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Citation	Springmann, Marco; Mason-D'Croz, Daniel; Robinson, Sherman; Garnett, Tara; Godfray, H. Charles J.; Gollin, Douglas; Rayner, Mike; Ballon, Paola; and Scarborough, Peter. Global and regional health effects of future food production under climate change: A modelling study. The Lancet. Article in press. First published online on March 3, 2016. http://dx.doi.org/10.1016/S0140-6736(15)01156-3
DOI	http://dx.doi.org/10.1016/S0140-6736(15)01156-3
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This study was made possible with support from the Oxford Martin Programme on the Future of Food and the Global Futures and Strategic Foresight (GFSF) project. GFSF is funded by the CGIAR Research Program on Policies, Institutions, and Markets (PIM), the Bill and Melinda Gates Foundation, and the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS).

Global and regional health impacts of future food production under climate change: a modelling study*

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Abstract

Background: One of the most important consequences of climate change could be its impact on agriculture. While much research has focused on questions of food security, less attention has been devoted to assessing the wider health impacts of future changes in agricultural production. We estimate excess mortality due to agriculturally mediated changes in dietary and weight-related risk factors by cause of death for 155 world regions in the year 2050.

Methods: We linked a detailed agricultural modelling framework, the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT), to a comparative risk assessment of changes in fruit and vegetable consumption, red-meat consumption, and body weight for deaths from coronary heart disease, stroke, cancer, and an aggregate of other causes. We calculated the change in the number of deaths due to climate-related changes in weight and diets for the combination of four emissions and three socio-economic pathways, which each included six scenarios with variable climatic inputs.

Findings: The model projects that by 2050 climate change will lead to per-capita reductions of 3.2% (± 0.4%), 4.0% (± 0.7%), and 0.7% (± 0.1) in global food availability, fruit and vegetable consumption, and red-meat consumption, respectively. Those changes were associated with 529,000 climate-related deaths globally (95% confidence interval (CI): 314,000-736,000), representing a 28% (95% CI: 26-33%) reduction in the number of deaths that would be avoided due to changes in dietary and weight-related risk factors between 2010 and 2050. Twice as many climate-related deaths were associated with reductions in fruit and vegetable consumption than with climate-related increases in the prevalence of underweight, and most climate-related deaths were projected to occur in South and East Asia. Adopting climate-stabilization pathways reduced the number of climate-related deaths by 29-71% depending on their stringency.

Interpretation: The health impacts of climate change from changes in dietary and weight-related risk factors could be significant, and exceed other climate-related health impacts that have been estimated. Climate change mitigation could prevent a substantial number of climate-related deaths. Strengthening public-health programmes aimed at preventing and treating diet and weight-related risk factors could be a suitable climate change adaptation strategy.

Funding: Oxford Martin Programme on the Future of Food.

Introduction

Climate change has been described as the biggest global health threat of the 21st century.[1] Health can be affected by climate change in various ways: directly, due to changes in temperature, precipitation, and the occurrence of heat waves, floods, droughts, and fires; or indirectly, due to ecological and social disruptions, such as crop failures, shifting patterns of disease vectors, and displacement of people.[2] The impacts on the food supply and food security may be one of the most important consequences of climate change due to the large number of people that may be affected.[2–4] Climate change impacts are expected to reduce the quantity of food harvested,[5] which could lead to higher food prices and reduced consumption,[6] and to an increase in the number of malnourished people.[7,8]

However, the relationship between agriculture and health goes beyond issues of food security and caloric availability.[9–11] Agricultural production and regional food availability also influence the composition of diets, which can have major importance for health.[12] The Global Burden of Disease study found that in 2010, the greatest number of deaths, worldwide and in most regions including developing countries, was attributable to dietary risk factors associated with imbalanced diets, such as those low in fruits and vegetables and high in red and processed meat.[13] In comparison, about ten percent more disability-adjusted life-years and seven times more deaths were attributed to dietary risk factors than to the common food security indicator of child and maternal undernutrition, up from ratios of one half and two, respectively, in 1990.[13] The growing importance of dietary risk factors reflects a general trend away from communicable diseases associated with undernutrition and poor sanitation to non-communicable diseases associated with high body weight and unbalanced diets.[14]

Here we present a first quantitative analysis of the global health implications of such dietary and weight changes in light of climate change and agricultural production. We estimate the impacts of climate change on dietary and weight-related health risks and associated cause-specific mortalities for 155 world regions in the year 2050.

Methods

The way future climate change impacts health via changes in food consumption and dietary and weight-related risk factors can be conceptualised as follows. Future food production and consumption is expected to increase, driven by population and income growth and mediated by market responses, such as changes in prices and management practices.[33,34] Relative to that, climate change leads to changes in temperature and precipitation, which is expected to reduce global crop productivity,[5,15] and via market responses, lead to changes in management intensity, cropping area, consumption, and international trade.[6] From a health perspective, changes in food availability and consumption affect dietary and weigh-related risk factors associated with an increased incidence of non-communicable diseases and mortality, such as low fruit and vegetable consumption,[16–18] high red meat consumption,[18–20] and increased body weight.[21,22]

In line with the conceptual framework, we devised a multi-step methodology, depicted in Figure 1, which leads from climate-change impacts on agricultural yields, through changes in food production and consumption, to changes in dietary and weight-related risk factors and associated mortalities. For that purpose, we linked a detailed agricultural modelling framework to a comparative risk assessment of dietary and weight-related risk factors for cardiovascular diseases and cancer.

Agricultural modelling framework

The agricultural modelling framework relied on the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) which uses economic, water, and crop models to simulate global food production, consumption, and trade of 62 agricultural commodities for 159 world regions. A detailed description of the IMPACT model is provided in Appendix A1 and elsewhere.[23,24] We used the IMPACT model to produce global food scenarios for the year 2050. Building on methods developed by the Agricultural Model Intercomparison and Improvement Project (AgMIP),[6] we analysed the range of potential climate impacts by comparing a reference “middle-of-the-road” development scenario without climate-change impacts to scenarios with high climate-change impacts. Panel 1 discusses the socio-economic and emissions pathways adopted, and Appendix A2 provides additional detail on the model inputs used for constructing the model scenarios.

The IMPACT model estimates commodity-specific food availability at the country level, which we used in a comparative risk assessment to analyse changes in the exposure of dietary and weight-related risks. For the dietary risk assessment, we converted the food availability estimates for fruit and vegetables and for red meat into food consumption estimates by using regional data on food wastage at the consumption level, combined with conversion factors into edible matter (see Appendix A3).[25] For the weight-related risk assessment, we estimated changes in weight as shifts in the baseline weight distribution by using the historical relationship between national food availability and mean body mass index (BMI). We estimated the baseline distribution by fitting a log-normal distribution to estimates from the World Health Organization (WHO) of mean BMI and the prevalence of overweight and obesity using a cross-entropy method,[26] which jointly minimizes the deviation of the prevalence of overweight and obesity for each mean BMI estimate (see Appendix A4). We derived the shifts in the weight distribution related to changes in food availability by pairing food availability data from the Food and Agricultural Organization of the United Nations (FAO) for the years 1980-2009 with WHO data on mean BMI for the same period, using a polynomial trend to describe their relationship ($R^2 = 0{\cdot}46$; $p < 0.001$) (see Appendix A4).

Health modelling framework

We analysed the health impacts associated with changes in food consumption by using a comparative risk assessment framework with four disease states and six diet and weight-related risk factors. The disease states included coronary heart disease (CHD), stroke, cancer (which is an aggregate of site-specific cancers), and an aggregate for all other causes. The three specific disease states accounted for about 60% of deaths from non-communicable diseases and for about 40% of deaths globally in 2010.[14] The weight-related risk factors corresponded to the four weight classes of underweight (BMI<18·5), normal weight (18·5<BMI<25), overweight (25<BMI<30), and obesity (BMI>30), and the diet-related risk factors included fruit and vegetable consumption and red meat consumption which, together, accounted for more than half of all deaths that were attributable to diet-related risks in 2010.[13] The dietary and weight-related risk factors included in this study accounted for 18% of all deaths in 2010 and for 33% of deaths attributed to specific causes.[13]

We estimated the mortality and disease burden attributable to dietary and weight-related risk factors by calculating population attributable fractions (PAFs). PAFs represent the proportions of disease cases that would be avoided when the risk exposure was changed from a baseline situation (the reference scenario without climate change) to a counterfactual situation (the climate change scenarios). For calculating PAFs, we used the general formula:[13,27]

$$PAF = \frac{\int RR(x)P(x)dx - \int RR(x)P'(x)dx}{\int RR(x)P(x)dx} \qquad (1)$$

where $RR(x)$ is the relative risk of disease for risk factor level x, $P(x)$ is the number of people in the population with risk factor level x in the baseline scenario, and $P'(x)$ is the number of people in the population with risk factor level x in the counterfactual scenario (see Appendix A5 for a detailed description). We assumed that changes in relative risks follow a dose-response relationship,[13,28] and that PAFs combine multiplicatively,[13,29] i.e. $PAF_{TOT} = 1 - \prod_i (1 - PAF_i)$ where the i's denote independent risk factors.

We used publically available data sources to parameterize the comparative risk analysis. Population and mortality data by region and 5-year age group for the year 2050 were adopted from IIASA and the United Nations Population Division, respectively. All-cause mortality rates for 2050 were decomposed into cause-specific ones for CHD, stroke, an aggregate of cancers, and an aggregate of all other causes by using burden of disease estimates for WHO member states in 2008, projected forward to 2050 for the dietary and weight-related risk factors focussed on here. Given that dietary and weight-related risk factors are predominantly associated with chronic, non-communicable disease mortality, we focused on the health implications of changes in those risk factors for adults (aged 20 and older). We restricted the selection of relative risk parameters to meta-analyses and pooled prospective cohort studies (see Appendix A6). The diet and weight-related relative risk parameters were adopted from pooled analyses of prospective cohort studies,[21,22] and from meta-analysis of prospective cohort and case-control studies.[19,20,16–18] The cancer associations have been judged as probable or convincing by the World Cancer Research Fund, and in each case a dose-response relationship was apparent and consistent evidence suggests plausible mechanisms.[18]

Uncertainty analysis

We undertook a comprehensive set of sensitivity analyses to quantify the main uncertainties associated with each model component, including climatic, socio-economic, and epidemiological uncertainties (Table A2.1 in Appendix A2). We quantified the climatic uncertainties associated with each socio-economic and emissions pathway by calculating the mean and standard deviation of six climate scenarios which represented the cross-section of three general circulation models and two crop models. For each climate scenario, we quantified the epidemiological uncertainties by calculating uncertainty intervals based on 1,000 iterations of a Monte Carlo analysis which randomly drew the relative risk parameters from their log-normal distributions. In a sensitivity analysis, we analysed the uncertainty associated with socio-economic development and emissions pathways by considering twelve combinations of three different socio-economic pathways and four different emissions pathways, which forms the complete set of common pathways developed by the climate change research community (Panel 1).

Role of the funding source

The funder of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report. All authors had full access to all the data in the study and the corresponding author had final responsibility for the decision to submit for publication.

Results

Food availability and consumption

Table 1 lists global and regional food availability and consumption in the baseline of 2010, for the reference scenario without climate change in 2050, and for the mean of the main climate change scenarios in 2050. Without climate change, the agriculture-economic model projects an increase in global food availability of 289 kilocalories per person per day (kcal/cap/day) between the years 2010 and 2050 (10·3%); global fruit and vegetable consumption, net of food waste, is projected to increase by 35·8 grams per person per day (g/cap/day), and global red meat consumption, net of food waste, to increase by 3·9 g/cap/day. Consumption changes in terms of million tonnes per year are larger, agree with the current range of projections,[30] and are reported in Appendix A8.

In line with previous estimates,[6,30] the agriculture-economic model projects that climate change will lead to reduced food availability, which mitigates the increases in food availability that are projected to occur between 2010 and 2050. The model scenarios with climate change project a relative reduction of global food availability, fruit and vegetable consumption, and red meat consumption in 2050 by 99 kcal/cap/day (3·2%; standard deviation of climate change scenarios (CC SD): 11 kcal/cap/day, 0.4%), 15·0 g/cap/day

(4·0%; CC SD: 2.7 g/cap/day, 0.7%), and 0·5 g/cap/day (0·7%; CC SD: 0.1 g/cap/day, 0.1%), respectively, when compared to the 2050 reference scenario without climate change. Consumption changes for other food items are reported in Appendix A8.

The climatic impacts on food availability and consumption were subject to large regional variation. Regional food availability was reduced above average in the low and middle-income countries of Africa (122 kcal/day (4·2%); CC SD: 13 kcal/day), South-East Asia (116 kcal/day (4·1%); CC SD: 13 kcal/day) and the Western-Pacific (111 kcal/day (3·2%); CC SD: 16 kcal/day); regional fruit and vegetable consumption was reduced above average in the low and middle-income countries of the Western Pacific (23·0 g/cap/day (3.8%); CC SD: 4·3 g/cap/day) and in high-income countries (15·4 g/cap/day (3·9%); CC SD: 2·7 g/cap/day); and regional red-meat consumption was reduced above average in high-income countries (1·1 g/cap/day (0·7%); CC SD: 0·2 g/cap/day), and in the low and middle-income countries of America (0·9 g/cap/day (0·9%); CC SD: 0·1 g/cap/day), the Western Pacific (0·6 g/cap/day (0·5%); CC SD: 0·1 g/cap/day), and Europe (0·6 g/cap/day (0·8%); CC SD: 0·1 g/cap/day). Country-level results are listed in Tables A8.3-A8.5 in Appendix A8.

Health impacts

Table A9.1 in Appendix A9 lists the health impacts associated with the changes in food availability and consumption for the future consumption scenarios with and without climate change. The basis for comparison is a baseline with 2010 levels of food consumption and weight levels, but with all-cause death rates and population structures of 2050. Adopting this baseline allowed us to isolate the health impacts of changes in dietary and weight-related risk factors between 2010 and 2050 when comparing it to the reference and climate change scenarios, and to estimate the impacts of climate change in 2050 by calculating the difference between the reference scenario and the climate-change scenarios. The increases in food availability and consumption in the reference scenario without climate change resulted in 1·9 million avoided deaths (95% confidence interval of the relative risk distribution (CI): 0·9-2·8 million) in 2050 compared to the baseline with 2010-levels of food availability and consumption. Climate change reduced the number of avoided deaths by 28% (95% CI: 26-33%), which lead to 529,000 climate-related deaths (95% confidence interval of the relative risk distribution averaged over all climate scenarios: 314,000-736,000; CC SD: 105,000) compared to the reference scenario in 2050 (Figure 2). Most climate-related deaths occurred in the low and middle-income countries of the Western Pacific (264,000; 95% CI: 178,000-354,000; CC SD: 53,000) and South-East Asia (164,000; 95% CI: 102,000-216,000; CC SD: 29,000).

Underlying the changes in the number of deaths are changes in specific risk factors in each region. Figure 2 shows the individual contribution of the specific risk factors. Globally, the greatest contributor to the climate-related deaths were changes in dietary risk factors. The negative health impacts associated with reductions in fruit and vegetable consumption led to 534,000 climate-related deaths (95% CI: 365,000-699,000; CC SD: 100,000), which far outweighed the health benefits associated with reductions in red meat consumption (29,000 avoided deaths; 95% CI: 27,000-32,000; CC SD: 4,000). Weight-related changes in the number of deaths were balanced globally. Lower caloric availability due to climate change increased the total number of underweight people, which led to 266,000 additional deaths (95% CI: 203,000-329,000; CC SD: 32,000), but it also reduced the number of overweight and obese people, which led to 35,000 avoided deaths (95% CI: -13,000-84,000; CC SD: 5,000) and 225,000 avoided deaths (95% CI: 198,000-254,000; CC SD: 26,000), respectively. Figure A9.1 in Appendix A9 details the associated causes of death.

The climate-related changes in dietary and weight-related risk factors vary greatly by region and income group (Figure 2). Corresponding to the changes in food availability and consumption (Table 1), changes in fruit and vegetable consumption were the primary risk factor for climate-related death in high-income countries (accounting for 58% of all changes in deaths; 95% CI: 49-64%) and in the low and middle-income countries of the Western Pacific (74%; 95% CI: 65-79%), Europe (60%; 95% CI: 46-69%), and the Eastern Mediterranean (42%; 95% CI: 29-51%). Changes in the prevalence of underweight were the primary risk factor in the low and middle-income countries of Africa (49%; 95% CI: 40-53%) and South-East Asia (47%; 95% CI: 39-51%), where the additional deaths due to more underweight exceeded the deaths avoided due to less overweight and obesity. Changes in the prevalence of overweight and obesity were the primary risk factors in the low and middle-income countries of America (44%; 95% CI: 35-55%), and the deaths avoided due to less overweight and obesity exceeded the additional deaths due to more underweight in several other regions, such as high-income countries (23-29% versus 6-12%) and in the low and middle-income countries of the Eastern Mediterranean (27-53% versus 16-20%), Europe (22-42% versus 1-3%), and partly the Western Pacific (6-23% versus 8-11%).

Figure 3 provides an overview of the climate-related deaths by country on a per-capita basis. Most countries (118 out of 155) experienced a climate-related increase in the number of deaths (Figure 3, upper panel, red shading), in particular in the Western Pacific and in South-East Asia. A high number of climate-related deaths per capita occurred in China (231 per million; 95% CI: 157-308 per million; CC SD: 47 per million) and India (105 per million; 95% CI: 68-136 per million; CC SD: 19 per million), the two countries with the highest number of absolute deaths (Table A9.2 in Appendix A9), but also in Vietnam (126 per million; 95% CI: 78-168 per million; CC SD: 23 per million), Greece (124 per million; 95% CI: 77-167 per million; CC SD: 26 per million), and South Korea (119 per million; 95% CI: 84-148 per million; CC SD: 25 per million) (Table A9.3 in Appendix A9). A smaller number of countries (37 out of 155) experienced a climate-related decrease in the number deaths (Figure 3, upper panel, green shading), in particular in Central and South America, the Eastern Mediterranean, and parts of Africa. In those regions, the changes in weight-related deaths exceeded the changes in consumption-related deaths (66 out of 155 countries) (Figure 3, middle panel), and the number of avoided deaths due to reductions in overweight and obesity exceeded the number of deaths related to increases in underweight (119 out of 155 countries) (Figure 3, lower panel). The total number of avoided deaths amounted to five thousand, which is less than one percent of all positive and negative changes in the number of climate-related deaths. Tables A9.3-A9.6 in Appendix 9 contain additional results by country in absolute and per-capita terms and by risk factor.

Sensitivity analysis

The magnitude of climate change impacts depends, among others, on assumptions about future emissions trajectories and socio-economic development. The main results were based on a “middle-of-the-road” development scenario, and compared a scenario without climate change to scenarios which follow a high emissions pathway. Table 2 lists the changes in diet and weight-related mortality for different socio-economic and emissions pathways. The different pathways are described in Panel 1 and Appendix A2. Compared to the main scenario, more ‘sustainable’ development (SSP1) led to more avoided deaths in 2050, and more ‘fragmented’ development (SSP3) led to less avoided deaths. However, the number of climate-related deaths, i.e. the difference between the reference scenario and the climate change scenarios, did not change substantially. For example, the mean and standard deviation (SSP SD) of climate-related deaths in all socio-economic pathways for the high emissions pathway (RCP8·5) was 552,000 and 27,000, respectively. In contrast, the number of climate-related deaths was substantially reduced when lower emissions pathways were adopted. Compared to the highest emissions pathway (RCP8·5), the number of climate-related deaths were reduced by 29% (SSP SD: 3%) and 32% (SSP SD: 2%) to 390,000 (SSP SD: 34,000) and 376,000 (SSP SD: 31,000) in two medium climate-stabilization scenarios (RCP6·0, RCP4·5), and by 71% (SSP SD: 1%) to 158,000 (SSP SD: 11,000) in a stringent climate-stabilization scenario (RCP2·6).

Discussion

Climate change leads to changes in temperature and precipitation which are expected to reduce global crop productivity,[5,15] lead to changes in food production and consumption,[6] and impact health by altering the composition of diets and, with it, the profile of dietary and weight-related risk factors and associated mortalities.[13] The results of this study indicate that even relative modest reductions in per-capita food availability could lead to changes in the energy content and composition of diets that are associated with significant, negative health implications. Whilst food availability and consumption is projected to be higher in 2050 than in 2010, we found that by 2050, climate change could lead to relative reductions of 3.2% (± 0.4%), 4.0% (± 0.7%), and 0.7% (± 0.1) in global food availability, fruit and vegetable consumption, and red meat consumption, respectively, compared to a projection without climate change. Based on the modelling exercise, those changes could lead to 529,000 climate-related deaths globally (95% CI: 314,000-736,000) due to changes in dietary and weight-related risk factors among the adult populations of 155 world regions.

The estimate of climate-related deaths represents a significant reduction in the progress towards greater food and nutrition security that is projected to occur until 2050. In our model projections, it amounts to a 28% (95% CI: 26-33%) reduction in the number of deaths that are avoided due to changes in dietary and weight-related risk factors between 2010 and 2050, and it far exceeds other climate-related health impacts that are projected to occur in 2050 (Panel 2 and Appendix A10). The sensitivity analysis indicated that climate change mitigation could substantially reduce the number of climate-related deaths. However, a negative net impact would remain even in a stringent climate-stabilization pathway which incorporates negative emissions.

Strengthening public-health programmes aimed at preventing and treating diet and weight-related risk factors could be a suitable climate change adaptation strategy aimed at reducing climate-related health impacts. We found that health impacts were highly differentiated by region and risk factors. Twice as many climate-related deaths were associated with changes in dietary risk factors, in particular with reductions in fruit and vegetable consumption, than with climate-related increases in the prevalence of underweight; and most climate-related deaths were projected to occur in South-East Asia and the Western Pacific, in particular in China and India. Health-related adaptation programmes should be region-specific and take into account both the scale and the composition of climate-sensitive risk factors (Panel 2).

Although we found that our overall estimate is robust with respect to changes in climatic, biophysical, socio-economic, and epidemiological parameters, several caveats apply. First, there is general agreement about the negative impacts that climate change is expected to have on major staple crops, in particular at low latitudes and at high levels of warming.[5] However, the impacts that climatic changes could have on crops that are relatively less important based on their land coverage and production, but of increased importance for health, such as fruits and vegetables, would greatly benefit from further research. The current state of global crop modelling allowed us to directly model climate change effects on most major crops, such as groundnuts, maize, potatoes, rice, sorghum, soybeans, and wheat,[5,15] but the impacts on other crops had to be inferred from biophysical similarities.[6,15]

Second, the economic responses of agricultural commodity markets to climatic shocks are subject to high uncertainty. A recent comparison of global economic models of agriculture showed a wide range of projections of production and consumption across models.[6,30] We used the harmonized scenario inputs developed for the comparison, and we adopted an economic model whose demand projections fell within the middle two quartiles of the range of model results.[30] This means that our economic analysis represents average economic impacts without economic uncertainty intervals. Adopting a suite of economic models would have allowed us to quantify the uncertainties related to projections of food demand. However, generating custom results with the IMPACT model as input for our health analysis allowed for greater regional detail and crop differentiation, and for more sensitivity analyses than would have been possible if we had relied on the necessarily more aggregated results from a model intercomparison or suite of models. Future economic model intercomparisons with greater regional and commodity-level aggregation are highly encouraged.

Third, a number of caveats apply to the comparative risk analysis framework.[28] For our analysis of weight-related risk factors, we derived future weight distributions based on the historical relationship between mean BMI and food availability. However, the relationship between changes in body weight and caloric availability might change in the future if other parameters, such as the amount of food waste is not controlled for. Our use of globally comparable waste percentages explicitly accounts for absolute changes in the amount of food wasted in response to changes in food availability, but it is possible that also the percentage of food waste changes.[31] We captured this effect indirectly by using a non-linear parameterization of the relationship between mean BMI and food availability. Using metabolic models of weight change would have been preferable, but current estimates of food consumption and waste are too imprecise to apply such models on the global level.[10,25,32,33]

Final caveats apply to the global databases used for our analysis, such as the food balance sheets produced by the FAO, which were used to calibrate the IMPACT model, and the health parameters adopted from the Global Health Observatory of the WHO, which were used in the health analysis. In producing a coherent global database, both databases have been subject to considerable adjustment.[10,32] In addition, their country-level aggregation might hide intra-regional inequalities that, when disaggregated, could increase the spread of results for specific regions and globally. For example, it is likely that different groups within a population would react differently to price increases, and that relatively food-secure subgroups can compensate for changes in food price without substantially changing food consumption (see Appendix A11 for a discussion on this point related to our weight estimates). Projections based on global databases can therefore best be seen as ballpark estimates of general magnitudes, and more detailed regional studies are encouraged to increase the evidence base.

Several factors not included in this analysis could change future estimates of climate-related mortality from dietary and weight-related risk factors. We summarize those in Appendix A11. They include explicit analyses of climate extremes, climatic impacts on fisheries and aquaculture, direct heat and water stress on livestock, climate impacts on the nutritional quality of foods, shocks to the food system not presently captured in the socio-economic and emissions pathways used, and longer-term analyses of climate impacts. Most of those factors can be expected to increase the climate-related health burden estimated in this study.

Contributors

MS and PS designed the study. MS conducted the literature review. MS, PS, DMD, SR compiled the models. MS conducted the analysis, with contributions from PS, DMD, SR. All authors interpreted the results. MS wrote the manuscript. All authors commented on the manuscript draft and approved the submission draft.

Declaration of interest

We have no competing interests.

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Panels

Panel 1: Future pathways of emissions and socio-economic development

In the lead up to the publication of the Fifth Assessment Report of the International Panel and Climate Change (IPCC), the research community developed a set of global scenarios which can be used by researchers of various disciplines to analyse the impacts of climate change under different assumption underlying the dynamics of the earth system and socio-economic developments.[34] A scenario matrix architecture was developed which allows researchers to construct climate change scenarios based on the combination of representative concentration pathways (RCPs), which describe emissions trajectories, and shared socio-economic pathways (SSPs), which describe development trajectories, including different approaches/challenges to climate-change mitigation and adaptation.[35]

For this study's main scenarios, we adopted a "middle-of-the-road" socioeconomic trajectory (SSP2), using GDP projections developed by the Organization for Economic Co-operation and Development (OECD) and population projections developed by the International Institute for Applied Systems Analysis (IIASA).[36,37] For analysing the sensitivity to different socio-economic pathways, we adopted two alternative socio-economic pathways in the sensitivity analysis: a "Sustainability"-termed socio-economic pathway (SSP1) which is characterized by medium to high economic growth and low population growth, and a "Fragmentation"-termed socio-economic pathway (SSP3) which is characterized by slow economic growth and high population growth.[38] The challenges to mitigation and adaptation increase when going from SSP1 to SSP3. Table A2.1 in Appendix A2 provides an overview of this study's model inputs and scenarios, Table A2.2 details the storylines associated with each socio-economic pathway, and Table A2.3 lists the associated GDP and population estimates.

In the main climate change scenarios, we adopted the highest emissions pathway (RCP8·5) to scope the full range of potential climate change impacts. That pathway leads to an increase in the global mean surface air temperature of 2·0 degrees C in 2046-2065 compared to the period 1986-2005.[39] For analysing the sensitivity to different emissions pathways, we adopted three alternative emissions trajectories in the sensitivity analysis: two medium climate-stabilization scenarios (RCP4·5, RCP6), and one stringent climate-stabilization scenario (RCP2·6) that is based, in part, on the use of negative emissions technologies, such as carbon capture and storage (CCS) and bio-energy.[40] The increases in global mean surface air temperature from the period 1986-2005 to 2046-2065 are 1·3 degrees C and 1·4 degrees C in the medium stabilization scenarios (RCP6·0, RCP4·5), and 1·0 degree C in the stringent stabilization scenario (RCP2·6). The changes in precipitation for a given change in temperature increase when going from the low emissions scenario to the higher emissions scenarios (from RCP2·6 to to RCP8·5).[39]

Regional projections of the agricultural impacts of climate change are subject to significant uncertainty.[5] We therefore used different combinations of general circulation models (GCMs), which project changes in temperature and precipitation, and crop models, which use those changes to project biophysical changes in crop yields, to generate a spread of input parameters for our agriculture and health assessment. The GCMs include HadGEM2-ES,[41] IPSL-CM5A-LR,[42] and MIROC-ESM-CHEM;[43] and the crop models include DSSAT and LPJmL.[44,45] The pair-wise combination of GCMs with crop models resulted in six climate change scenarios for each socio-economic and emissions pathway. We calculated the mean and standard deviation of the scenario endpoints (changes in food availability and consumption, and changes in mortality) that are associated with the different climate change scenarios, and we report those in the main text to simplify exposition.

Panel 2: Research in context

Systematic review:

Previous studies of the health impacts of climate change have either analysed complementary causes of death, or focused on the impacts of climate change on agriculture and health in terms of changes in food security and caloric availability.[2,3] A recent WHO report integrated several analyses that quantified climate-related mortality caused by heat, coastal flooding, diarrhoeal disease, malaria, dengue and undernutrition in 2050.[46] In the WHO report, it was projected that the most substantial health impacts of climate change in 2050 would be caused by heat (95,000 deaths) and undernutrition (85,000 deaths). The report, in particular the analysis of climate-related deaths caused by undernutrition, used a methodology similar to ours (including the same agricultural economic model), but it relied on older climate and socio-economic inputs that have been developed for the Third and Fourth Assessment Reports of the IPCC, compared to the ones developed for the Fifth Assessment Report used in this study.

Interpretation:

This study is novel, because it broadened the focus to include the composition of diets, in addition to caloric availability, as risk factor for climate-related health impacts. Figure A10 in Appendix A10 adopts the WHO report's central estimates and compares those to our results to illustrate the relevance of our focus. Our estimate of climate-related deaths due to changes in dietary and weight-related risks far exceeds the WHO estimate for the two greatest causes of climate-related deaths, even under a stringent climate-stabilization pathway. The estimate for a medium climate-stabilization pathway (RCP6·0), which is most similar to the emissions pathway used in the WHO report, exceeds the WHO estimate for the two greatest causes of climate-related deaths, heat and undernutrition, by factors of 4·1 to 4·6, and it is 1·6 times larger than the total sum of all causes of death considered in the WHO report. This suggests that the health impacts of climate change that are due to changes in dietary and weight-related risk factors, as estimated in this study, could be among the largest health impacts of climate change.

The WHO report and this study are complementary in the consideration or risk factors, the regional distribution of impacts, and with respect to the age groups included. The WHO report projected that most heat-related deaths would occur in high-income countries and in South and East Asia, and most undernutrition-related deaths among children would occur in Sub-Saharan Africa and in South Asia.[46] Corroborating the burden of heat stress and child undernutrition, our analysis projected that most diet-related deaths would occur in the Western Pacific (equivalent to East Asia in the classification of the WHO report), and most underweight-related deaths among adults would occur in South-East Asia and Africa (Figure 2). The presence of multiple burdens suggest that health-related climate-change adaptation programmes could leverage synergies, e.g. when addressing the exposure to heat and changes in fruit and vegetable consumption, or between child undernutrition and adult underweight. More broadly, our study also projected that a large number of climate-related deaths would be offset by climate-related reductions in obesity (also in regions with large numbers of underweight-related deaths, Figure 2) – something health-related climate-change adaptation programmes could take into account by adopting a more general focus on weight-related risk factors which would include both underweight and obesity.

Tables and Figures

Table 1: Global and regional food availability, and consumption of fruits and vegetables and red meat in 2010 and 2050 for the reference scenario without climate change and for the mean and standard deviation of the main climate change scenarios.

Region and consumption item	Baseline of 2010	Model scenarios of 2050	
		Reference scenario (without climate change)	Climate change scenarios (mean ± standard deviation)
Fruit and vegetable consumption [g/day]			
Global	342.2	378.0	363.1 ± 2.7
HIC	375.9	397.7	382.3 ± 2.7
AFR_LMIC	196.5	242.3	233.2 ± 1.8
AMR_LMIC	324.1	362.3	348.7 ± 1.8
EMR_LMIC	332.4	340.8	327.7 ± 2.1
EUR_LMIC	314.0	366.0	352.6 ± 3.1
SEA_LMIC	215.3	321.8	307.3 ± 2.6
WPR_LMIC	539.0	602.1	579.2 ± 4.3
Red meat consumption [g/day]			
Global	62.6	66.5	66.0 ± 0.1
HIC	135.8	133.9	132.8 ± 0.2
AFR_LMIC	18.2	36.4	36.0 ± 0.1
AMR_LMIC	89.8	99.3	98.4 ± 0.1
EMR_LMIC	19.4	37.1	36.9 ± 0.1
EUR_LMIC	70.8	78.8	78.2 ± 0.1
SEA_LMIC	9.1	14.1	14.0 ± 0.0
WPR_LMIC	101.7	126.0	125.3 ± 0.1
Total kcal availability [kcal/day]			
Global	2,817	3,107	3,008 ± 11
HIC	3,414	3,434	3,373 ± 11
AFR_LMIC	2,418	2,879	2,757 ± 13
AMR_LMIC	2,886	3,051	2,979 ± 11
EMR_LMIC	2,662	2,932	2,855 ± 15
EUR_LMIC	3,035	3,256	3,199 ± 16
SEA_LMIC	2,406	2,857	2,741 ± 13
WPR_LMIC	3,017	3,513	3,402 ± 16

Regional abbreviations follow the WHO-World Bank classification: HIC: high-income countries; AFR_LMIC: low and middle-income countries of Africa; AMR_LMIC: low and middle-income countries of America; EMR_LMIC: low and middle-income countries of the Eastern Mediterranean; EUR_LMIC: low and middle income countries of Europe; SEA_LMIC: low and middle-income countries of South-East Asia; WPR_LMIC: low and middle-income countries of the Western Pacific). Appendix A6 lists the countries included in each region.

Table 2: Deaths avoided (in thousands) due to changes in dietary and weight-related risk factors between 2010 and 2050 for different climate and socio-economic scenarios (see Panel 1 for a description), including the mean and standard deviation. NoCC denotes the reference scenario without climate change, and CC denotes the climate change scenarios with different representative concentration pathways (RCPs); ∆CC denotes the number of climate-related deaths in 2050, calculated as the difference between the reference scenario and the climate change scenarios.

Climate scenarios	Socio-economic scenarios			Statistics	
	SSP2 ("Middle of the Road")	SSP1 ("Sustainability")	SSP3 ("Fragmentation")	SSP mean	SSP st.dev.
Avoided deaths (in thousands) due to changes in dietary and weight-related risk factors between 2010 and 2050					
NoCC	1,877	2,712	1,108	1,899	655
CC(RCP8.5)	1,348	2,121	569	1,346	634
CC(RCP6.0)	1,495	2,277	754	1,509	622
CC(RCP4.5)	1,509	2,294	764	1,522	625
CC(RCP2.6)	1,722	2,538	960	1,740	644
Climate-related deaths (in thousands) in 2050 due to changes in dietary and weight-related risk factors					
∆CC(RCP8.5)	529	590	538	552	27
∆CC(RCP6.0)	381	435	354	390	34
∆CC(RCP4.5)	368	418	344	376	31
∆CC(RCP2.6)	154	174	147	158	11

Figure 1: Overview of modelling framework. General circulation models (GCMs) were used to project changes in temperature and precipitation associated with different emissions (radiative forcing) pathways. The changes in temperature and precipitation were used by globally gridded crop models (GGCMs) to project changes in biophysical crop yields. The changes in biophysical crop yields were transferred to the IMPACT global economic model to estimate the market responses to yield changes, including changes in agricultural prices, management intensity, land use, consumption, and international trade, subject to assumptions on socio-economic development. Finally, changes in food consumption were used in a purpose-built global health model to estimate changes in mortality associated with changes in dietary and weight-related risk factors, concentrating on changes in the consumption of fruits and vegetables, and red meat, and on changes in body weight associated with changes in overall caloric availability.

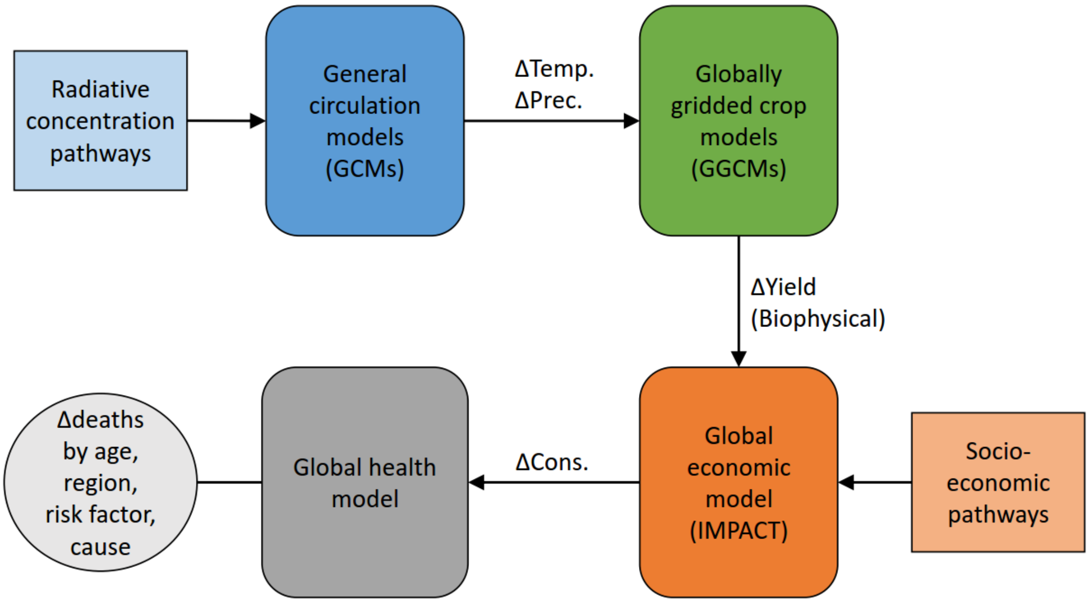

Figure 2: Climate-related deaths (in thousands) in 2050 by risk factor and region. The risk factors include changes in fruit and vegetable consumption (FVC), red-meat consumption (MTC), and the prevalence of underweight (UND), overweight (OVW) and obesity (OBS). The regional aggregates include all regions (Global), high-income countries (HIC), and low and middle-income countries of Africa (AFR_LMIC), the Americas (AMR_LMIC), the Eastern Mediterranean region (EMR_LMIC), Europe (EUR_LMIC), South-East Asia (SEA_LMIC), and the Western Pacific Region (WPR_LMIC). Confidence intervals are listed in Table A9.4 in Appendix A9.

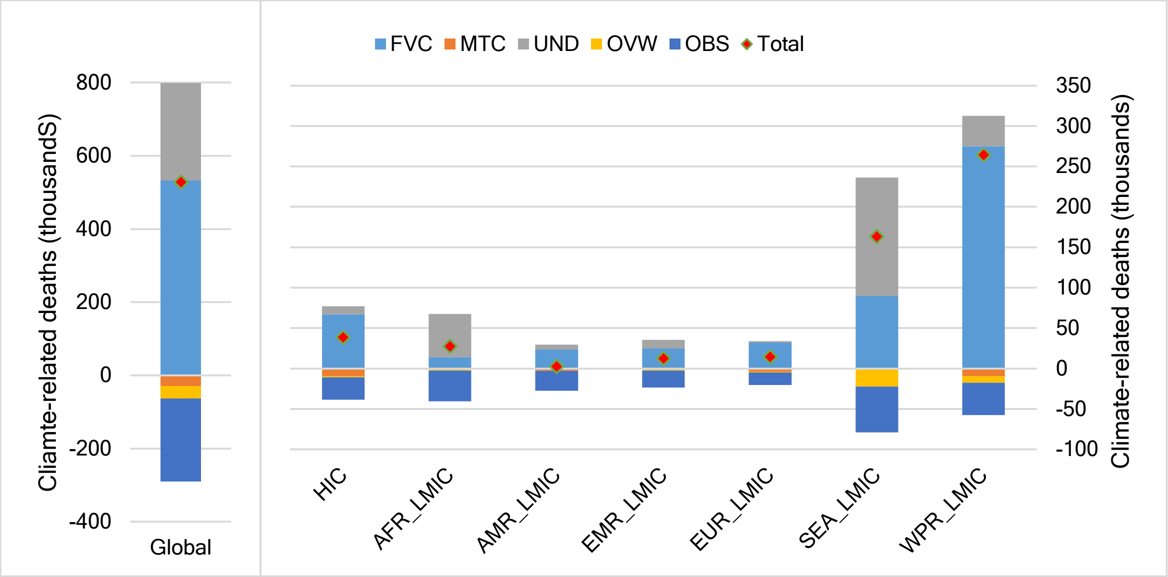

Figure 3: Climate-related deaths per capita (in deaths per million) in 2050 for changes in all dietary and weight-related risk factors (upper panel), for changes in consumption-related risk factors (middle panel), and for changes in weight-related risk factors (lower panel). Confidence intervals are listed in Table A9.3 in Appendix A9.