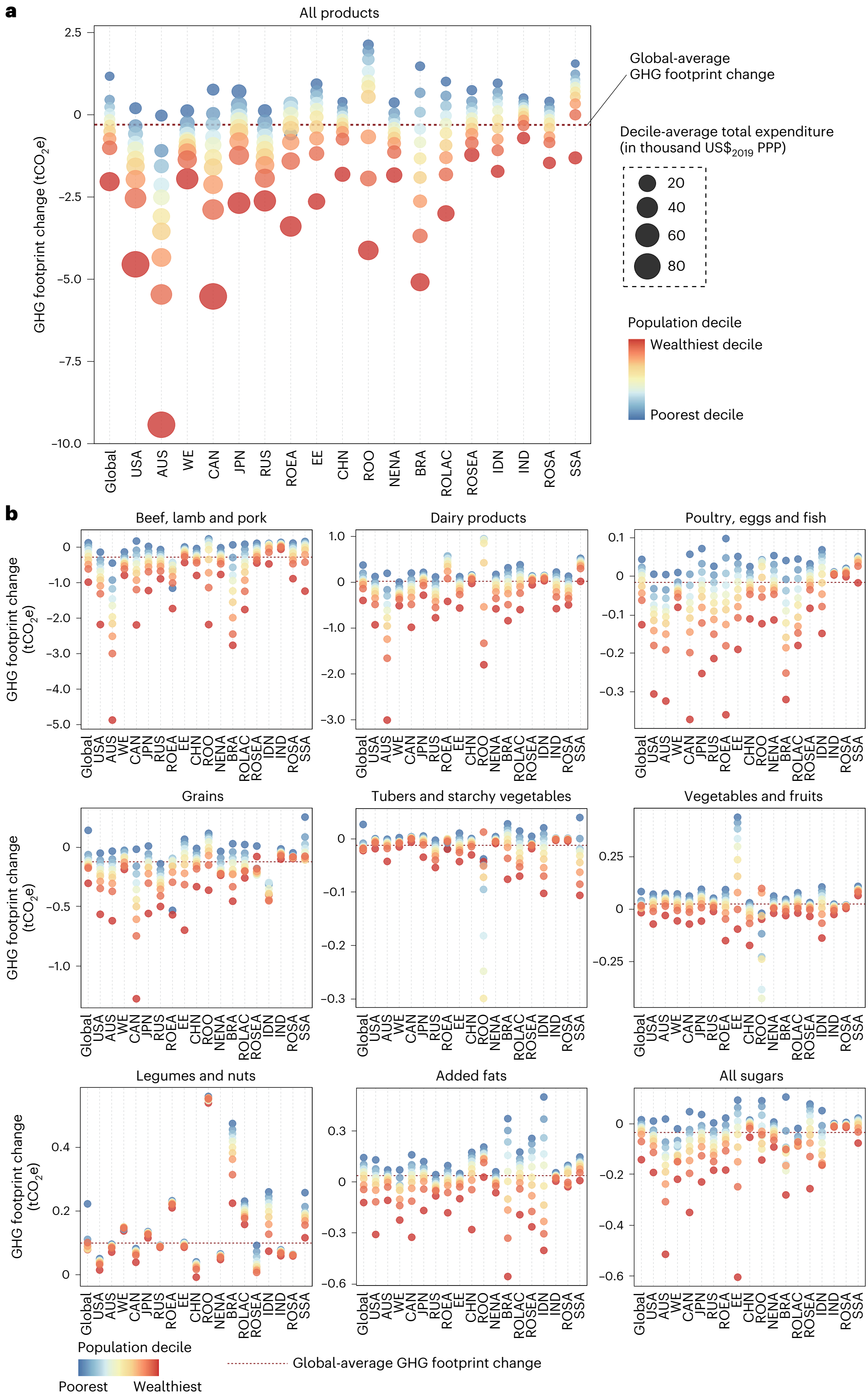

Fig. 6 | Changes in per capita dietary GHG emissions of each decile of global and regional populations for adopting the planetary health diet. a, Changes in GHG footprints from all types of food categories. The size of the bubble refers to the average total expenditure represented by the decile. **b**, Changes in GHG footprints from different food categories. The colours of bubbles in **a** and **b** indicate expenditure deciles ranging from the poorest in blue to the wealthiest in red and are comparable only within each region.

agricultural products and land in global markets, triggering spillover effects between different food categories or to other non-food sectors (for example, stimulating biofuel production) and partly offsetting the benefits of diet shifts. Therefore, policy-making should focus on alleviating these effects. Incentives such as increased subsidies or tax breaks can generate new economic opportunities and motivations for industries that need to scale up production to meet the heightened demand for products (for example, plant-based proteins). By contrast, for emission-intensive food industries that need to downsize, measures such as gradual crop substitution[25,79] could be adopted to optimize production and reduce the costs of production transformations while safeguarding the interests of producers.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-024-02084-1.

References

1. Springmann, M., Godfray, H. C. J., Rayner, M. & Scarborough, P. Analysis and valuation of the health and climate change cobenefits of dietary change. *Proc. Natl Acad. Sci. USA* **113**, 4146–4151 (2016).
2. Kesse-Guyot, E. et al. Sustainability analysis of French dietary guidelines using multiple criteria. *Nat. Sustain.* **3**, 377–385 (2020).
3. Crippa, M. et al. Food systems are responsible for a third of global anthropogenic GHG emissions. *Nat. Food* **2**, 198–209 (2021).
4. Tubiello, F. N. et al. Pre-and post-production processes increasingly dominate greenhouse gas emissions from agri-food systems. *Earth Syst. Sci. Data* **14**, 1795–1809 (2022).
5. Clark, M. A. et al. Global food system emissions could preclude achieving the 1.5 °C and 2 °C climate change targets. *Science* **370**, 705–708 (2020).
6. Ivanovich, C. C., Sun, T., Gordon, D. R. & Ocko, I. B. Future warming from global food consumption. *Nat. Clim. Change* **13**, 297–302 (2023).
7. Béné, C. et al. Five priorities to operationalize the EAT-Lancet Commission report. *Nat. Food* **1**, 457–459 (2020).
8. Navarre, N., Schrama, M., de Vos, C. & Mogollón, J. M. Interventions for sourcing EAT-Lancet diets within national agricultural areas: a global analysis. *One Earth* **6**, 31–40 (2023).
9. Laine, J. E. et al. Co-benefits from sustainable dietary shifts for population and environmental health: an assessment from a large European cohort study. *Lancet Planet. Health* **5**, e786–e796 (2021).
10. Craig, W. J. Health effects of vegan diets. *Am. J. Clin. Nutr.* **89**, S1627–S1633 (2009).
11. Afshin, A. et al. Health effects of dietary risks in 195 countries, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017. *Lancet* **393**, 1958–1972 (2019).
12. Willett, W. et al. Food in the Anthropocene: the EAT-Lancet Commission on healthy diets from sustainable food systems. *Lancet* **393**, 447–492 (2019).
13. *The State of Food Security and Nutrition in the World 2022: Repurposing Food and Agricultural Policies to Make Healthy Diets More Affordable* (FAO, 2022); https://www.fao.org/documents/card/en/c/cc0639en
14. Bajželj, B. et al. Importance of food-demand management for climate mitigation. *Nat. Clim. Change* **4**, 924–929 (2014).
15. Springmann, M. et al. Options for keeping the food system within environmental limits. *Nature* **562**, 519–525 (2018).
16. Li, Y. et al. Changes in global food consumption increase GHG emissions despite efficiency gains along global supply chains. *Nat. Food* **4**, 483–495 (2023).
17. Hubacek, K., Baiocchi, G., Feng, K. & Patwardhan, A. Poverty eradication in a carbon constrained world. *Nat. Commun.* **8**, 912 (2017).
18. *Sustainable Development Goals: 17 Goals to Transform Our World* (United Nations, 2017); https://www.un.org/sustainabledevelopment/sustainable-development-goals/
19. Humpenöder, F. et al. Projected environmental benefits of replacing beef with microbial protein. *Nature* **605**, 90–96 (2022).
20. Hasegawa, T., Havlík, P., Frank, S., Palazzo, A. & Valin, H. Tackling food consumption inequality to fight hunger without pressuring the environment. *Nat. Sustain.* **2**, 826–833 (2019).
21. Kim, B. F. et al. Country-specific dietary shifts to mitigate climate and water crises. *Glob. Environ. Change* **62**, 101926 (2020).
22. Denton, F. et al. in *Climate Change 2022: Mitigation of Climate Change* (eds Shukla, P. R. et al.) 1727–1790 (Cambridge Univ. Press, 2022).
23. Tilman, D. & Clark, M. Global diets link environmental sustainability and human health. *Nature* **515**, 518–522 (2014).
24. Springmann, M. 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* **2**, e451–e461 (2018).
25. Tuninetti, M., Ridolfi, L. & Laio, F. Compliance with EAT-Lancet dietary guidelines would reduce global water footprint but increase it for 40% of the world population. *Nat. Food* **3**, 143–151 (2022).
26. Semba, R. D. et al. Adoption of the 'planetary health diet' has different impacts on countries' greenhouse gas emissions. *Nat. Food* **1**, 481–484 (2020).
27. Guo, Y. et al. Environmental and human health trade-offs in potential Chinese dietary shifts. *One Earth* **5**, 268–282 (2022).
28. Sun, Z. et al. Dietary change in high-income nations alone can lead to substantial double climate dividend. *Nat. Food* **3**, 29–37 (2022).
29. Mbow, C. et al. in *Climate Change and Land* (eds Shukla, P. R. et al.) Ch. 5 (IPCC, 2019); https://www.ipcc.ch/site/assets/uploads/sites/4/2022/11/SRCCL_Chapter_5.pdf
30. Millward-Hopkins, J. & Oswald, Y. Reducing global inequality to secure human wellbeing and climate safety: a modelling study. *Lancet Planet. Health* **7**, e147–e154 (2023).
31. Guan, Y. et al. Burden of the global energy price crisis on households. *Nat. Energy* **8**, 304–316 (2023).
32. Hubacek, K. et al. Global carbon inequality. *Energy Ecol. Environ.* **2**, 361–369 (2017).
33. Mi, Z. et al. Economic development and converging household carbon footprints in China. *Nat. Sustain.* **3**, 529–537 (2020).
34. Bruckner, B., Hubacek, K., Shan, Y., Zhong, H. & Feng, K. Impacts of poverty alleviation on national and global carbon emissions. *Nat. Sustain.* **5**, 311–320 (2022).
35. He, P., Baiocchi, G., Hubacek, K., Feng, K. & Yu, Y. The environmental impacts of rapidly changing diets and their nutritional quality in China. *Nat. Sustain.* **1**, 122–127 (2018).
36. Rao, N. D. et al. Healthy, affordable and climate-friendly diets in India. *Glob. Environ. Change* **49**, 154–165 (2018).
37. He, P., Feng, K., Baiocchi, G., Sun, L. & Hubacek, K. Shifts towards healthy diets in the US can reduce environmental impacts but would be unaffordable for poorer minorities. *Nat. Food* **2**, 664–672 (2021).
38. Reynolds, C. J., Horgan, G. W., Whybrow, S. & Macdiarmid, J. I. Healthy and sustainable diets that meet greenhouse gas emission reduction targets and are affordable for different income groups in the UK. *Public Health Nutr.* **22**, 1503–1517 (2019).
39. Gustavsson, J., Cederberg, C., Sonesson, U., Van Otterdijk, R. & Meybeck, A. *Global Food Losses and Food Waste-Extent, Causes and Prevention* (FAO, 2011); https://www.fao.org/3/mb060e/mb060e00.htm

40. Kummu, M. et al. Lost food, wasted resources: global food supply chain losses and their impacts on freshwater, cropland and fertiliser use. *Sci. Total Environ.* **438**, 477–489 (2012).
41. Zhong, H., Feng, K., Sun, L., Cheng, L. & Hubacek, K. Household carbon and energy inequality in Latin American and Caribbean countries. *J. Environ. Manag.* **273**, 110979 (2020).
42. *Global Consumption Database* (World Bank, 2022); https://datatopics.worldbank.org/consumption/
43. Wier, M., Birr-Pedersen, K., Jacobsen, H. K. & Klok, J. Are CO_2 taxes regressive? Evidence from the Danish experience. *Ecol. Econ.* **52**, 239–251 (2005).
44. Hirvonen, K., Bai, Y., Headey, D. & Masters, W. A. Affordability of the EAT-Lancet reference diet: a global analysis. *Lancet Glob. Health* **8**, e59–e66 (2020).
45. *The State of Food Security and Nutrition in the World 2023* (FAO, 2023); https://doi.org/10.4060/cc3017en
46. *World Bank Country and Lending Groups* (World Bank, 2021); https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups
47. Okou, C., Spray, J. A. & Unsal, M. F. D. *Staple Food Prices in Sub-Saharan Africa: An Empirical Assessment* (International Monetary Fund, 2022); https://www.imf.org/en/Publications/WP/ Issues/2022/07/08/Staple-Food-Prices-in-Sub-Saharan-Africa-An-Empirical-Assessment-520567
48. Delgermaa, D., Yamaguchi, M., Nomura, M. & Nishi, N. Assessment of Mongolian dietary intake for planetary and human health. *PLoS Glob. Public Health* **3**, e0001229 (2023).
49. Burkhart, S., Underhill, S. & Raneri, J. Realizing the potential of neglected and underutilized bananas in improving diets for nutrition and health outcomes in the Pacific Islands. *Front. Sustain. Food Syst.* **6**, 805776 (2022).
50. Pingali, P. Agricultural policy and nutrition outcomes—getting beyond the preoccupation with staple grains. *Food Secur.* **7**, 583–591 (2015).
51. Sibhatu, K. T. & Qaim, M. Rural food security, subsistence agriculture and seasonality. *PloS ONE* **12**, e0186406 (2017).
52. Headey, D. D. & Alderman, H. H. The relative caloric prices of healthy and unhealthy foods differ systematically across income levels and continents. *J. Nutr.* **149**, 2020–2033 (2019).
53. Bai, Y., Alemu, R., Block, S. A., Headey, D. & Masters, W. A. Cost and affordability of nutritious diets at retail prices: evidence from 177 countries. *Food Policy* **99**, 101983 (2021).
54. Batis, C. et al. Adoption of healthy and sustainable diets in Mexico does not imply higher expenditure on food. *Nat. Food* **2**, 792–801 (2021).
55. Bennett, M. K. International contrasts in food consumption. *Geogr. Rev.* **31**, 365–376 (1941).
56. D'Odorico, P. et al. The global food–energy–water nexus. *Rev. Geophys.* **56**, 456–531 (2018).
57. *Traditional Pacific Island Crops* (Univ. Hawaii, 2024); https://guides.library.manoa.hawaii.edu/paccrops
58. *Fiji—Agricultural Commodities* (International Trade Administration, 2022); https://www.trade.gov/country- commercial-guides/fiji-agricultural-commodities
59. Hong, C. et al. Global and regional drivers of land-use emissions in 1961–2017. *Nature* **589**, 554–561 (2021).
60. Hong, C. et al. Land-use emissions embodied in international trade. *Science* **376**, 597–603 (2022).
61. Darmon, N., Lacroix, A., Muller, L. & Ruffieux, B. Food price policies improve diet quality while increasing socioeconomic inequalities in nutrition. *Int. J. Behav. Nutr. Phys. Act.* **11**, 66 (2014).
62. Poore, J. & Nemecek, T. Reducing food's environmental impacts through producers and consumers. *Science* **360**, 987–992 (2018).
63. Bacon, L. & Krpan, D. (Not) Eating for the environment: the impact of restaurant menu design on vegetarian food choice. *Appetite* **125**, 190–200 (2018).
64. Swinburn, B. A. et al. The global syndemic of obesity, undernutrition and climate change: the Lancet Commission report. *Lancet* **393**, 791–846 (2019).
65. Geyik, O., Hadjikakou, M., Karapinar, B. & Bryan, B. A. Does global food trade close the dietary nutrient gap for the world's poorest nations? *Glob. Food Secur.* **28**, 100490 (2021).
66. Pradhan, P., Fischer, G., Van Velthuizen, H., Reusser, D. E. & Kropp, J. P. Closing yield gaps: how sustainable can we be. *PloS ONE* **10**, e0129487 (2015).
67. Sánchez, P. A. Tripling crop yields in tropical Africa. *Nat. Geosci.* **3**, 299–300 (2010).
68. Huang, J., Pray, C. & Rozelle, S. Enhancing the crops to feed the poor. *Nature* **418**, 678–684 (2002).
69. *The State of Food Security and Nutrition in the World 2020. Transforming Food Systems for Affordable Healthy Diets* (FAO, 2020); https://www.fao.org/documents/card/en?details=ca9692en
70. Allcott, H. et al. Food deserts and the causes of nutritional inequality. *Q. J. Econ.* **134**, 1793–1844 (2019).
71. Springmann, M., Clark, M. A., Rayner, M., Scarborough, P. & Webb, P. The global and regional costs of healthy and sustainable dietary patterns: a modelling study. *Lancet Planet. Health* **5**, e797–e807 (2021).
72. Darmon, N. & Drewnowski, A. Contribution of food prices and diet cost to socioeconomic disparities in diet quality and health: a systematic review and analysis. *Nutr. Rev.* **73**, 643–660 (2015).
73. Baylis, K., Peplow, S., Rausser, G. & Simon, L. Agri-environmental policies in the EU and United States: a comparison. *Ecol. Econ.* **65**, 753–764 (2008).
74. Swinnen, J. The right price of food. *Dev. Policy Rev.* **29**, 667–688 (2011).
75. Headey, D. D. Food prices and poverty. *World Bank Econ. Rev.* **32**, 676–691 (2018).
76. Headey, D. & Hirvonen, K. Higher food prices can reduce poverty and stimulate growth in food production. *Nat. Food* **4**, 699–706 (2023).
77. Gatto, A., Kuiper, M. & van Meijl, H. Economic, social and environmental spillovers decrease the benefits of a global dietary shift. *Nat. Food* **4**, 496–507 (2023).
78. Puma, M. J., Bose, S., Chon, S. Y. & Cook, B. I. Assessing the evolving fragility of the global food system. *Environ. Res. Lett.* **10**, 024007 (2015).
79. Davis, K. F. et al. Alternative cereals can improve water use and nutrient supply in India. *Sci. Adv.* **4**, eaao1108 (2018).

Methods

Overview

In this study, we first assess the GHG emissions from diets comprising 140 products[16] (Supplementary Table 14) in 139 countries or areas (we collectively use the term 'country' because most of them are individual countries) (Supplementary Data 1) in 2019 based on the global consumption-based emission inventory of detailed food products from ref. 16. The inventory[16] provides data (in mass units) of GHG emissions (including CO_2, CH_4 and N_2O) generated during supply chain processes, including agricultural land use and land-use change (LULUC), agricultural activities and beyond-farm processes (excluding emissions from household and end of life)[4]. All emissions are allocated to final consumers of food products. The year 2019 (the latest year before the COVID-19 pandemic) is selected as a baseline year, which can reflect the level of present dietary intake without the interference of the pandemic[80,81]. Subsequently, dietary emissions from different expenditure groups are quantified by matching diets with the household-expenditure dataset[42] to reflect the differences and potential inequality of dietary emissions. Finally, to measure the magnitude of the emission impact of the global diet shift, we model the transition from diets in 2019 to the widespread adoption of the planetary health diet. The research framework of this study is shown in Supplementary Fig. 23.

The following data sources are mainly used in this study. The consumption-based food emissions inventory[16] is based on data derived from the FAOSTAT[82], comprising national emission accounts of supply chain processes and data on food trade and production. Data on food loss and waste throughout the global supply chain and at the household level as well as food supply data, all used for linking emissions with diets, are obtained from FAOSTAT[83] and previous research[25,39]. The household-expenditure data[41] are built on the basis of the WBGCD[42] and further refined and supplemented by consumer expenditure surveys from high-income countries[17,41] to bridge the dietary emissions with different expenditure groups. Detailed data sources used for calculation are provided in Supplementary Table 15. Data processing, assumptions and uncertainties for all calculations are also given.

Dietary energy intake and emissions

Accounting of food consumption and supply chain emissions. The estimation of the present dietary emissions and the emission changes for adopting the EAT-Lancet planetary health diet[12] is based on the accounting framework designed by ref. 16. They assess global GHG emissions induced by the consumption of food products in 181 countries based on the physical trade flow approach[84,85]. Consumption-based GHG emissions along global supply chains, including local production and international trade, are calculated as follows[16,84]:

$$E^{i,r} = \frac{\mathbf{G}^i}{\mathbf{P}^i}(I - A^i)^{-1}\frac{\mathbf{P}^i}{\mathbf{DMI}^i}\mathbf{DMC}^{i,r} = \mathbf{F}^i\mathbf{DMC}^{i,r} \quad (1)$$

where $E^{i,r}$ refers to the consumption-based GHG emission of product i in country r. $\mathbf{G}^i/\mathbf{P}^i$ represents the vector of direct emission intensity of product i from entire food supply chain processes, of which $\mathbf{G}^i$ denotes total emissions generated from entire supply chain process of product i, $\mathbf{P}^i$ is the production vector of product i. $(I - A^i)^{-1}$ is the trade structure of product i, of which A^i is the matrix of export shares and I is the identity matrix with the same dimension as matrix A^i. $\mathbf{DMI}^i$ refers to the vector of direct material input of product i and $\mathbf{DMC}^{i,r}$ is the vector of domestic material consumption of product i in country r with values set to zero for other countries. The **DMI** of a country is defined as the total inputs of products and the **DMC** is defined as the amount of products consumed domestically. **DMI** equals **DMC** plus exports of products (or production plus imports). $\mathbf{F}^i$ refers to the vector of total (or consumption-based) emission intensity of product i from food supply chain processes, that is, total emissions induced by per unit of domestic consumption of product i. All variables in equation (1) are in units of mass (metric tonnes).

Feed products are excluded from diets because emissions from feed crops have been allocated to livestock products that consume feed during production[16]. Food loss and waste (FLW) along supply chains and households are subtracted to quantify the net intake amount of food products from the household stage.

Dietary calorie conversions. We use the annual per capita food supply (FS) quantity of 140 food products from the supply utilization accounts of FAOSTAT[83] and population from the United Nations[86] to calculate the total supply amount of product i in country r ($FS^{i,r}$, in the unit of mass):

$$FS^{i,r} = FS^{i,r}_{per}p^r \quad (2)$$

where FS^i_{per} denotes the per capita supply of product i per year and p^r refers to the population in country r.

To be consistently matched with the **DMC**, the FS values should be limited within the coverage of the **DMC** and values that exceed this range are removed. At the same time, to aggregate food products into food categories and compare their nutritional contents with the reference level from the planetary health diet, we convert the quantity of food consumption or supply into calorie content using product-specific nutritive factors (calories per unit weight of product)[87,88] from FAO (Supplementary Table 14).

Subtracting food loss and waste at the household level. The food supply derived from FAOSTAT datasets does not exclude FLW that happens during household consumption[25]. FLW before dietary intake can be divided into two parts: the FLW during supply chain processes (including agricultural production, postharvest handling and storage, processing and packaging and distribution) as well as the FLW during the food preparation and supply for household consumption[39,40]. The food supply value provided by FAOSTAT only excludes FLW during supply chain processes. Therefore, we exclude household FLW using the method by ref. 25 to calculate the annual dietary intake for each product as follows:

$$DI^{i,r} = FS^{i,r}_{energy} \times \left(1 - f^{i,r}_{FLW}\right) \quad (3)$$

$$DI^{i,r}_{per} = FS^{i,r}_{energy\_per} \times \left(1 - f^{i,r}_{FLW}\right) \quad (4)$$

where $DI^{i,r}$ and $DI^{i,r}_{per}$ refer to the national and per capita caloric intake amount of product i in country r each year, respectively. $FS^{i,r}_{energy}$ and $FS^{i,r}_{energy\_per}$ are the national and per capita supply quantity (in calorie content) of product i annually, respectively. Parameter $f^{i,r}_{FLW}$ is the FLW factor in the household consumption stage[39] of food product i in country r. Others[39] provide regional FLW factors, expressed as the weight percentage of food that is lost or wasted at different stages of food production and consumption, for different food categories. As a result, household food waste is subtracted from the FS to obtain the dietary intake amount of each product. Detailed household FLW factors are shown in Supplementary Table 16.

Quantifying dietary GHG emissions. Our equation (1) can be transformed into the following equation to calculate the total emission intensity of food calorie consumption:

$$F^{i,r}_{energy} = \frac{E^{i,r}}{DMC^{i,r}_{energy}} = \frac{\mathbf{F}^i\mathbf{DMC}^{i,r}}{DMC^{i,r}_{energy}} \quad (5)$$

where $F^{i,r}_{energy}$ represents total emissions per unit of calorie content of product i in country r, $DMC^{i,r}_{energy}$ refers to total calorie content of product i consumed domestically in country r. Then, emissions from the

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dietary intake (without FLW) of product i in country r ($E_{\text{intake}}^{i,r}$) are calculated as follows:

$$E_{\text{intake}}^{i,r} = F_{\text{energy}}^{i,r} \text{DI}^{i,r} \tag{6}$$

Classification of food categories. The EAT-Lancet Commission report provides coverage of different food categories in the planetary health diet and their recommended caloric intake levels at 2,500 kcal for adults each day[12] (Supplementary Table 17). In this study, we classify 140 products into 13 aggregated food categories according to the planetary health diet[12], including grains, tubers or starchy vegetables, vegetables, fruits, dairy products, red meat (beef, lamb and pork), chicken and other poultry, eggs, fish, legumes, nuts, added fats (both unsaturated and saturated oils) and all sugars. On the basis of the data availability of the FAOSTAT[4,82], the food products in this study include both primary and processed products (primary and secondary food processing) which can be classified into specific food categories[16]. Ultraprocessed products that combine ingredients from several food categories, such as ice creams made from both dairy and sugar, are not considered. Detailed coverages of each food category and their mapping relationship with specific products are shown in Supplementary Table 18.

Matching diets with the household-expenditure dataset

We explore the dietary emissions from consumers with different expenditure levels (defined as expenditure groups) using the household-expenditure dataset[41] for the year 2011. The dataset, containing 116 countries and almost 90% of the global population (Supplementary Table 19), is primarily based on the household survey microdata from the WBGCD[42], supplemented by consumer expenditure surveys of national statistical offices from high-income countries such as the United States and European countries[17,41]. For every country in the dataset, 201 expenditure groups (grouped according to the per capita total expenditure of each group) and the corresponding population share are listed. The annual per capita expenditure of people in different expenditure groups ranges from <US$50 to ~US$1 million per year (expressed in 2011 Purchasing Power Parities, PPP)[31,34]. For each expenditure group, the expenditure for 33 different sectors of goods and services (including 11 food items) and the corresponding expenditure share in national consumption of each sector are provided[31,34,41]. For some affluent (or poor) countries that do not have a sufficient representative number of people at the bottom (or top) end of the expenditure spectrum, the population in the corresponding expenditure groups is empty. Expenditure shares of 11 food items are matched with the 140 products in this study (Supplementary Table 20). We calculate the dietary intake of different food products for each expenditure group in each country by multiplying the food expenditure share of groups with the total dietary intake amounts of food products of each country.

This study assumes that the amount of food consumption is proportionate to food expenditures and the purchasing price for the same product is unchanged across 201 groups ignoring higher prices for high-quality or luxury food items within the same food category. Although the assumption of an unchanged purchasing price is an unsolved limitation shared by similar studies using monetary expenditure data[31,34,41], household expenditures on food can still effectively highlight the differences in food consumption and emissions across consumer groups with different affordability of, and spending on, food. We also assume that the proportion of food sources from local production and trade for the same food category remains constant across the 201 groups. In other words, the magnitude of dietary emissions is solely determined by the size and pattern of food expenditure of each group and the associated supply chains for each food consumption item.

For countries that are major food consumers (and emitters) but without data in WBGCD, expenditure shares from countries with similar development levels and eating habits and neighbouring geographical locations are used to calculate the distribution of their food expenditure. We finally select 201 expenditure groups in 139 countries/areas, covering 95% of the global population in 2019 (Supplementary Table 3 and Supplementary Data 3). Details for dealing with missing data are provided in Supplementary Table 7. Countries or areas are then classified into 18 regions for comparison according to geographical locations (Supplementary Table 8). The WBGCD expenditure data from the year 2011 are adjusted to PPP in 2019 to represent the expenditure level of populations in figures. Results of emissions from 13 types of food categories of 201 expenditure groups at the national and regional levels are shown in Supplementary Data 8, 10 and 11.

Analysis of GF-Gini coefficients

Calculation of GF-Gini coefficients. This study uses the GF-Gini coefficient[33,89], which is based on the well-known Gini coefficient[90], to measure the inequality of GHG footprints from 201 expenditure groups within countries, regions and globally. The GF-Gini coefficient ranges from 0 to 1, indicating the emission distribution across expenditure groups changes from perfect equality to perfect inequality. The GF-Gini coefficient of each food category is calculated as[33]:

$$\text{Gini}^{j} = \sum_{m=1}^{201} D_m^j Y_m^j + 2\sum_{m=1}^{201} D_m^j \left(1 - T_m^j\right) - 1 \tag{7}$$

where Gini^j indicate the GF-Gini coefficient of food category j (including product i, $i = 1, 2, 3, \ldots, n$). Expenditure groups and their population are reordered in ascending order of per capita GHG footprint of food category j and m refers to the reordered number of groups ($m = 1, 2, 3, \ldots, 201$). D_m^j and Y_m^j represent the proportions of population and GHG footprints (of food category j) for each expenditure group, respectively. T_m^j is the cumulative proportion of GHG footprints of each expenditure group. The results of national, regional and global GF-Gini coefficients are shown in Supplementary Tables 9 and 10.

Regression analysis. We use the regression approach to examine the relationship between the national GF-Gini coefficients and the per capita GDP[91,92] of 139 countries/areas. The GF-Gini coefficient of each country is regarded as the dependent variable (y) and the national per capita GDP acts as the independent variable (x). Initially, locally weighted regression is applied to illustrate the trend lines within the scatterplot. Subsequently, we test different regression methods for validation based on the general trend. Ultimately, we found that logarithmic regression is the most fitting for dietary emissions of most food categories, particularly in the case of animal-based products. Thus, the logarithmic regression is applied.

Scenario of the planetary health diet

Scenario setting and assumptions. To estimate the emission changes resulting from the transition from the 2019 diet to the global planetary health diet, we build a hypothetical scenario by assuming that individuals belonging to 201 different expenditure groups in all countries will all reach the reference intake level of 13 types of food categories[12]. First, we assume that the proportion of food sources from local production and trade in each country is unchanged, that is, emission changes from dietary shifts would be calculated on the basis of emissions from local production and imports accounting for emissions along global food supply chains, similar to studies by refs. 25,26. At the same time, emission changes induced by decreased food consumption in countries following the planetary health diet, such as carbon uptake from agriculture abandonment[59] or emission increase from non-food biomass production in saved agricultural land[77], are not considered in this study. Second, we assume that agricultural and food-related production technology, trade patterns and emission intensities of food supply chain processes remain unchanged during the diet transition. Third, fluctuations in food prices induced by altered food demand or the affordability of the planetary health diet for different consumer groups are not considered in this study.

Diet gaps for different food categories. The diet gap (DG) reflects gaps between present dietary intake and the planetary health diet[12,25], as follows:

$$\mathrm{DG}_{\mathrm{per}}^{j,r} = \frac{\mathrm{DI}_{\mathrm{per}}^{j,r}}{\mathrm{DI}_{\mathrm{EAT\_per}}^{j}} = \frac{\mathrm{DI}_{\mathrm{per}}^{j,r}}{365 \times \mathrm{DI}_{\mathrm{EAT\_day\_per}}^{j}} \tag{8}$$

where $\mathrm{DG}_{\mathrm{per}}^{j,r}$ is defined as the percentage ratio of the present per capita caloric intake of food category j in country r each year ($\mathrm{DI}_{\mathrm{per}}^{j,r}$) to the annual reference level ($\mathrm{DI}_{\mathrm{EAT\_per}}^{i}$). $\mathrm{DI}_{\mathrm{EAT\_day\_per}}^{j}$ is the recommended per capita caloric intake of food category j each day[12] (Supplementary Table 17). We assume a uniform annual calorie reference level for each food category across all populations in all countries. We allow flexibility in local diets by keeping the composition of each food category unchanged, requiring only that the calorie content reaches the reference level. According to the definition, present food intake is considered insufficient compared with reference levels when DG is <100%, while it is deemed excessive and should be reduced when DG is >100%. Daily per capita caloric intake of food categories from 201 expenditure groups of countries or regions are shown in Supplementary Data 12 and 13. We calculate the DG for food categories of 201 expenditure groups at national and regional levels (Supplementary Data 14 and 15).

Emission changes from adopting the planetary health diet. According to equation (1), the total emissions per unit of calorie content of food category j in country r ($F_{\mathrm{energy}}^{j,r}$) can be calculated as:

$$F_{\mathrm{energy}}^{j,r} = \frac{E^{j,r}}{\sum_{i=1}^{n} \mathrm{DMC}_{\mathrm{energy}}^{i,r}} = \frac{\sum_{i=1}^{n} E^{i,r}}{\sum_{i=1}^{n} \mathrm{DMC}_{\mathrm{energy}}^{i,r}} \tag{9}$$

where $E^{j,r}$ refers to the national emissions due to consumption of food category j in country r. Thus, emission changes for adopting the planetary health diet are calculated as follows:

$$\Delta E_{\mathrm{intake}}^{j,r} = F_{\mathrm{energy}}^{j,r}\left(\mathrm{DI}_{\mathrm{EAT\_per}}^{j} - \mathrm{DI}_{\mathrm{per}}^{j,r}\right)p^{r} = E_{\mathrm{intake}}^{j,r}\left(\frac{1}{\mathrm{DG}_{\mathrm{per}}^{j,r}} - 1\right) \tag{10}$$

where $\Delta E_{\mathrm{intake}}^{j,r}$ represents the national emission changes of food category j in country r, $E_{\mathrm{intake}}^{j,r}$ is the national emissions from intake of food category j in country r. Changes in dietary emissions of food categories from 201 groups are shown in Supplementary Data 9. The number of people with increased/decreased emissions from 201 groups is shown in Supplementary Data 19.

Uncertainty analysis

We assess the uncertainty range of dietary emissions from different food products using a Monte Carlo approach, which simulates the uncertainties caused by activity data, emission factors and parameters in each emission process[16,59,93]. More details can be found in Supplementary Methods 1.

Limitations

This study has the following limitations regarding data analysis and scenario setting.

In terms of data analysis, this study is limited by the data availability. First, we use regional household food loss and waste factors of aggregated food categories without more detailed product division at the national level because of a lack of data. There might also be differences between calculated and actual food intake amounts that are unable to be removed, such as animal bones or fruit skins[25]. Second, we use the consumer household-expenditure dataset based on WBGCD for the year 2011, which provides the most precise and detailed differentiation of consumer groups and their consumption patterns within countries so far. We assume that the shares in food expenditure and population for each expenditure group are the same as in 2011. Third, we assume that the composition of different products aggregated in one category consumed by expenditure groups is the same as the national consumption composition and there is no difference in the price of food products purchased by people from different expenditure groups. In addition, data for some populous high- or upper-middle-income countries are missing from the household-expenditure dataset. However, the countries are the world's major food consumers and emitters, their emission changes due to diet shifts are important for the global food system. We use the expenditure shares of similar countries in the household-expenditure dataset to allocate the distributions of food expenditure in these countries.

In terms of scenario setting, we focus on the impact induced by changes in consumer choices without changing the proportion of food supply sources (domestic production and imports). We do not consider altering the proportions of supply sources and associated emissions in this study. However, future studies may explore the impacts of the production side and supply chains for diet shifts. Moreover, as we focus on the present emission inequality and mitigation potentials within the food system, we assume that the income and expenditure levels of expenditure groups remain unchanged. However, a shift in food supply may affect household income and subsequently alter the household food budgets, especially for populations employed in, or countries reliant on, food-related sectors. Additionally, as a result of data and model limitations, this study does not consider price fluctuations induced by food demand and subsequent changes in household affordability or spillover effects (between food categories or to non-food sectors). Future studies may combine assessment models incorporating elasticities to project the long-term feasibilities and consequences of diet shifts.

Reporting summary

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

Data availability

Data for LULUC, agricultural and beyond-farm emissions and data for physical food consumption are curated by the FAO and can be freely obtained from FAOSTAT[82], available from ref. 16. Data of food loss and waste rate are retrieved from FAOSTAT[82] and ref. 25. The global household-expenditure data are obtained from the World Bank[42] and refs. 17,41. Population data used in this study are obtained from World Population Prospects of the United Nations[86]. Data on per capita GDP in countries can be collected from the World Bank[91] and the International Monetary Fund[92]. Supplementary datasets are also available on Zenodo (https://doi.org/10.5281/zenodo.11934909)[94]. Source data are provided with this paper.

Code availability

Data collection is performed in MATLAB and Microsoft Excel. Code developed for data processing in MATLAB and R in this study is available from Zenodo (https://doi.org/10.5281/zenodo.11880402)[95].

References

80. Le Quéré, C. et al. Temporary reduction in daily global CO_2 emissions during the COVID-19 forced confinement. *Nat. Clim. Change* **10**, 647–653 (2020).
81. Shan, Y. et al. Impacts of COVID-19 and fiscal stimuli on global emissions and the Paris Agreement. *Nat. Clim. Change* **11**, 200–206 (2021).
82. *FAOSTAT Database* (FAO, 2022); https://www.fao.org/faostat/en/

83. *Supply Utilization Accounts, Food Blances, FAOSTAT Online Database* (FAO, 2022); https://www.fao.org/faostat/en/#data/SCL
84. Kastner, T., Kastner, M. & Nonhebel, S. Tracing distant environmental impacts of agricultural products from a consumer perspective. *Ecol. Econ.* **70**, 1032–1040 (2011).
85. Kastner, T., Erb, K.-H. & Haberl, H. Rapid growth in agricultural trade: effects on global area efficiency and the role of management. *Environ. Res. Lett.* **9**, 034015 (2014).
86. *World Population Prospects 2022* (United Nations, 2022); https://population.un.org/wpp/Download/Standard/Population/
87. *Food Balance Sheets—A Handbook* (FAO, 2001); https://www.fao.org/3/x9892e/X9892e05.htm#P8217_125315
88. *Nutritive Factors* (FAO, 2023); https://www.fao.org/economic/the-statistics-division-ess/publications-studies/publications/nutritive-factors/en/
89. Wiedenhofer, D. et al. Unequal household carbon footprints in China. *Nat. Clim. Change* **7**, 75–80 (2017).
90. Gini, C. Measurement of inequality of incomes. *Econ. J.* **31**, 124–125 (1921).
91. *The World Bank Data: GDP per Capita (Current US$)* (World Bank, 2023); https://data.worldbank.org/indicator/NY.GDP.PCAP.PP.CD
92. *Datasets, World Economic Outlook (April 2023): GDP per Capita, Current Prices* (IMF, 2023); https://www.imf.org/external/datamapper/NGDPDPC@WEO/OEMDC/ADVEC/WEOWORLD
93. Xu, X. et al. Global greenhouse gas emissions from animal-based foods are twice those of plant-based foods. *Nat. Food* **2**, 724–732 (2021).
94. Li, Y. et al. Supplementary Datasets for 'Reducing climate change impacts from the global food system through diet shifts'. *Zenodo* https://doi.org/10.5281/zenodo.11934909 (2024).
95. Li, Y. et al. Code for 'Reducing climate change impacts from the global food system through diet shifts'. *Zenodo* https://doi.org/10.5281/zenodo.11880402 (2024).

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Author contributions
Yanxian Li, Y.S. and K.H. designed the research. Yanxian Li performed the analysis with support from P.H., Yu Li, Y.H. and S.S. on analytical approaches and visualization. Yanxian Li led the writing with efforts from P.H., Y.S., F.R. and K.H. Y.S. and K.H. supervised and coordinated the overall research. All co-authors reviewed and commented on the manuscript.

Competing interests
The authors declare no competing interests.

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Software and code

Policy information about availability of computer code

Data collection	Data collection is performed in Matlab 2022b and Microsoft Excel.
Data analysis	Data analysis for calculating dietary emissions and scenario setting is performed in Matlab 2022b. The regression analysis and visualization are performed using R (Version 4.2.2). Code developed for data processing in MATLAB and R is available from Zenodo (https://doi.org/10.5281/zenodo.11880401).

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Data for LULUC, agricultural and beyond-farm emissions and data for physical food consumption are curated by the FAO and can be freely obtained from FAOSTAT, available from the previous publication (https://doi.org/10.1038/s43016-023-00768-z). Data of food loss and waste rate are retrieved from FAOSTAT (https://

www.fao.org/faostat/en/) and published research (https://doi.org/10.1038/s43016-021-00452-0). The global household expenditure data are obtained from the World Bank (https://datatopics.worldbank.org/consumption/) and published research (https://doi.org/10.1038/s41467-017-00919-4). Population data used in this study are obtained from World Population Prospects of the United Nations (https://population.un.org/wpp/Download/Standard/Population/). Data on per capita GDP in countries can be collected from the World Bank (https://data.worldbank.org/indicator/NY.GDP.PCAP.PP.CD) and the International Monetary Fund (https://www.imf.org/external/datamapper/NGDPDPC@WEO/OEMDC/ADVEC/WEOWORLD). Supplementary figures, tables, Source data, and Supplementary datasets used in this study can be found in the Supplementary Information files. Supplementary datasets are also available on Zenodo (https://doi.org/10.5281/zenodo.11934909).

Human research participants

Policy information about studies involving human research participants and Sex and Gender in Research.

Reporting on sex and gender	N/A
Population characteristics	N/A
Recruitment	N/A
Ethics oversight	N/A

Note that full information on the approval of the study protocol must also be provided in the manuscript.

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Study description	This study: 1) evaluates emissions along global food supply chains induced by current diets in 139 countries; 2) quantifies the dietary emissions from detailed products and population groups, and estimates the inequality of dietary emissions within countries; 3) simulates the scenario of global shifts towards the planetary health diet to explore potentials of emission mitigation from the food system.
Research sample	This study covers the diets composed with 140 types of food products (both animal- and plant-based products), classified into 13 food categories (according to the EAT-Lancet planetary health diet) in 139 countries in 2019. The emissions along supply chains include emissions from land use and land use change, agriculture production, and other beyond-farm activities. We use the World Bank household expenditure dataset to allocate dietary emissions into 201 expenditure groups, and exhibit results at the global, regional and national levels. The scenario setting is based the assumption that the global population all reach the same dietary intake level according to the planetary health diet.
Sampling strategy	We quantify the dietary emissions along global food supply chains of different food products by final consumers with different expenditure levels by bridging the detailed food consumption data with detailed household expenditure dataset. We further simulate the scenario of worldwide adoption of the EAT-Lancet planetary health diet to examine the global dietary emission changes from expenditure groups and products.
Data collection	Yanxian Li collected the data required for this study with support from Yuli Shan and Klaus Hubacek. The datasets for dietary emissions are extracted from FAOSTAT and can be freely obtained, available from the previous publication. The global household expenditure data are curated from the World Bank. Other datasets are obtained from database (e.g., the United Nations, IMF, etc.) and individual publications cited by this study.
Timing and spatial scale	We analyze the dietary emissions for the year 2019 as the baseline, using data collected from published database and individual publications. The data collection and analysis starts on 1/12/2022 and ends on 1/5/2023.
Data exclusions	No data is excluded in this study.
Reproducibility	We provide all the detailed methods and data sources, programming code and results in both the manuscript and supplementary information files to ensure the reproducibility of this work.
Randomization	This is not relevant to our study because our work is not an Experimental study. We use survey-based household datasets and published datasets of food consumption and emissions to perform the calculation.
Blinding	Blinding is not relevant to this study, because this study only uses published datasets and model simulation.

Did the study involve field work? ☐ Yes ☒ No

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