The use of environmental scenarios to project future health effects: a scoping review

Eartha Weber, George S Downward, Kristie L Ebi, Paul L Lucas, Detlef van Vuuren

Environmental risks are a substantial factor in the current burden of disease, and their role is likely to increase in the future. Model-based scenario analysis is used extensively in environmental sciences to explore the potential effects of human activities on the environment. In this Review, we examine the literature on scenarios modelling environmental effects on health to identify the most relevant findings, common methods used, and important research gaps. Health outcomes and measures related to climate change (n=106) and air pollution (n=30) were most frequently studied. Studies examining future disease burden due to changes or policies related to dietary risks were much less common (n=10). Only a few studies assessed more than two environmental risks (n=3), even though risks can accumulate and interact with each other. Studies predominantly covered high-income countries and Asia. Sociodemographic, vulnerability, and health-system changes were rarely accounted for; thus, assessing the full effect of future environmental changes in an integrative way is not yet possible. We recommend that future models incorporate a broader set of determinants of health to more adequately capture their effect, as well as the effect of mitigation and adaptation efforts.

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Introduction

Human health can be negatively affected by environmental pressures, such as climate change, air pollution, stratospheric ozone depletion, and ecosystem degradation and contamination.[1] Effects on health can occur directly (eg, extreme temperatures causing increased deaths from cardiovascular diseases) or indirectly (eg, changes in agricultural yields affecting food supplies and leading to food shortages.[2,3] If current policies, commitments, and goals (eg, the nationally determined contributions and the Paris Agreement) are not implemented, environmental changes are expected to intensify.[4] Thus, new strategies and policies are needed to reduce the magnitude and rate of environmental change, and to facilitate adaptation to the changes already occurring.[4,5] Information on potential future trends and the effectiveness of policy measures is therefore required.

Scenario analysis is a systematic way of projecting long-term future risks, and has been used to explore possible environmental changes and potential response strategies for several environmental changes, such as those forming part of the Intergovernmental Panel on Climate Change's assessment on climate.[5] Scenarios generally consist of a combination of qualitative narratives about the future in terms of how socioeconomic conditions will change (eg, population, education, urbanisation, and gross domestic product), and are then combined with systems models to quantify pre-existing relationships (eg, population change and energy use).[6]

Scenario analysis is also increasingly being used in sustainability science to model changes in the environment in relation to other Sustainable Development Goals (SDGs), such as SDG 3: "ensure healthy lives and promote wellbeing for all at all ages".[7,8] Scenario analysis can also be an effective tool to explore the health consequences of environmental change in the context of socioeconomic development. In this Review, we aim to answer the following research questions: (1) what is the current state of knowledge on scenarios projecting future health risks related to environmental change? (2) What are the important findings and common methods used in environmental health-related scenario literature? And (3) what are important gaps in the coverage and use of scenarios for projecting the future state of health?

Methods

Search strategy and selection criteria

The databases Scopus, PubMed, Embase, and GreenFILE were used to systematically review the literature. A predefined search strategy developed by Scopus for SDG 3 (ie, health and wellbeing) was used to identify health-related keywords and adapted to each specific database (eg, medical subject headings were used in PubMed).[9] We combined this search with various terms associated with integrated assessment modelling, future

Key messages

- Climate change in relation to heat stress and vector-borne diseases, and air pollution in relation to increased premature deaths from non-communicable diseases, were the most analysed environmental factors in scenario studies. Health outcomes related to access to nutritious food and safe water were studied the least.
- Studies mostly focused on individual exposure–risk relationships. Only a few studies looked at multiple environmental risk factors at the same time, or how they can act in relation to each other.
- Studies were mostly done on high-income countries and east Asia. Very few studies covered low-income countries, yet these countries are projected to be the most impacted by environmental change.
- We recommend an increased coverage of scenario analysis on future health effects from environmental change. Future studies can: (1) include a wider range of health outcomes; (2) analyse multiple environmental health risks simultaneously; (3) better include how socioeconomic circumstances, including demographic composition, health-system changes, and vulnerability can affect health outcomes; (4) focus on adaptation strategies; and (5) increase coverage of world regions.

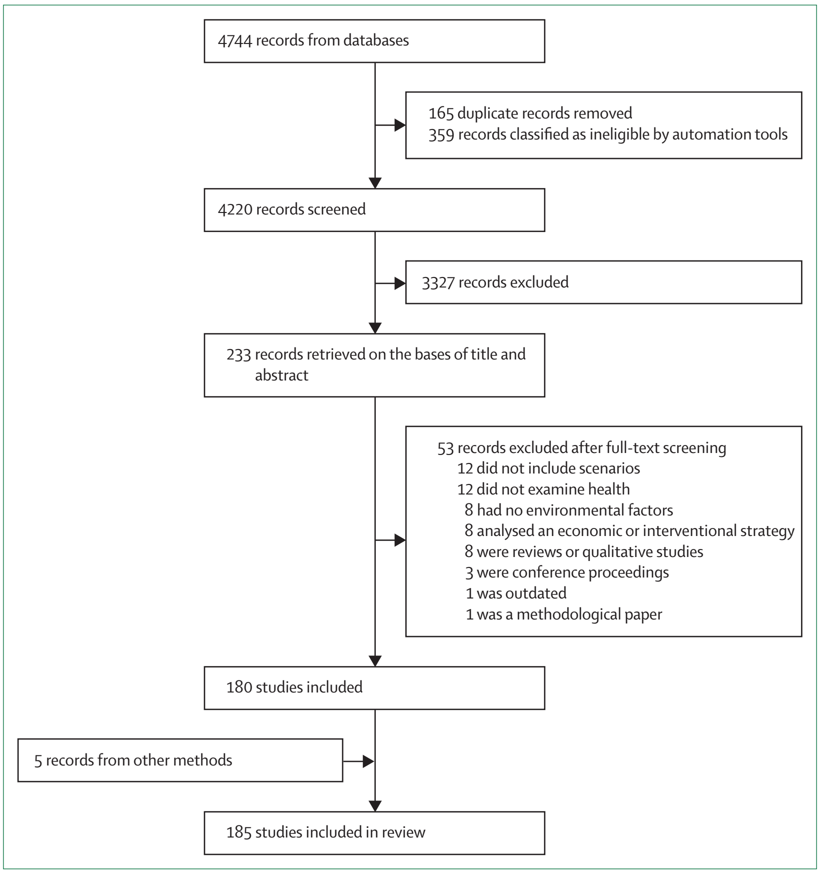

Figure 1: **PRISMA flowchart of record retrieval and selection**
Records were excluded when they did not meet eligibility criteria based on screening of the article's title and abstract.

See **Online** for appendix

years, scenarios, and synergies, to identify relevant articles published for the period Jan 1, 2006, to Feb 15, 2022. The full search strategy of terms used is in the appendix (pp 4–8). Original, English-language, quantitative modelling studies using scenarios to examine future environmental risk factors on health were included (figure 1). Exclusions were human health risk assessments that emphasised exposure to chemical contaminants or toxicology with no future projections, epidemiological studies referring to general exposure–response associations, retrospective studies, articles that referred to aspects of plant or ocean health not directly related to food production (eg, dead zones in the ocean), and conference proceedings. Articles not directly examining a health effect or measure were also excluded (eg, studies that only discussed environmental factors or health as a percentage of gross domestic product expenditure), as were systematic reviews or papers focused on diseases in animals. The relevance of the inclusions and exclusions were predominately assessed by the first author (EW), and three authors (EW, GSD, DvV) had access to the entire dataset on Rayyan. For quality control purposes, a second author (GSD) did masked assessments of 10% of the Rayyan database. In the event of discrepancies between the two authors, a third author (DvV) made the final decision.

Data analysis

Data from selected references were extracted via a predesigned extraction form in Microsoft Excel version 16 containing the following information: publication date, regions examined (including at the country or global level), environmental risk factor, health outcome or measure used, scenarios used, projected period, model type, methods, and results. The final database and extraction of all inclusions can be seen in the appendix (pp 13–124). The extracted articles were organised by the environmental risk categories: climate change, air pollution, food and water, ozone, and multiple (if risk factors were combined). Climate change incorporates extreme weather or heat events, and long-term change in temperatures. Heat stress can lead to acute increased mortality from short-term exposure, and heat-related or cold-related morbidity or mortality can also result from non-optimal temperatures. Heat stress or cold stress can lead directly to mortality, and non-optimal temperatures more often exacerbate or contribute to other health issues, such as respiratory or cardiovascular disease, so it was grouped as an independent heat or cold-related outcome.[10] A meta-analysis of the studies was not possible due to the heterogeneity of scenarios, methods, and outcomes. As this is a scoping review, no risk of bias or critical appraisal of individual assessments was conducted. A narrative covering common trends and storylines is reported. In addition, a conceptual schema (figure 2) was developed and used to categorise the literature and aid the reader in understanding how system dynamics thinking and modelling works. For brevity, some potentially relevant health outcomes were removed from the diagram as no appropriate papers were found (eg, for HIV and AIDS, or mental illness). We used the drivers, pressures, state, impact, and response framework[11] to design the schema. This framework links simplified cause-and-effect relationships and starts with driving forces, which are sectors used to provide human needs. Governmental policies that affect these drivers are often used to shape mitigation scenario narratives. Figure 2 distinguishes between indirect and direct governance. Indirect governance is representative of mitigation or top-down approaches and policies, as it can target underlying drivers of change. Direct governance is most comparable to adaptation or bottom-up responses, as it can occur after the environmental damage occurs. The examples of direct adaptation responses used in the schema are obtained from components 2–9 of WHO's operational framework for building climate-resilient health systems.[12] Environmental risk factors were obtained from the Global Burden of Disease Study 2019's level 2 environmental and occupational risks.[13,14] We added and reclassified dietary risks and child and maternal malnutrition from

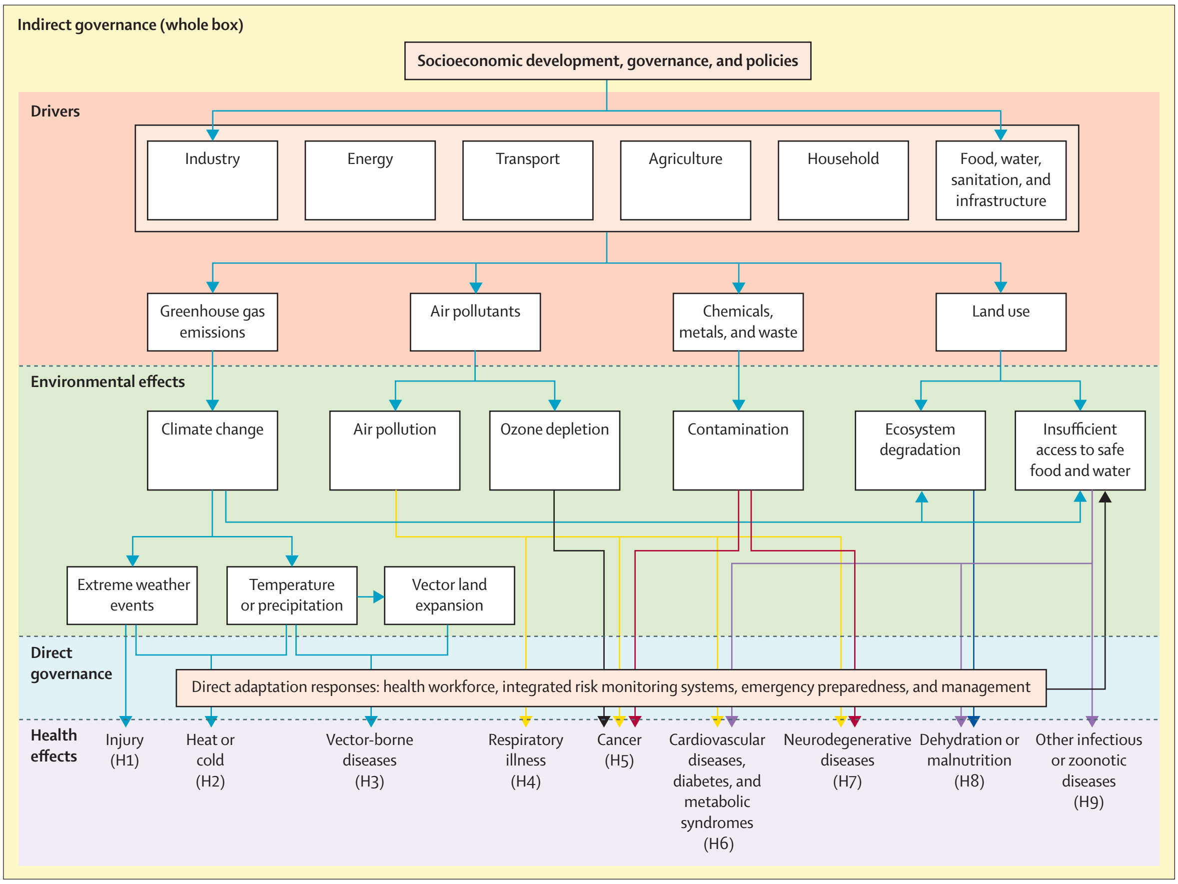

Figure 2: **Causal chain diagram showing important linkages between health outcomes and selected environmental effects**
The scheme indicates how socioeconomic development in different sectors (which can be manipulated within scenarios) is related to environmental change. Possible response strategies can occur with governance through the mitigation of environmental change or through the influence of the relationship between exposure and health outcome. Coloured arrows delineate health effects specific to environmental risk; the black arrow leading from direct adaptation responses is used to indicate the potential for a positive feedback loop, which potentially leads to reinforced environmental change over a long period, despite reducing health effects in the immediate term. The health effects (labelled H1–H9) and environmental effects were used to codify and organise the literature.

behavioural to environmental risks, due to the ability of long-term climate change to disrupt food supplies.

Results

Descriptive characteristics of included literature

Overall, 4744 records were identified from the database search. 165 duplicates were removed, and 359 records were automatically ineligible due to exclusion criteria (ie, publication year or symposium abstracts). The resulting 4220 articles were screened on the basis of the eligibility criteria. In the end, 185 studies were included (figure 1).

The number (and publication rate) of papers projecting the health risks of future environmental change rose from 2006 to 2021 across most risk factors (figure 3A). Of the 185 included studies, the majority (n=106) examined the effects of climate change, with a focus on temperature change (101/106). The effects of air pollution were examined by 30 of the 185 identified papers. Health risks from stratospheric ozone depletion (n=1) and malnutrition or water (n=10) were less examined overall (relative to climate change and air pollution). Although most papers examined single risk factors, 39 studies examined multiple risks (figure 3A), with the majority combining air pollution, climate change, or tropospheric ozone effects. Only three papers (8%) examined more than two environmental risks (see appendix p 10 for a breakdown of multiple risk factors).

Global studies accounted for about 20% of the identified literature; the remaining studies examined individual countries. Most papers focused on east Asia (30% of all papers), Europe (19%), and North America (15%) (figure 3B). Climate change was evaluated across all regions. A large proportion (41%) of the air pollution papers examined east Asia. Malnutrition was typically examined globally, with only one study focusing on Africa and the Middle East. Of the papers evaluating the effects of climate change in Europe, the majority (19/24) examined future temperature-related risks, and three examined potential vector expansion.

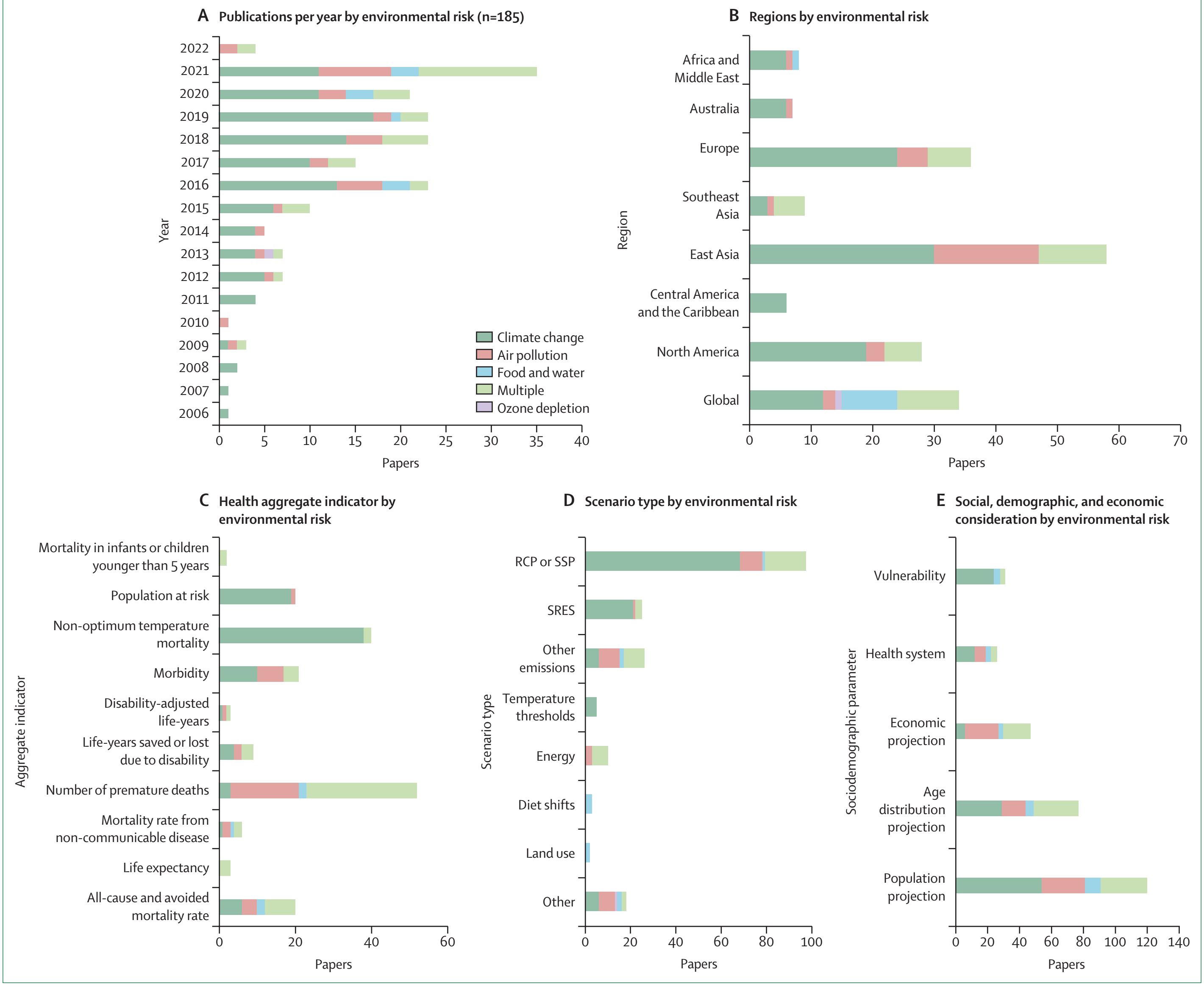

Figure 3: **Descriptive characteristics of identified scenario literature**

(A) Disaggregate publications by risk factor and year of publication. (B) Publications by region. (C) Publications that did not specify a singular health outcome related to environmental risk but reported a health aggregate indicator. (D) Most common scenario types used by environmental risk. (E) Articles that considered a sociodemographic paramteter change in addition to environmental risk change in their analysis. RCP=representative concentration pathway. SSP=socioeconomic pathway. SRES=special report on emissions.

Health effects tended to be reported in aggregate measures (which can be a result of more than one health condition or cause), such as premature mortality, with 147 papers using this approach. The remaining studies measured one health outcome or condition (figure 3C). The included studies are classified by environmental impact on a particular health outcome in the table. Projected heat-related or cold-related effects and vector-borne diseases were the most examined health outcomes in the scenario literature (all related to climate change). Cardiovascular and respiratory illnesses were examined in relation to air pollution and exposure to cold or heat. Cancer was the focus of 16 papers, with eight examining air pollution, six projecting multiple factors and lung cancer, one examining ozone depletion and skin cancer, and one evaluating dietary change in relation to all types of cancer.[13]

Few papers projected undernutrition.[15] One article examined phosphorus loading in water and amyotrophic lateral sclerosis.[16] No articles examined future injuries, road traffic accidents, HIV or AIDS, mental health outcomes (such as substance abuse or neurodevelopmental disorders), kidney dysfunction, or diabetes. The health aggregate measures used in the studies are shown in figure 3C. Premature death or attributable mortality was the most common measure (n=52) overall. Non-optimal temperature mortality was the most common measure in relation to the subcategory of climate change (n=38). In the literature focused on air pollution, premature mortality (n=18) or an economic health indicator (n=14) were often used. Two papers examined infant mortality or mortality in children younger than 5 years related to multiple environmental effects, and the other paper studied infant mortality connected with climate change-related air pollution.[15,17]

Health effects are not only determined by exposure, but also by changing socioeconomic conditions, demographic composition, vulnerability to environmental risk, and age. Approximately half of the climate change-related articles incorporated demographic change into their analysis. Most papers on air pollution accounted for future population growth, whereas others used census data and kept populations constant. Population projections were mostly embedded in shared socioeconomic pathways, scenario storylines, or were based on the UN's world population prospects (figure 3D, E). Few papers used cohort component modelling.[15] Less than half of the papers incorporated complex demographic changes (eg, age distribution and urbanisation).

When demographics were considered, projections were stratified by age and sometimes updated by the most recent census data of the region considered. Only 26% of papers accounted for changing economic conditions. Changes in vulnerability (ie, the sensitivity of the population, or a population's ability to respond or recover from change) were only incorporated into 14% of analyses; risks or health-system changes (eg, to the health workforce, safety policy for buildings and facilities, public health initiatives, and access to medicines) were only incorporated into 17% of analyses. This low level of incorporation implies an insufficiency of literature characterising the groups most in need of targeted, public health adaptation strategies. When vulnerability was assessed, few articles identified a relationship between exposure, adaptive capacity, or underlying vulnerability in a scenario by manipulating access to resources. Only articles examining climate change and health risks assessed vulnerability (ie, access to air-conditioning). For air pollution, age differences in vulnerability were sometimes included, but no other components of vulnerability were used. Finally, many articles used socioeconomic pathways in combination with representative concentration pathways (RCPs), but some used the earlier special report on emissions scenarios (68 of the climate papers, ten of the air pollution papers, and 18 of the multiple risks papers). Socioeconomic pathways assume a homogenous national distribution of the population and economic growth, but populations can alternatively grow more rapidly in higher risk areas, or in subregions within countries if large income or access to resource inequality persists.[18]

	Climate change (n=96)	Air pollution (n=15)	Food or water (n=8)	Multiple (n=27)	Total
Communicable					
Vector-borne diseases	37	0	1	2	40
Malaria	10	0	0	2	12
Dengue	11	0	0	0	11
Lyme disease	5	0	0	0	5
Other	12	0	0	0	12
Infectious and other zoonotic diseases	12	0	1	0	13
Chronic non-communicable					
Cancer	0	8	1	6	16
Lung	0	8	0	6	14
Skin*	0	0	0	0	1
Unspecified	0	0	1	0	1
Respiratory illness	7	11	NA	17	36
General	7	9	NA	16	32
Chronic obstructive pulmonary disease	2	6	NA	2	10
Cardiovascular diseases	9	11	0	10	23
Diabetes	0	0	0	0	0
Metabolic syndromes	0	0	0	2	2
Neurodegenerative disorders	0	2	0	1	3
Alzheimer's and dementia	0	1	0	0	1
Cerebrovascular disorders	0	1	0	0	1
Amyotrophic lateral sclerosis	0	0	0	1	1
Acute non-communicable					
Heat stress and cold stress	46	NA	NA	1	47
Heat-related illness or mortality	30	NA	NA	1	31
Cold-related illness or mortality	2	NA	NA	0	2
Both	12	NA	NA	0	12
Nutrition					
Dehydration	0	0	4	0	4
Malnutrition and undernourishment	0	0	1	2	3
Overweight	0	0	2	0	2

NA=not applicable. *One study examined the effect of skin cancer deaths avoided due to an ozone conservation policy, which was excluded from the columns. Total does not add to subcategory totals because some articles covered multiple health outcomes.

Table: **Number of papers by health effect and environmental risk (n=146)**

Publications examining malnutrition typically included a dietary shift scenario.

Common findings and methods by health effect

For studies examining cold stress and heat (and its related effects), acute cardiovascular and respiratory events were found to be the leading causes of temperature-related mortality. Most studies examined direct effects of temperature on mortality, but some also included other factors influencing the magnitude and pattern of projected effects, such as demographic change and adaptation. In general, heat-related mortality (and heat stress) was projected to increase across all scenarios. Projections stratified by age supported the theory that older people would continue to be most susceptible to future temperature changes.[19–21]

For temperature-related health projections, most studies used projections from climate models based on the RCP scenarios.[19,21–35] One method of evaluating the extent and exposure to temperature risk was using a range of temperatures above and below an optimal value to assess changes in mortality per degree difference.[36] Some projections used region-specific exposure–response functions to estimate health burdens under different greenhouse gas emission pathways.[37] Three projections estimated burdens separately for urban and rural populations.[37–39] Adaptation, if included, was mostly incorporated by shifting the optimal temperature or the slope (representing the rate of adaptation), therefore modifying the temperature–mortality relationship.[21,27,40] Other methods were to assess adaptive capacity by mapping the socioeconomic conditions of a region, such as household income and access to infrastructure, or to measure the amount of adapation risk reduction needed to maintain current burdens.[41,42]

Changes to temperature and precipitation, human behaviour, land use, and population dynamics can increase exposure to mosquitoes and ticks (among others) that can carry a wide range of vector-borne disease. The literature on vector-borne infectious disease primarily examined malaria, dengue virus, Lyme disease, or the spread of vectors responsible for these conditions (n=25). Whether the presence of disease-carrying vectors results in actual cases depends on various factors, including the strength of health systems, access to health care, infrastructure, and behaviour. Therefore, many models projected changes in the geographical areas and seasonality, and based the potential populations at risk on population projections.

Common methods used within vector-borne disease studies typically covered climate and land cover ranges, using methods such as ecological niche modelling, Poisson regression, and spatial regression. Examples of findings include a potential increase in the geographical range of ticks in current temperate zones depending on land-use choices and greenhouse gas emission pathways. Transmission is expected to increase aggregately with higher temperatures and higher emission pathways. The population at risk of *Plasmodium falciparum* (the protozoa of malaria) is projected to increase overall, depending on population density and land suitability. However, in Africa, a decrease in annual rainfall can lead to an overall increased risk in some regions but decreased risk in others.

Exposure to higher concentrations of air pollutants, including ambient ozone and particulate matter, can lead to respiratory illness and other health effects, such as lung cancer and heart disease. Global particulate matter concentrations are expected to decrease because of reduced household solid fuel use, emission policies, and enforcement of air quality limits and targets. However, demographic changes, such as population age structure and urbanisation, could increase the amount of vulnerable people exposed to air pollution and its corresponding health effects. Emissions scenarios were typically used to estimate grid-level air pollution concentrations. These concentrations were then used to identify health risks by use of exposure–response relationship estimates. Variation existed in terms of which sector was used in policy scenarios.[43,44] Studies also used these methods to identify the effects of air pollutant concentration on cancer and cardiovascular diseases.[45,46]

Studies examining cancer mostly showed the effect of air pollutants on lung cancer mortality in Asia. Despite the concentration of air pollutants being expected to decrease, an increase in mortality is probable due to Asia's ageing population; however, lung cancer exerted less of an effect relative to heart or respiratory illnesses.[47,48] Only one study examined the number of skin cancer cases avoided by preventing the depletion of the stratospheric ozone layer,[49] concluding that the world could avoid two million cases of skin cancer by 2030 because of existing policies, compared with an unmitigated scenario (ie, a world without the Montreal Protocol).

Common methods for identifying air pollutant-related changes in the concentration of particulate matter with a diameter of less than 2·5 μm ($PM_{2·5}$) were projected by use of climate models, and were then downscaled to the region of interest. Some $PM_{2·5}$ concentrations also corrected the estimates with bias-estimated spatial disaggregation methods. Exposure–response functions between the $PM_{2·5}$ concentration and lung cancer were used to estimate mortality on the basis of estimates of the exposed population to varying $PM_{2·5}$ concentrations. With regard to the effect of stratospheric ozone depletion, climate models were used to estimate grid-level ultraviolet dose, and the difference in skin cancer incidence was then assessed with a dose–effect relationship.[49]

Other non-communicable diseases—such as cardio-vascular diseases—are multifactorial, and the modifiable environmental determinants of such diseases include air pollutants, heat-related events, and poor diet. We found that ageing is an important non-modifiable risk factor, which is also expected to be a large contributor to the future burden of non-communicable disease.[46] Projections found that these diseases will increase in Europe in both optimistic and pessimistic scenarios, but optimistic scenarios resulted in people being disease free for longer.[46] Older populations are considered to be more vulnerable to $PM_{2·5}$ exposure than middle-aged people, and simultaneously can be exposed to $PM_{2·5}$ over a longer period of time. Diabetes and metabolic syndromes are thought to be related to dietary factors (among others); only one study examined dietary change based on the relationship between meat consumption and deaths avoided from type 2 diabetes.[13] This study found that monetised health benefits of dietary change were the greatest in high-income countries.[13]

Methods used to examine scenarios involving non-communicable diseases varied widely depending on the aim and design of the study. Studies examining cardiovascular diseases and other non-communicable diseases focused on a specific risk factor or an environmentally polluting sector (eg, traffic), or examined a climate policy or target that related to multiple risk factors. One example of a method used for studying heat-related cardiovascular events is based on a distributed lag non-linear model, which is used to examine the effect of temperature on mortality under future RCP and socioeconomic pathway scenarios.[50–52] Methods to assess the effect of air pollution on cardiovascular diseases varied depending on the source of the air pollution examined (eg, traffic, aviation, and the energy sector).[53] One method was to embed the number of heat events, access to healthy foods, and air pollution exposure into the scenario itself.[53–55] Other studies examining air pollution and cardiovascular diseases considered the co-benefits of reducing climate emissions on air pollution and health outcomes.

Three studies studied neurogenerative disease (namely, amyotrophic lateral sclerosis) in relation to phosphorus in water, and air pollution (ie, nitrous oxide and PM with a diameter of <2·5–10 μm) as it relates to Alzheimer's disease, dementia, and cerebrovascular disease.[16,56,57] The studies (all of which were based in Europe) found that if unmitigated climate change continues, the resultant pollution is expected to increase the incidence rate for Alzheimer's disease at the aggregate level, particularly in population-dense areas, and without accounting for population ageing.[57]

To project the future incidence of dementia and Alzheimer's disease in the European population older than 55 years under RCP8·5, a global exposure mortality model was used. In the scenario with a constant population, the incidence rate did not change much, but when accounting for demographic change and assuming no mitigation policy, the incidence increased drastically.[57] Another paper looked into future phosphorus load to water in relation to the incidence of amyotrophic lateral sclerosis.[16] The scenarios assumed specific policies to control PM emissions and calculated resulting concentrations to identify health-related benefits.

Several studies projected health outcomes related to nutrition, with outcomes or mediators such as micronutrient deficiencies, dehydration, undernutrition, and overweight. The projections considered variations in food waste, food sources (ie, animal or plant based), and agricultural investment policies.[13,58,59] One article looked more specifically at plant-based diets, and diets in line with global nutrient guidelines.[13] Another study examined the effect of undernutrition in combination with environmental and social health risk factors on the incidence of diarrhoea and pneumonia, linking them to child deaths from various causes.[15] Overall, studies reported that half of the world's population could be overweight by 2050, with the effects of underweight expected to decrease.[60] At the same time, the prevalence of chronic hidden hunger due to protein–energy undernutrition and micronutrient deficiencies was projected to increase by 2050 due to population increase and climate change.[60]

Common methods used for papers examining food or water-related health outcomes varied. Drivers such as income and demographics were sometimes obtained from socioeconomic pathway scenarios.[60] Another analysis focused on the interactions of net food production and food prices in relation to stunting under the RCPs in low-income countries.[61] In some papers, regressions based on historical data on calorie intake, basal metabolic rate, physical activity, and energy requirements were used to create a distribution of BMI categories for working-age populations and people older than 60 years. Regressions were based on food demand as a predictor of height (rather than on calorie availability) because of the strong influence of diet quality on adult height.[60] Changes in diet or sanitation access were also linked to mortality by use of relative risk estimates in relation to BMI.[13,15,54]

11 papers studied the potential role of climate change on the geographical range of other infectious diseases: gastroenteritis; bacillary dysentery; salmonella; schistosomiasis; Rift Valley fever virus, hand, foot, and mouth disease; pathogenic aerosols; leishmaniasis; hantavirus; and hepatitis A.[62–70] Findings generally indicated that without adaptation (in terms of public health measures) and with increased climate change, the transmission rate of infectious diseases increased at the aggregate level (however, within subregions this trend can vary). The only case in which this relationship was not found was in a study that examined gastroenteritis in Japan. Projected temperature increases could increase years of life lost due to bacillary dysentery (one cause of severe diarrhoea).[70] Cases of diarrhoea were projected to rise with increased greenhouse gas emissions, depending on factors such as access to safe water, improved sanitation, and quality housing.[71,72]

Some studies examining other infectious diseases used projections to establish average temperatures under different emission scenarios in combination with exposure–response estimates to estimate health effects. Another method used was a time-series modelling framework to combine statistical, epidemiological relationships under temperature-increase scenarios.[36,70–72]

Discussion

We examined how scenario analyses have been used to explore environmental change pathways that could affect future health burdens. We identified 185 papers that used quantitative scenarios to examine the health effects and risks of future environmental hazards. Papers predominately examined climate change in relation to temperature-related effects (n=45) and vector-borne diseases (n=37). Air pollution was the second most common environmental hazard studied, mainly as it related to respiratory and cardiovascular diseases and lung cancer. As scenario analysis originated in the field of climate modelling, unsurprisingly, most projections emphasised climate change effects. Areas in which the representation of environmental risk factors could be improved are the inclusion of contamination from chemicals, plastics, and other waste products, and the exploration of how ecosystem degradation, including the loss of biodiversity, could affect diverse health outcomes.[73] From the literature, we can conclude that ongoing climate change is projected to increase the burden of climate-sensitive health outcomes.

Some health effects were notable for their relative absence in the literature, such as neurodegenerative diseases, mental health, and maternal and child health. Notably, the few papers that did examine brain-related issues (ie, neurodegenerative disease) were based only in Europe.[16,56,57] Although neurodegenerative disease and mental health differ, they can share some underlying pathophysiological mechanisms and often co-occur.[74] Most people who currently have mental illness reside in low-income and middle-income countries, and numbers of affected individuals are only expected to increase by 2030.[75,76] Similarly, maternal and child malnutrition currently account for more disability-adjusted life-years than environmental risk factors.[77] Potential changes in future food and water supply can be affected by land use and agriculture, yet only two studies examined these factors in relation to maternal and child health risks (n=2).[15] This low number might be explained partly because we only included studies that specified a condition or outcome (such as malnutrition or underweight) and not simply calorie availability. The impacts of environmental change on agricultural yields and water scarcity are direct and indirect. Although the projected changes are expected to substantially affect future calorie availability, food security also includes access, use, and stability of supply.[52] Modelling the multidimensionality of food security is challenging, although some proxy measures are available, such as food purchasing power for assessing access or use.[53,78] Furthermore, undernutrition is a mediator of other health outcomes, particularly vector-borne and other infectious diseases.[15,62] Scenario modellers can both increase analysis related to food and health, or, more importantly, enhance representation of the quality of food available as it relates to biodiversity and land use. New scenarios that show how improving land use and agricultural practices can synergistically sustain healthy lives over a long period of time could provide great insight to policy makers. Although cash crops could provide economic benefits and enhanced food security in the short term, they could have long-term detrimental effects on biodiversity, and we found no analysis exploring this.[79] We found one study indicating that dams generally built with the intention of enhancing food security can increase malaria if emissions or climate change are unmitigated.[80] Regarding mental health, only nine countries have included mental health and psychosocial support in their national climate change plans. Increased representation in future analyses can assist national institutions with developing mental and psychosocial health climate plans and strategies.[81]

Our current work represents a systematic review of the scenario-based literature, with clear search terms and inclusion and exclusion criteria. However, several limitations exist for our study that should be considered. First, categorisations of environmental risk factors were broad and simplified (eg, all types of air pollution are grouped together, despite differences based on the sources of pollution). Projections can only be made with exposure–risk relationships already previously established, and for some relationships (eg, between plastics and health outcomes), research about the risk is quite new. Second, uniform synthesis of the results of the individual papers (eg, meta-analyses) was not possible due to the wide array of policies and assumptions used within them. For example, one scenario might explore legislation specific to a country's national air pollution standard, but another might examine the energy system and implications of technology change on emissions.[48,82,83] Finally, current scenarios include general market reform policies with incremental rates of change that could substantially underestimate health outcomes and economic co-benefits.[84,85] Other assumptions were value-laden and subject to possible cognitive bias due to the dominance of a few actors, mainly from high-income countries, formulating the most used scenarios. In response to this possible bias, modellers are developing new scenarios with more holistic, plausible futures, and co-creation of scenarios with localised stakeholders is ongoing, which could mean that future findings differ from the ones reported here.[86,87]

We have identified several research gaps that, if addressed, would better inform policy making. A particular gap is scenarios developed by and for low-income countries, including in Africa, parts of Asia, Latin America, the Caribbean, and the small island developing states. This development is important for region-specific projections of any changes in the burden of infectious illnesses, especially for areas in which health systems and socioeconomic factors are enhanced barriers to health care and health systems. Adaptive responses, health infrastructure, and emergency preparedness are also interesting avenues of future research. Furthermore, many health outcomes associated with environmental risks, such as injury, diabetes and metabolic syndromes, developmental disorders, and mental illness, were not assessed at all. We also highlight the poor incorporation of how socioeconomic development influences future health outcomes. This is a gap for policy development because accounting for population ageing, rapid urbanisation, and evolving health systems further complicates the relationship between health and the changing environment. Scenario analyses can provide insights into which of these drivers (among others) need to be addressed in the short, medium, and long term, but these analyses are hindered if we assume that historical relationships between socioeconomic variables and outcomes persist into the future. Future research should therefore be enhanced by multidimensional analyses of the upstream drivers of health outcomes. These analyses will help to inform the development of policies that have synergistic or compounding benefits across environmental risk factors and health and wellbeing (eg, air pollution and active transportation).[88] Analysing near-term mitigation efforts with available and implementable transformational policies would be valuable, as would studying their long-term effects on wellbeing.[89] Ultimately, broadening scenario analyses to incorporate more regions, environment–health relationships, and sociodemographic and health system changes will inform more effective planetary health strategies.

Contributors

EW and DvV conceptualised the study and the corresponding schema, with input from all authors. DvV acquired the funding. DvV, PLL, and GSD supervised the study. GSD reviewed 10% of the dataset. EW collected the data, did the analysis, and wrote the original draft. KLE and PLL revised and reviewed the manuscript. All authors have responsibility for the final revision, editing, and submission of the manuscript. All authors have access to the dataset used, and EW and GSD have verified the data.

Declaration of interests

We declare no competing interests.

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