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

Marco Springmann, Daniel Mason-D'Croz, Sherman Robinson, Tara Garnett, H Charles J Godfray, Douglas Gollin, Mike Rayner, Paola Ballon, Peter Scarborough

Summary

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

Methods For this modelling study, 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 bodyweight for deaths from coronary heart disease, stroke, cancer, and an aggregate of other causes. We calculated the change in the number of deaths attributable to climate-related changes in weight and diets for the combination of four emissions pathways (a high emissions pathway, two medium emissions pathways, and a low emissions pathway) and three socioeconomic pathways (sustainable development, middle of the road, and more fragmented development), which each included six scenarios with variable climatic inputs.

Findings The model projects that by 2050, climate change will lead to per-person reductions of 3·2% (SD 0·4%) in global food availability, 4·0% (0·7%) in fruit and vegetable consumption, and 0·7% (0·1%) in red meat consumption. These changes will be associated with 529 000 climate-related deaths worldwide (95% CI 314 000–736 000), representing a 28% (95% CI 26–33) reduction in the number of deaths that would be avoided because of 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. Adoption of climate-stabilisation pathways would reduce the number of climate-related deaths by 29–71%, depending on their stringency.

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

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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: both directly, due to changes in temperature, precipitation, and the occurrence of heatwaves, 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 effects on the food supply and food security could be one of the most important consequences of climate change in view of the large number of individuals that might be affected.[2–4] Climate change effects 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 association between agriculture and health goes beyond issues of food security and caloric availability.[9–11] Agricultural production and regional food availability also affect the composition of diets, which can have major consequences for health.[12] The Global Burden of Disease study reported 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 10% 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 0·5 and 2, respectively, in 1990.[13] The increasing importance of dietary risk factors represents a general trend away from

Research in context

Evidence before this study

Previous studies of the health effects of climate change have analysed either complementary causes of death, or have focused on the effects of climate change on agriculture and health in terms of changes in food security and caloric availability. A recent WHO report, *Quantitative risk assessment of the effects of climate change on selected causes of death, 2030s and 2050s*, integrated several analyses that quantified climate-related mortality caused by heat, coastal flooding, diarrhoeal disease, malaria, dengue, and undernutrition in 2050. In the WHO report, the most substantial health effects of climate change in 2050 were projected to be caused by heat (95 000 deaths) and undernutrition (85 000 deaths). The report, especially the analysis of climate-related deaths caused by undernutrition, used similar methods to ours (including the same agricultural economic model), but it relied on older climate and socioeconomic inputs that were developed for the Third and Fourth Assessment Reports of the Intergovernmental Panel on Climate Change, rather than the ones developed for the Fifth Assessment Report used in this study.

Added value of this study

This study is novel because it broadened the focus to include the composition of diets, in addition to caloric availability, as a risk factor for climate-related health effects. Appendix p 79 adopts the WHO report's central estimates and compares those against our results to illustrate the relevance of our focus. Our estimate of climate-related deaths attributable 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-stabilisation pathway. The estimate for a medium climate-stabilisation 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 4·1–4·6, and it is 1·6-times larger than the total sum of all causes of death considered in the WHO report. This finding suggests that the health effects of climate change that are caused by changes in dietary and weight-related risk factors, as estimated in this study, could be among the largest health impacts of climate change.

Implications of all the available evidence

The WHO report and this study are complementary in the consideration of risk factors, the regional distribution of effects, 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. Corroborating the burden of heat stress and child undernutrition, our analysis projected that most diet-related deaths would occur in the Western Pacific region (equivalent to east Asia in the classification of the WHO report), and most underweight-related deaths in adults would occur in Southeast Asia and Africa (figure 2). The presence of several burdens suggest that health-related climate-change adaptation programmes could leverage synergies, such as 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 many 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 that health-related climate-change adaptation programmes could take into account by adopting a more general focus on weight-related risk factors that would include both underweight and obesity.

communicable diseases associated with undernutrition and poor sanitation to non-communicable diseases associated with high bodyweight and unbalanced diets.[14]

In this Article, 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 effects of climate change on dietary and weight-related health risks and associated cause-specific mortalities for 155 world regions in the year 2050.

Methods

Study design

The way in which future climate change affects health through 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.[15,16] Meanwhile, climate change leads to changes in temperature and precipitation, which are expected to reduce global crop productivity[5,17] and, through 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 weight-related risk factors associated with an increased incidence of non-communicable diseases and mortality, such as low fruit and vegetable consumption,[18–20] high red meat consumption,[20–22] and increased bodyweight.[23,24]

In line with the conceptual framework, we devised a multi-step approach (figure 1), which leads from the effects of climate change on agricultural yields, through changes in food production and consumption, to changes in dietary and weight-related risk factors and associated mortalities. To represent each step, 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 pp 2–13 and elsewhere.[25,26] We used the 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 effects by comparing a reference “middle-of-the-road” development scenario without climate change effects to scenarios with high climate change effects. The panel discusses the socioeconomic and emissions pathways adopted, and appendix pp 14–20 provides additional detail about the model inputs used to construct the model scenarios.

The IMPACT model estimates commodity-specific food availability at the national 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 about food waste at the consumption level, combined with conversion factors into edible matter (appendix p 21).[39] For the weight-related risk assessment, we estimated changes in weight as shifts in the baseline weight distribution by using the historical association between national food availability and mean body-mass index (BMI). We estimated the baseline distribution by fitting a log-normal distribution to estimates from WHO of mean BMI for each of the world regions and the prevalence of overweight and obesity using a cross-entropy method,[40] which jointly minimises the deviation of the prevalence of overweight and obesity for each mean BMI estimate (appendix pp 22–34). 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=0·46, p<0·0001; appendix pp 22–34).

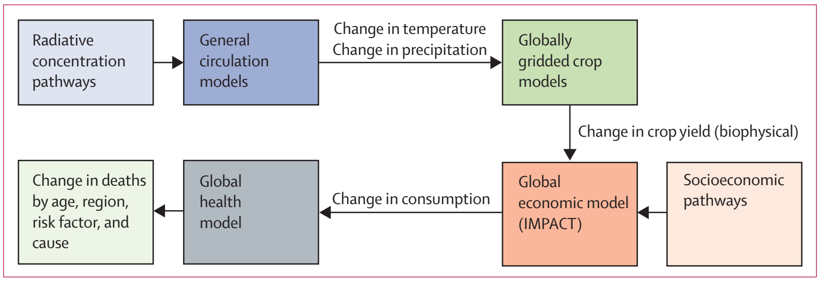

Figure 1: **Modelling framework**

General circulation models 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 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 about socioeconomic 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, with a focus on changes in the consumption of fruits and vegetables, and red meat, and on changes in bodyweight associated with changes in overall caloric availability. IMPACT=International Model for Policy Analysis of Agricultural Commodities and Trade.

Health modelling framework

We analysed the health effects 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 were coronary heart disease, stroke, cancer (which is an aggregate of site-specific cancers), and an aggregate of all other causes. The three specific disease states accounted for about 60% of deaths from non-communicable diseases and for about 40% of deaths worldwide in 2010.[14] The weight-related risk factors corresponded to the four weight classes of underweight (BMI <18·5 kg/m²), normal weight (BMI 18·5–25 kg/m²), overweight (BMI ≥25–30 kg/m²), and obese (BMI ≥30 kg/m²), and the diet-related risk factors were fruit and vegetable consumption and red meat consumption, which together accounted for more than half of all deaths 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]

See Online for appendix

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). To calculate PAFs, we used the following general formula:[13,41]

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

In this equation, $RR(x)$ 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 pp 35–36 for a detailed description). We assumed that changes in relative risks

Panel: Future pathways of emissions and socioeconomic development

In the lead-up to the publication of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, the research community developed a set of global scenarios that can be used by researchers of various disciplines to analyse the effects of climate change under different assumptions underlying the dynamics of the earth system and socioeconomic developments.[27] A scenario matrix architecture was developed that allows researchers to construct climate change scenarios based on the combination of representative concentration pathways (RCPs), which describe emissions trajectories, and shared socioeconomic pathways (SSPs), which describe development trajectories, including different approaches and challenges to climate-change mitigation and adaptation.[28]

For this study's main scenarios, we adopted a "middle-of-the-road" socioeconomic trajectory (SSP2), using gross domestic product projections developed by the Organization for Economic Co-operation and Development and population projections developed by the International Institute for Applied Systems Analysis.[29,30] To analyse the sensitivity of the results to different socioeconomic pathways, we adopted two alternative socioeconomic pathways in the sensitivity analysis: a sustainability-termed socioeconomic pathway (SSP1), characterised by medium to high economic growth and low population growth, and a fragmentation-termed socioeconomic pathway (SSP3), characterised by slow economic growth and high population growth.[31] The challenges to mitigation and adaptation increase with movement from SSP1 to SSP3. Appendix p 14 provides an overview of this study's model inputs and scenarios, appendix p 15 details the storylines associated with each socioeconomic pathway, and appendix p 16 lists the associated gross domestic product and population estimates.

In the main climate change scenarios, we used the highest emissions pathway (RCP8·5) to scope the full range of potential climate change effects. That pathway leads to an increase in the global mean surface air temperature of 2·0°C in 2046–65 compared to with 1986–2005.[32] To analyse the sensitivity of the results to different emissions pathways, we adopted three alternative emissions trajectories in the sensitivity analysis: two medium climate-stabilisation scenarios (RCP4·5 and RCP6·0), and one stringent climate-stabilisation scenario (RCP2·6) that is based, in part, on the use of negative emissions technologies, such as carbon capture and storage and bioenergy.[33] The increases in global mean surface air temperature from 1986–2005 to 2046–65 are 1·3°C and 1·4°C in the medium-stabilisation scenarios (RCP6·0 and RCP4·5), and 1·0°C in the stringent stabilisation scenario (RCP2·6). The changes in precipitation for a given change in temperature increase as one moves from the low-emissions scenario to the higher emissions scenarios (from RCP2·6 to RCP8·5).[32]

Regional projections of the agricultural effects of climate change are subject to substantial uncertainty.[5] We therefore used different combinations of general circulation models, which project changes in temperature and precipitation, and crop models, which use those changes to project biophysical changes in crop yields, to generate a range of input parameters for our agriculture and health assessment. The general circulation models include HadGEM2-ES,[34] IPSL-CM5A-LR,[35] and MIROC-ESM-CHEM,[36] and the crop models include DSSAT and LPJmL.[37,38] The pairwise combination of general circulation models with crop models resulted in six climate change scenarios for each socioeconomic and emissions pathway. We calculated the mean and SD 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.

follow a dose–response association,[13,42] and that PAFs combine multiplicatively,[13,43] ie, $PAF_{Total}=1-\prod_i(1-PAF_i)$ in which each i denotes an independent risk factor.

We used publicly available data sources to parameterise the comparative risk analysis. Population and mortality data by region and 5-year age group for the year 2050 were obtained from the International Institute for Applied Systems Analysis and the United Nations Population Division, respectively. All-cause mortality rates for 2050 were broken down into cause-specific mortality rates for coronary heart disease, stroke, an aggregate of cancers, and an aggregate of all other causes through the use of burden of disease estimates for WHO member states in 2008, projected forward to 2050 for the dietary and weight-related risk factors focused on here. In view of the fact that dietary and weight-related risk factors are mainly associated with chronic, non-communicable disease mortality, we focused on the health implications of changes in those risk factors for adults (aged ≥20 years). We restricted the selection of relative risk parameters to meta-analyses and pooled prospective cohort studies (appendix pp 37–40). The diet and weight-related relative risk parameters were obtained from pooled analyses of prospective cohort studies,[23,24] and from meta-analyses of prospective cohort and case-control studies.[21,22,18–20] The cancer associations have been judged as probable or convincing by the World Cancer Research Fund,[20] and in each case a dose–response association was apparent and consistent evidence suggests plausible mechanisms.[20]

Uncertainty analysis

We did a comprehensive set of sensitivity analyses to quantify the main uncertainties associated with each model component, including climatic, socioeconomic, and epidemiological uncertainties (appendix p 14). We quantified the climatic uncertainties associated with each socioeconomic and emissions pathway by calculating the mean and SD of six climate scenarios that represented the cross-section of three general circulation models and two crop models. For each climate change scenario, we quantified the epidemiological uncertainties by calculating uncertainty intervals based on 1000 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 socioeconomic development and emissions pathways by considering 12 combinations of three different socioeconomic pathways and four different emissions pathways, which forms the complete set of common pathways developed by the climate change research community (panel).

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

Table 1 presents global and regional food availability and consumption in the baseline year 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 kcal per person per day between the years 2010 and 2050 (a 10·3% increase); global fruit and vegetable consumption, net of food waste (ie, with food waste at the consumption level subtracted from the estimates), is projected to increase by 35·8 g per person per day, and global red meat consumption, net of food waste, to increase by 3·9 g per person per day. Consumption changes in terms of million tonnes per year are larger, agree with the current range of projections,[15] and are reported in appendix pp 46–60.

In line with previous estimates,[6,15] 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 in 2050 of 99 kcal per person per day (3·2% reduction; SD of climate change scenarios [CC SD] 11 kcal/person/day [0·4%]), of fruit and vegetable consumption in 2050 by 14·9 g per person per day (4·0% decrease; 2·7 [0·7%]), and of red meat consumption in 2050 of 0·5 g per person per day (0·7% decrease; 0·1 [0·1%]), when compared with the 2050 reference scenario without climate change. Consumption changes for other food items are reported in appendix pp 46–60.

Our model shows that the effects of climate change on food availability and consumption were subject to large regional variation. Regional food availability was reduced by more than the average in the low-income and middle-income countries of Africa (122 kcal/person/day [4·2%]; CC SD 13), Southeast Asia (116 kcal/person/day [4·1%]; CC SD 13) and the Western Pacific region (111 kcal/person/day [3·2%]; CC SD 16); regional fruit and vegetable consumption was reduced by more than the average in the low-income and middle-income countries of the Western Pacific (22·9 g/person/day [3·8%]; CC SD 4·3) and in high-income countries (15·4 g/person/day [3·9%]; CC SD 2·7); and regional red meat consumption was reduced by more than the average in high-income countries (1·1 g/per person/day [0·7%]; CC SD 0·2 g/person/day), and in the low-income and middle-income countries of the Americas (0·9 g/person/day [0·9%]; CC SD 0·1), the Western Pacific (0·7 g/person/day [0·5%]; CC SD 0·1), and Europe (0·6 g/person/day [0·8%]; CC SD 0·1). Country-level results are listed in appendix pp 47–59.

	Baseline in 2010	Model scenarios for 2050	
		Reference scenario (without climate change)	Climate change scenarios, mean (SD)
Fruit and vegetable consumption (g/person/day)			
Global	342·2	378·0	363·1 (2·7)
High-income countries	375·9	397·7	382·3 (2·7)
LMICs of Africa	196·5	242·3	233·2 (1·8)
LMICs of the Americas	324·1	362·3	348·7 (1·8)
LMICs of the Eastern Mediterranean	332·4	340·8	327·7 (2·1)
LMICs of Europe	314·0	366·0	352·6 (3·1)
LMICs of Southeast Asia	215·3	321·8	307·3 (2·6)
LMICs of the Western Pacific	539·0	602·1	579·2 (4·3)
Red meat consumption (g/person/day)			
Global	62·6	66·5	66·0 (0·1)
High-income countries	135·8	133·9	132·8 (0·2)
LMICs of Africa	18·2	36·4	36·0 (0·1)
LMICs of the Americas	89·8	99·3	98·4 (0·1)
LMICs of the Eastern Mediterranean	19·4	37·1	36·9 (0·1)
LMICs of Europe	70·8	78·8	78·2 (0·1)
LMICs of Southeast Asia	9·1	14·1	14·0 (0·0)
LMICs of the Western Pacific	101·7	126·0	125·3 (0·1)
Total kcal availability (kcal/person/day)			
Global	2817·5	3106·9	3008·3 (10·8)
High-income countries	3414·3	3433·6	3372·5 (10·8)
LMICs of Africa	2417·6	2878·7	2756·5 (12·9)
LMICs of the Americas	2886·4	3051·5	2979·0 (10·8)
LMICs of the Eastern Mediterranean	2661·5	2932·2	2855·4 (14·8)
LMICs of Europe	3035·4	3256·1	3198·8 (16·0)
LMICs of Southeast Asia	2406·5	2856·9	2740·6 (13·4)
LMICs of the Western Pacific	3016·9	3512·8	3401·5 (15·9)

LMICs=low-income and middle-income countries. Region names follow the WHO–World Bank classification. Appendix pp 37–40 lists the countries included in each region.

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 (SD) of the main climate change scenarios**

Appendix p 61 lists the health effects 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 bodyweight levels, but with the all-cause death rates and population structures of 2050. Use of this baseline allowed us to isolate the health effects of changes in dietary and weight-related risk factors between 2010 and 2050 when compared with the reference and climate change scenarios, and to estimate the effects 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% CI 0·9–2·8 million) in 2050 compared with 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 led to 529 000 climate-related deaths (95% CI of the relative risk distribution averaged over all climate scenarios 314 000–736 000; CC SD 105 000) compared with the reference scenario in 2050 (figure 2). Most climate-related deaths occurred in the low-income and middle-income countries of the Western Pacific region

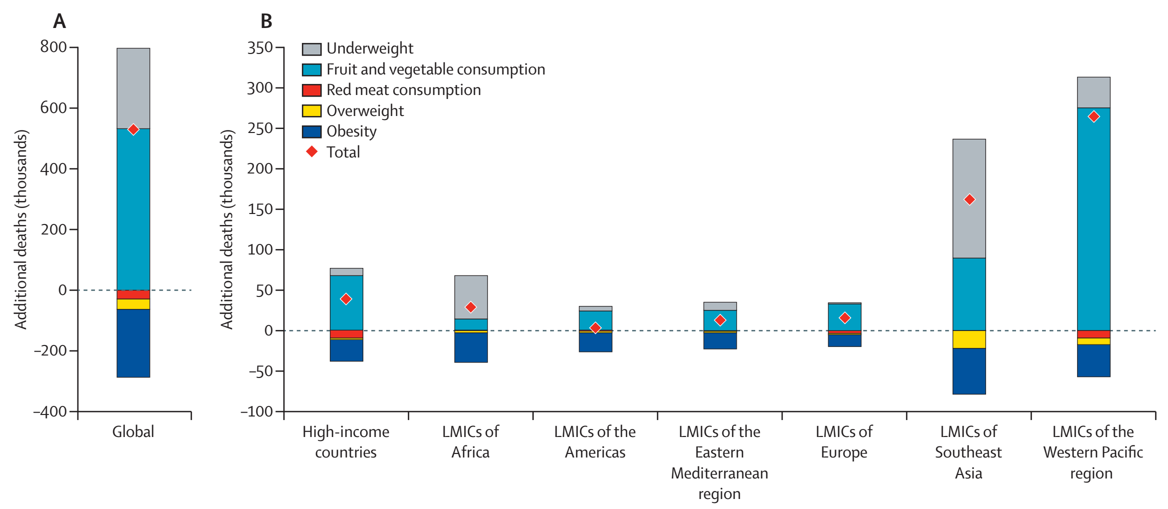

Figure 2: **Climate-related deaths (in thousands) in 2050 by risk factor**
(A) Climate-related deaths worldwide and (B) by region. The risk factors include changes in fruit and vegetable consumption, red meat consumption, and the prevalence of underweight, overweight, and obesity. The regional aggregates include all regions (global), high-income countries, and LMICs of Africa, the Americas, the Eastern Mediterranean region, Europe, Southeast Asia, and the Western Pacific Region. LMICs=low-income and middle-income countries. Confidence intervals are listed in appendix pp 67–70.

(264 000 [95% CI 178 000–354 000]; CC SD 53 000) and Southeast Asia (164 000 [102 000–216 000]; CC SD 29 000).

Changes in specific risk factors in each region underlie the changes in the number of deaths. Figure 2 shows the individual contributions of the specific risk factors. Globally, the greatest contributors to the climate-related deaths were changes in dietary risk factors, especially fruit and vegetable consumption. The negative health effects 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 consumption of red meat (29 000 avoided deaths [95% CI 27 000–32 000]; CC SD 4000). Weight-related changes in the number of deaths were balanced worldwide (figure 2A). Lower caloric availability because of 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 people, which led to 35 000 avoided deaths (95% CI −13 000 to 84 000; CC SD 5000) and the number of obese people, which led to 225 000 avoided deaths (95% CI 198 000–254 000; CC SD 26 000), respectively. Appendix p 62 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 main risk factor for climate-related death in high-income countries (accounting for 58% [95% CI 49–64] of all changes in deaths) and in the low-income and middle-income countries of the Western Pacific (74% [65–79]), Europe (60% [46–69]), and the Eastern Mediterranean (42% [29–51]). Changes in the prevalence of underweight were the primary risk factor in the low-income and middle-income countries of Africa (49% [95% CI 40–53]) and Southeast Asia (47% [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 main risk factors in the low-income and middle-income countries of the Americas (44% [35–55]), and the deaths avoided due to a reduction in overweight and obesity exceeded the additional deaths caused by more underweight people in several other regions, such as high-income countries (23–29% *vs* 6–12%) and in the low-income and middle-income countries of the Eastern Mediterranean region (27–53% *vs* 16–20%), Europe (22–42% *vs* 1–3%), and parts of the Western Pacific region (6–23% *vs* 8–11%).

Figure 3 shows an overview of the climate-related deaths by country in 2050 on a per-million population basis. Most countries (118/155) experienced a climate-related increase in the number of deaths (figure 3A), especially in the Western Pacific and in Southeast Asia. A high number of climate-related deaths per person occurred in China (231 per million [95% CI 157–308 per million]; CC SD 47 per million) and India (105 per million [68–136 per million]; 19 per million), the two countries with the highest number of absolute deaths (appendix p 62), but also in Vietnam (126 per million [78–168 per million]; 23 per million), Greece (124 per million [77–167 per million]; 26 per million), and South Korea (119 per million [84–148 per million]; 25 per million) (appendix pp 63–66). A smaller number of countries (37/155) had a climate-related decrease in the number deaths (figure 3A), especially in Central and South America, the Eastern Mediterranean, and parts of

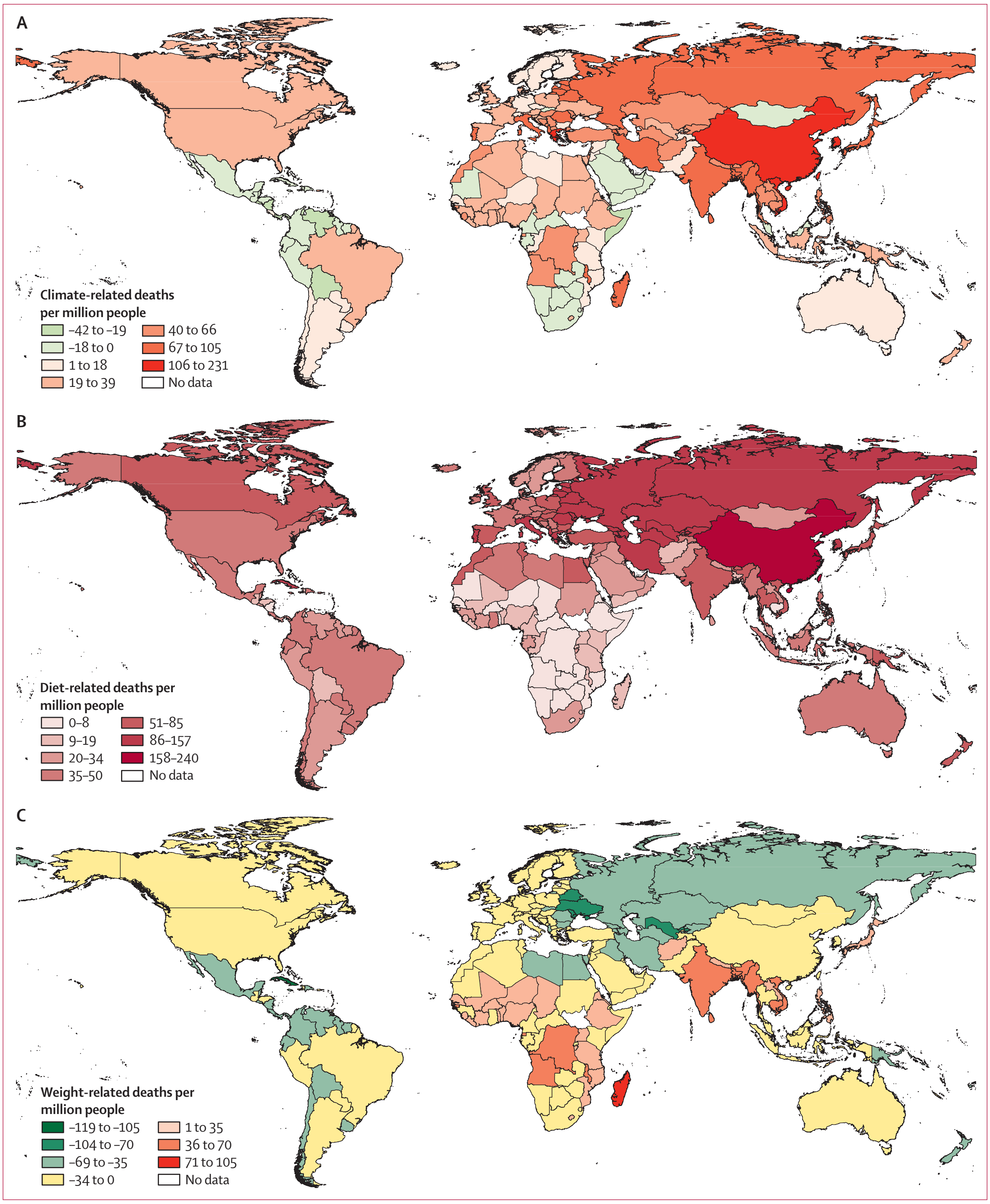

***Figure 3:* Climate-related deaths per million people in 2050**
Climate-related deaths per million people in 2050 for (A) changes in all dietary and weight-related risk factors, (B) changes in consumption-related risk factors, and (C) changes in weight-related risk factors. Confidence intervals are listed in appendix pp 64–66.

Africa. In these regions, the changes in weight-related deaths exceeded the changes in consumption-related deaths (66/155 countries; figure 3B), and the number of deaths avoided because of reductions in overweight and obesity exceeded the number of deaths related to increases in underweight (119/155 countries; figure 3C). The total number of avoided deaths amounted to 5000 globally, which is less than 1% of all positive and negative changes

	Socioeconomic scenarios			SSP mean (SD)
	SSP2 (middle of the road scenario)	SSP1 (sustainability scenario)	SSP3 (fragmentation scenario)	
Avoided deaths (thousands) due to changes in dietary and weight-related risk factors between 2010 and 2050, by climate scenario				
No CC	1877	2712	1108	1899 (655)
CC (RCP8·5)	1348	2121	569	1346 (634)
CC (RCP6·0)	1495	2277	754	1509 (622)
CC (RCP4·5)	1509	2294	764	1522 (625)
CC (RCP2·6)	1722	2538	960	1740 (644)
Climate-related deaths (thousands) in 2050 due to changes in dietary and weight-related risk factors				
ΔCC (RCP8·5)	529	590	538	552 (27)
ΔCC (RCP6·0)	381	435	354	390 (34)
ΔCC (RCP4·5)	368	418	344	376 (31)
ΔCC (RCP2·6)	154	174	147	158 (11)

SSP=shared socioeconomic pathway. CC=climate change. RCP=representative concentration pathway. RCP8·5 represents a high-emissions pathway, RCP6·0 and RCP4·5 two medium climate-stabilisation pathways, and RCP2·6 a stringent climate-stabilisation pathway. See panel for a description of the scenarios. No CC denotes the reference scenario without climate change, and CC denotes the climate change scenarios with different RCPs. ΔCC denotes the number of climate-related deaths in 2050, calculated as the difference between the reference scenario and the climate change scenarios.

Table 2: **Deaths avoided (in thousands) due to changes in dietary and weight-related risk factors between 2010 and 2050 for different climate and socioeconomic scenarios**

in the number of climate-related deaths. Appendix pp 63–78 contain additional results by country in absolute and per-capita terms and by risk factor.

The size of the effect of climate change depends on several assumptions, including those about future emissions trajectories and socioeconomic development. The main results were based on a "middle-of-the-road" development scenario (shared socioeconomic pathway 2 [SSP2]), and compared a scenario without climate change against scenarios that follow a high emissions pathway. Table 2 shows the changes in diet and weight-related mortality for different socioeconomic and climate change pathways. The different pathways are described in the panel and appendix pp 14–20. Compared with the main scenario (SSP2), more sustainable development (SSP1) led to more avoided deaths in 2050, and more fragmented development (SSP3) led to fewer avoided deaths. However, the number of climate-related deaths—ie, the difference between the reference scenario and the climate change scenarios—did not change substantially. For example, the mean number of climate-related deaths in all socioeconomic pathways for the high emissions pathway (RCP8·5) was 552 000 (SD 27 000). By contrast, the number of climate-related deaths was reduced substantially when lower emissions pathways were adopted (table 2). Compared with the highest emissions pathway (RCP8·5), the number of climate-related deaths were reduced by 29% (SSP SD 3%) and 32% (SSP SD 2%) in two medium climate-stabilisation scenarios (RCP6·0 and RCP4·5), and by 71% (SSP SD 1%) in a stringent climate-stabilisation scenario (RCP2·6).

Discussion

Climate change leads to changes in temperature and precipitation that are expected to reduce global crop productivity,[5,17] cause changes in food production and consumption,[6] and affect global population health by changing 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 quite modest reductions in per-person food availability could lead to changes in the energy content and composition of diets that are associated with substantial negative health implications. Although 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% (SD 0·4%) in global food availability, 4·0% (0·7%) in fruit and vegetable consumption, and 0·7% (0·1%) in red meat consumption, compared with a projection without climate change. Based on the modelling exercise, those changes could lead to 529 000 (95% CI 314 000–736 000) climate-related deaths worldwide by 2050 because of changes in dietary and weight-related risk factors in the adult populations of 155 world regions.

The estimate of climate-related deaths represents a substantial 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 could be avoided due to changes in dietary and weight-related risk factors between 2010 and 2050, and it far exceeds other climate-related health effects that are projected to occur in 2050 (appendix p 79).[44] The sensitivity analysis suggested that climate change mitigation could greatly reduce the number of climate-related deaths. However, a negative net effect would remain even in a stringent climate-stabilisation pathway that incorporates negative emissions.

Strengthening of public health programmes aimed at preventing and treating diet and weight-related risk factors could be a suitable climate change adaptation strategy with a goal of reducing climate-related health effects. 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, especially 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 Southeast Asia and the Western Pacific region, 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.

Although we found that our overall estimate is robust with respect to changes in climatic, biophysical, socioeconomic, and epidemiological parameters, several caveats do apply. First, general agreement exists about the negative effects that climate change is expected to have on major staple crops, especially at low latitudes and at high levels of warming.[5] However, the effects that climate changes could have on crops that are comparatively less important based on their land coverage and production, but are of high importance for health, such as fruit and vegetables, would benefit greatly from further research. The present 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,[5,17] but the effects on other crops had to be inferred from biophysical similarities.[6,17]

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.[6,15] We used the harmonised scenario inputs developed for the comparison, and we used an economic model whose demand projections fell within the middle two quartiles of the range of model results.[15] This approach means that our economic analysis represents average economic effects without economic uncertainty intervals. Adoption of a suite of economic models would have allowed us to quantify the uncertainties related to projections of food demand. However, generation of 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 strongly encouraged.

Third, several caveats apply to the comparative risk analysis framework.[42] For our analysis of weight-related risk factors, we derived future weight distributions based on the historical association between mean BMI and food availability. However, the relation between changes in bodyweight and caloric availability might change in the future if other parameters, such as the amount of food waste, are 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 the percentage of food waste might also change.[45] We captured this effect indirectly by using a non-linear parameterisation of the relation between mean BMI and food availability. Use of metabolic models of weight change would have been preferable to our approach, but existing estimates of food consumption and waste are too imprecise to apply such models at a global level.[10,16,27,46]

Final caveats apply to the global databases used for our analysis, such as the food balance sheets produced by the FAO that were used to calibrate the IMPACT model, and the health parameters adopted from the Global Health Observatory of WHO that were used in the health analysis. In the production of a coherent global database, both databases have been subject to substantial adjustment.[10,16] Additionally, their country-level aggregation might hide intra-regional inequalities that, when disaggregated, could increase the spread of results for specific regions and worldwide. For example, different groups within a population would probably react differently to price increases, and relatively food-secure subgroups would probably compensate for changes in food price without substantially changing food consumption (see appendix pp 80–81 for a discussion about this point related to our bodyweight estimates). Projections based on global databases can therefore be best viewed 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. These factors are summarised in appendix pp 80–81 and include explicit analyses of climate extremes, climatic impacts on fisheries and aquaculture, direct heat and water stress on livestock, the effects of climate on the nutritional quality of foods, shocks to the food system not presently captured in the socioeconomic and emissions pathways used, and longer-term analyses of climate impacts. Most of these factors can be expected to increase the climate-related health burden estimated in this study.

Contributors

MS and PS designed the study. MS did the literature review. MS, PS, DM-D, and SR compiled the models. MS did the analysis, with contributions from PS, DMD, and SR. All authors interpreted the results. MS wrote the report. All authors commented on the draft version of the report and approved the submission draft.

Declaration of interests

We declare no competing interests.

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