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Inge Schrijver, Paul Behrens, Rutger Hoekstra, René Kleijn

Climate change has broad and deep impacts on people's wellbeing; yet, these dynamics are largely excluded from integrated environment–society–economy (ESE) models. In this Review, we provide an overview of climate change–wellbeing impact pathways and explore which of these pathways have been quantified or modelled, or both. We assessed literature reviews and meta-analyses to describe how climate change affects specific wellbeing outcomes and which of these relationships are robust and amenable to parametrisation. We also conducted a review of 18 models that include one or more wellbeing impacts of climate change. Generally, more quantified pathways are available in the literature than those currently incorporated in ESE models. Temperature-related mortality, food security, and GDP are well represented in quantitative literature and to some extent in ESE models, whereas the impacts of climate change on infectious diseases; respiratory, cardiovascular, and neurological outcomes; mental health; adverse birth outcomes; occupational health and labour productivity; conflict; migration; poverty; air quality; and biodiversity loss have been quantified in the literature but are largely absent in ESE models. These relationships present promising steps towards a next generation of ESE models that could include more sophisticated interactions between environmental impacts and wellbeing.

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Introduction

Climate change has and will increasingly impact wellbeing around the world. The various effects of climate change, from rising temperatures to extreme weather events and from water scarcity to sea-level rise, impact communities in many ways.[1] Research has identified more than 400 different impact pathways through which societies experience climate stress and found that exposure to climate hazards is set to rapidly intensify even in the most aggressive mitigation scenarios.[2] Despite the gravity of these impacts, many forward-looking, policy-relevant integrated environment–society–economy (ESE) models do not include wellbeing impacts of climate change, or do so only partly. The wellbeing costs of climate change and wellbeing benefits of mitigation are either omitted or under-represented in these models.

For instance, process-based integrated assessment models (PB-IAMs), which are influential in Intergovernmental Panel on Climate Change (IPCC) reports, contain no or only rarely include climate–wellbeing impacts.[3–8] These models include demographic and economic developments, but they are assumed exogenous in the so-called shared socioeconomic pathways (SSPs). The SSPs provide five narratives about the future and each provides a plausible storyline about the underlying changes that will affect climate change up to 2100. SSPs are used to generate emissions and land-use scenarios (among others) for policy evaluation. However, no feedback loops exist that link climate change impacts to socioeconomic consequences.

The paucity of climate–wellbeing feedback loops is problematic, because when crucial elements are missing, a model cannot reflect important, policy-relevant dynamics. Exclusion of these dynamics can lead to suboptimal or incorrect guidance. For example, driving integrated assessment models (IAMs) with exogenous SSPs results in illogical outcomes. In one example, the SSP 5 fossil-fuelled development pathway, which estimates 5 degrees of warming by 2100, and the SSP 1 sustainable development pathway, which estimates 3 degrees of warming by 2100, result in the same (upward) trajectory in the human development index (HDI).[6] As Liu and colleagues[6] note, the implication that human development would be unaffected by an additional warming of 2 degrees is nonsensical. For helpful policy evaluation, it is therefore imperative that socioeconomic developments and climate change scenarios include feedback loops between them.

Another variety of models are the cost–benefit IAMs (CB-IAMs), which weigh future costs of climate change against mitigation costs and are used for calculating the social cost of carbon (SCC) and optimal policy pathways. These models do include some societal climate impacts, but in a limited way, focused on economic wellbeing (GDP) rather than broader wellbeing measures. Moreover, the economic damage functions of these models have been criticised for (among other issues) being oversimplistic, containing methodological errors, and using high discount rates, leading to an underestimation of damages from climate change.[9,10] Model outcomes also highly depend on parameters such as the discount rate, for which no scientific consensus exists. Choosing a high or low discount rate leads to different policy advice, for example, between rapid mitigation or slower mitigation and future negative emission technologies.[11,12]

For a third class of ESE models (ie, system dynamics (SD) models), including feedback loops is central to the approach.[3] SD models attempt to endogenise their drivers within the model structure, in a closed system driven by initial parameters. However, these models generally include only a few climate–wellbeing interactions. Although SD models attempt to represent important real-world dynamics, both PB-IAMs and CB-IAMs are generally much more influential in policy making and public debate, since they are the most used tools for climate policy assessment, for example, in their reporting in Working Group 3 of the IPCC assessment reports and their use to establish carbon prices.[13,14]

In this Review, we explored the inclusion of climate–wellbeing impacts in ESE models. Since we found that the impacts are incorporated in a limited way, and sometimes, without a clear theoretical basis, we also reviewed the empirical literature to explore the relationships that have been identified to date. This Review summarises climate–wellbeing impact pathways and identifies those that have been modelled or quantified, or both, and therefore, have the potential to be included in future ESE modelling work.

Methods

We approached wellbeing and its determinants in an interdisciplinary way, based on the study by Jansen and colleagues,[15] who reviewed and synthesised various schools of thought such as basic needs, subjective wellbeing, and welfare economics; and beyond-GDP measurement reports such as the Stiglitz-Sen-Fitoussi Commission report. These elements were clustered into ten wellbeing components, which synthesise the common denominators across wellbeing dimensions (appendix pp 3–5): health (mental and physical); material living standards (eg, nutrition, sanitation, and income); work and other activities (including leisure); education; safety, freedoms, and governance; social relationships; culture; subjective wellbeing and aggregate wellbeing (such as the HDI); environment; and inequalities. We used these ten components to identify causal links between climate change and wellbeing in the literature and in models (figure 1).

For more on the **Stiglitz-Sen-Fitoussi Commission report** see https://ec.europa.eu/eurostat/documents/8131721/8131772/Stiglitz-Sen-Fitoussi-Commission-report.pdf

See **Online** for appendix

Search strategy and selection criteria

We reviewed the impact of climate change on each of the wellbeing components via a literature search using Web of Science. Only review papers were included, as the relationships used in exploring wellbeing should be based on scientific consensus and need to be as robust as possible for modelling purposes (ie, not based on one finding but on a synthesis of findings). The search queries used were in the format of [("climate change" OR "global warming") AND (violence OR crime OR conflict)] (see appendix pp 6–7 for a full list of search terms). The search terms were defined on the basis of wellbeing components, synonyms, and descriptions from the identified literature. An additional search was carried out for meta-analyses, to supplement qualitative findings with quantifications. Only direct impacts of climate change on a specific wellbeing component were searched for, the cascading effects of one wellbeing component to another are not considered. Papers with a specific geographical scope (whether a country or continent) were excluded. When many reviews for a wellbeing component were found, priority was given to highly cited papers and those that provided quantification or specifically addressed modelling or future projection efforts, as judged from the title and abstract.

In reviewing ESE models, we examined those models described such that they might include environment–society feedbacks in Hardt and O'Neill's[16] review of ecological macroeconomic models, Capellán-Pérez's[3] review of IAMs, and the reviews of macroeconomic models by Van Eynde and colleagues[4] and Wiebe and colleagues,[17] in addition to the models included at a workshop organised at the Lorentz Center in the Netherlands in July, 2023 on Sustainable Development Goals modelling[18] involving many SD and PB-IAM practitioners. For each model, the available technical documentation was studied to search for specific climate change–wellbeing connections. Specific search terms were not used, but instead any terms that could correspond to the ten wellbeing components were investigated. The search identified 18 models that contained at least one climate–wellbeing impact (panel). See the appendix (pp 37–47) for an overview of each model, along with the environmental and wellbeing components and the climate impacts on wellbeing in the model.

Climate change–wellbeing impact pathways, quantifications, and modelling

We found various impact pathways, some quantified in literature and some modelled in existing ESE models. For a visual overview of all the identified pathways in the literature, whether qualitative or quantitative, see figure 2. For a visual representation of the pathways identified in the reviewed models, see figure 3. In this section, we briefly describe the climate change impacts on each wellbeing component and whether these impacts are quantified or present in the models. Further details on all aspects of this analysis are available in the appendix (pp 7–36) for the literature and appendix (pp 37–47) for the models.

Health

Health is the most heavily studied pathway. Rocque and colleagues[19] provided an overview of systematic reviews of the health effects of climate change. The authors highlighted the most studied topics with consistent findings, on which we consequently focused in this Review. One area of clear impact is infectious diseases, with strong relationships among vector-borne diseases such as malaria and dengue, increased temperature, and increased rainfall. The association between meteorological factors and food-borne and water-borne diseases, such as cholera and salmonella, is more varied. Non-communicable diseases, including respiratory, cardiovascular, and neurological conditions, are associated with high (heat) or low (cold) temperatures and (high) humidity. Both extreme weather events and temperature negatively affect nutritional health outcomes, which have been considered under the wellbeing component material living standards in this Review. Heat is negatively associated with pregnancy and neonatal health and with worker health. Worker health has been considered under the wellbeing component work and other activities in this Review. An association between temperature and heat and the increased use of health-care services has also been identified.

Apart from physical impacts, increased temperatures also have many mental health impacts, including increased psychological distress; self-reported mental health difficulties; fatigue; rates of psychiatric diagnoses such as depression, anxiety, and post-traumatic stress disorder; depressive language in social media posts; hospital admissions (due to mental health); and suicide.[19–21] Humidity can also aggravate heat effects.[21] For extreme weather events, symptoms are more severe with each subsequent exposure. The proportion of people psychologically affected versus physically affected by any form of disaster can be as high as 40:1.[21]

The health conditions discussed in the previous paragraphs can have impacts on mortality rates. Temperature-related mortality has also been specifically studied, and heat (including heat waves) is strongly associated with mortality.[19] The main causes of temperature-related mortality are cold and heat stress and acute cardiovascular and respiratory events.[22] One review listed meta-analyses for increased mortality (risk) due to various heat-related conditions.[23] Note that with climate change, cold-related mortality might be reduced, but this reduction most likely does not offset the increase in heat-related mortality.[24]

The most prominent contribution to projecting the impact of climate on health into the future is the *Lancet* Countdown report.[25] This report contains projections, for 2041–60 and 2081–2100, of heat-related mortality, malaria and dengue (vector-borne diseases), and exposure to heatwaves and to wildfire danger (among others). Many meta-analyses, scenario studies or impact functions, or both, for these relationships and other diseases, suicide, mental conditions, and adverse birth outcomes exist as well, which can be found in the appendix (pp 7–17). Health is, to some extent, represented in the ESE models, with ten models involving some relationships, especially temperature-related mortality (Earth4All [E4A], energy-rapid overview and decision support [En-ROADS] or climate-rapid overview and decision support [C-ROADS], within limits integrated assessment model [WILIAM]); malaria suitability and diarrhoea (Asia-Pacific integrated model [AIM], the climate framework for uncertainty, negotiation and distribution [FUND], global integrated sustainability model [GISMO]); and air quality consequences (ANEMI, International Futures [IFs], integrated global system modelling framework [IGSM], integrated Sustainable Development Goals [iSDG]), which have been considered under environment in this Review.

Material living standards

Changing temperature, precipitation and heat, and extreme weather events, such as droughts and flooding, can all have negative nutritional consequences due to crop production, food distribution, and food insecurity issues.[19,26,27] These nutritional impacts depend on the timing of events.[26] Wasting (low weight-for-height) and underweight (low weight-for-age) serve as indicators for acute malnutrition, making them more prevalent after extreme weather events. In contrast, stunting (low height-for-age) results from chronic malnutrition and generally appears after several years. For subsistence farmers, droughts increase the odds of wasting and underweight by nearly 50%.[26]

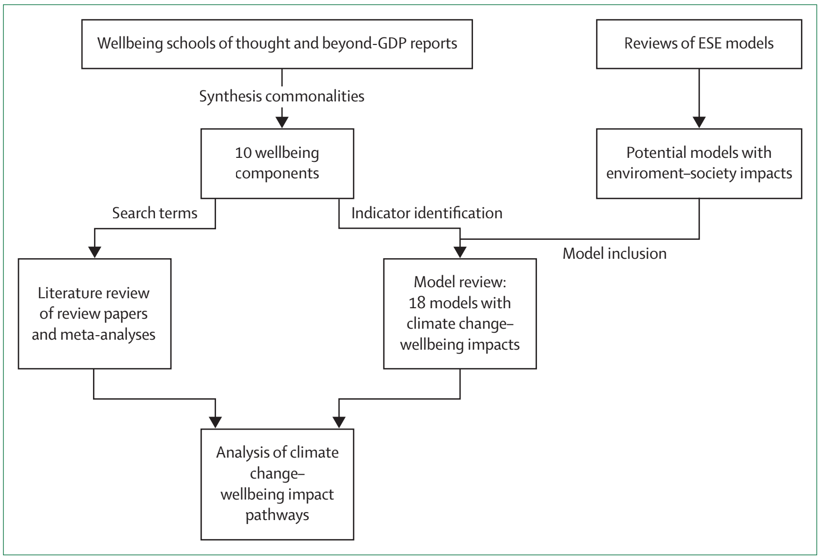

Figure 1: **Overview of the research process**
ESE=environment–society–economy.

Food security projections are available for maize, rice, wheat, sorghum, and soybean yields.[25,28] Food production is also represented in the ESE models to some extent, with ten models encompassing the impact of temperature increase, and sometimes of water availability or natural disasters, on crop yield. A few models link this impact further to undernourishment and mortality (GISMO and iSDG) or life expectancy (ANEMI). Some models focus on agricultural production, whereas others also model the demand side with inclusion of diets and food waste, which are crucial for both mitigation and adaptation (AIM, En-ROADS/C-ROADS, environmental impact and sustainability applied general equilibrium [ENVISAGE], GISMO, IFs, and WILLIAM). Apart from negative effects, some models include potential increases in arable land (ANEMI and FUND) and increases in yields due to CO_2 fertilisation (FUND, IFs, and IGSM), contrary to the scientific consensus that there will be reductions in arable land and although CO_2 fertilisation might increase yields in some crops, it also results in less nutritious food overall and has very large ramifications on food security via extreme weather events.[1]

Impacts of climate change on water, sanitation, and hygiene (WASH) include infrastructure damage due to flooding or storms; loss of water sources due to declining rainfall; changes in water quality due to droughts and

Panel: **The 18 ESE models reviewed that include some climate change–wellbeing impact, categorised by model type and listed alphabetically**

PB-IAMs
- DICE: dynamic integrated climate-economy model
- FUND: the climate framework for uncertainty, negotiation and distribution
- MERGE: model for evaluating regional and global effects of greenhouse gas reductions policies
- PAGE: policy analysis of the greenhouse effect

CB-IAMs
- AIM/Impact**:** Asia-Pacific integrated model's climate change impact model
- ENVISAGE: environmental impact and sustainability applied general equilibrium model
- GISMO: global integrated sustainability model of the integrated model to assess the global environment (IMAGE)
- IFs: International Futures
- IGSM: integrated global system modelling framework (coupling economic projection and policy analysis [EPPA] and MIT earth system model [MESM])
- NGFS: network of central banks and supervisors for greening the financial system's climate scenarios

SD models
- ANEMI (based on the feedback-rich energy economy (FREE) model)
- E4A: Earth4All
- En-ROADS/C-ROADS: energy-rapid overview and decision support/climate-rapid overview and decision support
- FREE: feedback-rich energy economy model
- iSDG: integrated Sustainable Development Goals
- LowGrow
- MEDEAS: modelling the energy development under environmental and socioeconomic constraints
- WILIAM: within limits integrated assessment model (based on MEDEAS)

CB-IAMs=cost–benefit integrated assessment models. ESE=environment–society–economy. PB-IAMs=process-based integrated assessment models. SD=system dynamics.

decreasing river flows, resulting in increased concentrations of chemicals and pathogens; water scarcity; reduced carrying capacity of waters receiving wastewater; survival of pathogens due to increased temperatures; and salinity due to sea-level rise.[29,30] Poor WASH results in diseases, most notably diarrhoea.[29] Disease outbreaks after extreme water-related weather events are associated with contamination of drinking water, and outbreaks are more likely in areas with poor WASH services.[29] A meta-analysis associated a 1°C increase in mean monthly temperature with an 8% increase in diarrhoeagenic *Escherichia coli*.[31] Three ESE models (AIM, FUND, and GISMO) consider the impact of temperature rise on diarrhoea.

The social cost of carbon (SCC) is often used for estimating the economic (GDP) impacts of climate change. The SCC is based on a monetised estimate of total future damages using an economic damage function, discounted to the present day. SCC is then the estimated cost of an additional tonne of CO_2 emitted in the present. SCC is a common analysis for guiding the pricing of carbon in policies but has long been critiqued for its high dependence on methodology and assumptions.[11,32] For example, outputs are strongly dependent on the discount rate which, in turn includes a mathematical term for the pure rate of time preference (PRTP). A higher PRTP means a higher preference for the present, so future damage costs weigh less (are discounted more), leading to a lower SCC.[33–35] The resulting large variation in SCC valuations is clear from two meta-analyses. Tol[36] found a range from –US$355 per metric tonne of carbon (tC) to +$587/tC, with a weighted average of $59/tC (and different values when using different parametrisation); and Wang and colleagues[35] found a range of –$50/tC to $8752/tC, with a mean value of $200/tC. Notably, both of these estimates include negative values; however, Van den Bergh and Botzen[34] argue for a lower bound of the SCC at $125, to take into account missing costs, uncertainties, and risk aversion. SCC estimates have systemically increased over time, in part due to reduced PRTPs, but also due to increasing cost estimation.[33,35] Tol[33] also calculated several economic impact functions from literature data and found that the central estimate is always negative, again with wide confidence intervals. The uncertainty is skewed towards catastrophic tail risks. Tol's estimates of cumulative impact until 2100 (with 4·1°C warming) vary on the basis of the approach used, being either 1·6%–2·2% or 36% of the GDP.

Despite this great degree of uncertainty, GDP is arguably the most important parameter for climate impacts in the ESE models explored in this Review, with 14 models encompassing impacts either with a direct economic damage function or through, for example, specific capital damages (see figures 3, 4 for specifics). With En-ROADS/C-ROADS, the user can choose between different impact functions or customise the parametrisation themself. Such an approach improves the validity of a model as a policy-informing tool, considering the range of uncertainty.

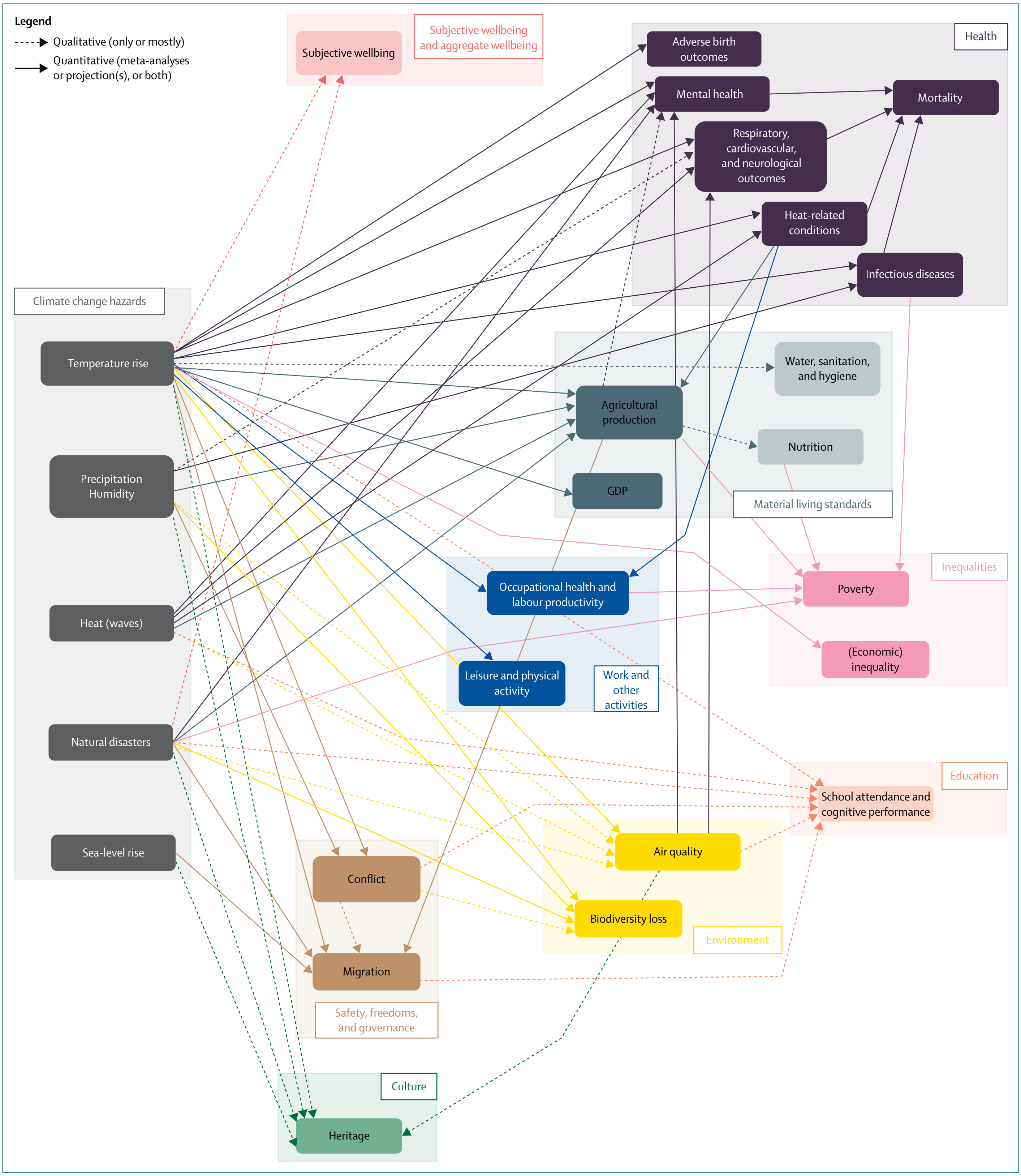

Figure 2: **Climate change–wellbeing impact pathways identified in the literature**
Solid arrows and boxes mean that the relationship has been quantified through meta-analyses or projection(s), or both. Dashed arrows and lighter shaded boxes represent pathways that are either described only qualitatively in literature or have little quantification (no meta-analysis is available for this impact). Each wellbeing component is presented in its own colour (same as in figure 3).

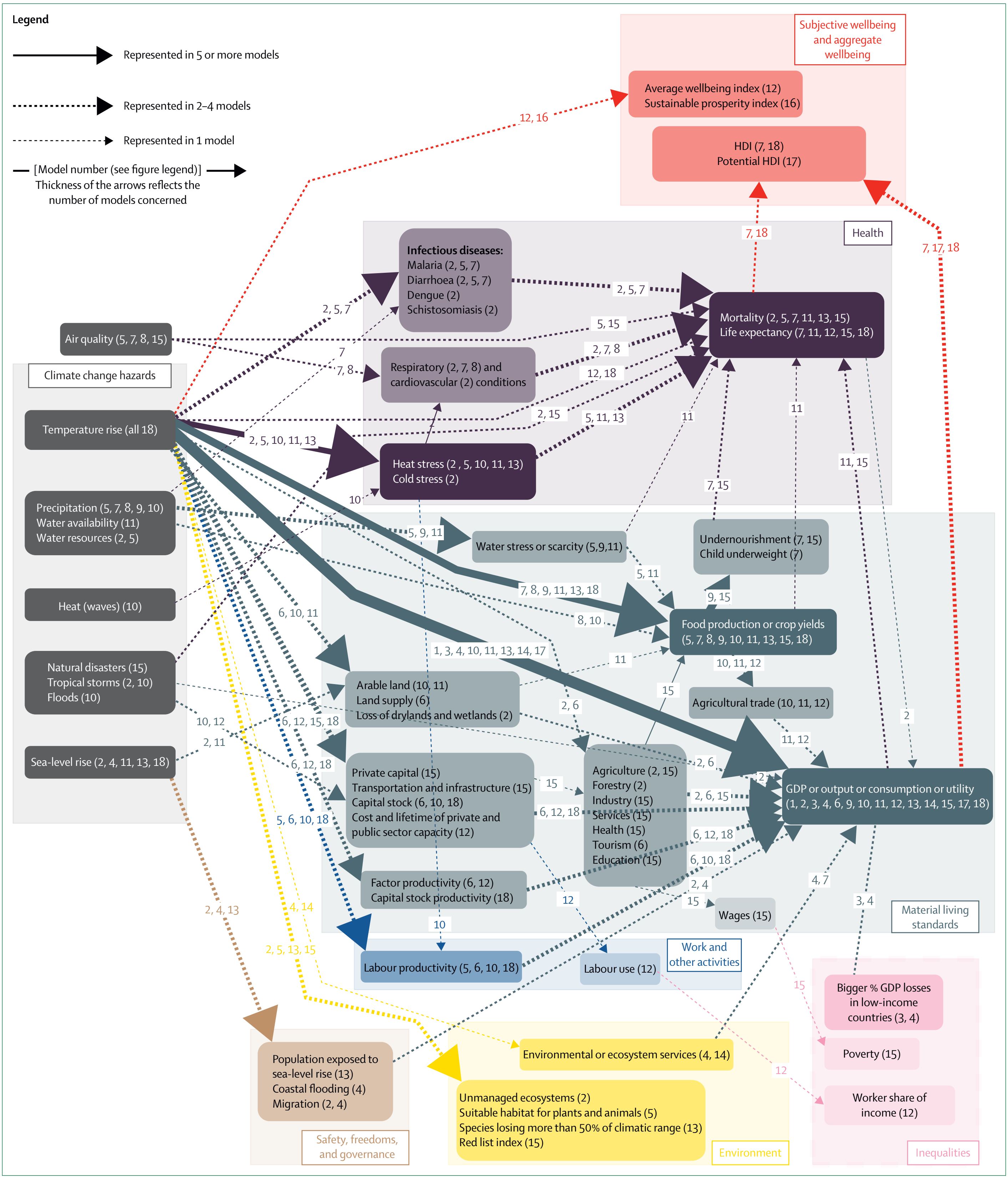

Figure 3: Climate change–wellbeing impacts identified in the reviewed ESE models

Work and other activities

Climate change has health consequences for workers. Climate change in general, and heat in particular, are related to heat strain, injuries, kidney diseases, respiratory and cardiovascular difficulties, mental and physical performance impairment, depression, and anxiety.[19,37] These impacts occur in many occupations, both outdoors and indoors. The main mechanisms are dehydration, fatigue, dizziness, confusion, reduced brain function, loss of concentration, and discomfort.[37] People working outdoors doing physical labour in (sub)tropical climates or indoors with no or poor air-conditioning are especially vulnerable, as are pregnant women, younger (15–24 years) and older workers, and people with obesity or medical conditions.[37] These health conditions, in turn, affect labour capacity and productivity. Romanello and colleagues[25] projected work hours lost for the period 2041–60 and quantified the loss of earnings for 2022. Dasgupta and colleagues[38] modelled both the number of hours worked and the productivity of workers in a 1·5°C, 2·0°C, and 3·0°C warming scenario for low-exposure and high-exposure sectors globally and regionally. In a modelling study on the impact of climate change on poverty, Hallegatte and Rozenberg[39] derived a literature-based estimate of the impact of warming on labour productivity. Of the ESE models, WILIAM, ENVISAGE, and a model produced for the network of central banks and supervisors for greening the financial system (NGFS) include the impact of climate change on labour productivity. Modelling sustainable energy system development under environmental and socioeconomic constraints (MEDEAS) contains jobs in the renewable energy sector, which is related to climate policy rather than climate impacts.

The relationship between temperature and various forms of physical activity, including walking, cycling, recreational physical activity, and use of outdoor public spaces such as parks, follows an inverted U-shaped curve, with increases up to some temperature and then a (rapid) decline.[40–42] Precipitation and physical activity are inversely related. In general, projection studies show a net increase in various leisure-time physical activities.[40] However, effects are heterogeneous across geographical locations, exercise modes, and seasons. Physical activity generally increases in colder areas and during winter, and sometimes in spring or fall, and decreases (severely) in warmer areas and during summer.[40,41] As studies report different outcome indicators, no meta-analysis is available.[40] No ESE model covers these aspects, except leisure being covered tangentially by ENVISAGE, which includes tourism revenues.

Education

Various climate change–education impact pathways exist. Extreme weather events often result in interrupted schooling, children taken out of school to work, and reduced food consumption, which leads to, for example, malnutrition and associated effects on cognitive development.[42,43] Disasters can also result in post-traumatic stress disorder with youth, and longitudinal studies showing an increased risk for psychiatric impairment in adulthood.[44] Climate-induced migration can limit or eliminate access to education.[44] Prenatal maternal stress, which could be caused by climatic events, also significantly influences child development, including cognitive, motor, socioemotional, and behavioural outcomes.[45] More directly, elevated temperatures result in deficits in cognitive performance, as evidenced by experimental literature.[42,44] Air pollution also has an impact, with school absenteeism tracking air pollution over time.[42] Only five partial quantifications of these impact pathways were found in the review papers, and no meta-analyses were found. Of the ESE models, only iSDG contains one impact pathway that links private capital and transport infrastructure damages to the education sector. IAMs generally include education exogenously.

Safety, freedoms, and governance

Changing climatic conditions increase the probability and intensity of conflict and have a net effect on conflict rates.[46,47] Experimental studies in psychology show that with increasing ambient temperatures, people are more likely to engage in violent behaviour.[46] Meta-analyses found that conflict risk increases systemically with climate change: one standard deviation change towards warmer temperatures or more extreme rainfall increases interpersonal violence such as assault or murder by 4% and intergroup conflict such as riots and civil war by 14% ($p<0{\cdot}001$, median estimates).[46,47] None of the studied models included the climate impact on conflicts.

Both physical and economic insecurity can lead to migration. Climate-related factors can both increase and decrease migration. On the one hand, weather shocks increase the vulnerability of staying by increasing (further) poverty risk, which motivates relocation; on the other hand, such conditions decrease the capability to migrate by

The numbers refer to the following models: (1) DICE, (2) FUND, (3) MERGE, (4) PAGE, (5) AIM/Impact, (6) ENVISAGE, (7) GISMO, (8) International Futures, (9) IGSM, (10) NGFS, (11) ANEMI, (12) E4A, (13) En-ROADS/C-ROADS, (14) FREE, (15) iSDG, (16) LowGrow, (17) MEDEAS, (18) WILIAM. The number of models that include a relationship is reflected in the size of the arrows (the thicker the arrow, the more models), the type of arrow (see legend), and shading of the boxes (darkest shade equals most models). Each wellbeing component is presented in its own colour (same as in figure 2). Note that the models do not model the impact of climate change on air quality, as air quality is only related to burning of fossil fuels. Additionally, only the climate change–wellbeing impacts are included in this Review, and models might contain more climate or wellbeing elements that are not linked, and therefore, not shown in this figure. AIM=Asia-Pacific integrated model's climate change impact model. DICE=dynamic integrated climate-economy model. E4A=Earth4All. En-ROADS/C-ROADS=energy-rapid overview and decision support/climate-rapid overview and decision support. ENVISAGE=environmental impact and sustainability applied general equilibrium model. ESE=environment–society–economy. FREE=feedback-rich energy economy model. FUND=the climate framework for uncertainty, negotiation and distribution. GISMO=global integrated sustainability model. IGSM=integrated global system modelling framework. HDI=human development index. iSDG=integrated Sustainable Development Goals. MEDEAS=modelling the energy development under environmental and socioeconomic constraints. MERGE=model for evaluating regional and global effects of greenhouse gas reductions policies. NGFS=network of central banks and supervisors for greening the financial system's climate scenarios. PAGE=policy analysis of the greenhouse effect. WASH=water, sanitation, and hygiene. WILIAM=within limits integrated assessment model.

	Wellbeing subcomponent	Literature quantifications	ESE models
Health	Temperature-related mortality	Multiple meta-analyses and projections	AIM, ANEMI, E4A, En-ROADS/C-ROADS, iSDG, WILIAM
	Infectious diseases	Multiple meta-analyses and projections	AIM, FUND, GISMO
	Respiratory, cardiovascular, and neurological outcomes	Multiple meta-analyses	FUND, GISMO, IFs
	Mental health	Multiple meta-analyses	None
	Health-care services	None overall (some in the above categories)	None
	Adverse birth outcomes	Meta-analysis	None
Material living standards	Food and nutrition	Multiple meta-analyses and projections	AIM, ANEMI, FUND, En-ROADS/C-ROADS, GISMO, IFs, IGSM, iSDG, NGFS, WILIAM
	WASH	None (diseases covered under Health)	None
	GDP or output or consumption or utility	Meta-analyses	ANEMI, DICE, E4A, En-ROADS/C-ROADS, ENVISAGE, FREE, iSDG, MEDEAS, MERGE, NGFS, PAGE, WILIAM
Work and other activities	Occupational health and labour productivity	Multiple meta-analyses and two projections	AIM, ENVISAGE, NGFS, WILIAM
	Leisure and physical activity	Quantifications but no meta-analysis, one projection	ENVISAGE
Education	School attendance and cognitive performance	Little quantification, no meta-analysis	iSDG
Safety, freedoms, and governance	Governance	None	None
	Conflict	Two meta-analyses, two projections on sub-Saharan Africa	None
	Migration	Multiple meta-analyses and projections	En-ROADS/C-ROADS, FUND, PAGE
Culture	Heritage	One quantification, no meta-analysis	None
Subjective wellbeing and aggregate wellbeing	Subjective wellbeing	One quantification, no meta-analysis	None
	Aggregate wellbeing	None	E4A, GISMO, LowGrow, MEDEAS
Social relationships	Trust, social capital	None	None
Environment	Air quality	Multiple meta-analyses and projections (not all climate related)	AIM, GISMO, IFs, iSDG
	Biodiversity loss	Multiple meta-analyses and projections	AIM, En-ROADS/C-ROADS, FUND, iSDG
Inequalities	Vulnerabilities	Quantifications for several of the wellbeing (sub)components	ANEMI, GISMO
	Poverty	Two projections and a modelling study using IFs	iSDG
	(Economic) inequality	One quantification and one projection	E4A, MERGE, PAGE

***Figure 4:* Overview of climate change–wellbeing impacts quantified in the literature or represented in ESE models, or both**
See the appendix (pp 7–36) for details on impacts quantified in the literature and appendix (pp 37–47) for details on impacts quantified in models. The third column indicates whether a wellbeing impact has been quantified in the literature with meta-analyses or projections, or both. The fourth column indicates whether a wellbeing impact has been included in any ESE models, and when included, which one(s). We used both the third and fourth columns to arrive at an indication in the second column of coverage of the wellbeing impact. Column 1 presents the wellbeing components. Column 3 presents the literature quantifications, where green=meta-analyses or projection(s) available, or both; and red=no meta-analyses available. Column 4 presents the ESE models, where green=5 or more models contain climate impact on that wellbeing component; yellow=2–4 models; and red=0 or 1 model. Note that this figure only includes wellbeing elements that are connected to climate change; models might contain more wellbeing elements that are not linked to climate change, and therefore, are not shown in the figure. Column 2 presents the wellbeing subcomponent, where green=both literature quantifications available and present in ESE models (ie, columns 3 and 4 are green); yellow=literature quantifications available but little to no presence in models (ie, column 3 is green and column 4 is yellow or red); and red=no literature quantifications and not present in models (ie, columns 3 and 4 are red). AIM=Asia-Pacific integrated model's climate change impact model. DICE=dynamic integrated climate-economy model. E4A=Earth4All. ESE=environment–society–economy. En-ROADS/C-ROADS=energy-rapid overview and decision support/climate-rapid overview and decision support. ENVISAGE=environmental impact and sustainability applied general equilibrium model. FREE=feedback-rich energy economy model. FUND=the climate framework for uncertainty, negotiation and distribution. GISMO=global integrated sustainability model. IGSM=integrated global system modelling framework. iSDG=integrated Sustainable Development Goals. MEDEAS=modelling the energy development under environmental and socioeconomic constraints. MERGE=model for evaluating regional and global effects of greenhouse gas reductions policies. NGFS=network of central banks and supervisors for greening the financial system's climate scenarios. PAGE=policy analysis of the greenhouse effect. WASH=water, sanitation, and hygiene. WILIAM=within limits integrated assessment model.

depleting household resources, which creates a poverty trap.[48–50]

Rapid-onset shocks such as floods generally limit the ability to migrate due to household resource depletion, whereas slow-onset shocks such as extreme temperatures and droughts increase migration. Weather shocks usually drive long-distance domestic migration rather than international or local migration.[49,50] In some cases, an increase in freshwater from river flooding can be beneficial for agricultural activity, whereas in other cases, riverbank erosion leads to loss of arable land, which induces migration.[51] Sea-level rise also poses various threats, not just by inundation but also through salinisation, flooding, and inland penetration of storms.[51,52] However, these factors might not directly lead to migration, as resistance to relocation is generally strong for social, cultural, and economic reasons.[52] There are competing definitions, and therefore, different calculations of populations at risk from sea-level rise, and currently, more work is needed to translate the number of those at risk into an estimate of the number of migrants.[52] See the appendix (pp 25–29) for some quantification studies. Of the ESE models, En-ROADS/C-ROADS includes population(s) exposed to sea-level rise; and FUND and policy analysis of the greenhouse effect [PAGE] monetise forced migration flows.

We did not find any literature reviews on the impact of climate change on freedoms and governance, we only found many studies on the governance of climate change. No ESE models included these impacts either, although IFs encompasses the relationship between water stress and state stability but not the impact of climate change on water stress.

Social relationships

We did not find any reviews specifically on the impact of climate change on social relationships, but only of the reverse (eg, the role of trust or social capital in climate mitigation or adaptation, or both). A review on vulnerabilities mentions that resource scarcity could weaken social cohesion and safety nets and cites a study that found a decline in social reciprocity and stress on social networks after droughts and floods in Mexico.[27] Note that interpersonal violence has been considered under safety, freedoms, and governance in this Review. Apart from conflict, other wellbeing components, such as migration, health, and education, have implications for social relationships as well. As this Review is restricted to first-order (direct) impacts, we did not review the impact of climate change through these components.

Culture

Most research into cultural impacts has been about tangible heritage (sites), whereas intangible heritage has been studied less.[53,54] Both outdoor and indoor assets are affected by climate change. Water is the main issue, with humidity and wetness causing mechanical, chemical, and biological decay of both buildings and artifacts.[54] Other risks include flooding, coastal erosion, changes in freeze-thaw cycles, and increase in diurnal temperature ranges. Most studies are based on specific case-studies, generally focused on Europe and the USA, thus making generalising or quantitatively synthesising results difficult.[53,55] No model includes climate impacts on heritage.

Subjective wellbeing and aggregate wellbeing

No reviews specifically focusing on climate impacts on subjective wellbeing or life satisfaction were found. Quality of life or wellbeing are mentioned in some articles but generally refer to mental health (which is considered under health in this Review). One review reported on a study finding that the warmer the coldest month of the year, the happier the country; and the warmer the hottest month, the less happy the country.[56] Subjective wellbeing indicators are not present in any model, so nor is the impact of climate change on subjective wellbeing.

Some models include an aggregate wellbeing index. GISMO can project the HDI, and MEDEAS calculates potential HDI based on economic outcomes. E4A and LowGrow construct their own wellbeing indexes, with a direct climate impact that decreases the index (although without a clear scientific basis).

Environment

We focused on the first-order impacts of climate change on the environment. These impacts constitute intermediary impacts rather than direct wellbeing impacts, since environmental factors themselves are not equated with (human) wellbeing but are instrumental for (mental) health and wellbeing. A full review of such environmental benefits for wellbeing is beyond the scope of this analysis (see Nature's contributions to people within the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services [IPBES] framework for such research).[57] We looked at climate impacts on air quality, as literature on climate and health often includes this parameter as an important health determinant and biodiversity loss as an existential threat alongside climate change.

Air quality is intertwined with climate change, as both share their main cause: burning fossil fuels. Mitigating climate change, therefore, simultaneously mitigates air pollution. Climate change itself also affects air pollution, as humidity and heavy precipitation increase moulds and bioallergens, (drought-related) wildfires produce (fine) particulate matter (PM) and gaseous pollutants, increased temperatures accelerate ozone production, and various meteorological factors influence ventilation and dilution of pollutants.[21,42,58] The specific impacts are difficult to quantify because disentangling climate and air quality effects is challenging. The (positive) impact of emission mitigation on air pollution and related health consequences appears to be much larger than the (negative) influence of climate change itself.[59,60] Of the ESE models, iSDG includes the impact of $PM_{2.5}$ exposure on mortality, both GISMO and IFs relate (indoor) solid fuel burning to respiratory diseases and subsequently mortality, and IGSM links air pollution to health (but the specifics are unclear). None relate climate change directly to air pollution.

Many human drivers other than climate change exist with respect to biodiversity loss, with the key factors being land-use change and species invasions.[61] With respect to climate changes, the question is to what extent species either manage to migrate to stay within their climatic niche or can adapt shifting their niche. The impact of precipitation changes seems to be more important than that of temperature changes.[61,62] Meta-analyses found negative impacts but generally used different methods and outcome indicators, and thus, assessing a consensus among them for quantifying biodiversity loss is challenging.[61–64] Three of the ESE models contain some assessment of the climate impact on biodiversity: En-ROADS/C-ROADS (using a relationship between temperature and loss of climatic range of species), FUND (using a damage function of temperature in unmanaged ecosystems), and iSDG (using a relationship between temperature and the red list index of extinction risk).

Inequalities

There are two sides to inequality: inequalities in the impacts of climate change depending on the different vulnerabilities of communities, and the impact of climate change on inequality. These dimensions are connected because already marginalised groups are often more vulnerable, so climate change generally exacerbates the existing vulnerabilities and inequalities.[27] The specific vulnerable populations for each wellbeing component are described in the appendix (pp 7–36). In the period between 1961 and 2010, climate change has most likely contributed to an increase of approximately 25% in population-weighted between-country inequality.[65] One modelling study found that by 2100 (with 2·5°C–3·1°C warming), within-country inequality will increase by 1·4 points on the Gini index due to climate change.[66]

The impacts of climate on poverty have been studied in several efforts. Hallegatte and colleagues[43] showed that poor people are both more exposed to and more vulnerable to the impacts of environmental shocks, stressors, and natural hazards. The two most important climate-related causes of poverty are agricultural impacts, with resulting effects on food prices for consumers; and health impacts, through malaria, diarrhoea, and stunting.[39,67] Other channels include agricultural effects on farm income, natural disasters, and labour productivity. Food prices and farm income have a special relationship. In some cases, adverse productivity shocks leading to increased prices can increase farm income,[68] but on a global scale, the negative effects of reduced yields are most likely to dominate.[39] Three of the ESE models include some form of poverty or inequality effects: model for evaluating the regional and global effects of greenhouse gas reductions (MERGE) has a larger percentage of GDP damage for low-income countries; iSDG connects private capital and transport infrastructure damages to education, which further connects with wages and poverty; and E4A links capital damages to labour use, which links to labour share of income (as compared with capital owners' earnings). Moreover, Moyer and colleagues[69] projected the impact of climate change on poverty towards 2070 with the IFs model.

Overview of quantified and modelled climate change–wellbeing impact pathways

For an overview of whether and how climate change–wellbeing impacts are quantified in the literature or models, or both, see figure 4. All quantification or modelling studies can be found in the appendix (pp 7–36). Some studies use smooth damage functions, whereas others cover shocks from extreme climate events. Depending on the ESE model, either or both can be used to inform (the shape of) climate impact functions.

Three wellbeing (sub)components are represented amply in literature quantifications and generally well in ESE models: temperature-related mortality, food security, and GDP. These (sub)components present the most obvious impacts to include more widely in ESE modelling. Food security currently mostly concerns crop yields, whereas the consequences of reduced yields, for example, malnutrition and health, need more attention. For GDP, various approaches exist with substantial differences in outcomes, most notably whether only direct one-off impacts on output are considered (level effects), or also factors, for example, capital and productivity damages that persist and affect economic growth (growth effects). Including such persistent effects generally results in 10–100 times greater economic impacts.[70]

Most other (sub)components have been quantified in the literature but are present in only a few or no ESE models: infectious diseases; respiratory, cardiovascular, and neurological outcomes; mental health; adverse birth outcomes; occupational health and labour productivity; leisure and physical activity; conflict; migration; air quality; biodiversity loss; vulnerabilities; and poverty. These areas present opportunities for model development. Particularly infectious diseases; respiratory, cardiovascular, and neurological outcomes; occupational health and labour productivity; air quality; and biodiversity loss are promising avenues for inclusion in modelling more widely, as some ESE modelling experiences and multiple meta-analyses and projections are available to build on for these components. Mental health; leisure and physical activity; and conflict will be more challenging, as these components themselves are generally not included in models, let alone the climate impact on them.

The remainder of wellbeing (sub)components are largely unquantified or even reviewed and are included in no or only one ESE model: health-care services; WASH; education; governance; heritage; subjective wellbeing; and (economic) inequality.

Discussion

The most obvious starting points for the integration of further climate–wellbeing impacts in ESE modelling are impacts that are well quantified in the literature and in ESE models. Further opportunities for model development are those impacts that do not often appear in models currently but have been quantified. Many of the quantified components affect mortality rates (ie, various diseases, suicide, and nutrition-related and temperature-related mortality). Therefore, mortality–or its impact on life expectancy–is a promising indicator to use for modelling climate change impacts.

The climate change–wellbeing impacts that have been described qualitatively but not quantitatively represent research gaps to be addressed. Of these, education is an important one, as education is often seen as a relevant indicator for the state of a country. Education is one of the dimensions of the HDI, a prominent aggregate wellbeing index. The other HDI dimensions, life expectancy and GDP, have been quantified, so if education is addressed better, then the climate impacts on the full HDI can be inferred.

In this Review, we have only examined quantifications currently within ESE models and impacts that could be added based on quantifiability; however, looking at the importance (size) of impacts as a criterion for prioritisation is also meaningful. Further research is needed to identify the most important determinants of wellbeing and identify the climate change impacts that are most crucial.

All the studied climate change–wellbeing pathways show that people experience different vulnerabilities to impacts based on demographic, geographical, and socioeconomic factors. Therefore, wherever possible, climate impacts should be modelled in a contextually specific manner. The specific vulnerable populations for each wellbeing component are included in the appendix (pp 7–37).

However, since papers with a specific geographical or demographic scope were not included in this Review, future work and modelling will be needed to make specific regional assessments. AIM, NGFS, and WILIAM could serve as potential examples, with their country-specific impact functions. Unfortunately, the paucity of data disaggregated by demographic or socioeconomic characteristics is often a limiting factor.[25] For historical data on combined environmental and mortality data at country and regional levels, the Multi-Country Multi-City (MCC) database covering 1150 locations in 54 countries is an important resource.[71]

We want to emphasise two important factors that were out of scope of this Review: adaptation and tipping points or non-linear dynamics. Adaptive capacity is unevenly distributed, and areas and people who are more likely to experience impacts also seem to be less able to adapt and are generally located in low-income and middle-income countries.[72] Currently, models largely omit adaptation and inequalities in adaptation;[72] in this Review, only ENVISAGE, iSDG, and PAGE incorporate adaptation in any way. Models also largely omit tipping points, thresholds beyond which non-linear changes occur, which can happen in the climate system but also socioeconomically in terms of mitigation or adaptation efforts. Given that tipping points exist, the historic relationships between climate change and impacts that most models and literature build on may not hold for future developments.

Incorporating climate–wellbeing impacts and accounting for vulnerabilities, adaptation, and tipping points add further complexity to the already elaborate models. Modellers need to know the specifics of the relationships they are adding, such as the drivers, moderating factors, the shape of the relationship, and potential tipping points. Feedback loops can be self-reinforcing or balancing, leading to different dynamics. That models try to incorporate these feedback loops, rather than using simple linear impact relationships with exogenous drivers, is important. Such incorporation presents key challenges for modelling teams, and sometimes, to the core model architecture used in some models. The number of feedbacks and parameters that can be included in models is always a trade-off. Including many parameters and feedbacks at once is both a computational and theoretical challenge. Generally, more parameters means fewer feedbacks (such as in PB-IAMs), and vice versa (such as in SD models). The same trade-off exists with having either more interacting components or more disaggregation.[3] There is work under way to better model dynamic systems in sustainability research and the latest advances have been reviewed by Selin and colleagues.[73]

NGFS presents an interesting modular approach, combining models in such a way that they do not just use outputs of various IAMs to model country-specific socioeconomic and financial impacts but have integrated these impacts to some extent back into the IAMs, creating a feedback loop. The NGFS model calculates climate damages, which are then used to rerun the IAM model with increased carbon taxes and adjusted carbon budgets, which influence the decision making of the agents in the model.

This Review has some limitations. As we only included first-order impacts and no interactions between wellbeing components, we do not provide a full view of wellbeing impacts. Further, only review papers and meta-analyses were included, and not individual papers with quantifications or projections; therefore, recent papers that postdate the included reviews have not been included. Finally, the modelling quality or approach of the reviewed models was not assessed. Some models treat climate dynamics more extensively and others are more simplistic or aggregated; some rely on neoclassical partial or general equilibrium economic approaches, whereas others are post-Keynesian. The appendix (pp 37–47) describes the various characteristics of the models, but we did not judge their quality or applicability to specific analyses.

Conclusion

This Review identifies that more quantified climate change–wellbeing pathways are available in the literature than currently incorporated in ESE models. Relationships between climate change and temperature-related mortality, food security, and GDP are available in the quantitative literature and sometimes included in ESE models, whereas the impacts of climate change on infectious diseases; respiratory, cardiovascular, and neurological outcomes; mental health; adverse birth outcomes; occupational health and labour productivity; conflict; migration; poverty; and air quality and biodiversity loss have been quantified in literature but are under-represented in models. These relationships present promising pathways to explore for inclusion in ESE models. This Review should serve as a guide for improved modelling of environment–wellbeing interactions in the future.

Contributors

IS, PB, and RH conceptualised this research. IS did the literature search, literature collection, and literature analysis; drafted the visualisations; and wrote the original draft of the manuscript. PB, RH, and RK supervised, reviewed, and edited the manuscript. All authors approved the manuscript and had the final responsibility for the decision to submit for publication.

Declaration of interests

We declare no competing interests.

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