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Small targeted dietary changes can yield substantial gains for human health and the environment

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To identify environmentally sustainable foods that promote health, we combined nutritional health-based and 18 environmental indicators to evaluate, classify and prioritize individual foods. Specifically for nutrition, we developed the Health Nutritional Index to quantify marginal health effects in minutes of healthy life gained or lost of 5,853 foods in the US diet, ranging from 74 min lost to 80 min gained per serving. Environmental impacts showed large variations and were found to be correlated with global warming, except those related to water use. Our analysis also indicated that substituting only 10% of daily caloric intake from beef and processed meat for fruits, vegetables, nuts, legumes and selected seafood could offer substantial health improvements of 48 min gained per person per day and a 33% reduction in dietary carbon footprint.

Dietary choices, human health and environmental sustainability are inextricably linked through food production and consumption[1]. Overconsumption of food detrimental to health and underconsumption of food beneficial for health are leading causes of health burden in the United States[2], responsible for more than 10,000,000 disability-adjusted life years (DALYs) due to non-communicable chronic diseases in 2016[3]. Dietary choices also influence food production, which is associated with multifaceted environmental impacts[4] such as anthropogenic greenhouse gas emissions[5] and land competition[6], while agriculture-related air pollution damages human health[7]. Although all food systems induce environmental impacts, the magnitude of these impacts differs substantially between commodities[5,6]. Several studies have discussed and proposed environmental limits for food systems that safeguard humanity and the Earth's system[8–12]. With health burdens and environmental impacts projected to increase further due to population growth, we are faced with an urgency in meeting current and future food security needs using healthy and sustainable solutions[13].

Previous studies suffer from several methodological barriers that cause them fail to capture the complexity of the food landscape and hinder dietary improvements. Separate guidance on environmental sustainability and nutrition[14] generates confusion among consumers[15]. Diet/dietary pattern recommendations with both nutritional and environmental considerations call for dietary shifts towards plant-based food[14,16], which are challenging to achieve[17,18]. Generally, diet-level recommendations can be difficult to translate into food choices[19] due to challenges associated with nutrition literacy[20], lack specific and actionable direction to motivate consumer behaviour change[21] and often fail to capture the magnitude between the best- and worst-performing individual foods nutritionally[22] and environmentally[6] within food groups. Therefore, we need improved and multiperspective approaches[23] to properly evaluate individual foods as part of our food systems (Fig. 1).

Life-cycle assessments (LCAs) can evaluate the production-related environmental impacts of different food systems[1,6,24]. However, the consumption-related health impacts of foods are equally important but have not been well integrated[25]. Methods to evaluate food-specific nutrition in both nutritional assessments and food LCAs have primarily relied on nutrient profiling models[22,26–28] but fail to directly link nutrition to health[29], with few exceptions focusing on diets[1,30,31].

Epidemiology-based nutritional assessments have characterized the health burden associated with individual nutrients and food risks at the population level, but are not applicable as such to individual foods[1–3,32]. We have previously piloted a promising adaptation of the Global Burden of Disease (GBD) approach at the food level, using the health effects of milk on colorectal cancer as an example[25]. However, the foods we consume are more complex, such as mixed dishes (multi-ingredients foods such as pizza, tacos and soups), and require the consideration of a large variety of dietary risks and health outcomes.

In this article we first develop a new epidemiology-based nutritional index and use it to evaluate the nutritional performance of 5,853 foods consumed in the US diet. We then compare the nutritional and environmental impacts of individual foods and classify them into prioritization classes (Fig. 1). We use the results to inform marginal dietary substitutions, which are realistic and feasible. We find that small, targeted, food-level substitutions can achieve compelling nutritional benefits and environmental impact reductions.

Results

Dietary risk factors. Using a comparative risk assessment and nutritional epidemiology evidence, we quantified for US adults (aged ≥25 yr) the marginal health burden associated with 15 dietary risks, defined as dietary risk factors (DRFs) and expressed in DALYs per g intake of risk component. Estimates cover health benefits, expressed in avoided DALYs, associated with milk, nuts and seeds, fruits, calcium, omega-3 fatty acids from seafood, fibres (fibre from fruits, vegetables, legumes and whole grains differentiated from other sources) and polyunsaturated fatty acids (PUFAs). DRF estimates also cover the health damages associated with

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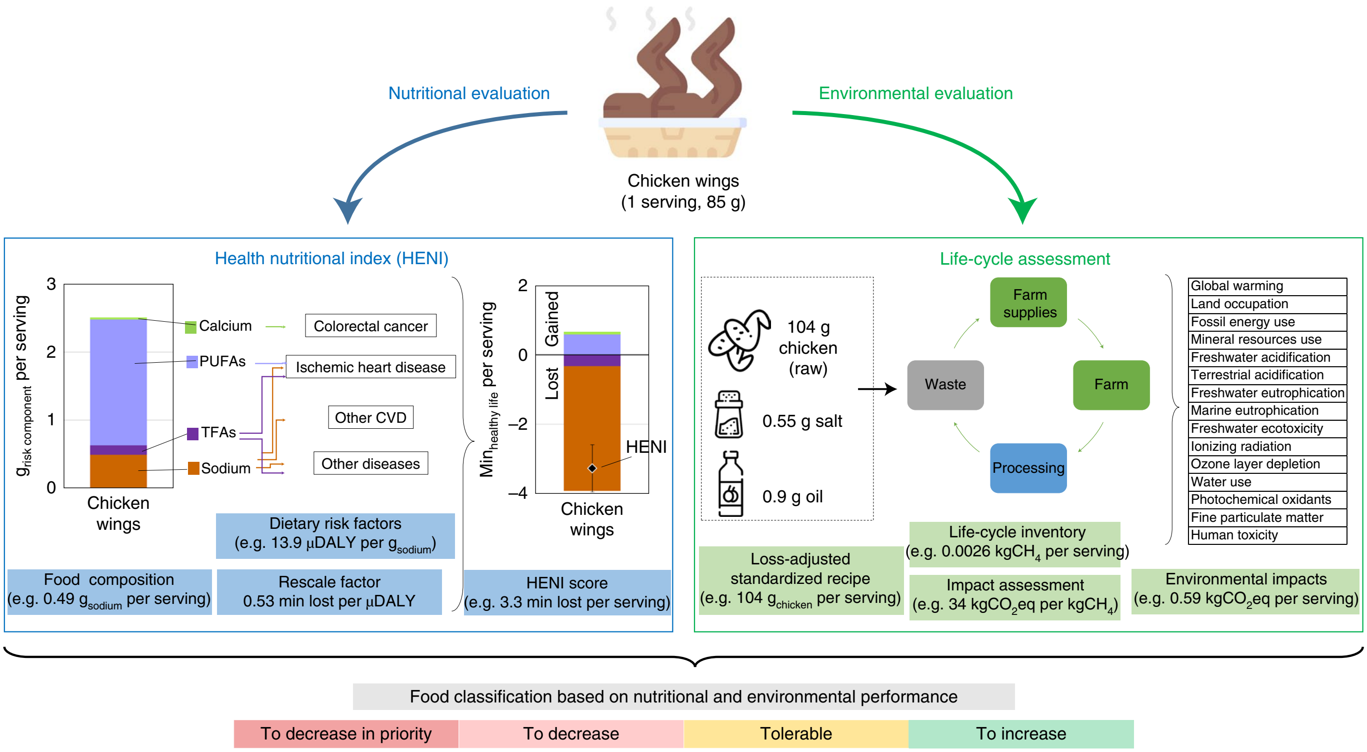

Fig. 1 | Proposed framework to evaluate and compare the nutritional and environmental performances of individual foods. This framework was used to identify, prioritize and inform dietary changes towards healthy and environmentally sustainable diets. Illustration based on a serving of chicken wings (85 g). CVD, cardiovascular disease. The icons used in the figure were made with Freepik from www.flaticon.com.

processed meat, red meat, *trans* fatty acids (TFAs), sugar-sweetened beverages (SSBs, mediated through body mass index) and sodium (mediated through blood pressure). These dietary risk components and their associations with adverse health effects were obtained from the 2016 GBD study[3] (Supplementary Table 1). The approach for determining risk-specific DRFs is described in the Methods and more details are provided in Supplementary Information, section 1. Energy-related dietary risk components such as TFAs and PUFAs were adjusted for daily energy requirements for US adults (Supplementary Table 2).

The health burden for most risks is driven by ischemic heart disease mortality (Fig. 2). The beneficial effects of calcium, fibre and milk are associated with avoided premature deaths from colorectal cancer. For red meat, the majority of the health burden associated with these risks is from diabetes morbidity (45%) and mortality (27%). For a US adult, the cumulative health burden attributable to a 1 g intake of each dietary risk ranges on average from a health benefit of 81 avoided µDALYs per g omega-3 fatty acids from seafood (95% confidence interval (CI), 37–113) to a health loss of 14 µDALY per g intake increase of sodium (95% CI, 11–16; Supplementary Table 3). These estimates are valid within the active intake ranges determined by the underlying epidemiological studies (see Supplementary Table 1). Typical intakes for these risks fall within these ranges for US adults[33]; thus, our estimates apply to the majority of the US adult population.

Characterizing the health burden associated with these dietary risks components informs the consumption-related health impacts of foods, which is currently missing in LCAs[34,35]. Introducing these DRFs into LCAs pioneers a nutritional human health damage approach that enables the comparison of environmental and nutritional impacts of foods and diets on human health in a common metric, µDALYs[25].

Health Nutritional Index. The health burden attributable to a given food or mixed dish, defined as the Health Nutritional Index (HENI), is calculated by combining the 15 DRFs with the corresponding risk component composition[36] (Supplementary Fig. 2). Each DRF is multiplied by the amount of risk component in g per reference amount of the considered food (for example, g sodium per serving of chicken wing). Aggregating risks and rescaling the net estimate from µDALYs to minutes of healthy life (through the formula 1 µDALY = 1 yr of healthy life lost × 365 (days per year) × 24 (hours per day) × 60 (minutes per hour) × 10^{-6} = −0.53 min of healthy life gained) yields a food-specific HENI score (nutritional evaluation in Fig. 1).

HENI is a continuous single score that quantifies the net minutes of healthy life gained (+) or lost (−) from all-cause mortality and morbidity per reference amount of food (for example, a standard serving size). Health gains or losses are attributable to the addition of a marginal reference amount of food to the current diet of US adults under the assumption that the health effect from multiple dietary risks is independent and additive and that food components not covered by the GBD have neutral health effects. In this analysis, the term ‘healthy food’ covers foods the consumption of which will benefit the health of most of the population by reducing the risk of developing adverse health outcomes (for example, foods with positive HENI scores). In contrast, foods with negative HENI scores indicate that consumption increases the risk of developing adverse health outcomes and will be detrimental to human health. This terminology is subject to limitations in the context of the overall diet.

Seven foods of diverse composition were selected to illustrate this approach, starting with a serving of chicken wings. According to its food composition[36], an 85 g serving of chicken wings contains four components affecting health, that is, calcium and PUFAs on

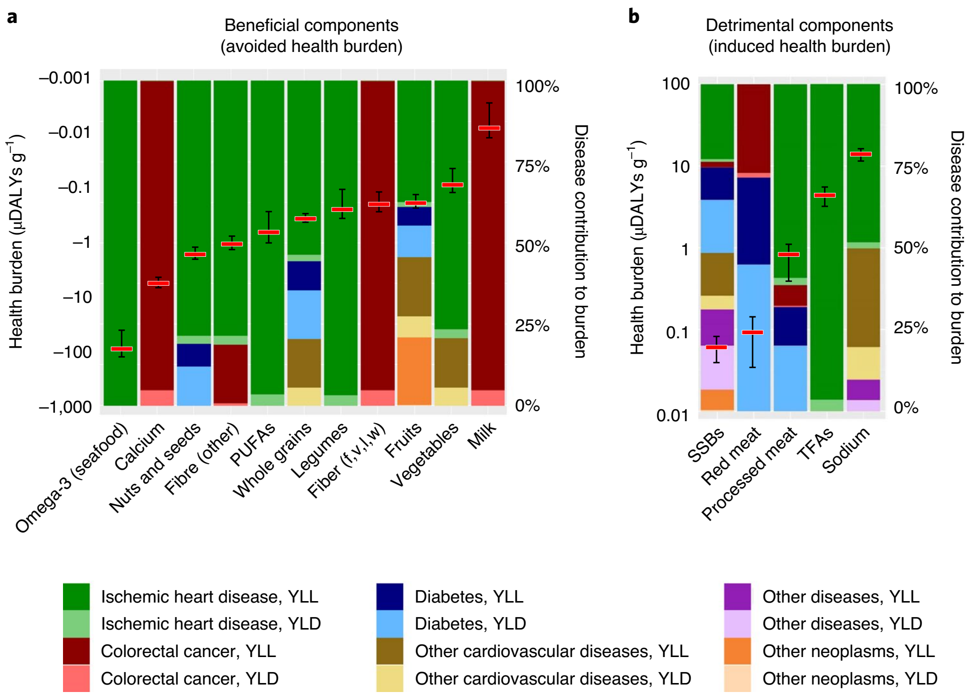

Fig. 2 | Beneficial and detrimental dietary risk factors. a,**b**, Cumulative gender- and age-adjusted dietary risk factors (DRFs) for beneficial (**a**) and detrimental (**b**) dietary risks. DRFs are measured in μDALYs per g risk component and represent the health burden for US adults (aged ≥25 yr). Red bars show mean DRF estimates and black lines the 95% CIs (left axis). Stacked bars show relative disease burden contribution (right axis). Fibre is divided into fruit, vegetables, legumes and whole grains (f,v,l,w) and other sources. Omega-3 fatty acids are restricted to those that originate from seafood sources. Other diseases considered are listed in Supplementary Table 4.

the beneficial side, and sodium and TFAs on the detrimental side (Figs. 1 and 3a). We multiply the amounts of these four risks by their corresponding DRFs to get the health burden associated with each risk (for example, $0.49\,g_{sodium}$ per serving × 13.9 μDALYs per g_{sodium} = 6.8 μDALYs per serving due to sodium). Aggregating the health burden across the four risks and rescaling the units from μDALYs to minutes of healthy life as described above yields the HENI score of a serving of chicken wings at 3.3 min of healthy life lost (95% CI, 2.5–3.9 min; see diamond in Figs. 1 and 3b, detailed calculation in Supplementary Information, section 2.2). The health burden attributable to a serving of beef hotdog on a bun is 36 min lost (95% CI, 22–45 min), largely due to the detrimental effect of processed meat (Fig. 3b). For vegetable pizza (1.4 min lost per serving; 95% CI, 0.061–2.8 min) and apple pie (1.3 min gained per serving; 95% CI, −0.42 to 2.9 min), the health benefits from some vegetables and fruits are offset by the detrimental health effects of sodium and TFAs, leading to an almost neutral HENI score. The beneficial health effects of seafood-sourced omega-3 fatty acids, nuts and legumes are highlighted in the cases of baked salmon, salted peanuts, and rice with beans, while sodium had relatively limited overall contributions to HENI for each individual food, but was present in most foods.

Minutes of healthy life gained or lost for all US foods. We estimated the HENI scores per standard serving for 5,853 foods consumed in the US diet (Fig. 4 and Supplementary Table 5). HENI scores show considerable inter- and intra-food category variability that could not be explained by food characteristics such as energy density and serving size (Supplementary Fig. 3). Median HENI scores by food category range from 35 min lost per serving of frankfurter sandwiches (N = 37; interquartile range (IQR), 31–41 min) up to 33 min gained per serving of peanut butter and jelly sandwiches (N = 17; IQR, 29–34 min). However, estimates can be as low as 71 min lost per serving for corned beef with tomato sauce and onion (95% CI, 38–91 min; the damaging effects of processed meat overpower the benefit of the small amounts of tomatoes and onions in that food) and up to 82 min gained per serving for sardines with a tomato-based sauce (95% CI, 37–115 min). No significant correlation was found between HENI scores and food energy density or serving size (Supplementary Fig. 3). Median uncertainties on HENI scores amount to ±1 min for absolute HENI values lower than 5 min, and to ±2.5 min for absolute HENI scores of around 10 min. Uncertainty continues to increase with HENI, with higher uncertainties for seafood-based items (Supplementary Fig. 4).

Interestingly, our results offer unambiguous and generalizable inferences for only a few food categories. HENI scores for frankfurter and breakfast sandwiches, burgers and red meat are almost exclusively negative, indicating that eating an additional serving of these foods is health-damaging. On the other hand, increasing the consumption of nuts and of peanut butter and jelly sandwiches (driven by nut content), legumes, seafood, fruits, snack bars, ready-to-eat cereals and non-starchy vegetables is health beneficial as most of these foods have positive HENI scores. The HENI range of the remaining food categories highlights the importance of identifying foods with positive or negative scores within each food category and stresses the need for food-specific recommendations. In general, variability within and across food categories is higher than the above-reported uncertainties for HENI estimates of individual foods.

Food categories rank similar to the serving-based results when evaluating foods per 100 kcal and 100 g (Supplementary Figs. 5–7), but we find larger differences in HENI scores at the individual food level. Also, it is only in certain food categories that HENI is sensitive to excluding elements (that is, TFAs) or expanding the model to include additional dietary risk components such as added sugar

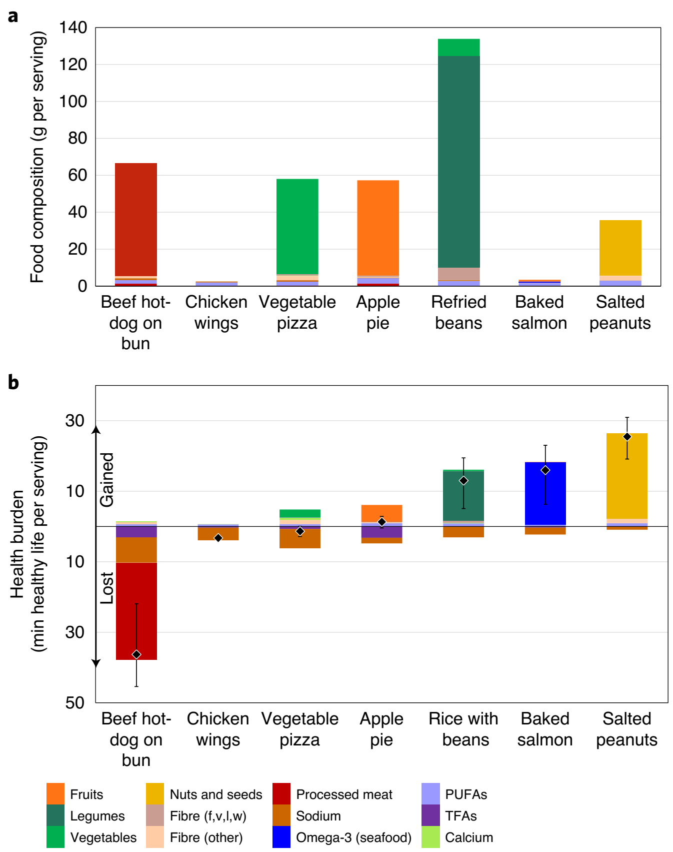

Fig. 3 | Nutritional health burden evaluation of selected foods in the US diet. a, Nutritional composition of foods by risk component in g per serving. **b**, Nutritional health burden by dietary risk in minutes of healthy life per serving. Black diamonds represent the net HENI score per serving and black lines its 95% CI. Fibre is divided into fruit, vegetables, legumes and whole grains (f,v,l,w) and other sources. Omega-3 fatty acids are restricted to those that originate from seafood sources.

or saturated fatty acids (see sensitivity studies in Supplementary Figs. 8–10 and Supplementary Table 6).

Overall, HENI offers a more nuanced and informative food evaluation. It enables quantification of the benefits or damages associated with a marginal consumption increase of individual foods, with scores primarily meant to be used for relative comparisons. HENI can shed light on the drivers and hidden health risks and benefits of foods, especially mixed dishes. Moreover, HENI translates complex nutritional information into a simple but meaningful score. Therefore, these results are clear, relatively easy to understand and can inform consumers and stakeholders[37].

Combined environmental and nutritional food classification. We combined HENI with the life-cycle environmental impacts of individual foods. We investigated 18 environmental indicators that characterize environmental impacts and damages on human health, ecosystems and resources from the IMPACT World+ life-cycle impact assessment method[38], complemented by improved assessments for consumptive water use and the human health damages from fine particulate matter ($PM_{2.5}$) formation (Supplementary Tables 7–10). We focused on the commonly consumed and median HENI foods from each food category ($N = 167$), as a representative sample of the diet. Environmental impacts were determined using LCAs and accounted for the complex multi-ingredient composition and ingredient losses of individual foods (see environmental assessment in Fig. 1 and Supplementary Figs. 11–14). We then classified foods into three colour-coded zones (green, amber and red) based on their combined nutritional and environmental performances (Fig. 5, Supplementary Figs. 15 and 16, and Supplementary Table 11).

The green zone contains foods that are both nutritionally beneficial (HENI > 0) and have low environmental impacts (below the 50th percentile, that is, shorter-term global warming impacts <0.32 $kgCO_2eq$ per serving). This classification constitutes a win–win solution, meaning that consumption of foods in this category can lead to healthy and environmentally sustainable diets. Foods in this zone are predominantly made out of nuts, fruits, vegetables, legumes, whole grains and some seafood. The nutritional performances of these primarily plant-based foods vary noticeably.

The red zone denotes foods that have either considerable negative nutritional or high environmental impacts, with scores exceeding the 75th percentile of foods (>3.2 min lost per serving or >0.61 $kgCO_2eq$ per serving, respectively). In this classification, nutritional impacts are primarily driven by the adverse health effects associated with processed meat and SSBs, whereas the climate change impacts are driven by beef, processed meat (mix of beef and pork), pork and lamb, which are known to be associated with considerable greenhouse gas emissions[26,39], cheese-based foods and some salmon dishes. The climate change load of these foods can reach up to 5.7 $kgCO_2eq$ per 244 g in the case of beef stew (factor 1.4 uncertainty), the equivalent of about 14 miles driven by an average passenger vehicle[40]. In the serving-based comparisons, we further differentiated the red zone to illustrate the 10% most nutritionally or environmentally impactful foods (dark red zone in Fig. 5a; HENI > 15 min lost per serving or >3.0 $kgCO_2eq$ per serving).

Finally, the amber zone offers choices of intermediate foods that are either slightly nutritionally detrimental (between 0 and 3.2 min lost, the 75th percentile of HENI) or generate moderate environmental impacts (between the 50th and 75th percentiles) and do not meet the green and red zone criteria. Most poultry, dairy (milk and yogurt), egg-based foods, cooked grains (for example, rice) and vegetables produced in a greenhouse fall into this intermediate zone.

Nutritional and environmental trade-offs of foods. The range of all indicators analysed varies substantially for the selected foods. For serving comparisons (Fig. 5), HENIs for the 167 foods range from 36 min lost to 33 min gained, shorter-term global warming impacts from 0.0005 to 5.7 $kgCO_2eq$, land occupation impacts from 0 to 4.0 ha-yr arable, $PM_{2.5}$-related human health damages range from 0.0001 to 1.5 min lost, and consumptive water use from <0.01 to 116 litres. Correlations between nutritional and environmental impacts are weak, regardless of indicator or comparison basis (Supplementary Fig. 17). In agreement with previous studies[41,42], this suggests that nutritionally beneficial foods might not always generate the lowest environmental impacts and vice versa. Most environmental indicators follow similar trends and correlate well with global warming impacts (Supplementary Figs. 15–17), with some nuances for freshwater eutrophication for which salmon and beef dishes generate the highest impacts per serving (Supplementary Fig. 15h) and per 100 kcal (Supplementary Fig. 16h). Consumptive water use estimates (for example, water used in a food's life cycle that is not returned to a stream, river or water treatment plant) show a very different food ranking compared to global warming impacts, with the highest estimate found in pork when foods are compared per serving (Fig. 5e) and also plant-based foods, such as rice, avocado, some fruits (for example, bananas and apples) and some nuts, when foods are compared per 100 kcal (Fig. 5f).

Uncertainties on the environmental impact scores of the 167 foods are characterized by the geometric squared standard deviation (GSD^2). As illustrated in Supplementary Figs. 15 and 16, median GSD^2 estimates typically vary by a factor 1.7 for global warming and fossil energy use, by a factor of 2–3 for the acidification

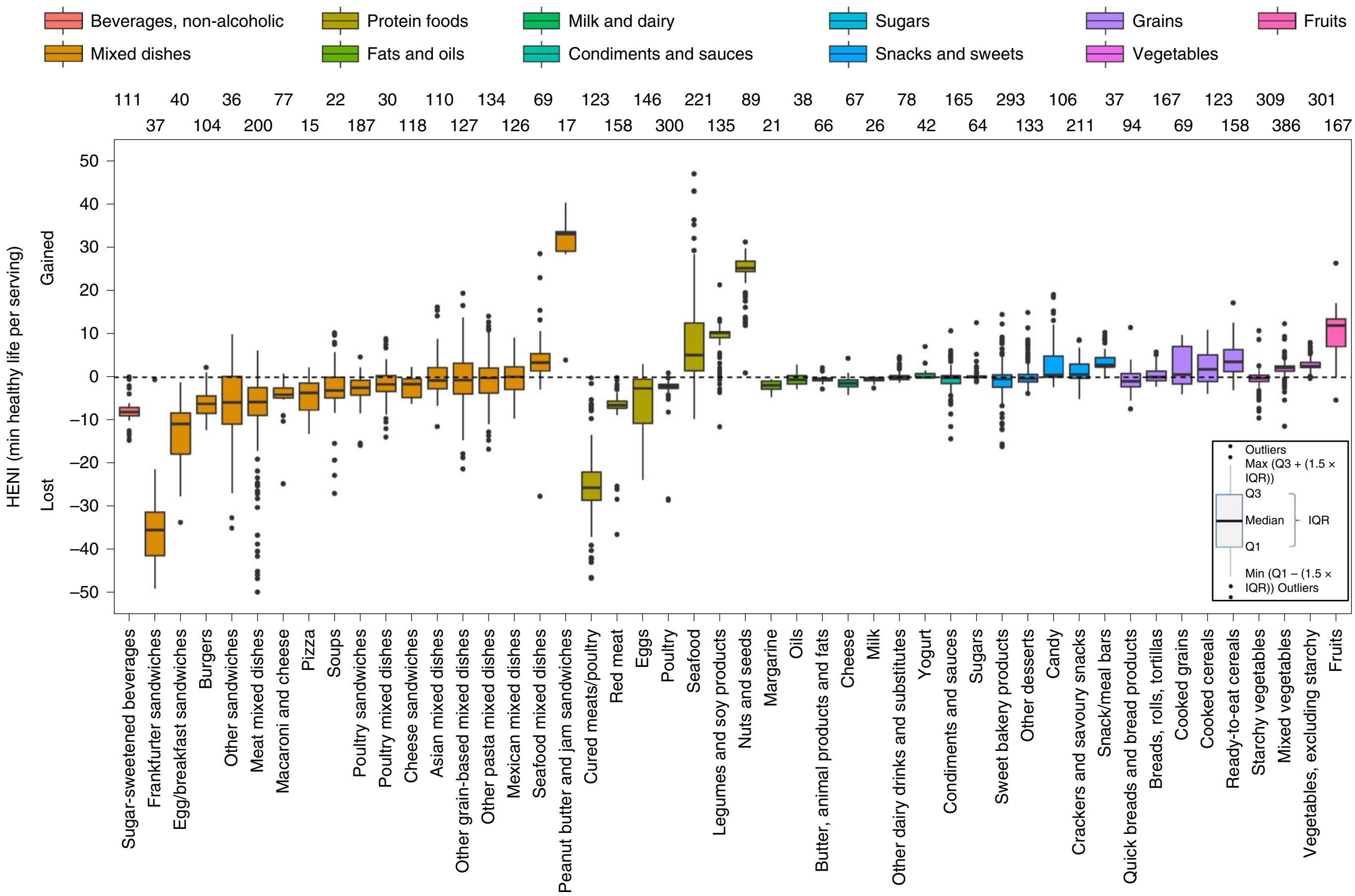

Fig. 4 | HENI score per serving for 5,853 foods in the US diet by food category. Positive scores indicate health benefits. Eleven foods are not shown (additional outliers). Numbers on top denote the number of foods in each category. Q1 = lower quartile of foods within the category; Q3 = upper quartile; IQR = Q3 − Q1.

and eutrophication categories as well as for consumptive water use and land occupation, and by a factor of 5–7 for human health and aggregated ecosystem quality damage, except for human toxicity, ecotoxicity and photochemical oxidant formation (GSD^2 a factor of ~20, see Supplementary Data 1 for food-specific estimates). For global warming, reported uncertainties show limited overlap within and across the different recommendation zones compared to individual food variability (Supplementary Fig. 15a). Overlap is higher in more uncertain impact categories such as human toxicity (Supplementary Fig. 15p).

Aggregating all health-related indicators (Supplementary Fig. 18) reveals that damages are often driven by nutrition. More specifically, health effects from nutrition are on average 1–2 orders of magnitude higher than human health damage generated by environmental impacts (for example, particulate matter, photochemical oxidants and global warming). This finding is to be taken with care due to the highly uncertain linkage between global warming impacts and health damage[38,43] and the differences in the exposed population and time period in which nutritional and environmental benefits are experienced. It nevertheless highlights the importance of nutritional health considerations in food sustainability assessments and the interest in using HENI to characterize nutritional health damage in a comparable metric as environmental health damages. This is particularly useful for food LCAs and risk assessments because DRFs can be used to introduce characterization factors for a new nutritional impact category.

A kcal-based comparison of foods brings complementary insights (Fig. 5b,f and Supplementary Fig. 16). Although the key findings remain the same, this comparison basis further differentiates beneficial foods to increase in priority and enables the identification of foods that bring maximum nutritional benefit per kcal. However, for foods associated with considerable environmental or nutritional impacts, which are often calorie-dense, a kcal-based evaluation is not suitable as it tends to lower their relative ranking both for environmental and nutritional impacts.

More detailed discussion of trade-offs is available in Supplementary Information, section 4.

Discussion

Generalized recommendations can be misleading. Previous studies investigating healthy or sustainable diets have often reduced their findings to a discussion of plant-based versus animal-based foods, with the latter stigmatized as the least nutritious and sustainable[1,14,33]. Although we find that plant-based foods generally perform better (Supplementary Fig. 19), there are considerable variations within both plant-based and animal-based foods that should be acknowledged before such generalized inferences are warranted. For example, nuts, seeds and fruits require water usage per serving of the same order of magnitude as animal-based dishes (Supplementary Fig. 19c).

Global warming impacts of animal-based foods vary by more than one order of magnitude per 100 kcal and serving, respectively, with beef dishes generating the highest (~2.5 $kgCO_2eq$ per serving on average, $GSD^2 = 1.4$) and cheese and poultry dishes the lowest estimates (~0.3 $kgCO_2eq$ per serving, median $GSD^2 = 1.7$; Fig. 5a,b). While reducing or eliminating animal-based foods from the US diet

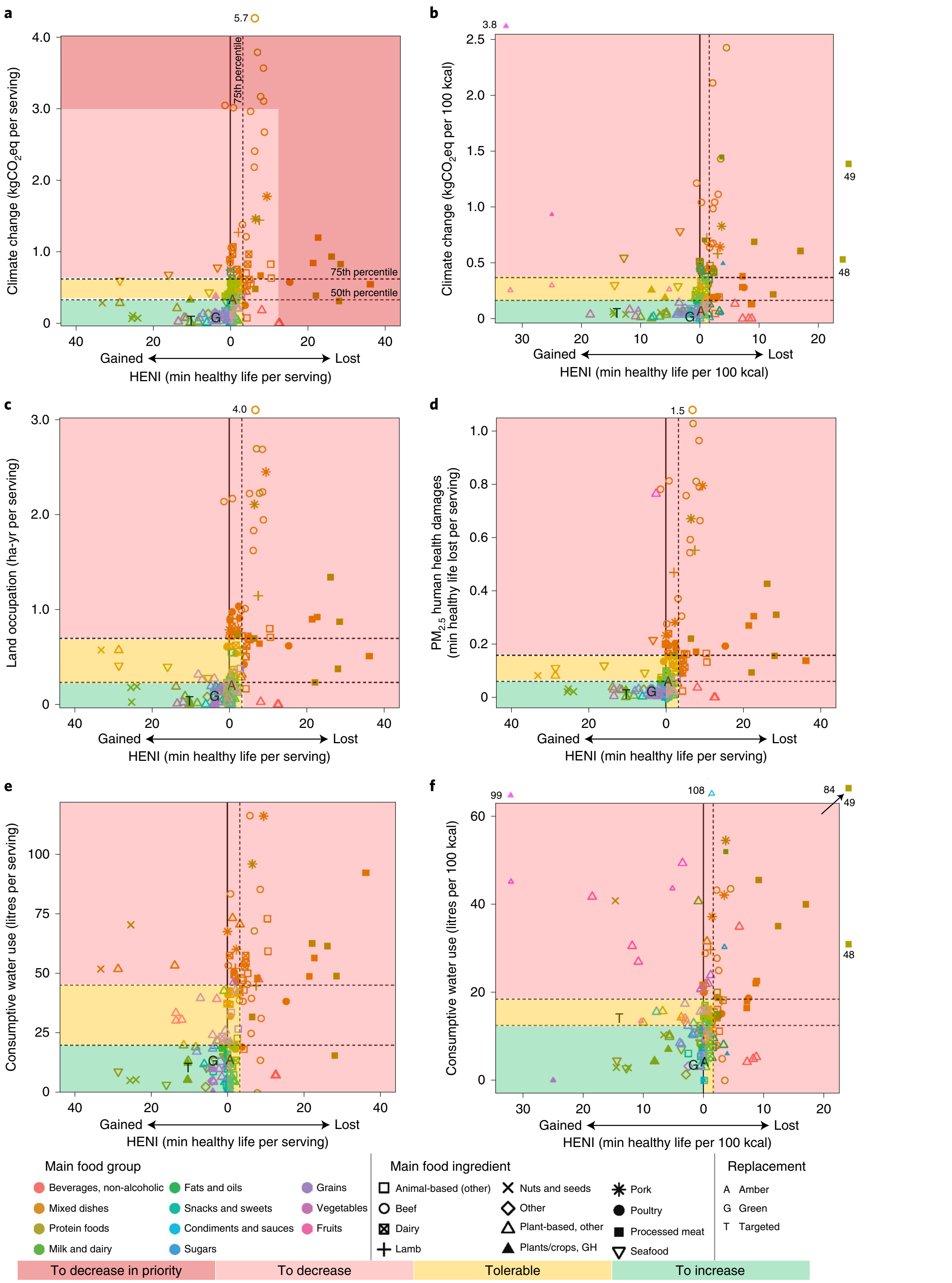

Fig. 5 | Environmental versus nutritional impacts for 167 foods representative for the US diet. a–e, Comparison of nutritional impacts of popular and median HENI foods ($N=167$) in the US diet with their environmental impacts for shorter-term global warming impacts per serving (**a**), per 100 kcal (**b**), for land occupation impacts per serving (**c**), for $PM_{2.5}$ health impacts per serving (**d**), and for consumptive water use per serving (**e**) and per 100 kcal (**f**). Markers represent individual foods. Smaller markers in **b** and **f** indicate foods of low caloric density for which 100 kcal exceeds two servings. Letters represent consumption-weighted food mixes of the amber (A) and green (G) zones, and a targeted mix of the most nutritionally beneficial foods from both zones (T, replacement analysis). GH, greenhouse. The uncertainty ranges for each food and all impact categories are presented in Supplementary Figs. 15 and 16.

can substantially decrease environmental impacts such as global warming, it might also generate nutrient availability challenges when certain foods are reduced, such as dairy products[44]. Nutritional differences among animal-based foods are even more substantial, with high health damages associated with foods high in processed meat (~6–37 min lost per serving) and considerable health benefits from omega-3 fatty acids from seafood (~5–28 min gained per serving depending on the species). Remarkably, the environmental impacts of seafood fluctuate depending on the species, classifying them in all three colour-coded zones. For example, the climate change impacts of catfish (green zone) are relatively low and about half the impacts of salmon-based dishes (red zone). It should be noted that the environmental performance of seafood production or harvesting can vary widely depending on the techniques used and allocation strategies[45,46]. Further work on sustainable seafood production is needed to ensure the high nutrition benefits of omega-3 acids are not associated with high environmental footprints.

Similarly, plant-based foods also have diverse environmental performances, often explained by differences in production systems and farming methods. For consumptive water use and freshwater ecotoxicity, the environmental impacts of certain plant-based foods are comparable and sometimes exceed the impacts of animal-based foods, with differences becoming more apparent when foods are compared on a caloric basis. In addition, heated greenhouse-grown crops generate considerably greater global warming impacts and $PM_{2.5}$ impacts than field-cultivated vegetables (Supplementary Fig. 13). However, we observe the opposite for land occupation impacts as the yield per unit area in greenhouses is higher than for open-field systems[47]. Overall, greenhouse-grown vegetables have higher environmental impacts when the system is heated; hence, greenhouse-grown vegetables are primarily classified in the amber zone.

Small dietary changes—big benefits. The large variations in performance found between individual foods offer promising opportunities for improvement. Using the reported average daily intake of US adults and upscaling results to the entire diet, we quantified the health burden and climate change reductions associated with a combined substitution strategy, replacing either the most nutritionally or the most environmentally detrimental foods (dark red zone of Fig. 5a). For comparison, substitutions were also prioritized based on nutrition only or climate change only (Supplementary Fig. 20). The order of foods to substitute in each scenario is listed in Supplementary Table 12. Three food mixes were studied as replacement examples, that is, a targeted food mix of the most nutritionally beneficial foods per kcal from the green and yellow zones (targeted replacement, T; Supplementary Table 13), and the consumption-weighted average of foods in the green (green replacement, G) and amber (amber replacement, A) zones (Supplementary Table 14).

A targeted 10% daily isocaloric substitution can generate substantial nutritional and environmental benefits. More specifically, substituting 190 kcal per person per day of the most nutritionally or environmentally detrimental foods simultaneously (substituting about half a serving or ~20 g of processed meat and half a serving or ~40 g of beef per day) with an isocaloric mix of nutritious foods (such as nuts, vegetables, fruits, legumes and low-environmental-impact seafood) results in a nutritional health gain of 48 min d^{-1} (95% CI, 28–62 min d^{-1}) and a 33% carbon footprint reduction (95% CI, 22–46%; solid blue curve in Fig. 6a). This combined targeted dietary change results in additional reductions of similar magnitude for all other 15 environmental impacts (Fig. 6 and Supplementary Fig. 21) except for consumptive water use (6% reduction; 95% CI, −9% to 26%; Fig. 6d) and freshwater ecotoxicity (14% reduction; 95% CI,−6% to 55%; Supplementary Fig. 21) since they are not highly correlated to global warming. This lower reduction for ecotoxicity reflects the relatively higher consumptive water use per 100 kcal for the targeted replacement scenario T, which is classified in the amber zone for water use (Fig. 6d and Supplementary Fig. 16m), contrary to being classified in the green zone for all other impact categories (Supplementary Fig. 16). Supplementary Fig. 22 confirms that the nutritional benefits extrapolated from the substitution of these 167 foods are representative of the entire diet. Building on the present study, it would be interesting to assess the level of acceptability adherence of the recommended substitutions, and how the HENI could further stimulate the move towards more sustainable and healthy products.

Simultaneously optimizing diets for nutrition and climate change offers a promising solution towards healthy and environmentally sustainable diets, generating comparable improvements to utmost nutritional benefits (dashed blue curve, Fig. 6a) and environmental reductions for most impact categories (dotted blue curve, Fig. 6 and Supplementary Fig. 21b). Remarkably, environmental reductions from this approach are about 2–5 times higher than the reductions stemming from only nutrition-based diet optimizations depending on the impact category (dashed blue curve, Fig. 6 and Supplementary Fig. 21). While nutritional benefits are sensitive to the replacement selected, for a given substitution prioritization strategy the replacement scenario has little influence on the environmental savings (Supplementary Table 15). Thus, food replacements should be selected primarily based on nutrition.

Recommendations for healthy and sustainable foods. Our analysis highlights important trade-offs between environmental and nutritional indicators, yet offers a realistic framework to provide improvements for both public health and the environment[48]. The three food classifications developed reflect these trade-offs and, similar to the traffic light nutritional labelling[49] or the double indicator categorization[50], facilitate an easy-to-use communication platform that conveys complex, multidisciplinary food-evaluation information derived by a sophisticated approach.

These food classes can inform several dietary recommendations transcending oversimplified messages such as plant-based versus animal-based foods and provide recommendations at the individual food level, which is extremely important given variation among foods in the same broad category. First, we should decrease the most impactful foods either nutritionally or environmentally, starting with those classified based on a serving basis in the dark red zone for global warming (Fig. 5a). This means prioritizing the reduction of consumption of foods high in processed meat, beef and shrimp, followed by pork, lamb and greenhouse-grown vegetables. Second, the most nutritionally beneficial foods on a kcal-basis from both the green and amber zones should be increased, such as field-grown fruits, vegetables, legumes, low-environmental-impact seafood and nuts. However, water usage should also be considered in the prioritization for these groups of foods. Finally, foods classified in the amber zone, such as dairy, poultry and several grain-based dishes, offer acceptable alternatives if used to substitute foods from the dark red zone or to meet specific nutrient requirements (for example, vitamins and minerals).

These recommendations and their consequences could improve the diets of most Americans, offering a baseline for further refinement. Adherence to these recommendations aim towards lowering rather than eliminating diet-related environmental impacts, as all foods generate emission and use resources. Because HENI is a marginal index, it is not applicable to substantial changes in diet. Likewise, the benefits from healthy food consumption are restrained by maximum intake levels for each dietary risk component in HENI (for example, 250 g d^{-1} fruits; for more information on this, see Supplementary Table 1) beyond which intake is not considered to bring additional benefits[3]. Ultimately, these guidelines should

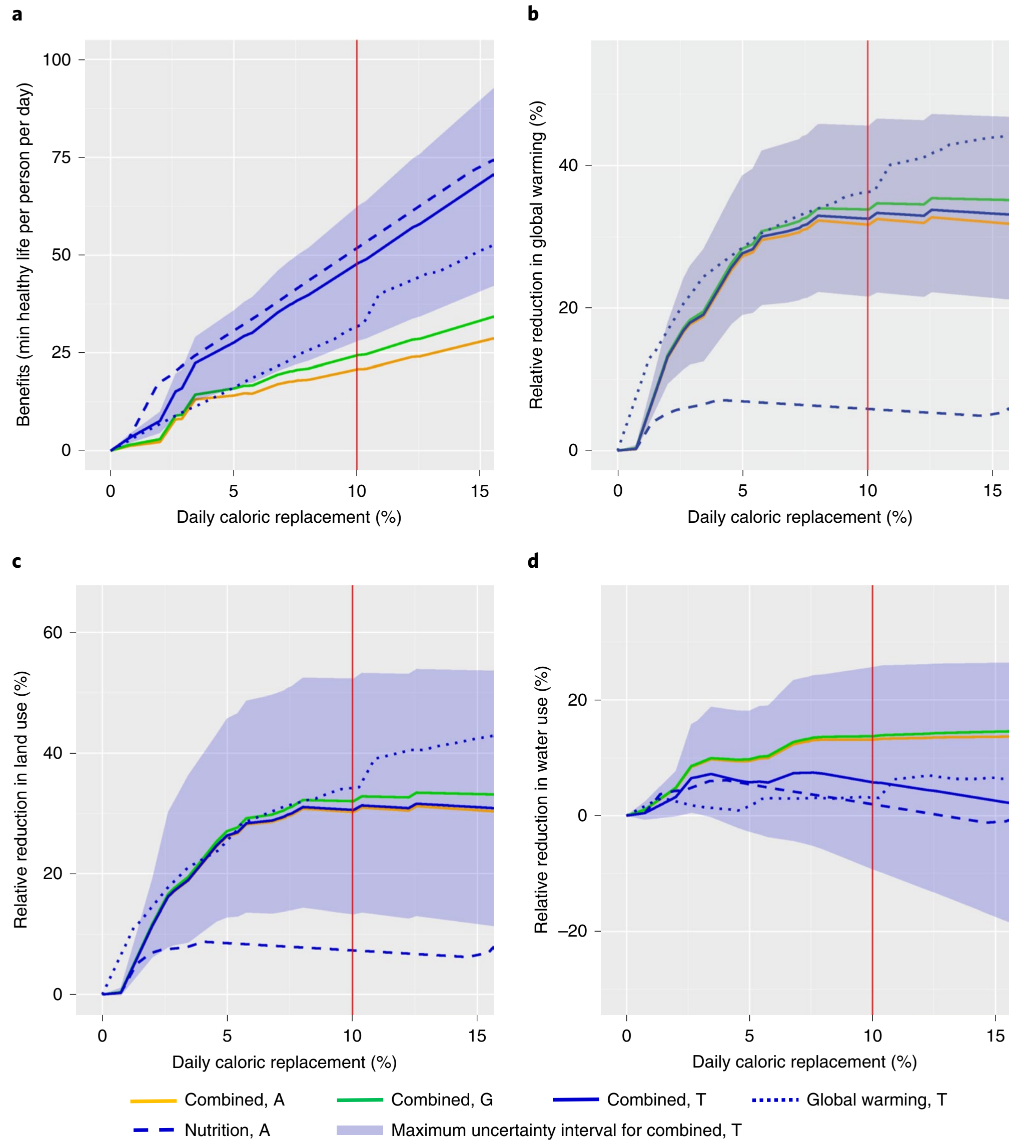

Fig. 6 | Nutritional health and environmental benefits from isocaloric substitutions of the most impactful foods in the US diet. a–d, Nutritional health benefits (**a**) and relative reductions in global warming (shorter term) (**b**), land occupation (**c**) and consumptive water use (**d**) from isocaloric substitutions of the most impactful foods in the US diet by select replacements, scaled at the diet level. Foods were substituted in priority based on nutrition only (dashed curve), global warming only (dotted curve) or combined (solid curve) performances per serving with food mixes from the amber zone (A, amber curve), the green zone (G, green curve) or a targeted mix of the most nutritionally beneficial foods per kcal from both zones (T, blue curve). The blue shaded area denotes a conservative estimate of the 95th CI of the targeted food replacement scenario (see legend to Supplementary Fig. 21).

be complemented with diet diversification strategies to ensure improvements that benefit both human health and ecosystems[51,52].

Conclusions

The urgency for dietary changes to improve human health and the environment is clear. Previous recommendations for improving health outcomes and reducing environmental impacts often demand drastic dietary changes, such as removing all animal products[1,32,53]. However, these are challenging recommendations to achieve and maintain[18] and might not be as necessary as previously believed. Our findings demonstrate that small, targeted substitutions offer a feasible and powerful strategy to achieve significant health and environmental benefits, without requiring dramatic dietary shifts at once.

We have compared nutritional and environmental impacts for individual foods, with the potential to integrate indicators relevant to human health in a common metric[25]. Our findings provide new insights for general and food-specific recommendations that support healthier diets based on food quality/composition rather than on calorie- and nutrient-dependent approaches[54]. We also show that while optimization based on the carbon footprint of foods offers co-benefits in other environmental indicators, there is only little reduction in water usage. This finding emphasizes the importance of sustainable food production systems and the need to perform complementary optimizations using production techniques to enhance the water efficiency of food systems[55,56]; it is also important to give more consideration to the high spatial variations in water use and availability in food water footprints[57]. Building on early[58] and recent studies[55,59–62] would enable improved food substitution optimizations that discourage foods with considerable water footprint per kcal in addition to limiting foods with high carbon footprints. Expanding the food production system boundaries[6,63] (for example, transportation, packaging and retail), alternative practices (for example, open field, heated/unheated greenhouse, organic)[6], and novel processes and technologies[64], all factors that influence the environmental performance of foods, could refine this analysis in the future.

While the present HENI model is based on a comprehensive list of established risk–outcome associations from the GBD studies, the list is not exhaustive and could evolve by incorporating new epidemiological information (for example, additional risk–outcome associations and higher resolution of underlying data). For example, although there is moderately strong evidence for a causal relationship between potassium supplementation and reductions in blood pressure, heterogeneity across studies, lack of evidence for an intake–response relationship and lack of supporting evidence for benefit of potassium on cardiovascular disease prevent the establishment of a potassium chronic disease risk reduction intake recommendation[65]; however, this may change over time as more research is conducted and HENI could incorporate these future findings. Additionally, further improvements to HENI could include differentiating within each dietary risk component for food specificities, and including health effects of nutrients of public health concern (for example, vitamin D and potassium), shortfall nutrients (for example, magnesium, vitamin C)[33], evaluating food processing[66,67] (for example, of ultraprocessed foods) and cooking[68], and by investigating non-marginal diet-level changes. Furthermore, as data become available on the bioavailability of different nutrients, dietary recommendations may change and HENI could be modified accordingly.

The present approach, if broadly adopted, could lead to personalized diet solutions where the consumer identifies trade-offs and substitutions they are willing to make (for example, less processed meat and more seafood) and assesses the corresponding benefits/damages for human health and the environment. Such a personalized approach has a better chance of leading to sustained behaviour change, as the consumer can factor in additional key variables that influence food choices, such as taste preferences, family considerations or affordability.

Additionally, our framework appears instrumental for policy reform and could inform government or non-government dietary guidelines and programmes, front-of-package labelling and education campaigns, in conjunction with other complementary information (for example, affordability). It enables decision-makers to quantitatively evaluate the performance of recommended diets and identify the best individual foods meeting these recommendations that will maximize health benefits while minimizing environmental impacts. Our findings provide evidence-based guidance to inform agricultural policy and health-promoting revisions of current food assistance programmes, accounting for both health and environmental considerations[69–71], and identifying which foods to incentivize, disincentivize or restrict[72]. It also constitutes a sound basis to combine in the future nutritional and environmental impacts with food production and purchasing costs, assessing trade-offs, and identifying the most affordable foods with maximum benefits for health and the environment. Overall, we hope this work inspires and empowers a transition towards healthy and environmentally sustainable diets, changing one food at a time.

Methods

The main elements of the method (Fig. 1) for the nutritional, the environmental and the food substitution assessments are described below and are further detailed in the Supplementary Information.

Food database. This analysis is based on the 5,853 distinct foods reported to be consumed by US adults (aged ≥25 yr, excluding pregnant/lactating women) in the WWEIA 2011–2016 database[73], based on day 1 dietary recall data. We focused on solid foods and specific beverages (SSBs, milk) consumed by adults, while baby foods, infant formulas, 100% fruit and vegetable juices, alcoholic beverages, water, coffee and tea, diet beverages and 'other' foods were not considered. Foods were classified into 11 main groups and 48 food categories (Supplementary Table 5) adapted from the US Department of Agriculture Food Coding Scheme[74] and evaluated per reference amount customarily consumed servings[75], 100 kcal (food items with zero energy not considered) and 100 g. Nutritional performances were calculated for each of the 5,853 distinct foods. To relate both environmental and nutritional performances for representative foods, we selected for each of the 48 food categories the most popular foods based on reported daily mass and energy intakes (up to four), as well as the foods closest to each category's median HENI scores per serving. We also considered seven additional foods, two representing lamb dishes and five representing dishes with greenhouse-grown ingredients due to expected differences in environmental performance[26,76], and excluded two foods for which the mass coverage of environmental data was below 75% of all the ingredients. This yielded a total of 167 foods that corresponded to ~27% of the total daily caloric intake (562 kcal person d^{-1}). The list of all selected food items and their characteristics is available in Supplementary Data 1.

DRFs. DRFs measure the health burden (disease morbidity and mortality) that an individual would have experienced with a marginal intake shift standardized for 1 g of dietary risk, expressed in DALYs per g consumed of a given risk component. Estimates can be positive or negative, indicating induced (detrimental effect) or avoided (beneficial effect) health burdens, respectively. Building on the GBD approach, DRFs were calculated using a comparative risk assessment framework adapted for marginal intake (exposure) changes, corresponding to an individual food added/removed from a diet. More specifically, we determined the population-attributable fraction of a specific disease that is attributable to a marginal difference between the baseline and counterfactual intake ($\Delta x \to 0$ under the assumption of a log-linear dose–response relationship[3]:

$$\begin{aligned} \mathrm{DRF} &= \lim_{\Delta x \to 0} \frac{\mathrm{PAF}(\Delta x)}{\Delta x} \times \mathrm{BR} = \lim_{\Delta x \to 0} \left(\frac{\mathrm{RR}^{\Delta x/\mathrm{Ref}} - 1}{\Delta x} \right) \times \frac{\mathrm{BR}}{\overline{\mathrm{RR}}} \\ &= \lim_{\Delta x \to 0} \left(\frac{\mathrm{RR}^{\Delta x/\mathrm{Ref}} - 1}{\Delta x} \right) \times \frac{\mathrm{BR}}{\sum_x P_x \times \mathrm{RR}^{x/\mathrm{Ref}}} \overset{\text{Taylor expansion series}}{\Rightarrow} \mathrm{DRF} \\ &= \frac{\ln(\mathrm{RR})}{\mathrm{Ref}} \times \frac{\mathrm{BR}}{\sum_x P_x \mathrm{RR}^{x/\mathrm{Ref}}} \end{aligned} \quad (1)$$

where RR is the relative risk for a given risk–outcome combination, Ref is the corresponding reference 'exposure' for the RR reported in g d^{-1}, BR is the outcome-specific burden rate in μDALYs per person per day, and P_x is the fraction of people in the population with x-level daily intake for the given risk. $\overline{\mathrm{RR}} = \sum_x P_x \times \mathrm{RR}^{x/\mathrm{Ref}}$ represents the average population-weighted relative risk. $\widehat{\mathrm{BR}} = \frac{\mathrm{BR}}{\overline{\mathrm{RR}}}$ represents the hypothetical burden rate that would have been experienced by the population if the dietary intake level equalled the theoretical minimum risk level. Morbidity (years of life disabled, YLDs) and mortality (years of life lost, YLLs) burdens were first reported separately and them summed up to yield DALYs: YLDs + YLLs = DALYs. DRFs are valid under the assumption that the current risk intake is within an active intake (Supplementary Table 1), which corresponds to the vast majority of the US population.

For the 15 dietary risk components in our analysis, we identified 479 risk–outcome distinct RRs in the 2016 GBD[3], with age-specific and sometimes gender-specific RRs available for 15 age groups (in 5 yr age groups starting from 25 yr old). When an RR was only available for both genders or both burden metrics, the same RR was used in the gender-specific and burden-specific calculations, respectively. For two of the dietary risks (SSBs and sodium), RRs were further differentiated to account for mediations and effect modifiers. In particular, the association between SSBs and health outcomes is 100% mediated via body mass index with body mass index status modifying the association, while the relationship between sodium and health outcomes is mediated by systolic blood pressure and modified by race and hypertension status[3]. Additional steps were required to estimate DRFs for these mediated risks; these are described in Supplementary Information, section 1.2. Finally, the cardiovascular effects of fibre were mediated through fruits, vegetables, legumes and whole grains[3]. Hence, we developed distinct DRFs for fibre for the different sources of fibre to avoid double counting. Overall we determined a total of 6,195 RRs (resulting in 6,195 risk (r)-, age group (a)-, gender (g)-, modifier (m)-, outcome (o)- and burden (b)-specific $\mathrm{DRF}_{r,o,b}^{a,g,m}$). The reference 'exposures' (Refs) were obtained from the GBD studies[3]; for energy-related nutrients such as TFAs and PUFAs, Refs were determined based on age- and gender-specific daily energy requirements for US adults (Supplementary Table 2) and an estimate of 9.25 kcal $\mathrm{g_{fat}}^{-1}$. We adapted US disease-specific burden rates ($\mathrm{BR}_{o,b}^{a,g}$, YLLs and YLDs) by age group and gender, based on 2016 estimates from the GBD Results Tool[77]. The fraction of people in the US population at different consumption levels of the dietary risks by age group and gender ($P_{x_r}^{a,g}$) were determined using the National Health and Nutrition Examination Survey (NHANES) 2011–2016[73].

As the lag time between exposure and disease onset varies, the age distribution of DRFs is only indicative and must be taken with care. Thus, we estimated the cumulative age-, gender-, health outcome- and modifier-adjusted DRF for a given dietary risk r ($\overline{\mathrm{DRF}}_r$) assuming that the effect from all outcomes is additive in a marginal context:

$$\overline{\mathrm{DRF}}_r = \sum_g \sum_a \sum_o \sum_b \sum_m \left(f_{a,g,m} \times \mathrm{DRF}_{r,o,b}^{a,g,m}\right) = \sum_g \sum_a \sum_o \sum_b \sum_m \left(f_{a,g,m} \times \frac{\ln \mathrm{RR}_{r,o,b}^{a,g,m}}{\mathrm{Ref}_r} \times \frac{\mathrm{BR}_{o,b}^{a,g}}{\sum_x P_{x_r}^{a,g} \mathrm{RR}_{r,o,b}^{a,g,m\ (x_r/\mathrm{Ref}_r)}}\right) \quad (2)$$

where $\mathrm{DRF}_{r,o,b}^{a,g,m}$ is the marginal DRF for outcome o and burden b due to dietary risk r in age group a, gender g, burden b and effect modifier class m in μDALYs g^{-1}, and $f_{a,g,m}$ is the fraction of population in age group a, gender g and effect modifier class m. The latter was determined using the distribution of the US population by effect modifier class from NHANES 2011–2016[73] rescaled to population estimates based on the 2016 US population according to the GBD[78].

HENI. HENI is a health burden-based continuous single-score nutritional metric built on the dietary risk assessment from the GBD. HENI quantifies the marginal health burden in minutes of healthy life gained (+) or lost (−) from all-cause premature mortality and morbidity per reference amount of food based on the 16 selected dietary risk components. The HENI score of food item i is calculated by multiplying the cumulative DRFs by the corresponding amount of dietary risk component in the food in grams, then summing up, and rescaling from μDALYs to minutes of healthy life:

$$\mathrm{HENI}_i = -0.53 \times \sum_r \overline{\mathrm{DRF}}_r \times d_{i,r} \quad (3)$$

where $\overline{\mathrm{DRF}}_r$ is the cumulative age- and gender-adjusted marginal DRF per g of dietary risk r in μDALYs g_r^{-1} (equation (2)), and $d_{i,r}$ is the amount of dietary risk component r in food item i, for example, in g_{sodium} per serving$_i$. The constant −0.53 represents the minutes of healthy life per μDALYs, considering that there are 31.6 million seconds in a year, and therefore a μDALY is equivalent to 31.6/60 = 0.53 min of healthy life lost. The negative sign rescales the damage-oriented metric of μDALYs to beneficial estimates (that is, avoided μDALYs). For 'milk' and 'flavoured milk' products, we excluded $\overline{\mathrm{DRF}}_{\mathrm{calcium}}$ when calculating HENI scores to avoid double counting the health benefits on colorectal cancer (already captured in the $\overline{\mathrm{DRF}}_{\mathrm{milk}}$). The $d_{i,r}$ estimates were determined using the approach by Fulgoni et al.[36] (details available in Supplementary Information, section 2.1). For the marginal dietary changes investigated in this analysis, HENI is built on the assumption that the aggregated health effect from multiple dietary risk components is additive and independent unless evidence suggests that there is a mediation mechanism between risks[79]. The structure of HENI is illustrated in Supplementary Fig. 2.

Environmental assessment. We used LCAs to quantify the 'cradle to farm/processing gate' environmental impacts for the most consumed and median HENI food items from each of the 48 food categories. In a step-wise fashion, we developed life-cycle inventories (LCIs) that quantify the resource extractions and environmental emissions of a given food, since LCIs are primarily available for the main agricultural commodities and not prepared multi-ingredient foods[80]. More specifically, we first deconstructed each food to individual ingredients using standardized recipes. Ingredient amounts were adjusted for cooked-to-raw losses, supply chain losses and waste, and closely matched with available LCIs. Information is then compiled to develop an aggregate LCI for each food that is used to calculate the life-cycle environmental impacts of each food (Supplementary Fig. 11). We set a minimum mass coverage of 75% of all the ingredients of each food item, achieving this level for 167 foods.

We estimated midpoint impacts (relative impacts within different specific impact categories) and endpoint damages on ecosystems, human health and resource use for 18 environmental indicators. The list of environmental indicators includes global warming, land occupation, freshwater and terrestrial acidification, freshwater and marine eutrophication, freshwater ecotoxicity, blue water use, ionizing radiation, photochemical oxidant formation, fine particulate matter formation ($PM_{2.5}$), cancer and non-cancer human toxicity, ozone layer depletion, fossil energy use and mineral resources use (for description, see Supplementary Table 7). Aggregated endpoint damages are also reported for human health and ecosystem quality. Indicators were calculated using the default factors of Impact World+ v.1.4[38], except for $PM_{2.5}$ and blue water use for which we developed specific evaluations that utilize improved[81] or spatialized data[61,62,82].

A detailed description of the environmental assessment methodology followed is available in Supplementary Information, sections 3.1–3.4.

Food substitution analysis. We investigated marginal dietary change scenarios ($N = 9$) based on three diet optimization strategies (nutrition only, climate change only, combined nutrition and climate change; see Supplementary Fig. 20) and three nutritionally beneficial food mixes (amber, green, targeted; Supplementary Tables 16 and 17) that isocalorically replace foods identified to be replaced. Diet-optimization strategies are determined from the serving-based performance of foods, as shown in Fig. 5a. The foods to be replaced in priority are identified as either the most nutritionally or the most environmentally detrimental foods, in percentiles of all considered foods. The selection of foods for the replacement mixes are determined based on the nutritional performance of foods on a kcal basis. The 'amber' (A) and 'green' (G) replacement mixes are defined as the daily consumption-weighted average of the respective zones, for example, as shown in Fig. 5b. The targeted replacement mix (T) was defined as a caloric weighted mix of select foods from the amber and green zones that generate the highest nutritional health benefits per kcal. For each scenario we estimated the nutritional and environmental performance for all indicators of food substitutions as a function of daily caloric intake. For more information, see Supplementary Information, section 5.

Uncertainty analysis. We employed Monte Carlo simulations to characterize the uncertainty of DRFs and HENI scores for each food item. Simulations were performed for 10,000 iterations with SAS 9.4 using the uncertainty distributions reported in the GBD studies[3]. More specifically, we assumed log-normal distributions for the RRs, BRs and the sodium to systolic blood pressure conversion factors, and normal distributions for the other conversion factors (SSBs to weight gain and urinary to dietary sodium). For each set of input parameters we generated random variables based on the mean, lower limit (assumed 2.5th percentile) and upper limit (assumed 97.5th percentile) estimates obtained from the GBD sources and assuming independence (for example, separate random draw). However, for age- and gender-dependent parameters, we generated random variables using the same random draw for all strata since these are dependent parameters that the GBD typically extrapolates from a single estimate. To characterize the HENI uncertainty of each food, we combined the DRF replications with the corresponding food composition, assuming that the uncertainty of the food composition is negligible compared to the uncertainty of the DRFs. Our analysis included a total of 6,041 probability distributions for the considered input variables.

To evaluate the uncertainty of each environmental indicator for a given food, we employed the approach by Hong et al. using a Taylor series expansion approach to account for uncertainties associated with LCIs and impact-assessment factors[83]. Under the assumption that these factors follow a log-normal distribution, their uncertainty was characterized using the squared geometric standard deviation (GSD^2), indicating that 95% of the estimates fall within the median divided by GSD^2 and the median multiplied by GSD^2. For each food-impact category pair we estimated an overall GSD^2 by combining base uncertainty (specific to the LCI flows and impact characterization of each impact category) and uncertainty associated with data pedigree for three categories (LCI match, loss/waste factor, consumable amounts). A detailed description of the approach is available in Supplementary Information, section 3.5.

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

Data availability

Data are available from the corresponding author upon reasonable request.

Code availability

Code is available from the corresponding author upon reasonable request.

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Author contributions

K.S.S., O.J. and V.L.F. conceptualized the study, devised the methodology, curated the data, and reviewed and edited the paper. K.S.S. performed the formal analysis and wrote the original draft.

Competing interests

K.S.S. declares no conflicts of interest. V.L.F. conducts data analyses of the National Health and Nutrition Examination Survey for numerous members of the food industry. O.J. has received funding on unrelated projects from the US Environmental Protection Agency, the US Department of Agriculture, the American Chemistry Council Long-Range Research Initiative and Unilever, and became part, after submission of the present manuscript, of the Sustainable Nutrition Scientific Board created with unrestricted support from Nutella. The funding organizations did not have a role in the manuscript development.

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Software and code

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Data collection	All data used were obtained from publicly available sources, except for the life cycle inventories that were accessed using SimaPro v8.3. All data sources have been fully described in the manuscript and supplementary material.
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The underlying data for HENI scores were obtained from publicly available sources and are fully described in the manuscript and supplementary materials. Indicatively, data used in the analysis were obtained from the Global Burden of Disease studies (GBD; Data Input Sources Tool: http://ghdx.healthdata.org/gbd-2016/data-input-sources; Results Tool: http://ghdx.healthdata.org/gbd-results-tool), the National Health and Nutrition Examination survey (NHANES, https://wwwn.cdc.gov/nchs/nhanes/Default.aspx), and other NHANES-compatible databases such as the Food Pattern Equivalent Database (FPED, https://www.ars.usda.gov/northeast-area/beltsville-md-bhnrc/beltsville-human-nutrition-research-center/food-surveys-research-group/docs/fped-databases/) and the USDA National Nutrient Database for Standard Reference, Legacy Release (https://data.nal.usda.gov/dataset/usda-national-nutrient-database-standard-reference-legacy-release).

The underlying data for the LCA analysis were obtained from ecoinvent v3.352 (https://www.ecoinvent.org), World Food LCA Database (WFLDB) v3.153 (https://quantis-intl.com/metrics/databases/wfldb-food), and ESU World food LCA database (http://esu-services.ch/data/fooddata). In addition, we utilized data from the publically available Food Commodity Intake Database (FCID, https://fcid.foodrisk.org/) and the life cycle impact method Impact World+ (described in Bulle et al., 2019)

All information regarding the select subset of foods evaluated in this study is described within the supplementary material and available in the additional excel file. HENI scores for all food items in this study are available from the authors upon reasonable request.

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Study description	This study characterizes and compares the human health burden from nutrition and the environmental performance using multiple indicators of diverse foods within the US diet
Research sample	We estimated health burden scores using the Health Nutritional Index (HENI) for 5,853. For 167 foods, we also provide scores for 18 environmental indicators.
Sampling strategy	The selections of 5,853 foods was based on the reported intake of Americans between 2011-2016 according to a nationally representative sample from the National Health and Nutrition Examination Survey. The 167 food items were selected on a food category basis representing foods with the highest reported daily consumption per mass or caloric intake and foods with HENI scores equal or similar to the median for the category.
Data collection	All data were obtained from publicly available sources, except for the life cycle inventories from ecoinvent v3.352 (https://www.ecoinvent.org), World Food LCA Database (WFLDB) v3.153 (https://quantis-intl.com/metrics/databases/wfldb-food), and ESU World food LCA database (http://esu-services.ch/data/fooddata) that were accessed using SimaPro v8.3.
Timing and spatial scale	Reported food intakes and characteristics in the US from 2011-2016. Disease burden and population demographics for American adults from 2016.
Data exclusions	Baby foods, infant formulas, 100% fruit and vegetable juices, alcoholic beverages, water, coffee and tea, diet beverages, and "other" foods were not considered in this study because of lack of data to properly evaluate their effect on human health, according to the epidemiological data considered.
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