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2 **Title: The multiple health and environmental impacts of foods**  
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17

18 **Abstract**

19 Food choices are shifting globally in ways that are negatively affecting both human  
20 health and the environment. Here we consider how consuming an additional serving per  
21 day of each of 15 foods is associated with five health outcomes and five aspects of  
22 agriculturally-driven environmental degradation. We find that while there is substantial  
23 variation in the health outcomes of different foods, foods associated with a larger  
24 reduction in disease risk for one health outcome are often associated with larger  
25 reductions in disease risk for other health outcomes. Likewise, foods with lower impacts  
26 on one metric of environmental harm tend to have lower impacts on others. Additionally,  
27 of the foods associated with significantly improved health (whole grain cereals, fruits,  
28 vegetables, legumes, nuts, olive oil, and fish), all except fish have among the lowest  
29 environmental impacts, and fish has markedly lower impacts than red meats and  
30 processed meats. Foods associated with the most negative health impacts do not always

have large harmful environmental impacts, but foods with the largest negative environmental impacts—unprocessed and processed red meat—are consistently associated with the largest increases in disease risk. Thus, dietary transitions toward greater consumption of healthier foods would generally improve environmental sustainability, although processed foods high in sugars or refined starches harm health but have relatively low environmental impacts. These findings could help consumers, policy makers, and food corporations to better understand the multiple health and environmental implications of food choices.

#### **Keywords**

*Diet, environment, health, relative risk, sustainability*

#### **Significance Statement**

Changing dietary choices are a leading global cause of mortality and environmental degradation, and threaten the attainability of the UN's Sustainable Development Goals and the Paris Climate Agreement. To inform decision making and to better identify the multifaceted health and environmental impacts of dietary choices, we describe how consuming 15 different food groups is associated with five health outcomes and five aspects of environmental degradation. We find that foods associated with improved health also often have low environmental impacts, indicating that the same dietary transitions that would lower incidences of non-communicable diseases would also help meet environmental sustainability targets.

#### **Main text**

Dietary choices—the types and amounts of foods that individuals consume—are a major determinant of human health and of environmental sustainability. Nine of the top fifteen risk factors for global morbidity result from poor dietary quality, while diseases associated with poor dietary quality, including coronary heart disease (CHD), type II diabetes, stroke, and colorectal cancers, account for nearly 40% of global mortality (1, 2). Furthermore, agricultural food production emits ~30% of global greenhouse gasses (GHGs) (3, 4); occupies ~40% of Earth's land (5); causes nutrient pollution that

profoundly alters ecosystems and water quality (6); and accounts for ~70% of Earth's freshwater withdrawals from rivers, reservoirs, and ground water (7), among other negative environmental effects (8, 9).

Here we examine the potentially complex and multifaceted food-dependent linkages between and among five different diet-dependent health outcomes—type II diabetes, stroke, coronary heart disease, colorectal cancer and mortality—and five different environmental impacts of producing the foods. Such information could help consumers, food corporations, and policy makers make better decisions about food choices, food products and food policies, potentially increasing the likelihood of meeting international sustainability targets such as the UN's Sustainable Development Goals or the Paris Climate Agreement (10, 11). Previous analyses have examined the overall health and environmental impacts of dietary patterns (e.g., refs (12, 13)), but have not decomposed these multifaceted impacts to individual foods at quantities consumed on a daily basis. Moreover, analyses looking at individual foods commonly examine the health (e.g., ref (14)) or environmental impacts (e.g., ref (15)) in isolation of the other.

In particular, we explore the multiple human health and environmental impacts of 15 different food groups: chicken, dairy, eggs, fish, fruits, legumes, nuts, olive oil (which we include as an indicator for vegetable oils high in unsaturated fatty acids because of data availability; see the discussion in the Supplementary Information), potatoes, processed red meat, refined grain cereals, sugar-sweetened beverages (SSBs), unprocessed red meat, vegetables, and whole grain cereals. Our analysis includes the five health outcomes mentioned above and five environmental outcomes—greenhouse gas (GHG) emissions, land use, scarcity weighted water use (water use availability after demand from humans and aquatic ecosystems has been met) (16), and two forms of nutrient pollution—acidification and eutrophication. We first consider the health and environmental impacts of these foods separately (“Health outcomes” and “Environmental outcomes”), and then explore them jointly (“Combined health and environmental outcomes” and “Associations between health and environmental outcomes”).

We selected these foods and these health and environmental outcomes because plausible causal metabolic mechanisms between food consumption and health outcomes exist for these foods, and because the health and environmental impacts of these foods have been well documented through meta-analyses. The health outcomes reported here are the relative risks (RR) of disease resulting from consuming an additional serving of a food per day relative to the range of (and often less than healthy) intake observed in the cohort studies, where a  $RR > 1$  indicates that food consumption is associated with increased disease risk compared to the average risk of that disease, and a  $RR < 1$  indicates food consumption is associated with decreased disease risk. The food-dependent health data are from 19 dose-response meta-analyses (see Table S1 in the SI Appendix for complete list) (17–35), which follow populations through time to estimate how food consumption is associated with disease risk while statistically controlling for confounding factors such as age, body mass index, sex, and history of smoking. The five environmental outcomes reported here are the impacts of producing a serving of each food group as estimated by meta-analyses of life cycle assessments (LCAs) that account for the environmental impacts of plant and animal production, including the production, manufacture, and use of agricultural inputs, seed, equipment, and cropland (15), but not transport, processing, retail, and food preparation. Because most food groups contain multiple foods, the environmental impact per serving of each food group is weighted by the global average consumption of the foods within each food group (5).

## **Results**

### ***Health outcomes***

We found several broad trends from the data we synthesized. First, we found few tradeoffs among the health impacts of different foods. That is, no food associated with a significant (at  $P < 0.05$ ) reduction in disease risk for one health outcome is associated with a significant increase in disease risk for any other health outcome (Fig. 1). When examining rank-order correlations, the association between a food and a health outcome is positively correlated with its association for the four other health outcomes. In particular, 8 of the 10 Spearman ranked correlations for the 10 pairwise comparisons of

the 5 health outcomes were significant and positive ( $P < 0.05$ ; Table S2 in the SI Appendix), while none of the correlations were significant and negative.

More specifically, minimally processed whole grains, fruits, vegetables, nuts, legumes, olive oil, and fish are associated with significantly ( $P < 0.05$ ) reduced mortality and/or reduced risk for one or more diseases (Fig. 1). Consuming an additional serving per day of these 7 foods is associated with a significant reduction in disease risk for 20 of the 34 health endpoints for these foods (6 foods by 5 health outcomes; dose-response data for the association between olive oil and colorectal cancer was not available) and no significant change in disease risk for 14 of 34 health outcomes. We note, however, that because the health benefit of increasing consumption of these seven foods is often non-linear, the health benefit of consuming a second additional serving per day is often smaller than the health benefit of consuming the first additional serving per day. While data from dose-response cohort meta-analysis was available for olive but not other vegetable oils high in unsaturated fatty acids, other types of health analyses have suggested that other vegetable oils low in saturated fats and high in polyunsaturated fats might have health benefits similar to those of olive oil (36).

Daily consumption of an additional serving of dairy, egg, and chicken is not significantly associated with disease incidence for 12 of the 14 health endpoints (3 foods by 5 health outcomes; dose-response data for chicken and stroke were not available); however, inability to fully control for potential dietary confounders (e.g., reduced consumption of red meat when chicken consumption increases) likely influences the observed associations between consumption of chicken and disease risk in particular, and between food consumption and health outcomes more generally (33). Similarly, consuming an additional 30g of refined grain cereals was also not associated with a significant change in disease incidence, although consuming larger amounts of refined grain cereals has been associated with increased risk of diabetes and substituting whole grain cereals for refined grain cereals has been associated with reductions in disease incidence (37, 38).

Consumption of SSBs, unprocessed red meat, and processed red meat are consistently associated with increased disease risk. SSB consumption is associated with a significant increase in CHD, type II diabetes, and stroke, but not total mortality or colorectal cancer. Consumption of unprocessed and processed red meat is associated with significant increases in disease risk for all five health outcomes examined here. Of all the foods examined, a daily serving of processed red meat is associated with the largest mean increase in risk of mortality and incidences of CHD, type II diabetes, and stroke.

The health outcomes reported here were originally estimated by tracking the dietary patterns and health outcomes of tens of millions of individuals. While it is likely that individuals of a wide variety of ethnicities, ages, and economic statuses who consumed a diverse array of dietary patterns were included in the primary analyses, the majority of individuals included in these studies lived in higher-income countries such as those in Europe, the US, or Canada, and a smaller number in Asian countries and other regions (see Table S4). As such, the health outcomes reported here are most relevant and applicable to individuals whose diets are similar to those typically found in higher-income regions (e.g., high in calories and animal source foods, and low in whole grains), but may also be broadly applicable in other contexts because they are believed to reflect underlying biological pathways. In addition, the health outcomes reported here control for body-mass index. As such, the potential health implications of consuming an additional serving of one food without reducing consumption of another food (i.e., thereby leading to increased calorie intake and possibly weight gain) are not included in the health estimates reported here despite the known health implications of excess caloric consumption (25).

### ***Environmental outcomes***

The mean GHG emissions, land use, acidification, and eutrophication per serving of food produced for the 15 food groups differed by two orders of magnitude (Fig 1.). While mean scarcity-weighted water use per serving of food produced does not significantly vary across these 15 foods, unprocessed red meat has twice the water impact of dairy, nuts, and processed red meat (which has a smaller serving size than unprocessed red

meat), and olive oil, which in turn have more than twice the impacts of the remaining foods. This general pattern, and the large variation around the mean scarcity-weighted water use, merit further exploration.

To better examine similarities across different environmental indicators, we report all environmental impacts relative to the impact of producing a serving of vegetables. When looking across the different environmental indicators, we found that foods that have a low mean relative environmental impact per serving for one environmental indicator often also have low mean relative environmental impacts for the other four environmental indicators. Indeed, Spearman ranked correlations for 9 of the 10 pairwise comparisons between the 5 types of environmental impacts are positive and significant ( $P < 0.05$ ; Table S2 in the SI Appendix); only the association between GHG emissions and scarcity weighted water use is non-significant ( $P = 0.145$ ). Minimally processed plant source foods, olive oil, and SSBs consistently have among the lowest environmental impacts for all indicators, often having a relative environmental impact of less than 5 for all five environmental indicators. Dairy, eggs, fish, and chicken have relative environmental impacts that range from 3–40 for GHGs, acidification, eutrophication, and land use. Producing a serving of unprocessed red meat has the highest impact for all five environmental indicators, with a relative environmental impact ranging from 16 to 230. Producing a serving of processed red meat has the second highest mean impact on acidification, GHG emissions, and land use and the third highest mean impact for eutrophication. In our analysis, we weighted food production impacts based on global production location and methodology to arrive at an average global estimate of the environmental impact per unit of food produced. While our environmental data primarily come from life cycle assessments (LCAs), other methodologies estimating the environmental impacts of producing different foods show that while the environmental impacts of food production per unit produced varies across regions, the relative rankings of the environmental impacts of producing different foods is often similar (39, 40).

### ***Combined health and environmental outcomes***

Combining all data into a “radar plot” for each food facilitates comparison across the multiple health and environmental impacts of each food (Fig. 2, Fig. S1). Plotting the 5 health and 5 environmental impacts of each food on quantitative axes, where points closer to the origin are healthier or have lower relative environmental impact, shows that foods with among the lowest environmental impacts often have the largest health benefits (lowest relative risks of disease or mortality), and that the foods with the largest environmental impacts—unprocessed and processed red meat—often have the largest negative impacts on human health. These patterns are particularly clear when foods are ranked by each of the health or environmental impacts (Fig 2), but are also apparent when the absolute impacts are plotted (Fig. S1). Producing a serving of unprocessed and processed red meats has environmental impacts 10 to 100 times larger than those of plant source foods for GHG emissions, land use, acidification, and eutrophication.

The variation around the mean health and environmental impacts (Figs 1 and 3) can result from differences among foods within each food group, food preparation, or production methodology. For instance, consumption of leafy green vegetables has been associated with a significant reduction in type II diabetes risk, whereas some other vegetables have not (14). Similarly, per unit of food produced, rice production emits more GHGs than other cereals because methane is produced when rice paddies are flooded. For red meats, ruminant meat (beef, sheep, and goat) has higher environmental impacts than pork because ruminant meat production uses more agricultural inputs than pork per unit of meat produced and because ruminants emit methane when digesting food (15). For health but not for environmental impacts, variation around the mean also results from differences in food preparation method; for instance, frying fish can negate its potential health benefits (17). For environmental but not for health impacts, variation can also result from differences in production location or methodology. For instance, the GHG emissions of fish production are highly variable, in part because of the variety of fish production methods. Bottom trawling fisheries and recirculating aquaculture systems emit more GHG per amount of fish produced than do other fish production system because of their higher levels of energy use (41). Further description and explanation of



the variation around the mean impact for each food group is in the Supplementary Information in the SI Appendix.

### ***Associations between health and environmental outcomes***

Finally, to look for broad and general associations between the health and environmental impacts of food types, we compare the diet-related mortality of each food group to the group's averaged relative environmental impact ("AREI", the average of a food's relative environmental impact per serving across all 5 environmental indicators).

Foods associated with significant reductions in mortality consistently have a low averaged relative environmental impact (Fig. 3): whole grain cereals, fruits, vegetables, nuts, and olive oil have an AREI of 4 or less per serving. Fish, the other food group that is associated with a significant reduction in mortality, has an AREI of 14 per serving. Foods associated with a significant increase in mortality have variable environmental impacts (Fig. 3): unprocessed red meats (AREI = 73) and processed red meats (AREI = 37) have the highest AREIs while SSBs (AREI=0.95) have the lowest AREIs of all foods in this analysis. The associations between a food's impact on morbidity (which is calculated by weighting the relative risk for each disease by its contribution to total morbidity as measured in years lost to disability (2)) and its AREI follow a similar trend (Fig. S3).

### **Conclusions:**

The same dietary changes that could help reduce the risk of diet-related non-communicable diseases could also help meet international sustainability goals. Focusing diets on foods consistently associated with decreased disease risk would likely also reduce diet-related environmental impacts. Foods with intermediate environmental impacts or that are not significantly associated with health outcomes, such as refined grain cereals, dairy, eggs, and chicken, could also contribute to meeting international health- or environmental-focused sustainability targets if they are used to replace foods that are less healthy or have higher environmental impacts such as sugar-sweetened beverages, unprocessed red meat, and processed red meat (42).

Other foods, such as trans fats, ultra-processed foods, and added sugar, were not included in this analysis because there were no dose-response meta-analyses examining the association between consumption of these foods and health outcomes. However, health analyses using different methodologies have linked consumption of trans fats and ultra-processed foods with increased disease risk (35, 43). Furthermore, added sugar consumption has been associated with an increase in risk of cardiovascular disease (44), but has not been associated with increased risk of total mortality in individual cohort studies (45), although this may be because cohort studies often control for body weight, and the impact of added sugar consumption on risk of total mortality is at least partially caused by weight gain. Added sugars tend to have lower environmental impacts, as do ultra-processed foods if they contain no or small amounts of animal source foods (15).

Food consumption and production are directly linked with other aspects of human health and environmental degradation beyond those included in this analysis. For instance, vitamin A deficiency resulting from poor dietary quality is a major source of poor eyesight, blindness, and childhood mortality in developing regions, while reduced air quality resulting from food production is responsible for ~20% of deaths from air pollution (9, 46). Similarly, food production is the largest stress to biodiversity through habitat destruction and nutrient pollution, with food production threatening >70% of birds and mammals that are listed as threatened with extinction by the IUCN (47).

Global patterns of food consumption have been shifting towards foods associated with increased disease risk or higher environmental impacts, and have been projected to lead to rapid increases in diet-related diseases and environmental degradation (48–50). Slowing this trend and instead increasing consumption of whole grain cereals, fruits, vegetables, nuts, legumes, fish, and olive oil and other vegetable oils high in unsaturated fats—foods that are consistently associated with decreased disease risk and low environmental impacts—would have multiple health and environmental benefits globally. Public and private solutions could help shift food consumption towards healthier and more environmentally sustainable outcomes.

306

## 307 **Methods**

308 We first analyzed the impact on health of consuming an additional serving of food per  
309 day for 15 food groups. We synthesized results from 19 recent dose-response meta-  
310 analyses to determine how five health outcomes—incidences of colorectal cancer,  
311 coronary heart disease (CHD), type II diabetes, and stroke, as well as risk of total  
312 mortality—were impacted by consuming an additional serving of each type of food per  
313 day (see Table S1 in the SI Appendix for the dose-response meta-analyses included in  
314 this analysis and Table S3 in the SI Appendix for the serving sizes reported by the dose-  
315 response meta-analyses). We limited our analyses to these 15 food groups because dose  
316 response meta-analyses for these foods were available. The existence of dose-response  
317 relationships from multiple cohorts, together with plausible pathways that explain the  
318 change in disease risk, suggest that the risk relationships are reflective of biological  
319 processes and are broadly applicable. Because there were no dose-response meta-  
320 analyses examining the association between olive oil consumption and risk of total  
321 mortality, we estimated this association by weighting disease-specific contributions (e.g.,  
322 CHD, stroke, and diabetes) to mortality by disease-specific relative risk (2).

323

324 We then determined, for each of the 15 food groups, how agricultural production of a  
325 serving of each food impacted five types of environmental degradation—greenhouse gas  
326 (GHG) emissions, land use, scarcity weighted water use, and acidification and  
327 eutrophication (two forms of nutrient pollution)—using data from recent life cycle meta-  
328 analyses (15, 41). While data from life cycle meta-analyses are primarily from high-  
329 income and high-input nations, other methodologies of estimating the environmental  
330 impacts of food production have shown that while the environmental impacts of food  
331 production per unit of food produced varies across regions, the relative rankings of the  
332 environmental impacts of different foods is similar across regions (39, 40). Using meta-  
333 analyses of LCAs can be considered more reliable and reflective of the general  
334 magnitudes of environmental impacts of different foods than individual LCAs because of  
335 potential variation between individual LCAs.

336

To better allow broad comparisons between the overarching health and environmental impact of different foods, we also calculated the average morbidity and averaged environmental impact of each food. We estimated the average morbidity impact by weighting the reported relative risk for CHD, colorectal cancer, type II diabetes, and stroke with their relative contribution to morbidity, measured by years of life adjusted for disability (YLDs) as reported by the Global Burden of Disease (2). We also estimated the 95% confidence intervals around the average morbidity impact by using the upper and lower 95% confidence intervals reported in the dose-response health meta-analyses reported here. We estimated the averaged environmental impact of a given food by first calculating the impact of producing a food for each indicator relative to the impact of producing vegetables. The averaged relative environmental impact was then calculated as the average of the relative impacts for the five environmental outcomes examined here. As such, a food group with an averaged relative environmental impact of 5 indicates that producing a serving of that food group results, on average, in 5 times the environmental impacts across the five environmental outcomes examined here than does producing a serving of vegetables.

The serving sizes used in this analysis are 225g for SSBs; 200g for dairy; 150g for potatoes; 100g for chicken, red meat, fish, fruits, and vegetables; 50g for processed red meat, eggs, and legumes; 30g for refined grains and whole grain cereals; 28g for nuts; and 10g for olive oil. In cases where dose-response meta-analyses reported health outcomes at different serving sizes, we calculated the reported RR of disease risk for the aforementioned serving sizes by accounting for linearities and non-linearities in the association between food consumption and disease risk.

We also estimated how consuming a serving of food per day was associated with morbidity, measured as years lost to disability, by weighting the RR and 95% confidence intervals for each disease incidence by the relative contribution each disease to morbidity (2). When doing so, we accounted for variation in the RR estimates as well as potential error in morbidity as reported by the Global Burden of Disease.

368 *Statistics:*

369 Statistics in the scope of this study are reported in two ways. First, associations between  
370 food consumption and health outcomes are reported as “significant” if the association is  
371 reported as having a P-value < 0.05 in the relevant dose-response meta-analysis. Second,  
372 significant associations between pairwise Spearman Ranked Correlations for the health  
373 and environmental outcomes were tested using the function “rcorr” from the package  
374 “Hmisc” in R. Data used for the Spearman Ranked Correlations and associated P-Values  
375 are in Table S2.

376  
377 *Data availability:*

378 All data used in this study are available in the Supplemental Tables and Supplemental  
379 Data in the SI Appendix.

380  
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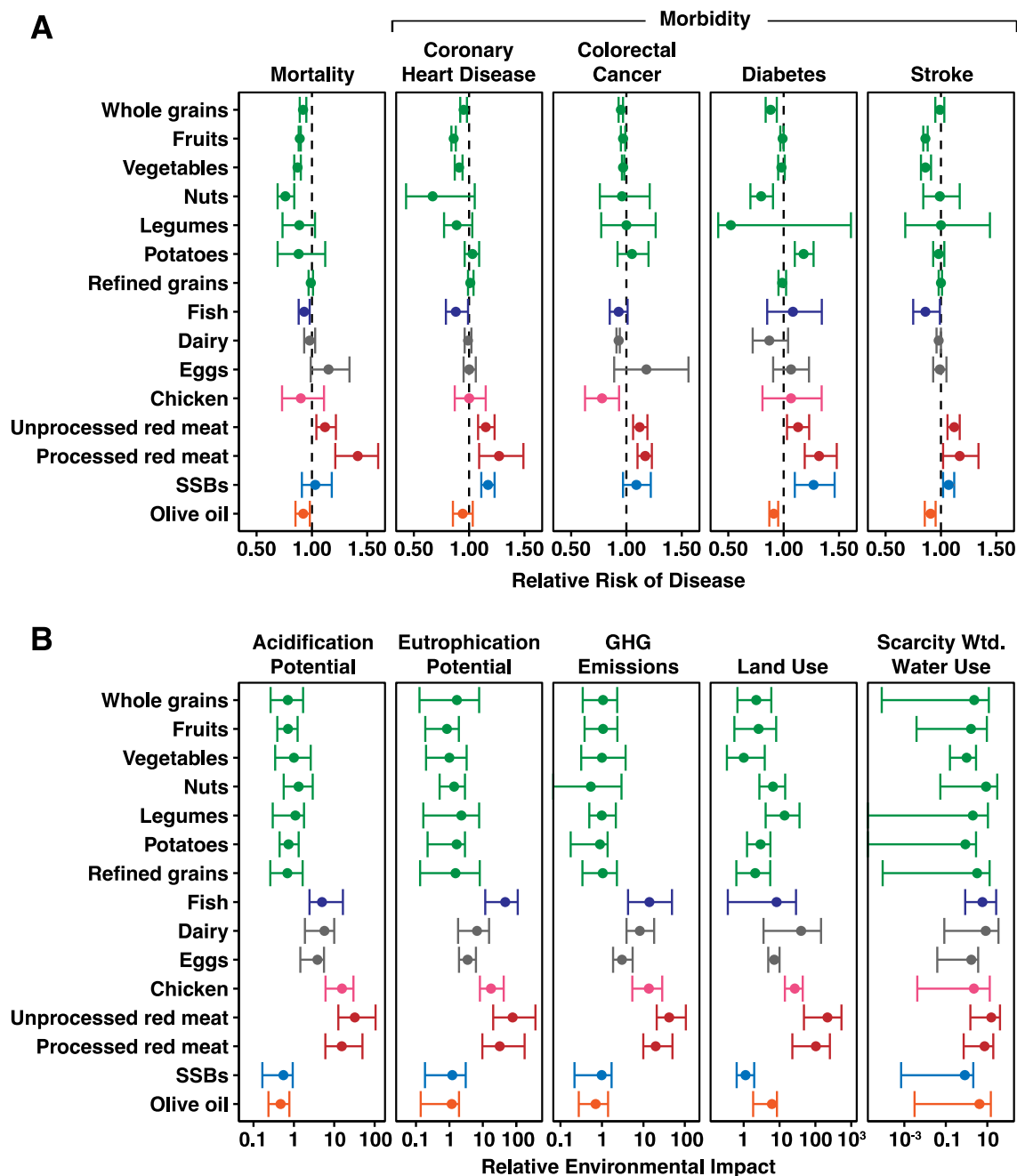
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395 **Data availability:** All data are available in the tables and supplementary materials.

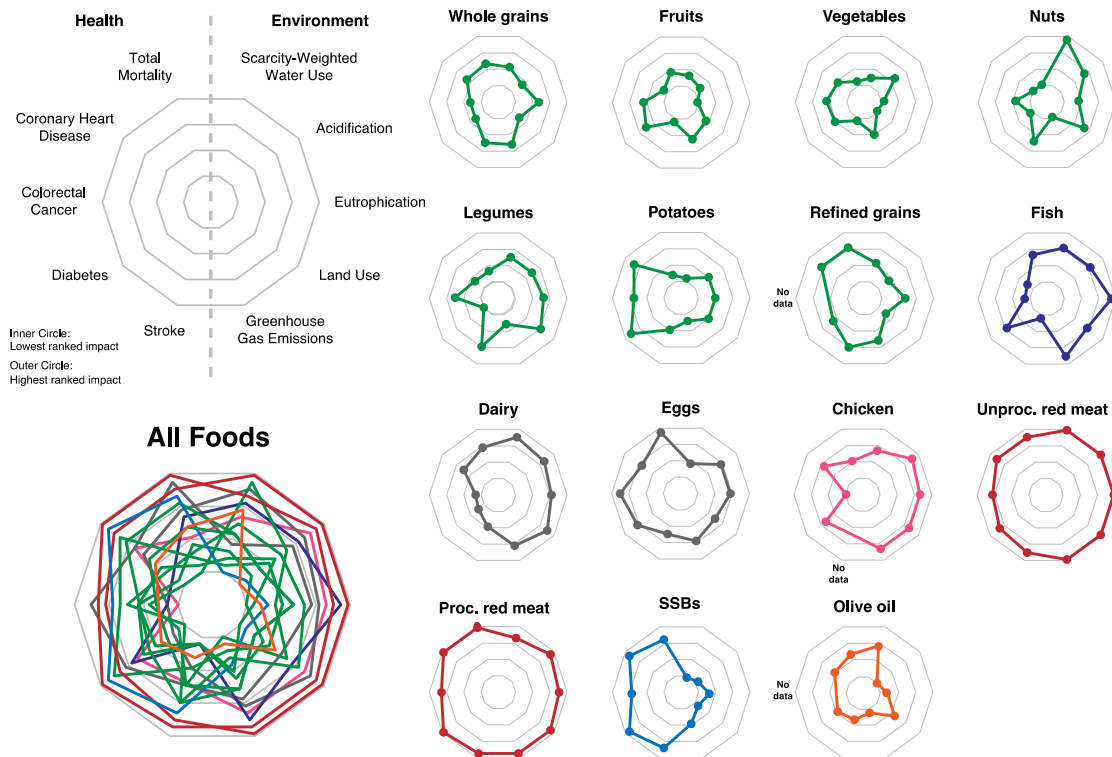
396  
397 **Author Contributions:**

MC, MS, and DT proposed the project. MC, DT, and JH analyzed the data. All authors helped write the manuscript.



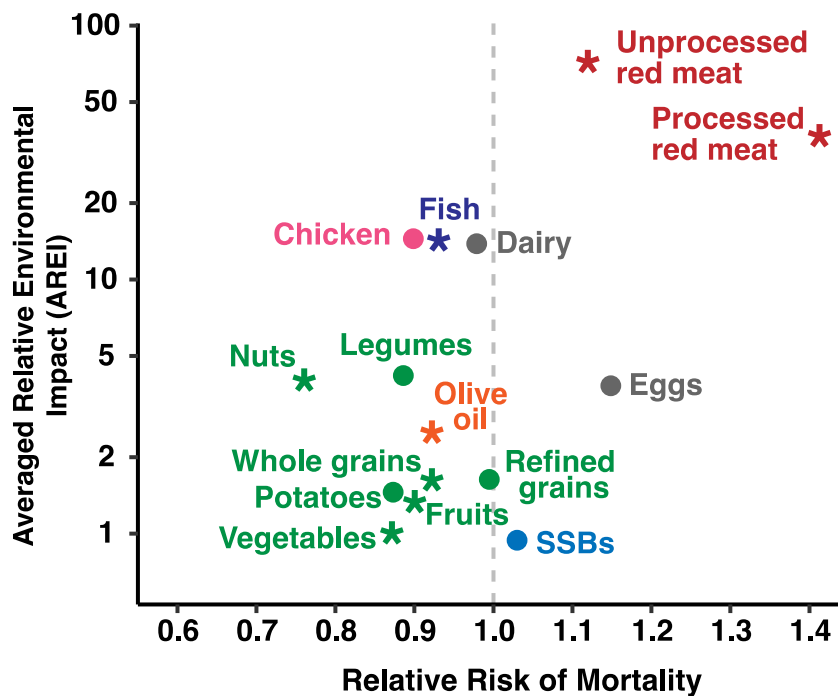
**Fig. 1. Summary of health and environmental data.** Health data are reported as the relative risk (RR) of disease per serving of food consumed, where an RR < 1 indicates that food consumption is associated with decreased disease risk and an RR > 1 indicates

that food consumption is associated with increased disease risk. Error bars for the health data indicate the 5<sup>th</sup> and 95<sup>th</sup> percentile confidence intervals. Environmental data are shown as the relative environmental impact per serving of food produced, where a value of 1 indicates that producing a serving of food has the same environmental impact as producing a serving of vegetables. Environmental impacts are plotted on a log10 scale, and error bars for the environmental data indicate the 5<sup>th</sup> and 95<sup>th</sup> percentile impacts per serving of food produced. Water use is reported as scarcity weighted water use, which accounts for regional variation in water availability. Data used to create the plots is available in the Supplemental Data in the SI Appendix. The association between total mortality and olive oil was estimated by weighting disease-specific contributions (e.g., CHD, stroke, and diabetes) to mortality by disease-specific relative risk (2).



**Fig. 2. Radar plots of rank-ordered health and environmental impacts per serving of food consumed per day.** Data are plotted on a rank order axis such that the food group with the lowest mean impact for a given indicator has a value of 1 (inner-most circle), and the food group with the highest mean impact for a given indicator has a value of 15 (outer-most circle). As such, small circles indicate food groups that consistently have among the lowest mean impacts for all 10 outcomes examined, whereas large circles indicate food groups that consistently have among the highest mean impacts for all 10 outcomes examined. The “All Foods” radar plot contains data from the radar plots for the 15 food groups superimposed onto a single plot. Data used to create the plot is available in the Supplemental Data in the SI Appendix. Labels are ACM = total mortality; CHD = coronary heart disease; CRC = colorectal cancer; DIA = type II diabetes; STR = stroke; AP = acidification; EP = eutrophication; GHG = greenhouse gas emissions; LU = land use; and H2O = scarcity weighted water use. Indicators with strikethroughs indicate that data for the indicator and that food is not available (colorectal cancer and olive oil colorectal cancer and refined grain cereals, and stroke and chicken). The association between total mortality and olive oil was estimated by weighting disease-specific contributions (e.g., CHD, stroke, and diabetes) to mortality by disease-specific relative risk (2).





435

436 **Fig. 3.** Association between a food group's impact on mortality its averaged relative  
 437 environmental impact (AREI) of consuming a serving of food per day. Y-axis is plotted  
 438 on a log scale and is the AREI of producing a serving of each food group across five  
 439 environmental outcomes relative to the impact of producing a serving of vegetables (not  
 440 including starchy roots and tubers). X-axis is the relative risk of mortality, where a  
 441 relative risk > 1 indicates that a food group is associated with increased disease risk and a  
 442 relative risk < 1 indicates that a food group is associated with decreased disease risk.  
 443 Labels and points are colored with green = minimally processed plant-based foods; dark  
 444 blue = fish; grey = dairy and eggs; pink = chicken; red = unprocessed red meat (beef,  
 445 lamb, goat and pork) and processed red meat; and light blue = sugar-sweetened  
 446 beverages; and orange = olive oil. Food groups associated with a significant change in  
 447 risk of mortality (at  $P < 0.05$ ) are denoted by \*. Serving sizes for the food groups are:  
 448 whole grains (30g dry weight); refined grains (30g dry weight); fruits (100g); vegetables  
 449 (100g); nuts (28g); legumes (50g dry weight); potatoes (150g); fish (100g); dairy (200g);  
 450 eggs (50g); chicken (100g); unprocessed red meat (100g); processed red meat (50g);  
 451 SSBs (225g); olive oil (10g). Data used to create the plot is available in the Supplemental

Data in the SI Appendix. The association between total mortality and olive oil was estimated by weighting disease-specific contributions (e.g., CHD, stroke, and diabetes) to mortality by disease-specific relative risk (2).

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## Supplementary Information for

### Multiple health and environmental impacts of foods

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#### **This PDF file includes:**

Supplementary text  
Fig. S1  
Fig. S2  
Tables S1 to S3  
References for SI reference citations

#### **Other supplementary materials for this manuscript include the following:**

Datasets S1

### **Supplementary Information Text**

#### **Materials and Methods**

##### ***Health***

##### *Description of dose-response meta-analyses, and data sources:*

Prospective cohort studies follow populations through time as a way to examine the health outcomes of changes in risk factors, such as consumption of different foods or dietary patterns. Prospective cohort studies analyze health outcomes in one of three ways: 1) dose-response analyses; 2) quintile analyses; or 3) substitution analyses. Dose-response analyses report the health impact of consuming a serving of food per day, for example, the health impact of consuming an additional serving of red meat per day. Studies comparing quintiles of consumption often report the health impact of extreme quintiles, for example, the health outcome of the subgroup that consumes the least red meat against the health outcome of the subgroup that consumes the most red meat. Studies examining food substitution report the health outcome of substituting one food for another, for example the health outcome of substituting one serving of red meat per day with an equivalent amount of chicken per day.

Meta-analyses use data from numerous individual studies to derive a more general relationship and to reduce the risk of bias that might be present in any individual study. In our health analysis, we used meta-analyses that used data from individual cohorts to derive dose-response relationships that are believed to indicate relationships between food consumption and disease risk, and are also supported by the existence of plausible pathways that explain risk mediation.

We used dose-response meta-analyses analyses in this analysis for several reasons. First, they allow for more direct comparison of the health and environmental outcome of different foods in quantities that might be consumed at a single meal. For instance, the serving sizes reported in dose-response meta-analyses vary

from 20 – 200g per day and are often similar in size to what is consumed at a meal (see Table S3 in the SI Appendix for serving sizes as reported in the dose-response meta-analyses). In addition, there are dose-response meta-analyses for most commonly consumed food groups. In total, we collected data from 19 dose-response meta-analyses that examined the health impact of consuming an additional serving of food per day for 15 food groups (17–35) (see Table S1 in the SI Appendix for publication list).

Dose-response meta-analyses control for confounding variables when reporting the health outcomes of food consumption. For instance, age, sex, history of smoking, race, and economic status are commonly controlled for in meta-analyses because they are known to influence health outcomes. Many dose-response meta-analyses report the health outcomes of consuming an additional serving of food per day when controlling for different amounts of confounding variables. When the outcomes of analyses with different amounts of confounding variables were reported, we used the health outcome from the analysis that controlled for the largest number of confounding variables to minimize the potential impact that uncontrolled confounding variables may have on the health outcomes of food consumption. In addition, we chose the dose-response meta-analysis that was most recently published when there were multiple dose-response meta-analyses examining the same food because these analyses often contained more studies and more individuals, and are thus more likely to represent the real health impact of consuming an additional serving of food per day. Dose-response meta-analyses that were funded in part by industry were not included in this analysis.

Many of the dose-response meta-analyses included in this analysis examine populations that are primarily Caucasian. However, the health impact of food consumption can differ depending on food preparation method (17), between individuals without and with pre-existing diseases (51), or between individuals that have different baseline dietary habits (e.g., ref (20)). For example, type II diabetes incidence is higher in men than women in Chinese, South Asian, and white populations (52), whereas African Americans have higher cancer rates for many cancers than Hispanics, Asian Americans, and Caucasians (53). However, while the results of the dose-response analyses included here are primarily based on Caucasian populations, the causal mechanisms of the health impacts of food consumption are assumed to hold irrespective of ethnicity. As such, it is unlikely that using analyses that examined non-Caucasian populations would have a large impact on the health outcomes reported here.

The underlying health data shows that consuming an additional serving per day of many of the foods examined here is associated with reduced disease risk. However, the marginal health benefit of increasing consumption of whole grain cereals, fruits, vegetables, nuts, and fish decreases as more of these foods are consumed (20, 22, 54, 55). Further, because excess caloric consumption and resultant weight gain lead to negative health outcomes (56), it is possible that eating more of a healthy food without decreasing consumption of other foods may not be beneficial to health. In addition, the dose-response health meta

analyses control for BMI, which means that the RR estimates used here do not account for the potential health impact of weight gain.

#### *Estimating morbidity from disease-specific endpoints*

We also estimated how consuming a serving of food per day is associated with morbidity, measured as years lost to disability, by weighting the RR for disease-specific endpoints by the relative contribution each disease to morbidity, measured as years lost to disability (2). For instance, if the RR for CHD is 1.1, the RR for stroke is 1.2, the RR for type II diabetes is 1, and the RR for colorectal cancer is 1.05, and the relative contribution of CHD, stroke, type II diabetes, and colorectal cancer to global morbidity is 0.45 (e.g., 45% of mortality from these three disease-specific endpoints), 0.35, 0.1, and 0.1, respectively, our estimate of total mortality for that food would be  $1.11 (1.1 * 0.45 + 1.2 * 0.34 + 1 * 0.1 + 1.1 * 0.1)$ . The upper and lower confidence intervals for morbidity were calculated in the same way, except using the upper and lower confidence intervals reported for disease-specific endpoints, while also accounting for uncertainty in the contribution of different diseases to morbidity.

#### *Estimating risk of mortality for olive oil*

We estimated the association between olive oil consumption and risk of total mortality because there is not a dose-response meta-analysis examining this association. To estimate the mean RR, we weighted the RR risk for disease-specific endpoints based on their relative contributions to global mortality as estimated by the Global Burden of Disease (2). For example, because the mean RRs for olive oil consumption and risk of CHD, diabetes, and stroke are 0.94, 0.91, and 0.90, respectively, and the relative contribution of CHD, diabetes, and stroke to total mortality are 0.477, 0.095, and 0.428, respectively, the estimated mean RR for olive oil consumption and total mortality is thus  $0.94 * .477 + 0.91 * 0.095 + 0.90 * 0.428$ , or 0.92. The estimated RR for the lower and upper confidence intervals were estimated in the same way, and are estimated to be 0.86 and 0.99, respectively.

### ***Environment***

#### *Description of life cycle analyses and data sources*

Life cycle assessment (LCAs) is a standardized method to estimate the environmental impacts per unit of food production. The meta-analysis of LCAs from which estimates of greenhouse gas (GHG) emissions, land use, nutrient runoff (specifically eutrophication) per gram of food were obtained estimated the environmental impacts from cradle to consumption (15). This system boundary accounts for all impacts that occur from pre-farm and on-farm activities such as fertilizer production and application, infrastructure construction, and on-farm fossil fuel, as well as post-farm activities such as transportation, processing, refrigeration, and cooking. GHG emissions from land-use change are also included in these estimates. Where possible, the estimates of environmental impacts per unit of food production were weighted

nationally and internationally to be representative of current global average production location and methodology.

The impacts of producing a given food often differs in environmental impact across geographical regions and production methodology (39, 40). Using non-weighted estimates of the environmental impacts of producing a serving of food (e.g., estimates from certain locations or from certain types of production systems, such as organic) would change the estimates of the absolute impacts and relative impacts per serving of food produced. However, using non-weighted estimates would not change the broad rankings of the environmental impacts of producing a serving of different foods. That is, plant source foods would often have the lowest environmental impacts; dairy, chicken, and eggs would have intermediate environmental impacts; and unprocessed and processed red meat would have the highest environmental impacts (39, 40). Using results from existing meta-analyses that are weighted based on current global production methodologies rather than from individual studies is in line with the broad scope of our analysis and reduces the risk of any potential data biases resulting from using data that is indicative of a single production location or methodology.

Scarcity-weighted water use is a metric that accounts for regional variation in water availability as well as the water used for food production (16). It is calculated by weighting the water used for food production by the amount of water available after accounting for water used in natural and agricultural processes. The southwest United States, Australia, the Middle East, Central Asia, Northern Africa, Southern Africa (South Africa, Namibia, Botswana, Mozambique, and Zimbabwe), and Chile have high scarcity water weightings. In contrast, Southeast Asia, New Zealand, Scandinavia, the eastern United States, Central America, northern South America (Colombia, eastern Ecuador, eastern Peru, Venezuela, Suriname, Guyana, French Guiana), and the Amazon Basin have low scarcity water weightings.

#### *Agricultural production method*

Agricultural production method can also influence a food's environmental impact. Producing organic foods, for example, often requires more land and causes more nutrient pollution per unit of food produced than non-organic systems (41, 57), whereas grass-fed beef tends to result in more GHG emissions and nutrient runoff than grain-fed beef (41). We controlled for agricultural production methodology by weighting the impacts per serving of food produced based on current global production from e.g. organic and conventional systems.

#### *Estimating the environmental impacts of fish production*

The environmental impact of fish production is highly dependent on production methodology. Trawling fisheries emit  $\sim 3 \times$  more GHGs than other types of fisheries while recirculating aquaculture emits  $\sim 3 \times$  more GHGs than non-recirculating aquaculture (41). Further, while production of wild-caught fish requires

no land, uses no irrigation water, and results in very small amounts of eutrophication, production of fish in aquaculture systems requires land, often uses irrigation water, and results in larger amounts of eutrophication.

Because of the differences in the environmental impact of fish production, we estimated the environmental impact per serving of fish by first assuming that half of fish are produced in wild-caught fisheries and half of fish are produced in aquaculture, which is approximately equivalent to the current breakdown of global fish production (58). To estimate the impact of wild-caught fish, we further assumed that 20% of wild-caught fish are produced via bottom trawling or dredging and 80% are produced using other capture methodologies, which is in-line with estimates reported in Watson et al (2006).

#### *Relative environmental impact*

Because the absolute magnitude of the environmental impact of food production varies across environmental indicators, we reported the environmental impact in this analysis as the relative environmental impact, or the environmental impact relative to a serving of vegetables. As such, a relative environmental impact of 1 indicates that producing a serving of food has the same environmental impact as vegetables, a relative environmental of 0.5 indicates that producing a serving of food has half the environmental impact of vegetables, while a relative environmental impact of 2 indicates that producing a serving of food has twice the environmental impact of vegetables.

To examine the averaged relative environmental impact of food production (Fig. 3) across all indicators, we averaged the relative environmental impact of a food across all five environmental indicators examined here. For example, if a food has a relative environmental impact of 2 for GHGs, 3 for land, 10 for eutrophication, 6 for acidification, and 4 for scarcity weighted water use, the averaged relative environmental impact of that food would be 5 ( $[2 + 3 + 10 + 6 + 4] / 5$ ).

Because we place equal weight on the 5 environmental indicators, we inherently assume that each environmental indicator is equally important. Other weightings, for instance weighting by proximity of current impacts to international environmental sustainability targets (e.g. the SDGs or the Paris Climate Agreement (10, 11)), could be useful to explore in further applications.

#### **Spearman's Ranked Correlations**

To examine the correlation between the pairwise combinations of the 5 health outcomes and 5 environmental indicators, we used Spearman's Ranked Correlations tests using the R function "rcorr" from the package "Hmisc". As used here, Spearman's Ranked Correlation tests examine whether the ranked impacts (1 = lowest) of consuming a food are correlated. As such, significant P-Values ( $P < 0.05$ ) indicate

that a food that has among the largest health benefit (or smallest environmental impact) for one outcome also has among the largest health benefit (or smallest environmental impact) for another outcome.

Of the 10 pairwise correlations between the 5 health outcomes, 8 Spearman's Ranked Correlation tests were significant at  $P < 0.05$  (Table S2 in the SI Appendix). Of the 10 pairwise correlations between the 5 environmental outcomes, 9 Spearman's Ranked Correlation tests were significant at  $P < 0.05$  (Table S2 in the SI Appendix).

#### **Additional discussion of each food group**

##### ***Whole grain cereals:***

In dose-response meta-analyses, consuming an additional serving per day of whole grain cereals (30g dry weight) has been associated with a significant reduction in risk of total mortality, CHD, type II diabetes, and colorectal cancer, but not of stroke (23, 24, 27, 28). Consuming an additional serving of whole grain cereals has among the largest health benefit for total mortality and type II diabetes of all foods included in this analysis (Fig. 1 and Fig. S1 in the SI Appendix). However, the health benefit of whole grain cereals is often non-linear, with the potential health benefits of a second (or third) serving being smaller than the first (or second serving). As such, large health benefits are often observed when increasing consumption of whole grain cereals when  $< 100\text{g/day}$  is consumed, while smaller health benefits are observed when increasing whole grain cereals when more than when  $> 100\text{g/day}$  is already consumed (28).

Per serving produced, whole grain cereals often have low mean environmental impacts, although there is large variation in the GHG emissions and water use per serving of whole grain cereals produced (Figs. 1–2, and Figs. S1–S2 in the SI Appendix). The variation in GHG emissions from whole grain cereals primarily results from differences between cereals. Rice production has 100–200% higher GHG emissions per serving produced than other cereals because methane, a greenhouse gas that has greater radiative forcing and thus warming potential than carbon dioxide, is released via anaerobic decomposition when rice paddies are flooded (15). There is also regional variation in the GHG emissions per serving of cereals produced, with higher GHG emissions resulting from production systems that use nutrients (fertilizer and manure) less efficiently or that are in regions with large carbon stores (e.g., peatlands) (40). Similarly, scarcity weighted water use per serving of whole grain cereal production, and for many other foods examined here, is highly variable, although is more dependent on the location of production rather than the type of cereal being produced. Scarcity weighted water use in whole grain cereal production, as well as production of other foods, is high in regions with limited water availability, such as North Africa, the Middle East, Central Asia, southeastern Australia, southwestern North America, and the west coast of South America, but is low in regions with large amounts of water availability, such as Amazonia, Southeast Asia, the eastern United States, and the United Kingdom (16).

**Nuts:**

“Nuts” includes both peanuts and tree nuts because consumption of peanuts and tree nuts has a similar impact on health outcomes. In meta-analyses, consuming an additional serving per day of nuts has been associated with significant reductions in total mortality and type II diabetes, but not for CHD, stroke, or colorectal cancer (23, 24, 27, 31) (Fig. 1). A significant reduction in risk of total mortality is observed even when small quantities of nuts are consumed. For instance, increasing nut consumption from 0 to 5g/day is associated with an approximately 7% reduction in risk of total mortality ( $P < 0.05$ ) (24). As with whole grain cereals, the health benefit of nut consumption is non-linear, with smaller health benefits when  $> 30\text{g/day}$  of nuts are already consumed (24).

Nut production has low mean environmental impacts for GHG emissions, land use, acidification, and eutrophication (Figs. 1–2 and Figs. S1–2 in the SI Appendix). Scarcity weighted water use for nuts is highly variable because of variations in regional water availability where nuts are produced and because producing different nuts uses different amounts of water. Chestnut and peanut production, for instance, uses small quantities of water ( $< 200\text{ m}^3$  of irrigation water per tonne produced); hazelnut, walnut, and almond production uses intermediate amounts of water (from 1,000 to 2,000  $\text{m}^3$  of irrigation water per tonne produced); and pistachio production uses large quantities of water ( $> 7,000\text{ m}^3$  of irrigation water per tonne produced) (59). Acidification resulting from nut production systems is also variable, largely because differences in fertilizer application rates and fertilizer use efficiencies in different cropping systems.

**Legumes:**

In dose-response meta-analyses, consuming an additional serving per day of legumes is not significantly associated with a change in any of the five health outcomes examined (23, 24, 27, 31) (Fig. 1). Analyses examining the extreme quantiles of legume consumption found that individuals who consumed the largest amount of legumes were at a significantly reduced risk of CHD and total mortality, but not stroke or colorectal cancer (23, 24, 27).

Producing a serving of legumes results in particularly low mean GHG emissions, acidification, and eutrophication (Figs. 1–2 and Figs. S1–2 in the SI Appendix). The GHG, acidification, and eutrophication impact of legume production is low because legumes have the ability to fix nitrogen (convert atmospheric nitrogen into nitrogen usable by the plant), which in turn reduces fertilizer input requirements, and resultantly the GHG emissions, acidification, and eutrophication impacts of legume production because these impacts often stem from fertiliser application and runoff.

**Fruits:**

In dose-response meta-analyses, consuming an additional serving per day of fruit has been associated with a significant reduction in risk of total mortality, CHD, stroke, and colorectal cancer, but not of type II

diabetes (19, 22, 27) (Fig. 1). Individual fruits vary in their impact on health, with starchy fruits (e.g., bananas) being less beneficial to health than many other fruits (22). The health benefit of fruit consumption is non-linear, with smaller additional health benefits observed when > 300g/day of fruits are already consumed. However, additional health benefits from consuming fruits are often observed when consuming up to 800g/day (22).

Fruits have low mean environmental impacts for every environmental indicator examined, although there is large variation in scarcity weighted water use (Figs. 1–2 and Figs. S1–2 in the SI Appendix). Moreover, the method of fruit production is also a determinant of a fruit’s environmental impact. For instance, while fruit production primarily occurs in open fields, fruit production can also occur in heated greenhouses. Producing a serving of fruit in heated greenhouses emits 200% more GHG emissions but uses 25% the land of producing a serving of fruit in an open field (41). However, the GHG emissions of fruit produced in greenhouses could be reduced if energy is sourced from renewable energy sources.

#### ***Vegetables:***

In dose-response meta-analyses, consuming an additional serving per day of vegetables has been associated with a significant reduction in risk of total mortality, CHD, stroke, and colorectal cancer, but not of type II diabetes (19, 22, 27) (Fig. 1). Individual vegetables may vary in their health benefit; leafy green vegetables such as spinach and kale are often associated with larger reductions in disease risk than many other types of vegetables, and have also been associated with a significant reduction in risk of type II diabetes (14, 22). The health benefit of vegetable consumption is non-linear, with smaller additional health benefits observed when > 300g/day of vegetables are already consumed. However, additional health benefits from consuming vegetables are often observed when consuming up to 800g/day of vegetables are consumed (22).

Vegetable production has low mean environmental impacts for each environmental indicator examined (Figs. 1–2 and Figs. S1–2 in the SI Appendix). There is, however, moderate variation around the mean impact for most environmental indicators, likely because of the diverse array of vegetables that are produced and consumed, but also because of regional differences in e.g. water availability or fertilizer application rates. However, as with fruits, vegetables can also be grown in heated greenhouses, which increases the GHG emissions but decrease the land use per serving of vegetables produced (41).

#### ***Potatoes:***

Consuming a serving of potatoes (150g) per day has been significantly associated with increased risk of type II diabetes, but is not significantly associated with risk of total mortality, coronary heart disease, stroke, or colorectal cancer (26) (Fig. 1). Comparing the health outcomes of the highest and lowest potato consumers found that individuals who consumed the largest amount of potatoes was also not significantly associated with disease risk for coronary heart disease, stroke, colorectal cancer, or total mortality (26).



Potato production has low mean environmental impacts for most environmental indicators (Figs. 1–2 and Figs. S1–2 in the SI Appendix).

***Refined grain cereals:***

Consuming a serving per day (30g dry weight) of refined grain cereals has not been associated with a significant change in health risk for any of the health outcomes examined here (20, 23, 24, 27) (Fig. 1).

Consuming larger quantities of refined grain cereals, however, may be detrimental for health. For instance, epidemiological studies that compared the health outcomes of individuals who consumed the largest quantity of refined grains with individuals that consumed the smallest quantity of refined grains found that individuals who consumed the largest quantity of refined grain cereals tended to be at increased risk of CHD (23). Similarly, consuming large quantities of white rice has been significantly associated with increased risk of type II diabetes (37).

Refined grain cereals have similar environmental impacts to whole grain cereals.

***Eggs:***

In dose-response meta-analyses, eggs have not been associated with a significant change in health for any of the five health outcomes examined here (21, 23, 24, 27) (Fig. 1). However, increasing egg consumption for individuals with pre-existing type II diabetes has been associated with a significant increase in risk of CHD mortality (51).

Egg production has low to intermediate mean environmental impacts for all five environmental indicators examined here (Figs. 1–2 and Figs. S1–2 in the SI Appendix). With the exception of water use, the variation in the environmental impact per serving of eggs produced is small.

***Dairy:***

In dose-response meta-analyses, dairy consumption has been associated with a significant decrease in risk of colorectal cancer, but not for total mortality or incidences of type II diabetes, stroke, or heart disease (18, 23, 24, 27) (Fig. 1). It is unclear whether skim and whole fat dairy products differ in their impact on health; the evidence that exists is limited and is often contradictory. See Mullie et al. (2016) (60) for a more in-depth discussion.

Producing a serving of dairy products has an intermediate environmental impact for GHG emissions, land use, acidification, and eutrophication, although there is considerable variation around the mean impact for each indicator (Figs. 1–2 and Figs. S1–2 in the SI Appendix). The 5<sup>th</sup> and 95<sup>th</sup> percentile scarcity weighted

water use and eutrophication impacts of dairy production, for instance, vary by more than an order of magnitude.

Ruminants (e.g., cows, sheep, goats, and camels) are able to convert grasses and other low-protein, fibrous plant material into higher-protein and micronutrient rich human edible foods. This is particularly important in regions with limited access to markets and with limited arable land that is suitable for crop production. Furthermore, ruminant production is a major source of income for some of the more rural populations, particularly those in Eastern Africa (e.g., Kenya and Ethiopia). In regions where food production is inconsistent and where food insecurity is a constant threat, ruminant production for both meat and dairy can be an integral source of nutrition security (61).

#### ***Fish:***

In dose-response meta-analyses, consuming an additional serving per day of fish has been associated with a significant reduction in risk of total mortality, CHD, and stroke, but not of type II diabetes or colorectal cancer (17, 23, 24, 27) (Fig. 1). The health benefit of fish consumption is non-linear. For instance, smaller additional reductions in CHD mortality are observed by increasing fish consumption when > 50g/day of fish are already consumed (23).

The mean environmental impact per serving of fish produced varies across the environmental indicators examined (Figs. 1–2 and Figs. S1–2 in the SI Appendix). This is likely because the environmental impact of fish production differs by fish type and by production methodology (41). Wild-caught fish occupy no land, use minimal or no freshwater water, and results in very low acidification and eutrophication. However, wild-caught fish contribute to fishery depletion, with over 30% percent of fisheries currently being harvested unsustainably and 58% being fully fished (58). In contrast, producing a gram of aquaculture-raised fish occupies similar amounts of land, emits a similar amount of GHGs, and results in a similar amount of acidification as poultry production, but uses a similar amount of water and results in a similar amount of eutrophication as red meat. The GHG emissions of fish production are highly variable. Production of wild-caught fish via line, net seine, or midwater trawl fisheries, or aquaculture-raised fish by pond, net pen, or unfed aquaculture systems emits approximately one quarter the GHGs of bottom-trawling fisheries or recirculating aquaculture systems, respectively (41). Trawling fisheries also have higher rates of by-catch than other capture methodologies, while bottom-trawling fisheries also contribute to ecosystem degradation by dragging a net across the sea floor (62).

#### ***Chicken:***

In dose-response meta-analyses, consuming an additional serving per day of chicken is not significantly associated with a reduction in total mortality or reductions in the incidences of type II diabetes, heart disease, or stroke (25, 30, 33) (Fig. 1). In some dose-response meta-analyses (33), but not in others (63),

chicken consumption has been associated with significant reductions in colorectal cancer risk. However, the association between chicken consumption and colorectal cancer is complicated because of potential dietary confounding variables, such as the fact that consumption of red meat (which is associated with increased risk of colorectal cancer (27, 63)) often decreases when consumption of chicken increases. Ability (or lack thereof) to properly control for potential dietary confounding variables may influence the association between poultry consumption and colorectal cancer in specific (and other associations more generally), and partially explain why there is a lack of clarity around the association between chicken consumption and risk of colorectal cancer. While increasing consumption of chicken in the absence of other dietary changes is not associated with reduced mortality, substituting chicken for red or processed red meat has been associated with a significant reduction in risk of total mortality (64).

Producing a serving of chicken has higher mean environmental impacts than most other foods except fish and unprocessed and processed red meat (Figs. 1–2 and Figs. S1–2 in the SI Appendix). Producing a serving of chicken has higher environmental impacts than most other foods because of the amount of feed required to produce it: on average, producing a gram of chicken requires  $4.7 \pm 0.27\text{g}$  of feed.

#### ***Unprocessed and processed red meat:***

In dose-response meta-analyses, consumption of unprocessed and processed red meat (e.g., pig, beef, sheep, and goat meat) have both been associated with significant increases in disease risk for every health endpoint included in this analysis (23, 24, 27, 29) (Fig. 1). Despite the smaller average serving size of processed red meat (50g vs 100g for unprocessed red meat), processed red meat is often associated with larger increase in disease risk than is unprocessed red meat. This is likely because of the higher levels of nitrate, nitrate, and sodium in processed meats (65).

Unprocessed and processed red meat have the highest mean environmental impact of all foods examined here for most environmental indicators (Figs. 1–2 and Figs. S1–2 in the SI Appendix). The GHG emissions from red meat production are high largely because of the amount of feed required to produce red meat ( $5.7 \pm 0.6\text{g}$  of feed per gram of edible pork;  $14.5 \pm 0.2\text{g}$  of feed per gram of edible sheep or goat meat; and  $20.0 \pm 0.8\text{g}$  of feed per gram of edible beef produced (66)), but also because ruminants produce methane when digesting food through a process called enteric fermentation (66). In industrial (i.e., confined animal operation) livestock systems, red meat production has high environmental impacts for the other environmental indicators examined here largely because of the amount of feed required to produce red meat. While pasture-based ruminant production systems do not use as much or any concentrate feed as industrial operations, pasture-based ruminant meat does not necessarily have lower environmental impacts than ruminant meat from industrial systems (41). Lifetime methane emissions from pasture-raised ruminants are greater than those in industrial systems because pasture-raised ruminants live longer than ruminants produced in industrial systems. In addition, acidification and eutrophication from pasture-based

ruminant systems can be particularly large, especially if the manure is not collected from the pastures and treated.

***Sugar-sweetened beverages:***

Dose-response meta-analyses have found that added sugars are significantly associated with an increased risk of CHD but not for total mortality (44, 45) (Fig 1). However, individual cohorts have found a positive association between added sugar consumption and risk of total mortality (44). While dose-response meta-analyses examining the association between added sugars and type II diabetes, stroke, and colorectal cancers do not yet exist, reviews have repeatedly shown that added sugar consumption is associated with increased risk of type II diabetes (e.g., ref (67)). Consuming a serving of SSBs each day is significantly associated with increased risk of type II diabetes, CHD, and stroke, but not with risk of total mortality or colorectal cancer risk of type II diabetes (e.g., ref (67)).

Producing a serving of added sugars or SSBs has among the lowest environmental impact for GHG emissions, acidification, and eutrophication (Figs. 1–2 and Figs. S1–2 in the SI Appendix), although scarcity weighted water use is highly variable and dependent on where the sugar is produced.

***Olive oil:***

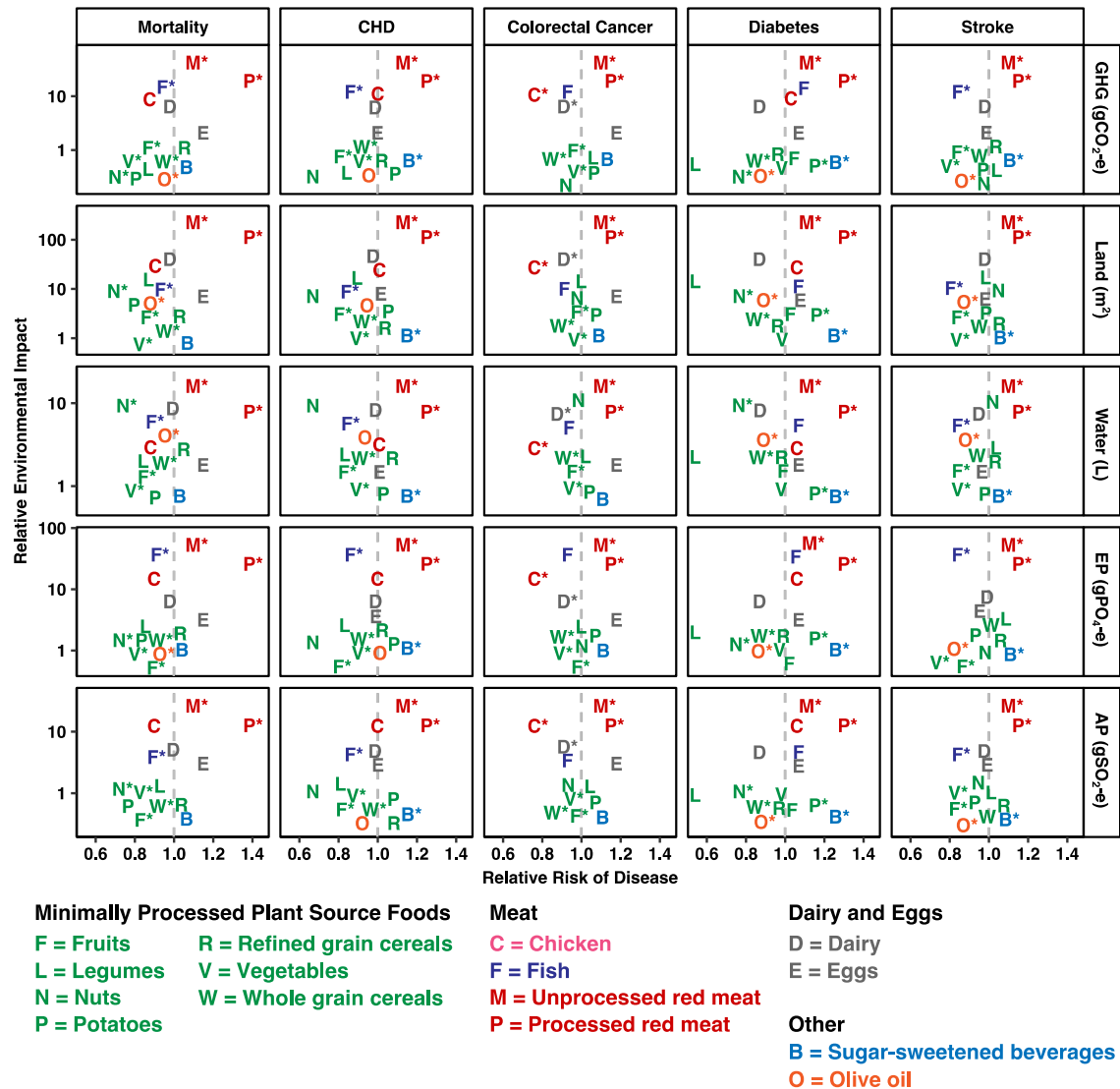
Consuming an additional serving of olive oil per day has been associated with statistically significant reductions in risk of type II diabetes and stroke, but not for CHD (32, 68) (Fig. 1). While there is no data for the association between olive oil consumption and risk total mortality from dose-response meta-analyses, we estimated that the RR of total mortality of consuming an additional 10g serving of olive oil per day is 0.92 (range = 0.86 – 0.99) by using the RR of disease-specific endpoints (CHD, stroke, and diabetes) and their relative contributions to global mortality as estimated by the Global Burden of Disease (2) (see Methods in the SI Appendix). Consuming other oils high in polyunsaturated fatty acids and low in saturated fatty acids when consumed in place of hydrogenated oils has been associated with a significant reduction in risk of heart disease and total mortality (36, 69). Dose-response meta-analyses examining the association between olive oil consumption and colorectal cancer have not yet been published.

Producing a serving of olive oil production has low mean environmental impacts for each environmental indicator examined (Figs. 1–2 and Figs. S1–2 in the SI Appendix). As with many other foods, however, the scarcity weighted water use impact is highly variable and is dependent on total water availability where olives are produced.



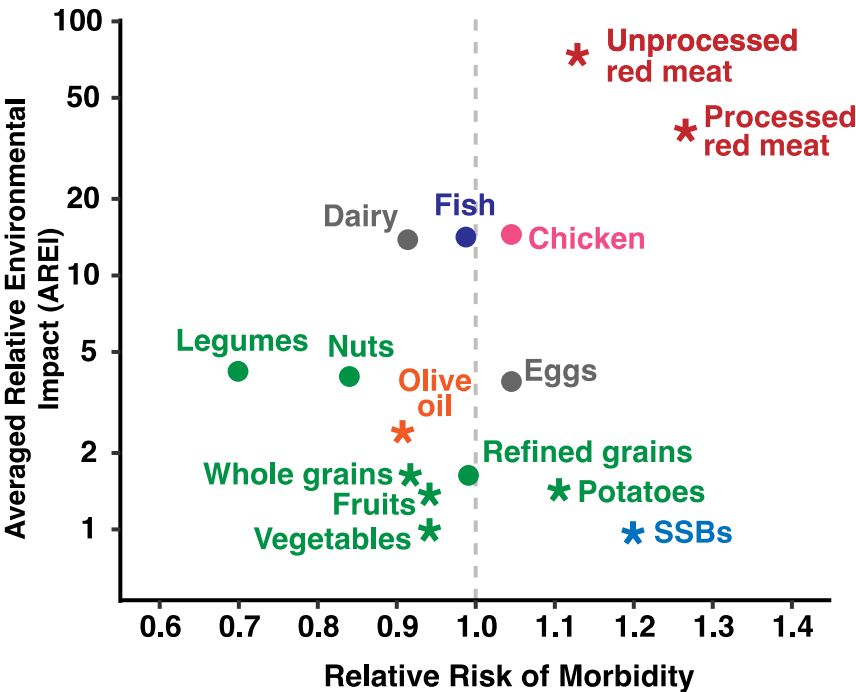
**Fig. S1. Radar plots of relative health and environmental impacts per serving of food consumed per day.** Solid line indicates mean impact per serving, and shading indicates 95% confidence intervals around the mean. Points closer to the origin are healthier, for the left-hand-side of each figure, and have lower environmental impacts, for the right-hand-side of each figure. For health outcomes, inner circle indicates a relative risk (RR) of 0.65 (or a 35% reduced risk of disease per additional serving consumed), middle circle indicates an RR of 1.00 (no change in disease risk), and outer circle indicates a RR of 1.35 (35% increased disease risk). For environmental outcomes, environmental impacts are plotted on a linear scale, where the inner circle indicates lowest mean impact per serving of food produced across the 15 foods examined, the outer circle indicates the highest mean impact, and the middle circle indicates environmental impacts that are halfway between the lowest and highest mean impact per serving (e.g., (lowest impact + highest impact) / 2). The “All Foods” radar plot contains data from the radar plots for the 15 food groups superimposed onto a single plot. Data used to create the plot is available in the Supplemental Data in the SI Appendix. Labels are ACM = total mortality; CHD = coronary heart disease; CRC = colorectal cancer; DIA = type II diabetes; STR = stroke; AP = acidification; EP = eutrophication; GHG = greenhouse gas

emissions; LU = land use; and H2O = scarcity weighted water use. Indicators with strikethroughs indicate that data for the indicator and that food is not available (colorectal cancer and olive oil, colorectal cancer and refined grain cereals, and stroke and chicken). The association between total mortality and olive oil was estimated by weighting disease-specific contributions (e.g., CHD, stroke, and diabetes) to mortality by disease-specific relative risk (2).



**Fig. S2.** Association between each pairwise comparison of the health and environmental impacts of 19 food groups of consuming a serving of food per day. Y-axis is the environmental impact of producing a serving of each food group relative to a producing a serving of vegetables (not including starchy roots and tubers),

plotted on a log scale. X-axis is the relative risk of disease per serving of food consumed per day, where a relative risk > 1 indicates that a food group is associated with increased disease risk and a relative risk < 1 indicates that a food group is associated with decreased disease risk. Letters denote food group, are jittered to avoid overlap, and are colored where green = minimally processed plant-based foods; dark blue = fish; grey = dairy and eggs; pink = chicken; red = unprocessed red meat (beef, lamb, goat and pork) and processed red meat; light blue = sugar-sweetened beverages; and orange = olive oil. Food groups associated with a statistically significant change in disease incidence (at  $P < 0.05$ ) are denoted by \*. Data used to create the plot is available in the Supplemental Data.



**Fig. S3.** Association between a food group's impact on morbidity and its averaged relative environmental impact (AREI) of consuming a serving of food per day. Y-axis is plotted on a log scale and is the AREI of producing a serving of each food group across five environmental outcomes relative to the impact of producing a serving of vegetables (not including starchy roots and tubers). X-axis is the relative risk of morbidity, where a relative risk > 1 indicates that a food group is associated with increased disease risk and a relative risk < 1 indicates that a food group is associated with decreased disease risk. Labels and points are colored with green = minimally processed plant-based foods; dark blue = fish; grey = dairy and eggs; pink = chicken; red = unprocessed red meat (beef,

lamb, goat and pork) and processed red meat; and light blue = sugar-sweetened  
beverages; and orange = olive oil. Food groups associated with a significant change in  
disease risk (at  $P < 0.05$ ) are denoted by \*. Serving sizes for the food groups are: whole  
grains (30g dry weight); refined grains (30g dry weight); fruits (100g); vegetables (100g);  
nuts (28g); legumes (50g dry weight); potatoes (150g); fish (100g); dairy (200g); eggs  
(50g); chicken (100g); unprocessed red meat (100g); processed red meat (50g); SSBs  
(225g); olive oil (10g). Data used to create the plot is available in the Supplemental Data  
in the SI Appendix.



Lead Author	Year Published	Journal	Title
<b>Wallin</b>	2012	Diabetes Care	Fish consumption, dietary long-chain n-3 fatty acids, and risk of type 2 diabetes
<b>Aune</b>	2013	AJCN	Dairy products and the risk of type 2 diabetes: a systematic review and dose-response meta-analysis of cohort studies
<b>Aune</b>	2013	European Journal of Epidemiology	Whole grain and refined grain consumption and the risk of type 2 diabetes: A systematic review and dose-response meta-analysis of cohort studies
<b>Feskens</b>	2013	Current Diabetes Reports	Meat Consumption, Diabetes, and Its Complications
<b>Abete</b>	2014	Journal of Nutrition	Association between total, processed, red and white meat consumption and all-cause, CVD and IHD mortality: a meta-analysis of cohort studies
<b>Afshin</b>	2014	AJCN	Consumption of nuts and legumes and risk of incident ischemic heart disease , stroke , and diabetes : a systematic review and meta-analysis
<b>Martinez-Gonzalez</b>	2014	British Journal of Nutrition	Olive oil consumption and risk of CHD and/or stroke: a meta-analysis of case-control, cohort, and intervention studies
Shi	2014	European Journal of Nutrition	Dose-response meta-analysis of poultry intake and colorectal cancer incidence and mortality
<b>Imamura</b>	2015	BMJ	Consumption of sugar sweetened beverages, artificially sweetened beverages, and fruit juice and incidence of type 2 diabetes: systematic review, meta-analysis, and estimation of population attributable fraction
<b>Wu</b>	2015	Nutrition, Metabolism & Cardiovascular Diseases	Fruit and vegetable consumption and risk of type 2 diabetes mellitus: A dose-response meta-analysis of prospective cohort studies
<b>Aune</b>	2016	BMJ	Whole grain consumption and risk of cardiovascular disease , cancer , and all cause and cause specific mortality : systematic review and dose-response meta-analysis of prospective studies
Wallin	2016	Diabetologia	Egg consumption and risk of type 2 diabetes: a prospective study and dose_response meta-analysis
<b>Aune</b>	2017	International Journal of Epidemiology	Fruit and vegetable intake and the risk of cardiovascular disease, total cancer and all-cause mortality_a systematic review and dose- response
Bechthold	2017	Critical Reviews in Food Science and Nutrition	Food groups and risk of coronary heart disease, stroke and heart failure: A systematic review and dose-response meta-analysis of prospective studies
<b>Mohammadi</b>	2017	Clinical Nutrition ESPEN	Dietary poultry intake and the risk of stroke: a dose-response meta-analysis of prospective cohort studies

Schwingshaki	2017	AJCN	Food groups and risk of all-cause mortality: a systematic review and meta-analysis of prospective studies
Schwingshaki	2017	Nutrition and Diabetes	Olive oil in the prevention and management of type 2 diabetes mellitus: a systematic review and meta-analysis of cohort studies and intervention trials
Schwingshaki	2018	International Journal of Cancer	Food groups and risk of colorectal cancer
Schwingshaki	2018	European Journal of Nutrition	Potatoes and risk of chronic disease: a systematic review and dose-response meta-analysis

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1153 **Table S1.** Dose-response health analyses used in this analysis.

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Health			Environment		
Health Outcome 1	Health Outcome 2	P-Value	Environmental Impact 1	Environmental Impact 2	P-Value
Total Mortality	Coronary Heart Disease	0.005	Acidification Potential	Eutrophication Potential	<.001
Total Mortality	Colorectal Cancer	0.139	Acidification Potential	GHG Emissions	0.002
Total Mortality	Type II Diabetes	0.027	Acidification Potential	Land Use Scarcity	<.001
Total Mortality	Stroke	0.035	Acidification Potential	Weighted Water Use	0.008
Coronary Heart Disease	Colorectal Cancer	0.021	Eutrophication Potential	GHG Emissions	<.001
Coronary Heart Disease	Type II Diabetes	0.002	Eutrophication Potential	Land Use Scarcity	<.001
Coronary Heart Disease	Stroke	0.008	Eutrophication Potential	Weighted Water Use	0.015
Colorectal Cancer	Type II Diabetes	0.022	GHG Emissions	Land Use Scarcity	0.034
Colorectal Cancer	Stroke	0.027	GHG Emissions	Weighted Water Use	0.145
Type II Diabetes	Stroke	0.294	Land Use	Weighted Water Use	<.001

**Table S2.** P-values of the Spearman's Ranked Correlations between the pairwise health and environmental outcomes. All correlations are positive.

Food Group	Mortality	CHD (Coronary Heart Disease)	Colorectal Cancer	Stroke	Diabetes
<b>Chicken</b>	100	100	100	NA	100
<b>Dairy</b>	200	200	200	200	200
<b>Eggs</b>	50	50	50	50	21.4
<b>Fish</b>	100	100	100	100	100
<b>Fruits</b>	100	100	100	100	100
<b>Legumes</b>	50	50	50	50	50
<b>Nuts</b>	28	28	28	28	28
<b>Olive oil</b>	10	10	NA	10	10
<b>Potatoes</b>	150	150	150	150	150
<b>Processed meat</b>	50	50	50	50	50
<b>Red meat</b>	100	100	100	100	100
<b>Refined grains</b>	30	30	NA	30	30
<b>SSBs</b>	25	25	25	25	25
<b>Vegetables</b>	100	100	100	100	100
<b>Whole grains</b>	30	30	30	30	30

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**Table S3.** Serving sizes, as grams per serving, as reported in the dose-response health meta-analyses (Table S1), and thus as used in this analysis. Serving sizes for refined grain cereals and whole grain cereals are reported in dry weight; serving size for SSBs (sugar-sweetened beverages) is reported as grams of sugar. “NA” indicates that health data for the food group and health outcome were not available from dose response meta-analyses.

Food Group	Disease	Asia	Canada/USA	Europe	Oceania	Other or Not Specified
Chicken	ACM	23% (30%)	32% (39%)	45% (32%)	-	-
	CHD	27% (32%)	31% (38%)	42% (30%)	-	-
	CRC	4% (3%)	47% (45%)	43% (47%)	6% (5%)	-
	Stroke	40% (61%)	60% (39%)	-	-	-
Dairy	ACM	33% (33%)	14% (14%)	49% (49%)	0% (0%)	4% (4%)
	CHD	0% (0%)	50% (49%)	50% (51%)	-	-
	CRC	6% (7%)	48% (47%)	46% (46%)	-	-
	Diabetes	7% (14%)	84% (76%)	8% (9%)	1% (2%)	-
	Stroke	-	78% (72%)	22% (28%)	-	-
Eggs	ACM	6% (6%)	10% (10%)	84% (84%)	-	-
	CHD	0% (0%)	50% (49%)	50% (51%)	-	-
	CRC	53% (78%)	-	47% (22%)	-	-
	Diabetes	10% (24%)	22% (20%)	68% (56%)	-	-
	Stroke	-	78% (72%)	22% (28%)	-	-
Fish	ACM	33% (33%)	16% (16%)	50% (50%)	1% (1%)	-
	CHD	0% (0%)	50% (49%)	50% (51%)	-	-
	CRC	12% (13%)	43% (33%)	44% (52%)	1% (2%)	-
	Diabetes	44% (44%)	50% (50%)	6% (6%)	-	-
	Stroke	-	78% (72%)	22% (28%)	-	-
Fruits	ACM	14% (18%)	9% (6%)	73% (67%)	5% (9%)	-
	CHD	32% (36%)	30% (28%)	37% (35%)	0% (1%)	-
	CRC	8% (8%)	56% (64%)	37% (28%)	-	-
	Diabetes	9% (24%)	88% (73%)	3% (4%)	-	-
	Stroke	33% (38%)	40% (39%)	26% (23%)	-	-
Legumes	ACM	41% (41%)	0% (0%)	53% (53%)	0% (0%)	6% (6%)
	CHD	0% (0%)	50% (49%)	50% (51%)	-	-
	CRC	18% (19%)	34% (46%)	48% (35%)	-	-
	Diabetes	58% (64%)	42% (36%)	-	-	-
	Stroke	-	78% (72%)	22% (28%)	-	-
Nuts	ACM	21% (21%)	27% (27%)	48% (48%)	0% (0%)	4% (4%)
	CHD	0% (0%)	50% (49%)	50% (51%)	-	-
	CRC	3% (2%)	71% (58%)	26% (40%)	-	-

	Diabetes	8% (20%)	88% (77%)	3% (2%)	-	-
	Stroke	-	78% (72%)	22% (28%)	-	-
				100%		
	CHD	-	-	(100%)	-	-
Olive Oil	Diabetes	-	87% (78%)	13% (22%)	-	-
				100%		
	Stroke	-	-	(100%)	-	-
	ACM	-	50% (39%)	50% (61%)	-	-
	CHD	-	40% (42%)	60% (58%)	-	-
Potatoes	CRC	6% (5%)	41% (57%)	53% (38%)	-	-
	Diabetes	6% (18%)	87% (66%)	5% (8%)	3% (9%)	-
	Stroke	-	50% (53%)	50% (47%)	-	-
	ACM	-	53% (58%)	47% (42%)	-	-
	CHD	4% (3%)	50% (55%)	46% (42%)	-	-
Processed Red Meat	CRC	6% (7%)	60% (57%)	33% (35%)	2% (2%)	-
	Diabetes	-	-	-	-	100% (100%)
	Stroke	-	78% (72%)	22% (28%)	-	-
	ACM	20% (26%)	42% (42%)	38% (32%)	-	-
	CHD	18% (22%)	43% (44%)	40% (34%)	-	-
Red Meat	CRC	11% (13%)	63% (58%)	24% (28%)	2% (1%)	-
	Diabetes	-	-	-	-	100% (100%)
	Stroke	-	78% (72%)	22% (28%)	-	-
	ACM	2% (2%)	98% (98%)	-	-	-
	CHD	0% (0%)	50% (49%)	50% (51%)	-	-
Refined Grains	Diabetes	-	80% (84%)	20% (16%)	-	-
	Stroke	-	78% (72%)	22% (28%)	-	-
	ACM	7% (7%)	58% (58%)	35% (35%)	-	-
	CHD	0% (0%)	50% (49%)	50% (51%)	-	-
SSBs	CRC	-	25% (15%)	-	-	75% (85%)
	Diabetes	9% (17%)	75% (65%)	16% (18%)	-	-
	Stroke	-	78% (72%)	22% (28%)	-	-
				5%		
	ACM	15% (19%)	9% (6%)	71% (65%)	(10%)	-
	CHD	11% (9%)	56% (61%)	33% (30%)	0% (1%)	-
Vegetables	CRC	9% (9%)	54% (63%)	37% (28%)	-	-
	Diabetes	19% (40%)	73% (54%)	7% (6%)	-	-
	Stroke	19% (17%)	34% (39%)	47% (44%)	-	-
	ACM	0% (0%)	70% (70%)	30% (30%)	-	-
	CHD	0% (0%)	50% (49%)	50% (51%)	-	-
Whole Grains	CRC	-	68% (73%)	32% (27%)	-	-
	Diabetes	-	91% (90%)	9% (10%)	-	-
	Stroke	-	78% (72%)	22% (28%)	-	-

**Table S4.** Geographic distribution of study participants in the dose-response meta-analyses used here. Estimates are divided by food group and disease outcome, and are reported for person years (number of participants).

**Additional data table S1 (separate file)**

Additional Data Table S1 contains all of the data used to make Figs. 1–4 and Fig. S1.

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