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Exploring the representation of climate change impacts in integrated assessment modelling: the case of health and place

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Abstract

Well-being impacts of climate change, particularly on human integrity (Health) and living conditions (Place), are severe but often underrepresented in Integrated Assessment Models (IAMs). When included, these impacts are typically modelled using simplistic top-down approaches, while bottom-up representations linking hazards to impacts, which offer high transparency and process detail, are largely overlooked. Recent trends connecting IAMs with the Impact, Adaptation, and Vulnerability (IAV) community offer an opportunity to improve the representation of well-being damages. Here, we conduct a scoping review resulting in a mapping of 37 modelling studies, revealing a diverse range of approaches, with variation in hazards, impacts, and modelling choices. Key gaps include weak representation of inequality, a lack of multi-channel assessments, and an overrepresentation of northern regions. We propose a roadmap to enhance climate impacts representation on Health and Place in IAMs, using improved data and large-scale multiregional models to generate results that better support decision-making.

Keywords Integrated assessment models · Climate change damage · Climate change impacts · Impact representation.

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1 Introduction

Climate change threatens multiple dimensions of human well-being. In the framework proposed by Adger et al. (2022), Health and Place are identified as two key components especially vulnerable, which can be affected through pathways like extreme events that cause displacement and mortality, disruptions to ecosystem-based livelihoods, deterioration of health services, loss of place attachment, and damage to physical and cultural heritage. Quantitative assessments indicate that impacts on human health and displacement could be particularly severe (Ciscar et al. 2019; Lenton et al. 2023; Cattaneo et al. 2024).

Despite their importance, climate change impacts on Health and Place are poorly represented in traditional Integrated Assessment Models (IAMs), distorting estimates of climate change's socioeconomic consequences (Rothman et al. 2003; Adger et al. 2011; Bosello et al. 2012). IAMs often represent climate impacts on well-being through top-down methods like aggregated damage functions linking GDP and global temperature, which estimate total socioeconomic at a macro scale in a single metric (Diaz and Moore 2017; Capellán-Pérez et al. 2020). These approaches overlook individual impact channels, unlike bottom-up methods that offer greater transparency in explaining climate change impact processes (Piontek et al. 2021). Furthermore, simplistic damage modelling in turn limits adaptation and inequality representation, reducing insights into adaptive capacity and vulnerability reduction (Dennig et al. 2015; Emmerling and Tavoni 2021; Asefi-Najafabady et al. 2021; Schwarze et al. 2022). For example, analyzing Health and Place climate-related impacts (such as extreme heat, which raises mortality and reduces urban habitability) in a bottom-up way can improve understanding and guide targeted and concrete adaptation policies (e.g., urban greening and heat-resilient housing).

To address these limitations, the expanded definition of IAMs given by Fisher-Vanden and Weyant (2020) is particularly relevant. It goes beyond traditional global models focused on deriving greenhouse gas (GHG) emissions scenarios by including under the term IAMs those modelling frameworks coupling natural and human systems, thereby widening the field for climate impact and adaptation assessment. This shift has led to the emergence of Impacts, Adaptation and Vulnerability IAMs (IAV-IAMs), highlighted in recent reports (Moss et al. 2016; Kling et al. 2017). Identifying these models within the integrated assessment community is essential for better climate damage representation and fostering collaboration between IAV and mainstream IAM research.

While previous reviews have examined well-being-related climate impacts in IAMs (Diaz and Moore 2017; Rising et al. 2022b), they have not systematically applied a review method aiming at identifying integrated models capturing bottom-up impact channels on Health and Place instead of top-down aggregated damage modelling. To fill this gap, we conduct a scoping review to provide a mapping and preliminary assessment of the available studies on integrated assessment modelling showing bottom-up impact channels on the well-being categories of Health and Place proposed by Adger et al. (2022). We focused on Health and Place because they combine high vulnerability to climate change with limited representation in traditional Integrated Assessment Models. In this study, Health refers to human physical and mental health and health systems, while Place encompasses the physical, social, and cultural dimensions of a location, including heritage, identity, and the impacts of migration or displacement. The review is classified as a scoping review because it aims to map evidence, synthesise diverse study designs, and identify literature gaps in underexplored areas (Mays et al. 2001; Arksey and O'Malley 2005; Munn et al. 2018). We also use an expanded definition of IAMs aligned with the IAV-IAM approach to ensure the field is widened to find bottom-up impact channels.

Our review results in a database of studies that we analyze for hazards and impacts, modelling approaches, heterogeneity and inequality, geographical assessment, and key findings. This paper reviews the progress made to date in the field and provides recommendations for future work in the representation of climate impacts on Health and Place in IAMs, including identification of key gaps, promising methodologies for further exploration and potential new approaches to investigate. These insights aim to guide future integrated modelling efforts and contribute a valuable resource for researchers working on climate change impact assessments.

The remainder of the paper is structured as follows: Sect. 2 explains the methodology followed for the scoping review; Sect. 3 provides the main results from the database analysis; Sect. 4 includes the discussion (including gaps identification and roadmap), and Sect. 5 offers a conclusion.

2 Methodology

The methodology of this paper involves conducting a scoping review, followed by the creation of a database of modelling studies (Supplementary Data).

Scoping reviews share systematic elements like transparency and replicability but tend to be more exploratory and less exhaustive than full systematic reviews (Grant and Booth 2009). As a type of systematic review, scoping reviews follow reproducible steps to minimize bias (Tranfield et al. 2003; Moher et al. 2009). We followed and adapted the stages of the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework (Page et al. 2021) as in previous scoping reviews (Santo et al. 2024). This paper uses two parallel searches, one for Health and one for Place, which were later merged for joint analysis. Figure 1 presents flowcharts for each search, outlining key stages: identification, screening, and inclusion.

In the identification phase, we defined keywords and a search protocol. Health and Place keywords were selected to align with the operationalization of the concepts discussed, using Adger et al. (2022) as a reference. These were combined with keywords related to climate change impacts and integrated assessment modelling, which were chosen aiming to cover as much literature as possible, based on knowledge of typical keywords used in the research field. Thus, the Health Boolean search was (*"climat* change" OR "sea-level rise" OR "extreme weather event" OR "extreme event") AND ("impact*" OR "damage") AND ("health" OR "death" OR "morbidity" OR "disease" OR "mortality" OR "nutrit" OR "healthcare") AND (("integrated assessment" AND "model") OR "integrated model*")* and the Place Boolean search was *("climat* change" OR "sea-level rise" OR "extreme weather event" OR "extreme event") AND ("impact*" OR "damage") AND ("migra*" OR "displacement" OR "place" OR "cultur*" OR "heritage") AND (("integrated assessment" AND "model") OR "integrated model*").* We searched for these keyword combinations in titles, abstracts, and keywords in the Scopus database on March 27, 2024,

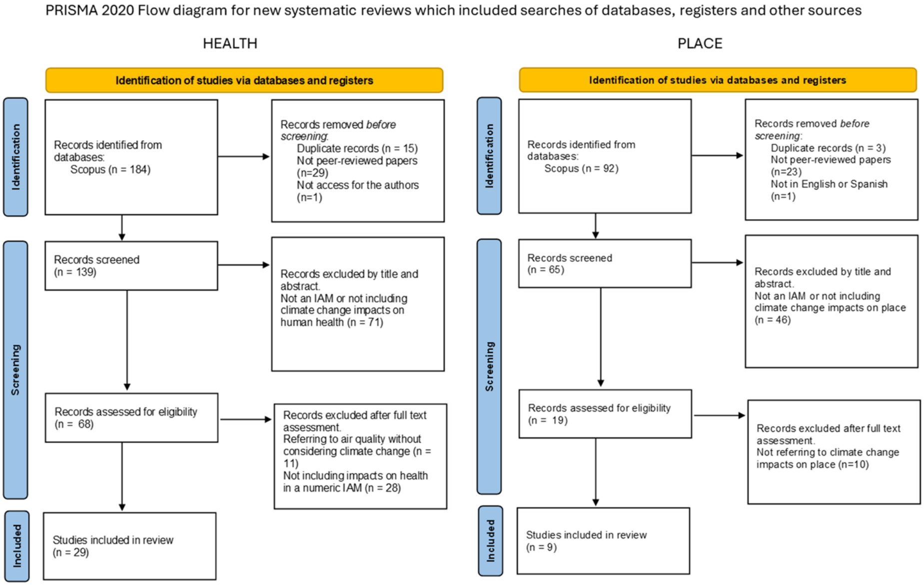

Fig. 1 Adaptation of the PRISMA 2020 flowchart of the article selection process

covering 1995–2024. Only peer-reviewed journal articles were included[1], excluding books, book chapters, conference papers, and reports, following similar reviews (Pastor et al. 2020; Jungell-Michelsson and Heikkurinen 2022). Duplicates, inaccessible articles, and non-English papers were removed.

The screening phase is subdivided in two stages: screening and eligibility. Screening involves reviewing abstracts and applying inclusion and exclusion criteria (Table 1). When it is unclear whether a paper meets the criteria by reading the abstract, we move it to the eligibility stage. Eligibility involves full-text reading[2] and the application of the same criteria. Once eligibility is completed, we moved to the inclusion phase, which refers to including the selected records in a final database for the analysis.

The review resulted in 38 papers: 29 from the Health search and 9 from the Place search. These were compiled into a final database, which can be consulted in the Supplementary Data, along with other information about the search, identified records, and the final papers selected.

In the database, each line represents a study or modelling exercise, not necessarily one paper. Studies were grouped by model application to climate impact analysis, not by IAM. After reviewing the papers, some were split or combined, resulting in 37 studies.

The created database (Supplementary Data) provides a structured framework for mapping available evidence and identifying gaps. It includes the following information, analysed in the Results section:

[1] We additionally examined the most updated documentation of the five IAMs commonly used by the IPCC for their scenario analysis (IMAGE, GCAM, MESSAGE, AIM/CGE, REMIND) but we did not find any additional information to include in the review that was not already captured.

[2] This process was carried out twice to ensure the correct interpretation of the results.

Table 1 Inclusion and exclusion criteria for the screening and eligibility

Inclusion criteria	Exclusion criteria
i) The paper contains a modelled representation of climate change effects on areas related to Health —encompassing human health (including aspects such as mortality, diseases, and nutrition) and healthcare systems— and/or Place, represented in terms of migrations, displacement and physical and cultural heritage. ii) The paper contains a representation of impact channels through specific hazards and impacts. iii) The paper contains an integrated and quantitative model (or set of models), including all those that self-refer to their model as an IAM, integrated model (IM) or similar (e.g. Integrated Modelling Framework (IMF), Integrated Assessment Modelling Framework, etc.). The model should align with the following definition of IAM, based on the category of IAV-IAM proposed by Fisher-Vanden and Weyant (2020): a tool or modelling framework of coupled detailed system models that capture interactions between natural and human systems across spatial and temporal scales. It should also be able to provide future scenarios and projections.	iv) The paper includes impacts of climate change mitigation, but not the effects of climate change as a climate hazard. v) The paper includes impacts from natural phenomena such as extreme weather events or other greenhouse gases emissions-related problems (e.g., air pollution), but it does not explicitly relate them to climate change. vi) The paper does not provide a numerical and computational integrated assessment modelling exercise. vii) The paper does not include future scenarios or projections. viii) The paper includes effects of climate change on environmental quality indicators or ecosystem health without explicitly including human health or emplacement assessment. ix) The paper does not explicitly include climate change impacts on human health or place-related variables.

- Basic Information, with information about the number of studies, the references, publication year, and DOI (Digital Object Identifier).
- Hazards and impacts, including information on the variables and indicators used in the studies (Sect. 3.1).
- Methods, including diverse methodological information on the models used or developed (Sect. 3.2).
- Geographical Information, including details of the geographical case studies, the level of disaggregation, and the funding region (Sect. 3.3).
- Heterogeneity and Inequality, including the type of representation of inequality, if any (Sect. 3.4).
- Findings, including a synthesis of the main findings from the impact modelling exercise (Sect. 3.5).

To extract, analyse, and present the results of the scoping review, we followed the recommendations of Pollock et al. (2023). Our approach primarily relied on qualitative content analysis, using mainly inductive extraction[3] and analysis to categorize the information emerging from the modelling studies. For the hazards and impacts, we adopted an inductive-deductive approach, considering the climate change pathways framework of McMichael et al. (2006) as a starting point for generating the thematic groups. Additionally, we used techniques such as frequency counts and tabular/graphical presentation (see Results) to map the information.

[3] According to Pollock et al. (2023), inductive analysis involves developing categories or frameworks during the extraction process, whereas in deductive analysis, a predefined framework is used.

3 Results

This section presents a synthesis of the main results obtained after the content analysis. For details, consult the extensive information available for each paper in the database (Supplementary Data).

3.1 Hazards and impacts

Hazards and impacts are categorized to better understand the impact channels represented by each modelling study. This structure helps to identify specific bottom-up causal chains. Figure 2 shows the frequency of each hazard and impact relative to the total hazards and impacts identified across all studies.

Tables 2 and 3 expand on how hazards (Fig. 2a) and impacts (Fig. 2b) are defined in this study and represented in the models through different indicators and variables, respectively.

We also assessed how many modelling studies incorporate multiple impact channels, such as various hazards or impacts, as this is key to realistically representing climate damage. Figure 3 shows that most studies focus on the representation of a single hazard or impact, while some of them are 'multi-channel' but with a limit of 3 impacts and 4 hazards as much (Liu et al. 2024). Among those multi-channel studies, we found that these typically cover mortality impacts associated with various climate change hazards (Zhao et al. 2020; Pottier et al. 2021), morbidity impacts of different hazards (Ikefuji et al. 2014), or both mortality and morbidity impacts of only one hazard (Reilly et al. 2013; Geels et al. 2015; Saari et al. 2019). There are also a few cases in the Health category covering the effects of multiple hazards and multiple impacts (Ibarrarán et al. 2010; Ikefuji et al. 2014; Oda et al. 2023; Liu et al. 2024).

3.2 Modelling methodologies

The expanded definition of IAM followed in this work allows us to capture a wide variety of models using different modelling methods, leading to a high diversity of methodologies. We categorize the methodologies of the studies based on three key dimensions: (i) how climate change hazards are represented; (ii) the model's degree of integration; and (iii)

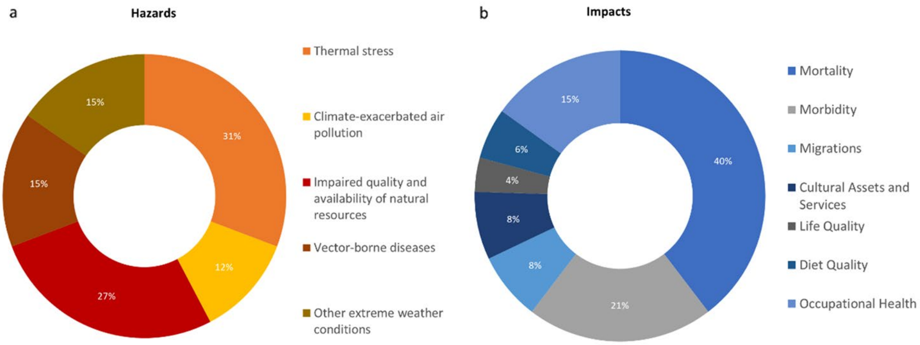

Fig. 2 Distribution of hazard (**a**) and impact (**b**) types, shown as percentages of total hazards and impacts identified across all studies

Table 2 Hazard categories, definitions, and modelling examples

Hazard	Definition	Representation in the studies
Thermal stress	Harm caused by exposure to temperatures beyond tolerable thresholds, including heatwaves and cold spells.	Heat stress is often represented using global or regional surface temperature increases (Nakajima et al. 2020; Lupi and Marsiglio 2021; Pottier et al. 2021), while some studies use the Wet Bulb Globe Temperature (WBGT) (Takakura et al. 2018; Matsumoto et al. 2021). Cold stress is also considered in certain analyses (Ciscar et al. 2019; Bressler et al. 2021).
Impaired quality and availability of natural resources	Degradation or reduction of essential resources due to climate-related processes.	Deterioration of water resources is represented through potable water quality-related variables (Bertone et al. 2019) or as total ammonium load spilled on water estuaries (Pouso et al. 2019). Water and food quality reduction is represented through diarrheal prevalence (Liu et al. 2024). Impacts on food availability are represented through plant productivity (Lüdeke et al. 1999) and food production losses (Malik et al. 2022). Others model a general resource deprivation through economic variables affected by temperature (Benveniste et al. 2020, 2022; Cruz and Rossi-Hansberg 2024).
Vector-borne diseases	Illnesses transmitted by climate-sensitive vectors (e.g., mosquitoes, ticks) whose range, abundance, or activity is influenced by climatic changes.	Mainly refers to climate change-induced malaria (Martens 1995; Tol 2008; Ikefuji et al. 2014; Semakula et al. 2017). Some also include climate change-induced dengue (Zhao et al. 2020; Pottier et al. 2021; Chen et al. 2023; Liu et al. 2024).
Climate-exacerbated air pollution	Deterioration of air quality caused or intensified by climate (mainly temperature) factors.	Increase in fine particles (PM2.5) and ozone (O3) due to temperature increase or changing weather (Knowlton et al. 2008; Reilly et al. 2013; Geels et al. 2015; Hendriks et al. 2016; Saari et al. 2019; Shen et al. 2022)[a].
Other extreme weather conditions	Hazardous meteorological events outside the thermal category.	Floods (Oda et al. 2023; Tierolf et al. 2023; Liu et al. 2024), droughts (Ibarrarán et al. 2010; Liu et al. 2024), heatwaves and cyclones (Malik et al. 2022), snow disasters and freezing (Liu et al. 2024), heavy precipitation, humidity, solar radiation, wind or air pressure (Andersson et al. 2015; Kirchner et al. 2015; Kaspersen and Halsnæs 2017). Some extreme events are modelled using direct drivers (e.g., Oda et al. (2023) uses projected annual maximum inundation extent) or indirect ones such as average temperature change (Liu et al. 2024).

[a]As mentioned in Table 1, climate-exacerbated air pollution is only included when explicitly related to climate change, representing the phenomena such as the known as 'climate penalty effect' (Yin et al. 2023).

how climate change impacts are represented. Figure 4 illustrates this mapping, with the frequency of each methodological approach across dimensions. Hazards (i) and impacts (iii) mark the start and end of the bottom-up chains analysed, making their representation central to understanding the different modelling approaches. We examined whether hazards arise from scenarios (exogenous) or climate modelling (endogenous), as this reveals the level of integration, feedback accounting, and transparency. The way impacts are expressed also shapes the conceptualization and interpretation of results later used in policy making (see Discussion for more details). Finally, we assessed the integration level (ii) to distinguish fully linked IAMs from softer connections within integrated modelling frameworks, allowing us to map prevailing approaches.

Table 3 Impact categories, definitions, and modelling examples

Impact	Definition	Representation in the studies
Mortality	Climate-related increase in the frequency or likelihood of death within a population.	Excess of deaths (Sharma et al. 2022), the number of premature deaths (Shen et al. 2022), the mortality rate (Ciscar et al. 2019), daily deaths (Knowlton et al. 2008), the relative risk of mortality (Hendriks et al. 2016) or the disability-adjusted life years (DALYs) (Martens 1995).
Morbidity	Adverse health conditions or diseases linked to climate drivers.	DALYs (Martens 1995; Ikefuji et al. 2014; Oda et al. 2023; Liu et al. 2024), hospital admissions and the number of cases of nonfatal acute myocardial infarction and respiratory symptoms (Saari et al. 2019).
Migrations	Permanent or temporary displacement of people triggered or intensified by climate-related factors.	Migration flows, either international flows (Benveniste et al. 2020, 2022) or national flows (Barbieri et al. 2010; Tierolf et al. 2023). Population density is also used as a proxy of migration (Cruz and Rossi-Hansberg 2024).
Cultural Assets and Services	Loss or alteration of material, symbolic, or experiential values associated with cultural heritage and natural environments.	Historical and cultural assets (Kaspersen and Halsnæs 2017), proxies of cultural services such as a recreational fishing satisfaction index (Pouso et al. 2019), a recreational forest service index (Andersson et al. 2015) and the Shannon Diversity Index (an indicator for measuring landscape aesthetic) (Kirchner et al. 2015).
Diet Quality	Changes in the nutritional adequacy, diversity, and safety of available food affecting human health.	Macronutrients and micronutrient losses, energy intake losses and monetary consumption losses (Malik et al. 2022). Production of dietary nutrients, particularly vitamin A, expressed in consumer units that can be fed given the production level (Kozicka et al. 2020). Nutritional Index as a proxy of the protein consumption per capita (Ibarrarán et al. 2010).
Occupational Health	Impacts on the ability to perform work safely and effectively under climate-related conditions.	(Matsumoto et al. 2021; Chen et al. 2023; Oda et al. 2023), labour force levels losses (Ikefuji et al. 2014; Takakura et al. 2018), and their associated economic losses. Also work loss days and minor restricted-activity days (Saari et al. 2019).
Life Quality	Broader dimensions of human well-being, including aspects related to Health and Place not covered in the other sub-groups.	Climate impacts on fertility rate and life expectancy (Ibarrarán et al. 2010), damages on natality rates (Cruz and Rossi-Hansberg 2024). representing damages on natality rates.

Regarding how climate change hazards are represented, we identify two main strategies: using specific and exogenous hazard scenarios and using climate models (which endogenously compute the hazards). The first strategy is followed by 16% of the studies and is computationally simpler. One example is Malik et al. (2022) using eight climate change scenarios differing in crop and food production losses due to different assumptions on climate change, adaptation, and extreme weather events impact. Similarly, Kozicka et al. (2020) introduce climate change through exogenous scenarios of climate variables affecting biophysical variables. As examples of the second strategy, we find modelling frameworks including a climate module. Here, we find two different sub-strategies: using simple climate models (38% of occurrence) (e.g., Bressler (2021) or using complex climate models (46%) such as Global Circulation Models (GCMs) or Earth System Models (ESMs) (e.g., Shen et al. (2022). Integrated models using climate models use greenhouse gas (GHG) emission projections to feed climate variables. While some of them use Intergovernmental Panel on Climate Change (IPCC) standard emissions scenarios (Andersson et al. 2015; Pottier et al. 2021), others (17%) endogenously compute the emissions (Saari et al. 2019; Shen et al. 2022), therefore better capturing hazard-impact feedbacks.

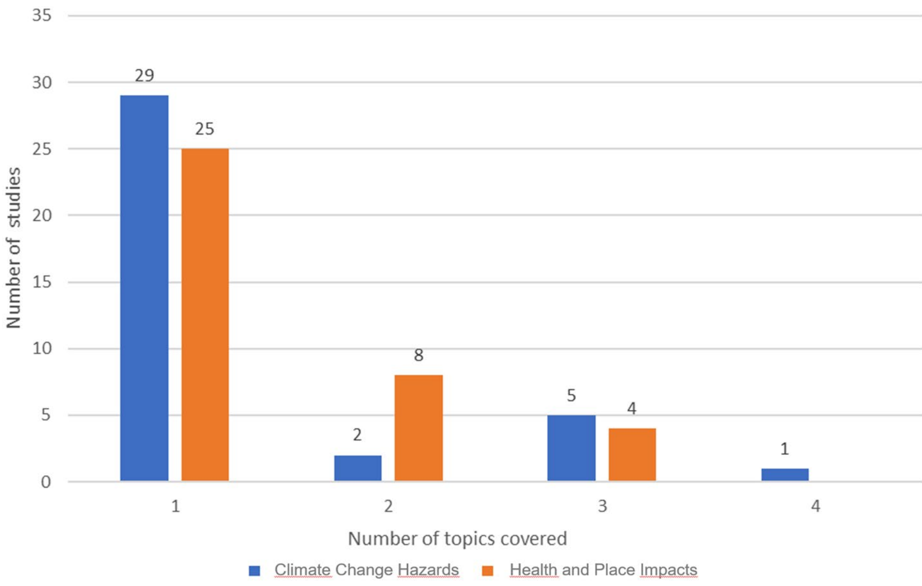

Fig. 3 Number of studies by number of hazards and impacts covered

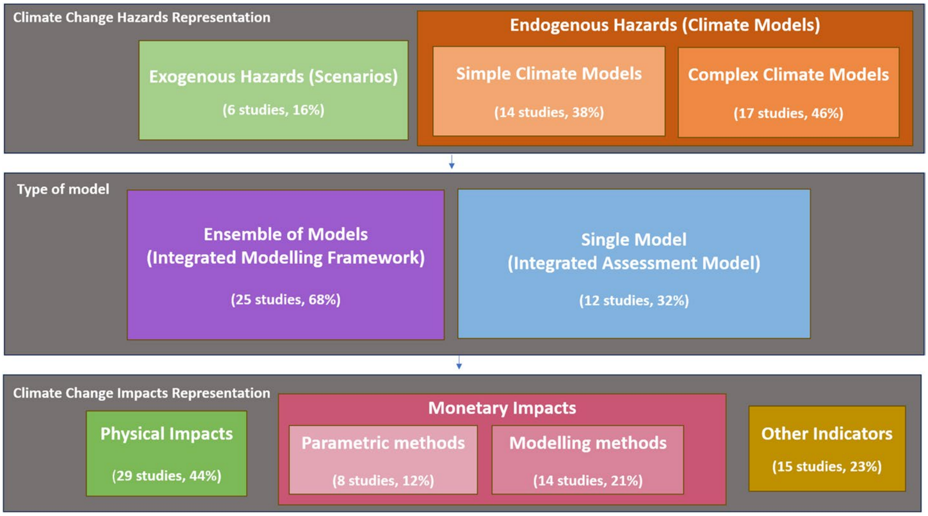

Fig. 4 Mapping of the methods used by the different studies

By analyzing the type of modelling study and the level of integration, we identify two major approaches: (1) modelling frameworks composed of different models linked between them (68%), and (2) single models composed of different modules fully integrated (32%). Within each major category, we find various methodological approaches. Examples of modelling ensembles are the Danish Integrated Assessment System (DIAS) (Kaspersen and Halsnæs 2017), which includes climate data processing (downscaling and extreme value analysis), hydrological and agricultural impact models, and economic valuation. Another example is Kirchner et al. (2015), which links climate, forest, crop, land use and input-output models into a common framework. In the single model category, we also find diverse strategies ranging from system dynamic models (Bertone et al. 2019) to agent-based models (Tierolf et al. 2023), input-output models (Malik et al. 2022), cost-benefit analysis (CBA) (Bressler 2021) and fuzzy-logic models (Lüdeke et al. 1999), among others. We also find well-known IAMs used by governmental institutions or the IPCC to make political recommendations. Some examples include applications of DICE (Lupi and Marsiglio 2021; Sharma et al. 2022), FUND (Tol 2008; Zhao et al. 2020), IMAGE (Martens 1995), MESSAGE-GLOBIOM (Shen et al. 2022) and AIM/CGE (Oda et al. 2023).

Regarding the climate change impacts, we observe three general approaches for their calculation: physical impacts, monetary impacts and other indicators. The physical impacts approach is the most common (44% of occurrence), with examples such as deaths (Pottier et al. 2021) or dietary nutrients (Kozicka et al. 2020). Climate change impacts analysed here are frequently represented in monetary terms (33%), especially in studies calculating the monetary costs of mortality (Zhao et al. 2020; Bressler 2021) but not exclusively. Monetization of damage is also done for morbidity impacts and or occupational health losses (Ciscar et al. 2019; Matsumoto et al. 2021). We also find differences regarding the methods used for monetization: parametric methods (12%), such as the Value of Statistical Life (VSL), directly multiply physical losses by a monetary cost (Zhao et al. 2020), while modelling methods (21%), like the use of Computable General Equilibrium (CGE) or Input-Output models include more complex dynamics (Reilly et al. 2013). The calculation of an endogenous VSL is also found in one study (Benveniste et al. 2020, 2022). Concerning the calculation of other indicators (23%), we find a high heterogeneity. Examples are the DALYs, the fertility rate or the cultural indicators mentioned above (Ibarrarán et al. 2010; Ikefuji et al. 2014; Andersson et al. 2015; Kirchner et al. 2015).

3.3 Geographical scale and coverage

We analyze both their geographical scale (global, regional -defined as a group of countries-, national or subnational level) and geographical coverage (areas included). Many studies extend across the entire world but provide disaggregated information at lower levels. If a study provides only one value for the entire world, it is considered global. However, if it provides disaggregated data for all world countries, it is categorized as global, regional, and national. If a study uses Geographical Information Systems (GIS) to present global data at subnational levels, it is categorized as global, regional, national, and subnational. Analysis of the geographical scales in the database (Fig. 5) shows that the subnational level is most common (29% of occurrences), followed by national (26%), regional or multi-country (25%), and global (21%).

Concerning the geographical coverage, we find that, from the 16 studies covering the whole world, 14 studies provide spatially disaggregated information at sub-global level, varying on the level of disaggregation. Figure 6 shows the distribution of the studies among geographical areas. This shows that northern and developed regions receive more attention in research compared to southern regions. Europe stands out as the continent with the highest number of modelling exercises, with specific studies focusing on certain European

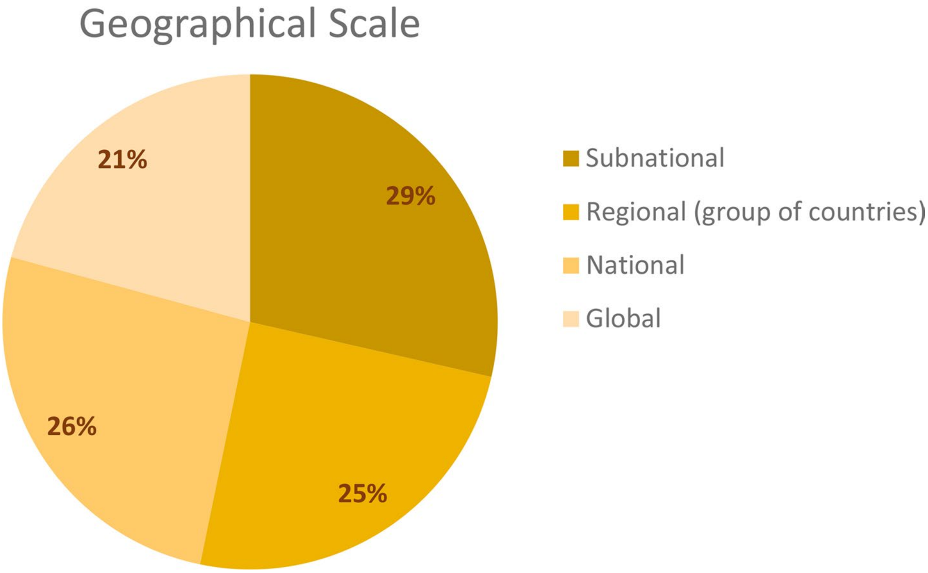

Fig. 5 Distribution of geographical scales, expressed as a percentage of the total times each scale appears

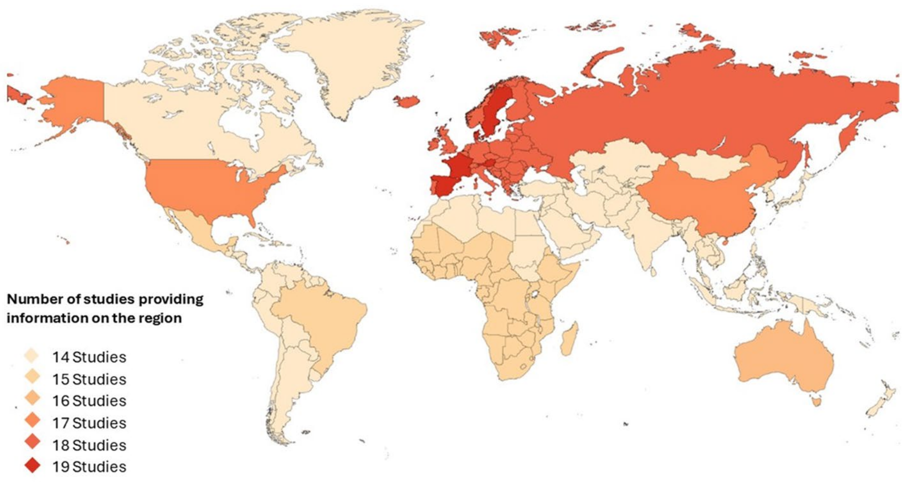

Fig. 6 Number of studies by geographical coverage. Subnational studies are coloured at national level

countries. The United States and China also have dedicated modelling studies. Conversely, South America, Asia, and South Africa are significantly less studied in comparison.

By crossing information on hazards and impacts and geographical coverage we find that all the climate change hazards are covered by studies at global level. In terms of the impact areas affected, we find that Diet Quality and Cultural Assets and Services are only addressed by certain national and subnational studies.

3.4 Heterogeneity and inequality

We analysed how the studies account for heterogeneity and inequality in assessing the varying impacts of climate change. From our sample, we observe that most of them represent heterogeneity or inequality somehow (73%). However, most of the studies represent this by simply disaggregating in geographical terms (26 studies, 70%). There are certainly numerous differences among the studies which represent geographical heterogeneity, varying in the level of detail, as explained in the previous section. The second most common type of heterogeneity representation is age heterogeneity, available in four studies (11%). The level of detail and the construction of the different age groups also vary. For instance, Pottier et al. (2021) provide impacts for five age cohorts whereas Geels et al. (2015) only differentiate between two groups: children and adults.

Social class inequalities are also available, represented by five studies that use different ways for representing them. We find studies measuring income differences (Benveniste et al. 2020, 2022; Tierolf et al. 2023) and economic sectors differences (manifesting different levels of occupational health damages depending on industry-based differences in the job exposure to heat stress) (Takakura et al. 2018; Matsumoto et al. 2021). Malik et al. (2022) consider many inequality dimensions related to social class and racial elements. For instance, since they differentiate across vulnerable communities considering elements like living on rural or urban areas, being indigenous, the education level, and the attainment and tenure. The study of Tierolf et al. (2023) also creates different household classifications and uses elements such as place attachment, income and even risk perception to differentiate them and thus to analyze the implications of these elements in the coastal migration decisions. The representation of sex inequality is present in one study (Pottier et al. 2021).

3.5 Findings

Scoping reviews typically do not compare or synthesize findings like meta-analyses or full systematic reviews. This study focuses on exploring the diversity of representations rather than comparing results, given the varied geography, scenarios, methods, time frames, and impact channels of the studies analysed. Here, we present a qualitative appraisal of key findings (see Supplementary Data for details on each study).

Studies consistently support some well-known patterns: a strong positive link between emissions and impacts, the crucial yet limited role of mitigation and adaptation (which are important for reducing damages but unable to eliminate them entirely), and disproportionate harm to poorer and southern populations. However, there is no strong consistency in identifying the most severe damages or their extent.

For Health, a study in China assessing various hazards ranks extreme weather conditions on mortality among the most significant (Liu et al. 2024), while another, also considering these effects, finds occupational health most harmful in monetary terms (Oda et al. 2023). Also, while most studies agree that climate change will have severe and worsening impacts on health, some project modest effects (Pottier et al. 2021) and even positive effects in certain regions (Reilly et al. 2013; Matsumoto et al. 2021). Consistent findings include pronounced occupational health impacts in outdoor sectors like agriculture (Matsumoto et al. 2021; Chen et al. 2023). Two global studies also identify China and India as thermal stress hotspots (Ikefuji et al. 2014; Nakajima et al. 2020) and Sub-Saharan Africa for malaria

(Martens 1995; Tol 2008). Also, studies assessing Health alongside other impacts not covered in this review (e.g., agriculture, coastal, energy) consistently rank health impacts (particularly mortality) among the most severe (Ciscar et al. 2019; Zhao et al. 2020; Liu et al. 2024).

For Place, findings are very varied. We identified a study that found damages to cultural assets in Austria to be minimal (Kirchner et al. 2015) and some counterintuitive results and mixed findings among migration studies. For instance, Cruz and Rossi-Hansberg (2024) project increased migration from the Global South to the North, while Benveniste et al. (2020, 2022) suggest the opposite: South-to-North migration (conceived as an adaptation strategy in this study) decline, particularly among low-income households, due to climate-driven resource immobility.

4 Discussion

4.1 Discussion on the results and gaps identification

Our exploratory scoping review reveals a broad spectrum of hazards and impacts, methods, geographies, representations of heterogeneities and inequalities, and findings in the representation of climate impacts on Health and Place in IAMs; however, many gaps remain.

While studies cover many hazards and impacts, most focus on just one or two (Fig. 3). Some exceptions cover multi-hazard and multi-impact modelling exercises (Ikefuji et al. 2014; Oda et al. 2023; Liu et al. 2024). However, no studies cover all the hazard and impact categories, and only two studies address impacts in both the Health and Place categories (Benveniste et al. 2020, 2022; Cruz and Rossi-Hansberg 2024). A systemic approach that integrates multiple impact channels within a single modelling framework—enabling a holistic understanding of climate change impacts on Health and Place, including interrelationships and trade-offs—remains largely absent.

According to the IPCC (2022, pp. 1127–1128), key climate-sensitive outcomes related to Health and Place are vector-borne diseases, water-borne diseases, infectious diseases, heat-related diseases, mental health, undernutrition, and migration and displacement due to acute events (e.g. extreme events) or chronic changes (e.g., changing climate conditions). While certain studies cover some of these impacts, some areas remain unexplored. Mortality due to acute climate events is covered by only one recent study (Liu et al. 2024), and mental health effects are not covered at all. Impacts on healthcare systems are completely absent as well. Key phenomena like involuntary migrations and displacement due to extreme weather in the world's southern regions (IPCC 2022, p. 52) are absent in our review. We found one study covering this for France, whose methodological approach could be used for upscaling SLR-induced migration at global scale (Tierolf et al. 2023). The nexus between climate change, migration, and health (Issa et al. 2023) is largely unexplored, with only two studies examining it (Benveniste et al. 2020, 2022; Cruz and Rossi-Hansberg 2024).

Regarding methods, we find a wide diversity of approaches in the database. Models can use exogenous hazard scenarios or generate them endogenously within their climate modules. Exogenous approaches are simpler and more flexible but reduce coherence between hazards-impacts relationship and subsequent socioeconomic pathways. Endogenous generation captures feedbacks and improves scenario consistency yet increases complexity.

The choice between using a single model or an ensemble of models also shapes results: single models can represent feedback loops in greater detail but face computational and data-linking challenges, whereas model ensembles facilitate cross-sector analysis but rely more heavily on exogenous data and are limited in capturing real-time inter-module connections. Also, various metrics and indicators are used to quantify impacts, with monetization of climate change impacts still common, though less prevalent than deriving physical impacts. The debate on monetization limits is ongoing and present in our sample of studies, with critiques regarding ethical implications, uncertainty, and ineffectiveness (Purushothaman et al. 2013). Pottier et al. (2021) explicitly reject monetizing mortality impacts due to concerns about arbitrariness and ethical decisions inherent in assigning a monetary value to life. Another study advocates for presenting *'non-market effects in original units without monetization'* in addition to monetary impacts, aiming to enhance transparency and enable users to form their own assessments of the value of climate change impacts (Bressler 2021, p. 6). All these design decisions affect both the robustness and policy relevance of impact assessments. While our review cannot determine how much differences in impact magnitudes stem from valuation methods, model structures, assumptions, scenarios, or other factors, it is important to openly recognize that choices can shape the perceived importance of sectors in policy debates. For instance, using both physical and monetary indicators helps capture the full range of societal impacts and supports a more balanced discussion of adaptation priorities (Nyborg 2000). The variety of methodologies offers valuable perspectives but also reveals fragmentation and a lack of harmonization, which complicates intercomparison (Robertson 2021).

In relation to this, the analysed studies also demonstrate a poor representation of uncertainty, often limited to different emissions or climate scenarios and lacking in other types of uncertainties, such as those related to the data used for the impact calibration or the structural model limitations (Pastor et al. 2020; Rising et al. 2022a). One study (Saari et al. 2019) acknowledges the importance of evaluating uncertainty in the data used to calibrate impact functions, while another tests different monetary valuation methods (Ciscar et al. 2019). Also Geels et al. (2015) test implications of using different models within the ensemble of models. However, most fail to transparently discuss assumptions and data, despite uncertainties in climate change socioeconomic impacts are well-known (Keen 2021).

Additionally, the representation of causal chains triggered by direct impacts (often referred to as indirect impacts or cascading climate impacts) is also very poorly represented in the database (Botzen et al. 2019). The modelling of feedback loops between temperature and impacts is crucial (Matsumoto et al. 2021) but deficient (only 24% compute emissions after damages). This underscores the need for a broader definition of IAMs to capture bottom-up damage assessments and highlights that traditional, fully linked IAMs, which model endogenous emissions, still fail to incorporate impact channels by fully representing the impact-emissions loop.

The geographic analysis indicates an overrepresentation of northern areas (especially Europe) compared to other regions, despite the consensus that the southern regions will be more affected by climate change (IPCC 2022, p. 9). This relates to the distribution of funding and public support, which typically favors overrepresented regions. Our database shows that funding influences study focus, with collected funding information compared to the region under study. In addressing heterogeneity and inequality, the predominant approach is regional disaggregation, as suggested in literature (Emmerling and Tavoni 2021), while effects on income inequality is lacking in most of the analyses (only shown in three studies). However, we found minority but interesting modelling exercises representing inequality in a multidimensional way, such as Malik et al. (2022), aligning with concepts like vulnerability and intersectionality.

4.2 A roadmap for the IAM community

Our review confirms a wide diversity of integrated assessment modelling exercises beyond the traditional top-down approach based on aggregated damage functions (Scovronick et al. 2019), moving closer to bottom-up modelling of impact channels. This strategy offers higher transparency and process detail in representing climate damages (Piontek et al. 2021). Nevertheless, as outlined in Sect. 4.1, important gaps remain (i.e., lack of multi-channel approaches, uneven geographic coverage, and representation of inequalities). Additionally, fragmented methodologies, scarce globally accessible health and socio-economic datasets, and limited integration of feedback and cascading effects still prevent a complete representation of climate change impacts on Health and Place in IAMs, potentially leading to underestimation of damages.

Improving how IAMs represent Health and Place impacts is key for generating results that inform policy design. A sound treatment of these impacts can guide adaptation planning by identifying where the largest losses occur, locating vulnerability hotspots, supporting mitigation strategies, ensuring policy priorities reflect the real scale of damages beyond GDP, and providing stronger evidence for climate negotiations.

Here, we outline priority actions for future work in improving climate change bottom-up impact representation on Health and Place:

First, better data on impacts is needed. Databases like ISIMIP compile multiple estimates of biophysical impacts and some socioeconomic impacts for potential integration into IAMs[4]. More multi-sectoral and multi-regional assessments, such as those in earlier biophysical impact intercomparison studies (Warszawski et al. 2014; Arnell et al. 2016), are needed for Health and Place. Some studies in our database already provide harmonized information useful for IAMs, such as Bressler et al. (2021) on mortality damage functions, while others may require deeper methodological review to enable extrapolation. Insights from specific sectoral studies like climate migration-focused studies (Adams and Kay 2019) and up-to-date epidemiological studies (Scovronick et al. 2019) can also be integrated. To address data fragmentation, enhancing data sharing, documentation, and transparent communication of assumptions should be a priority (Skea et al. 2021).

Second, advancing toward comprehensive large-scale IAMs that integrate multiple bottom-up direct and indirect impacts, while retaining heterogeneity to reflect inequality and geographical diversity, is the best approach to improve socioeconomic pathways accuracy (Rosen and Guenther 2015). Process-based IAMs reported by the IPCC are suited to this, though they often exclude climate damages due to complexity and mitigation focus (Nikas et al. 2019). Their emphasis on physical rather than purely monetary variables also enable broader well-being assessments. Likewise, agent-based IAMs (e.g., Lamperti et al. (2018) excel at capturing distributional impacts but could also integrate more channels on Health and Place to better assess total effects on vulnerable communities (Dennig et al. 2015).

[4] The NEVERMORE Project (https://www.nevermore-horizon.eu/), which supported this work, aims, among other objectives, to integrate ISIMIP data into the WILIAM IAM.

Even though achieving full damage quantification, as top-down methods aim for, may be technically challenging through a bottom-up approach, integrating impact channels into hard-linked IAMs can still provide a comprehensive assessment of damages by capturing interdependencies and feedback loops (van Vuuren et al. 2012). Despite existing challenges, the ultimate goal for IAMs should be to integrate as many impact channels as possible to align with concepts like Dangerous Climate Change (Dietz et al. 2007) and minimize claims that damages are low (e.g., Pottier et al. 2021) due to the inclusion of only a limited number of impacts. In any case, a transparent discussion of results and explicit recognition of model limitations (including a critical self-assessment and explanation of potential underestimations) remain essential, especially for deep uncertainties, tipping points, and non-linear climate transitions (Weitzman 2012; Rising et al. 2022a).

Third, it is key to co-design impact modelling with other disciplines and policy actors. This ensures robust impact conceptualization and more relevant indicators for decision-making. Quantitative modelling may not always be the best approach to assess certain damage channels, so integrating qualitative tools, such as conceptual frameworks and climate impact storylines (Carter et al. 2021; van den Hurk et al. 2023), can add context. Social sciences can also help operationalize inequality-related frameworks for mitigation and adaptation policy planning (Thomas et al. 2019; Kehler and Birchall 2021).

This paper supports these priority areas by providing a database (Supplementary Data) that maps specific modelling examples to impact channels, covering both well-known IAMs (e.g., FUND, IMAGE) and targeted studies. All share methodological foundations (mathematical language, scenario projections, nature–human integration), facilitating information exchange and enabling progress on these priorities. This paper could contribute to enhancing large-scale IAMs' capacity to represent bottom-up multi-impact channels, as we identify channels through which climate change affects Health and Place, and map specific modelling examples to them. Our database (Supplementary Data) includes well-known IAMs (e.g., FUND, IMAGE) and more focused assessment exercises, all of which share methodological foundations that facilitate information exchanges, supporting the integration of the outlined methodologies into further model developments.

4.3 Limitations of the review and further work

While this work provides valuable insights on the representation of climate change impacts on Health and Place in IAMs, it is also crucial to acknowledge its limitations. As with any review, our dataset of studies is conditioned by the keywords and criteria (Table 1) used, so there can be IAMs including these impacts that are not present in our dataset. Also, we did not conduct a quantitative comparison of findings, such as a meta-analysis of the outputs, due to the high diversity of models and scenarios and the scoping nature of our review. IAM community is very extensive, and while this scoping review aimed to shed light on modelling studies that might be overlooked in non-systematic reviews and mainstream IAM networks, the design of the study is exploratory and aims at a preliminary assessment of the field, but more systematic reviews could be conducted, for instance incorporating more literature (e.g., grey literature, additional databases) as well as more well-being impact areas.

In our database (Supplementary Data), we also assessed whether the studies model adaptation or not, finding that 41% do so in some capacity. Further work could explore in depth how models approach adaptation.

5 Conclusions

The need for improvement in the representation of the wellbeing-related impacts of climate change in Integrated Assessment Models (IAMs) is acknowledged in the literature (Diaz and Moore 2017; Dellink et al. 2019). In this study, we conducted a scoping review to explore the strategies employed by the IAM community for representing well-being-related impacts of climate change, with a specific focus on the areas of Health and Place (Adger et al. 2022). Our aim was to identify IAMs including bottom-up impact channels that map hazards and impacts. This strategy offers high transparency and process detail in representing climate damages, as opposed to top-down methodologies that typically establish a general relationship between well-being (often measured by GDP) and temperature (Piontek et al. 2021; Keen 2021). To do this, we embraced an expanded definition of IAM following literature defending a closer relationship of the IAM community to the Impact, Adaptation, and Vulnerability (IAV) community (Fisher-Vanden and Weyant 2020), which helps widening the IAM dimension according to our aim. Our review results in a database of very diverse 37 integrated modelling studies that can be consulted in the Supplementary Data.

We analysed the studies in terms of hazards and impacts, methods, geographical level, inequalities represented, and findings to provide a mapping of the available evidence. We observe a broad diversity of approaches and impact channels, with considerable variation in hazards, impacts, and modelling strategies. However, this diversity also reflects a high fragmentation of approaches, which contributes to considerable uncertainty in the results. Some hazards and impacts are represented more prominently than others, while notable gaps remain, such as the absence of multi-channel impact assessments, limited treatment of inequality, and an overrepresentation of northern regions like Europe.

We identify priority actions for improving the representation of Health and Place in IAMs: enhancing impact data, advancing towards large-scale IAMs, and strengthening connections with other disciplines and policymaking. In our view, developing hard-linked global and multiregional IAMs that cover multiple impact channels offers the most effective way to capture interdependences within a consistent framework. This study provides a basis for that effort by mapping impact channels and modeling studies, enabling better model intercomparison and a more robust representation of these climate change impacts.

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Data availability The dataset generated during the current study is available in the Supplementary Data.

Declarations

Ethics approval and consent to participate Not applicable. This study did not involve human participants or animals; hence no ethics committee approval or participant consent was required.

Consent for publication Not applicable. No individual person's data in any form are included in this manuscript.

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References

Adams H, Kay S (2019) Migration as a human affair: integrating individual stress thresholds into quantitative models of climate migration. Environ Sci Policy 93:129–138. https://doi.org/10.1016/j.envsci.2018.10.015

Adger WN, Barnett J, Chapin FS III, Ellemor H (2011) This must be the place: underrepresentation of identity and meaning in climate change decision-making. Glob Environ Politics 11:1–25. https://doi.org/10.1162/GLEP_a_00051

Adger WN, Barnett J, Heath S, Jarillo S (2022) Climate change affects multiple dimensions of well-being through impacts, information and policy responses. Nat Hum Behav 6:1465–1473. https://doi.org/10.1038/s41562-022-01467-8

Andersson M, Kellomäki S, Gardiner B, Blennow K (2015) Life-style services and yield from south-Swedish forests adaptively managed against the risk of wind damage: a simulation study. Reg Environ Change 15:1489–1500. https://doi.org/10.1007/s10113-014-0687-8

Arksey H, O'Malley L (2005) Scoping studies: towards a methodological framework. Int J Soc Res Methodol 8:19–32. https://doi.org/10.1080/1364557032000119616

Arnell NW, Brown S, Gosling SN et al (2016) The impacts of climate change across the globe: A multi-sectoral assessment. Clim Change 134:457–474. https://doi.org/10.1007/s10584-014-1281-2

Asefi-Najafabady S, Villegas-Ortiz L, Morgan J (2021) The failure of integrated assessment models as a response to 'climate emergency' and ecological breakdown: the emperor has no clothes. Globalizations 18:1178–1188. https://doi.org/10.1080/14747731.2020.1853958

Barbieri AF, Domingues E, Queiroz BL et al (2010) Climate change and population migration in brazil's northeast: scenarios for 2025–2050. Popul Environ 31:344–370. https://doi.org/10.1007/s11111-010-0105-1

Benveniste H, Oppenheimer M, Fleurbaey M (2020) Effect of border policy on exposure and vulnerability to climate change. Proc Natl Acad Sci U S A 117:26692–26702. https://doi.org/10.1073/pnas.2007597117

Benveniste H, Oppenheimer M, Fleurbaey M (2022) Climate change increases resource-constrained international immobility. Nat Clim Change 12:634–641. https://doi.org/10.1038/s41558-022-01401-w

Bertone E, Sahin O, Richards R, Roiko A (2019) Assessing the impacts of extreme weather events on potable water quality: the value to managers of a highly participatory, integrated modelling approach. H2Open J 2:9–24. https://doi.org/10.2166/H2OJ.2019.024

Bosello F, Eboli F, Pierfederici R (2012) Assessing the economic impacts of climate change - an updated. CGE Point of View

Botzen WJW, Deschenes O, Sanders M (2019) The economic impacts of natural disasters: A review of models and empirical studies. Rev Environ Econ Policy 13:167–188. https://doi.org/10.1093/reep/rez004

Bressler RD (2021) The mortality cost of carbon. Nat Commun 12. https://doi.org/10.1038/s41467-021-24487-w

Bressler RD, Moore FC, Rennert K, Anthoff D (2021) Estimates of country level temperature-related mortality damage functions. Sci Rep 11. https://doi.org/10.1038/s41598-021-99156-5

Capellán-Pérez I, de Blas I, Nieto J et al (2020) MEDEAS: a new modeling framework integrating global biophysical and socioeconomic constraints. Energy Environ Sci 13:986–1017. https://doi.org/10.1039/C9EE02627D

Carter T, Benzie M, Campiglio E et al (2021) A conceptual framework for cross-border impacts of climate change. Glob Environ Change. https://doi.org/10.1016/j.gloenvcha.2021.102307. 69:

Cattaneo C, Massetti E, Farinosi F, Dasgupta S (2024) Climate variability and worldwide migration: current evidence and future projections. Environ Res Lett 19:124083. https://doi.org/10.1088/1748-9326/ad91cb
Chen S, Li M, Wang C (2023) The primary benefits of the nationwide emission trading scheme in China. Mitig Adapt Strateg Glob Change 28:46. https://doi.org/10.1007/s11027-023-10084-3
Ciscar J-C, Rising J, Kopp RE, Feyen L (2019) Assessing future climate change impacts in the EU and the USA: insights and lessons from two continental-scale projects. https://doi.org/10.1088/1748-9326/ab281e. EnvironResLett 14:
Cruz J-L, Rossi-Hansberg E (2024) The economic geography of global warming. Rev Econ Stud 91:899–939. https://doi.org/10.1093/restud/rdad042
Dellink R, Lanzi E, Chateau J (2019) The sectoral and regional economic consequences of climate change to 2060. Environ Resource Econ 72:309–363. https://doi.org/10.1007/s10640-017-0197-5
Dennig F, Budolfson MB, Fleurbaey M et al (2015) Inequality, climate impacts on the future poor, and carbon prices. Proc Natl Acad Sci U S A 112:15827–15832. https://doi.org/10.1073/pnas.1513967112
di Santo N, Giudice TD, Sisto R (2024) Policy mixes in rural areas: a scoping literature review. Italian Rev Agricultural Econ (REA) 79:83–99. https://doi.org/10.36253/rea-15149
Diaz D, Moore F (2017) Quantifying the economic risks of climate change. Nat Clim Change 7:774–782. https://doi.org/10.1038/nclimate3411
Dietz S, Hope C, Patmore N (2007) Some economics of dangerous climate change: reflections on the stern review. Global Environ Change 17:311–325. https://doi.org/10.1016/j.gloenvcha.2007.05.008
Emmerling J, Tavoni M (2021) Representing inequalities in integrated assessment modeling of climate change. One Earth 4:177–180. https://doi.org/10.1016/j.oneear.2021.01.013
Fisher-Vanden K, Weyant J (2020) The evolution of integrated assessment: developing the next generation of Use-Inspired integrated assessment tools. Annual Rev Resource Econ 12:471–487. https://doi.org/10.1146/annurev-resource-110119-030314
Geels C, Andersson C, Hänninen O et al (2015) Future premature mortality due to O3, secondary inorganic aerosols and primary PM in Europe — Sensitivity to changes in climate, anthropogenic emissions, population and Building stock. Int J Environ Res Public Health 12:2837–2869. https://doi.org/10.3390/ijerph120302837
Grant MJ, Booth A (2009) A typology of reviews: an analysis of 14 review types and associated methodologies. Health Inform Libr J 26:91–108. https://doi.org/10.1111/j.1471-1842.2009.00848.x
Hendriks C, Forsell N, Kiesewetter G et al (2016) Ozone concentrations and damage for realistic future European climate and air quality scenarios. Atmos Environ 144:208–219. https://doi.org/10.1016/j.atmosenv.2016.08.026
Ibarrarán ME, Malone EL, Brenkert AL (2010) Climate change vulnerability and resilience: current status and trends for Mexico. Environ Dev Sustain 12:365–388. https://doi.org/10.1007/s10668-009-9201-8
Ikefuji M, Magnus JR, Sakamoto H (2014) The effect of health benefits on climate change mitigation policies. Clim Change 126:229–243. https://doi.org/10.1007/s10584-014-1204-2
IPCC (2022) Climate change 2022: impacts, adaptation, and vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [. IPCC
Issa R, Sarsour A, Cullip T et al (2023) Gaps and opportunities in the climate change, migration and health nexus: insights from a questionnaire based study of practitioners and researchers. J Migration Health 7:100171. https://doi.org/10.1016/j.jmh.2023.100171
Jungell-Michelsson J, Heikkurinen P (2022) Sufficiency: A systematic literature review. Ecol Econ 195:107380. https://doi.org/10.1016/j.ecolecon.2022.107380
Kaspersen PS, Halsnæs K (2017) Integrated climate change risk assessment: A practical application for urban flooding during extreme precipitation. Clim Serv 6:55–64. https://doi.org/10.1016/j.cliser.2017.06.012
Keen S (2021) The appallingly bad neoclassical economics of climate change. Globalizations 18:1149–1177. https://doi.org/10.1080/14747731.2020.1807856
Kehler S, Birchall SJ (2021) Social vulnerability and climate change adaptation: the critical importance of moving beyond technocratic policy approaches. Environ Sci Policy 124:471–477. https://doi.org/10.1016/j.envsci.2021.07.025
Kirchner M, Schmidt J, Kindermann G et al (2015) Ecosystem services and economic development in Austrian agricultural landscapes - The impact of policy and climate change scenarios on trade-offs and synergies. Ecol Econ 109:161–174. https://doi.org/10.1016/j.ecolecon.2014.11.005
Kling CL, Arritt RW, Calhoun G, Keiser DA (2017) Integrated assessment models of the Food, Energy, and water nexus: A review and an outline of research needs. Annual Rev Resource Econ 9:143–163. https://doi.org/10.1146/annurev-resource-100516-033533
Knowlton K, Hogrefe C, Lynn B et al (2008) Impacts of heat and ozone on mortality risk in the new york city metropolitan region under a changing climate

Kozicka M, Gotor E, Ocimati W et al (2020) Responding to future regime shifts with agrobiodiversity: a multi-level perspective on small-scale farming in Uganda. Agric Syst 183. https://doi.org/10.1016/j.agsy.2020.102864
Lamperti F, Dosi G, Napoletano M et al (2018) Faraway, so close: coupled climate and economic dynamics in an Agent-based integrated assessment model. Ecol Econ 150:315–339. https://doi.org/10.1016/j.ecolecon.2018.03.023
Lenton TM, Xu C, Abrams JF et al (2023) Quantifying the human cost of global warming. Nat Sustain 6:1237–1247. https://doi.org/10.1038/s41893-023-01132-6
Liu J, Shi X-Z, Yang L et al (2024) Assessment of climate damage in China based on integrated assessment framework. Adv Clim Change Res 15:124–133. https://doi.org/10.1016/j.accre.2024.01.012
Lüdeke MKB, Moldenhauer O, Petschel-Held G (1999) Rural poverty driven soil degradation under climate change: the sensitivity of the disposition towards the Sahel syndrome with respect to climate. Environ Model Assess 4:315–326. https://doi.org/10.1023/A:1019032821703
Lupi V, Marsiglio S (2021) Population growth and climate change: a dynamic integrated climate-economy-demography model. Ecol Econ 184: https://doi.org/10.1016/j.ecolecon.2021.107011.
Malik A, Li M, Lenzen M et al (2022) Impacts of climate change and extreme weather on food supply chains cascade across sectors and regions in Australia. Nat Food 3:631–643. https://doi.org/10.1038/s43016-022-00570-3
Martens WJM (1995) Climate change and malaria: exploring the risks. Med War 11:202–213. https://doi.org/10.1080/07488009508409240
Matsumoto K, Tachiiri K, Su X (2021) Heat stress, labor productivity, and economic impacts: analysis of climate change impacts using two-way coupled modeling. Environ Res Commun 3. https://doi.org/10.1088/2515-7620/ac3e14
Mays N, Roberts E, Popay J (2001) Synthesising research evidence. In: Studying the organisation and delivery of health services. Routledge
McMichael AJ, Woodruff RE, Hales S (2006) Climate change and human health: present and future risks. Lancet 367:859–869. https://doi.org/10.1016/S0140-6736(06)68079-3
Moher D, Liberati A, Tetzlaff J, Altman DG (2009) Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. BMJ 339:b2535. https://doi.org/10.1136/bmj.b2535
Moss R, Fisher-Vanden K, Delgado A et al (2016) Understanding dynamics and resilience in complex interdependent systems
Munn Z, Peters MDJ, Stern C et al (2018) Systematic review or scoping review? Guidance for authors when choosing between a systematic or scoping review approach. BMC Med Res Methodol 18:143. https://doi.org/10.1186/s12874-018-0611-x
Nakajima T, Ohara T, Masui T et al (2020) A development of reduction scenarios of the short-lived climate pollutants (SLCPs) for mitigating global warming and environmental problems. Prog Earth Planet Sci 7. https://doi.org/10.1186/s40645-020-00351-1
Nikas A, Doukas H, Papandreou A (2019) A detailed overview and consistent classification of Climate-Economy models. In: Doukas H, Flamos A, Lieu J (eds) Understanding risks and uncertainties in energy and climate policy: multidisciplinary methods and tools for a low carbon society. Springer International Publishing, Cham, pp 1–54
Nyborg K (2000) Project analysis as input to public debate: environmental valuation versus physical unit indicators. Ecol Econ 34:393–408. https://doi.org/10.1016/S0921-8009(00)00180-4
Oda T, Takakura J, Tang L et al (2023) Total economic costs of climate change at different discount rates for market and non-market values. Environ Res Lett 18:084026. https://doi.org/10.1088/1748-9326/accdee
Page MJ, McKenzie JE, Bossuyt PM et al (2021) The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ n71 https://doi.org/10.1136/bmj.n71
Pastor AV, Vieira DCS, Soudijn FH, Edelenbosch OY (2020) How uncertainties are tackled in multi-disciplinary science? A review of integrated assessments under global change. CATENA 186:104305. https://doi.org/10.1016/j.catena.2019.104305
Piontek F, Drouet L, Emmerling J et al (2021) Integrated perspective on translating biophysical to economic impacts of climate change. Nat Clim Chang 11:563–572. https://doi.org/10.1038/s41558-021-01065-y
Pollock D, Peters MDJ, Khalil H et al (2023) Recommendations for the extraction, analysis, and presentation of results in scoping reviews. JBI Evid Synthesis 21:520. https://doi.org/10.11124/JBIES-22-00123
Pottier A, Fleurbaey M, Méjean A, Zuber S (2021) Climate change and population: an assessment of mortality due to health impacts. Ecol Econ 183. https://doi.org/10.1016/j.ecolecon.2021.106967
Pouso S, Borja Á, Martín J, Uyarra MC (2019) The capacity of estuary restoration to enhance ecosystem services: system dynamics modelling to simulate recreational fishing benefits. Estuar Coast Shelf Sci 217:226–236. https://doi.org/10.1016/j.ecss.2018.11.026

Purushothaman S, Thomas BK, Abraham R, Dhar U (2013) Beyond money metrics: alternative approaches to conceptualising and assessing ecosystem services. Conserv Soc 11:321. https://doi.org/10.4103/0972-4923.125739

Reilly J, Paltsev S, Strzepek K et al (2013) Valuing climate impacts in integrated assessment models: the MIT IGSM. Clim Change 117:561–573. https://doi.org/10.1007/s10584-012-0635-x

Rising J, Tedesco M, Piontek F, Stainforth DA (2022a) The missing risks of climate change. Nature 610:643–651. https://doi.org/10.1038/s41586-022-05243-6

Rising JA, Taylor C, Ives MC, Ward RET (2022b) Challenges and innovations in the economic evaluation of the risks of climate change. Ecol Econ 197. https://doi.org/10.1016/j.ecolecon.2022.107437

Robertson S (2021) Transparency, trust, and integrated assessment models: an ethical consideration for the intergovernmental panel on climate change. WIREs Clim Change 12:e679. https://doi.org/10.1002/wcc.679

Rosen RA, Guenther E (2015) The economics of mitigating climate change: what can we know? Technol Forecast Soc Chang 91:93–106. https://doi.org/10.1016/J.TECHFORE.2014.01.013

Rothman DS, Amelung B, Polomé P (2003) Estimating non-market impacts of climate change and climate policy

Saari RK, Mei Y, Monier E, Garcia-Menendez F (2019) Effect of health-Related uncertainty and natural variability on health impacts and cobenefits of climate policy. Environ Sci Technol 53:1098–1108. https://doi.org/10.1021/acs.est.8b05094

Schwarze R, Oberpriller Q, Peter M, Füssler J (2022) Modelling the cost and benefits of adaptation. A targeted review on integrated assessment models with a special focus on adaptation modelling. In: Kondrup C, Mercogliano P, Bosello F et al (eds) Climate adaptation modelling. Springer International Publishing, Cham, pp 5–10

Scovronick N, Vasquez VN, Errickson F et al (2019) Human health and the social cost of carbon: A primer and call to action. Epidemiology 30:642. https://doi.org/10.1097/EDE.0000000000001057

Semakula HM, Song G, Achuu SP et al (2017) Prediction of future malaria hotspots under climate change in sub-Saharan Africa. Clim Change 143:415–428. https://doi.org/10.1007/s10584-017-1996-y

Sharma S, Bressler RD, Bhopal A, Norheim OF (2022) The global temperature-related mortality impact of earlier decarbonization for the Australian health sector and economy: a modelling study. PLoS ONE 17. https://doi.org/10.1371/journal.pone.0271550

Shen J, Cai W, Chen X et al (2022) Synergies of carbon neutrality, air pollution control, and health improvement — a case study of China energy interconnection scenario. Glob Energy Interconnect 5:531–542. https://doi.org/10.1016/j.gloei.2022.10.007

Skea J, Shukla P, Al Khourdajie A, McCollum D (2021) Intergovernmental panel on climate change: transparency and integrated assessment modeling. Wiley Interdiscip Rev Clim Change 12. https://doi.org/10.1002/wcc.727

Takakura J, Fujimori S, Takahashi K et al (2018) Limited role of working time shift in offsetting the increasing Occupational-Health cost of heat exposure. Earth's Futur 6:1588–1602. https://doi.org/10.1029/2018EF000883

Thomas K, Hardy RD, Lazrus H et al (2019) Explaining differential vulnerability to climate change: a social science review. Wiley Interdisciplinary Reviews: Clim Change 10. https://doi.org/10.1002/wcc.565

Tierolf L, Haer T, Botzen WJW et al (2023) A coupled agent-based model for France for simulating adaptation and migration decisions under future coastal flood risk. Sci Rep 13. https://doi.org/10.1038/s41598-023-31351-y

Tol RSJ (2008) Climate, development and malaria: an application of FUND. Clim Change 88:21–34. https://doi.org/10.1007/s10584-007-9253-4

Tranfield D, Denyer D, Smart P (2003) Towards a methodology for developing Evidence-Informed management knowledge by means of systematic review. Br J Manag 14:207–222. https://doi.org/10.1111/1467-8551.00375

van den Hurk BJJM, Baldissera Pacchetti M, Boere E et al (2023) Climate impact storylines for assessing socio-economic responses to remote events. Clim Risk Manage 40:100500. https://doi.org/10.1016/j.crm.2023.100500

van Vuuren DP, Kok MTJ, Girod B et al (2012) Scenarios in global environmental assessments: key characteristics and lessons for future use. Glob Environ Change 22:884–895. https://doi.org/10.1016/j.gloenvcha.2012.06.001

Warszawski L, Frieler K, Huber V et al (2014) The Inter-Sectoral impact model intercomparison project (ISI–MIP): project framework. Proc Natl Acad Sci USA 111:3228–3232. https://doi.org/10.1073/pnas.1312330110

Weitzman ML (2012) GHG targets as insurance against catastrophic climate damages. J Public Econ Theor 14:221–244. https://doi.org/10.1111/j.1467-9779.2011.01539.x

Yin L, Bai B, Zhang B et al (2023) Climate penalty on air pollution abated by anthropogenic emission reductions in the United States. Res Sq rs.3.rs-3245771 https://doi.org/10.21203/rs.3.rs-3245771/v1

Zhao Z-J, Chen X-T, Liu C-Y et al (2020) Global climate damage in 2°C and 1.5°C scenarios based on BCC_SESM model in IAM framework. Adv Clim Change Manage 11:261–272. https://doi.org/10.1016/j.accre.2020.09.008