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Guidelines to quantify climate change exposure and vulnerability indicators for the future: an example for heat stress risk across scales

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Summary

This report provides guidelines for the development of socioeconomic indicators to assess future exposure and vulnerability to future climate hazards and inform science-policy assessments. Current climate risk assessments primarily rely on static indicators or linear extrapolations, which do not fully capture dynamic socio-economic drivers like urbanization, aging, and income distribution with more qualitative variables relating to vulnerability. This report proposes integrating insights from Shared Socioeconomic Pathways (SSPs) to create scenario-based risk assessments that reflect future societal trends, making climate indicators more relevant for policy and planning.

The methodology combines single-indicator and index-based approaches, emphasizing participatory methods to define indicators that capture complex, context-specific vulnerabilities. Two case studies illustrate the approach: the first at a European scale and the second at a metropolitan scale for the Helsinki metropolitan region in Finland. We demonstrate that the application of SSP-based vulnerability projections can maintain coherence across scales yet allows tailoring at the appropriate scale with an efficient use of resources through effective participatory processes. Emphasis is placed on addressing non-climatic factors in climate resilience planning, with the goal of ultimately enhancing human well-being by providing future-generation oriented climate risk assessments for Europe.

1 Introduction

1.1 Motivation

The European Environment Agency (EEA) develops indicators to support environmental policymaking across various stages, from policy design to evaluation and communication. These indicators track trends in environmental phenomena over time, providing insights into whether specific policy goals are being achieved and helping policymakers understand progress toward targets.

In the context of climate change adaptation, the EEA focuses on using 15 impact indicators[1] that derive from hazard indicators based on existing data. However, there is a need to improve how these indicators reflect future non-climatic impact drivers of health risks, particularly in terms of exposure and vulnerability. This report aims to explore how future exposure, and vulnerability can be better represented in risk assessments and EEA products, making them more relevant for climate services and future projections.

To address the limitations in current indicators and improve the assessment of future exposure and vulnerability, this report incorporates insights from the Shared Socioeconomic Pathways (SSPs) framework. SSPs were developed as part of the global climate change research agenda to describe different trajectories of societal development, each with unique implications for climate vulnerability, exposure, and adaptive capacity (Moss et al., 2010). By categorizing potential futures into various socio-economic narratives—such as sustainability-focused or fossil-fuel-driven scenarios—SSPs enable a structured, scenario-based approach for assessing non-climatic drivers that influence human vulnerability to climate hazards. In particular, as synthesised in the first European Climate Risk Assessment (EUCRA), SSPs allow for projections of socio-economic factors such as urbanization, aging, and wealth distribution, providing a foundation for more dynamic and contextually relevant risk assessments that incorporate both climatic and non-climatic drivers of risk (Pedde et al., 2024).

Ultimately, this report suggests a pathway to a possible 2nd European Climate Risk Assessment (EUCRA2) currently in its initial planning stages, where socio-economic scenarios could play a larger role to systematise climate risk and their cascading effects. Specifically, we demonstrate how scenario-based approaches can offer a richer understanding of future climate vulnerabilities by including coherent projections, rather than extrapolations, of urbanization, economic inequality, and demographic trends as core elements in risk evaluation. The lessons and methodologies outlined here could serve as critical groundwork for EUCRA2, informing more nuanced climate resilience strategies that reflect dynamic socio-economic changes across European regions and scales.

1.2 Improving exposure and vulnerability indicators

The risk of harm from climate change is defined as a function of biophysical change (hazard), the degree to which a system is exposed to those changes (exposure), and the sensitivity and adaptive capacity of the system (vulnerability). While current assessments often focus on historical and present-day data (Maes et al., 2022), there is growing recognition that future projections need to incorporate dynamic social, economic, and environmental factors. This is reflected in the ongoing extensions of SSP-based indicators, this report aims to and aligns with current projects and efforts aimed at tailoring SSPs in this direction. For example, the SPARCCLE project[2] takes the SSP approach

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[1] https://www.eea.europa.eu/en/analysis/indicators (assessed 31 October 2024)

[2] https://sparccle.eu (assessed 8 November 2024)

further to assess population's vulnerabilities and capacities at the regional level using tools, such as the Atlas of Demography[3] developed by European Commission's Joint Research Centre (JRC). While this is ongoing work using the updated SSP projections, several authors have already developed methods to regionalise projections that prioritise stakeholder and policy needs, and this is the focus of these guidelines.

A critical question is how we can integrate future exposure and vulnerability into existing frameworks. **Exposure** reflects the presence of people or assets in hazard-prone areas, while **vulnerability** refers to the characteristics that make populations more susceptible to harm, such as socio-economic status or age (cf. Figure 1). Definitions, summarized in IPCC reports (IPCC, 2023), have been further refined recently in global studies that address the linkages between physical hazards and justice (see Gupta et al., 2024, p. 8) and H2020 projects supporting the EU Mission on Adaptation (see for example the online Handbook on Climate Risk Assessment[4] by the CLIMAAX project). Such advances also address the distinction between vulnerability and exposure, which can be still subtle but is essential for accurate risk assessment.

1.3 Key definitions

1.3.1 Vulnerability vs exposure

Vulnerability is often defined as the degree to which a population, system, or asset is susceptible to harm from climate hazards, considering not only sensitivity but also **adaptive capacity**—the ability to cope with, adapt to, or recover from these hazards. Vulnerability encompasses social, economic, and sometimes institutional factors. For example, low-income communities may be more vulnerable to heat stress due to limited access to healthcare, air conditioning, or resilient infrastructure. According to the 6th IPCC assessment report (IPCC, 2023), vulnerability is the propensity or predisposition to be adversely affected. Vulnerability thus encompasses **exposure, sensitivity, and lack of adaptive capacity**. It is influenced by structural, broad socioeconomic factors such as inequality, governance, and access to resources. We propose, in line with recent academic and policy perspectives, that addressing the structural socio-political and institutional determinants of vulnerability and adaptive capacity includes a better understanding how factors like inequality, governance, cultural resilience, and social justice play significant roles in determining how communities can respond to and recover from climate impacts.

Exposure, on the other hand, refers to the physical presence of people, infrastructure, or ecosystems in areas likely to be affected by hazards, such as heatwaves, floods, or droughts. Exposure is location-based and can be quantified using spatial data.

Adaptive capacity is a component of vulnerability (together with sensitivity). It refers to the ability of a system, community, or individual to adjust to potential damage, take advantage of opportunities, or cope with the consequences of climate hazards. Higher adaptive capacity can reduce vulnerability, as it enables better preparation, response, and recovery from adverse events.

1.3.2 Current Definitions

Initially, vulnerability was linked directly to impacts in climate assessments, interpreted as the outcome of exposure to a hazard or multiple hazards. However, recent frameworks such as those from the IPCC and EEA have evolved to recognize that vulnerability must also reflect the capacity of populations to respond or adapt. This shift acknowledges that the impacts of climate change are not

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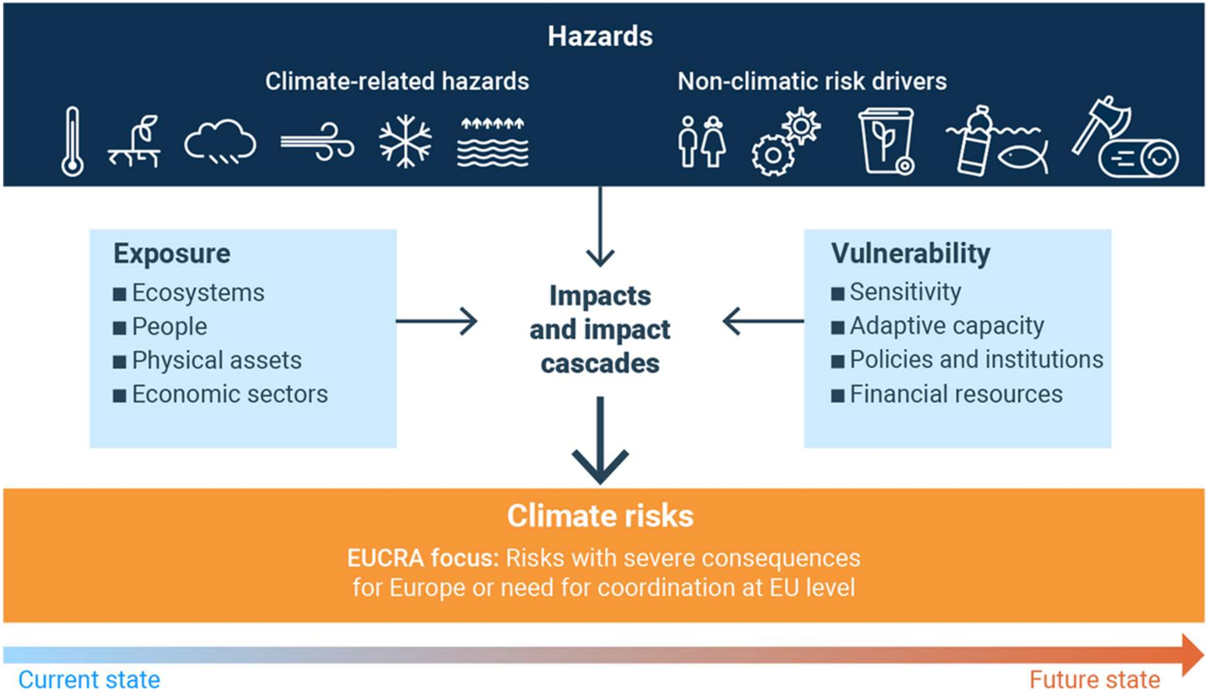
[3] https://migration-demography-tools.jrc.ec.europa.eu/atlas-demography/stories/S4.01?selection=EU27_2020#S4.01-02 (assessed 7 November 2024)

[4] https://handbook.climaax.eu (assesses 8 November 2024)

solely dependent on the severity of the hazard but also on the ability of populations to withstand or recover from them.

Figure 1. IPCC Risk framework used at EEA – comparing indicators used at EEA with using SSP-based indicators (Source: European Environment Agency, 2024)



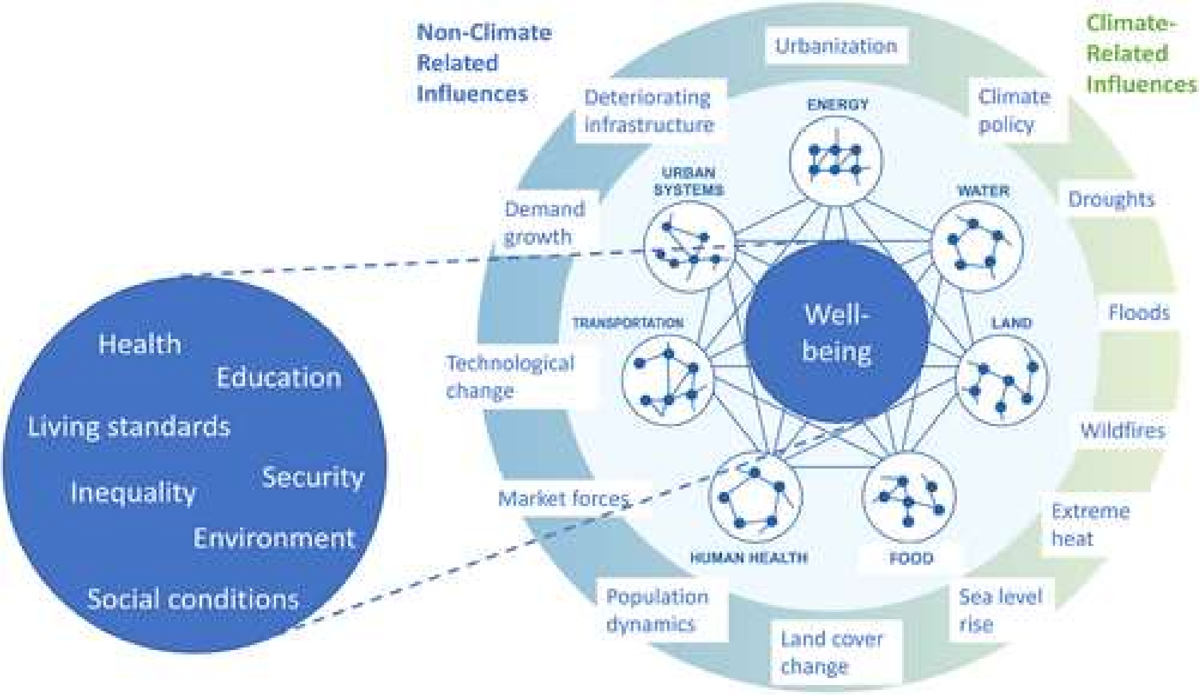
In this line of thinking, and with vulnerability and exposure as critical components of climate risk assessment, there is growing recognition that these elements ultimately contribute to a broader goal: protecting and enhancing human well-being. In recent climate change research involving the Shared Socioeconomic Pathways, there has been a shift towards "outcome-based" scenarios, which emphasize well-being and resilience as key objectives of climate adaptation strategies. These scenarios focus on the end results that climate resilience efforts seek to achieve, such as health security, poverty alleviation, and access to essential resources like food, water, and energy.

This well-being perspective complements traditional vulnerability assessments by framing risks in terms of their direct impact on the quality of life for affected communities. Rather than viewing vulnerability solely as a function of exposure and adaptive capacity, an outcome-oriented approach positions vulnerability as a pathway through which climate hazards impact societal well-being. This includes considering factors such as energy poverty, food security, health outcomes, and social stability. Communities with high adaptive capacity are better able to protect well-being outcomes—such as health, income, and social stability—despite facing significant risks. Higher adaptive capacity can reduce vulnerability, as it enables better preparation, response, and recovery from adverse events.

In the context of the Shared Socioeconomic Pathways (SSPs), the integration of well-being metrics offers a way to not only project future exposure and vulnerability but also understand how these dynamics affect overall societal resilience. By linking SSP-based vulnerability indicators with well-being outcomes, policymakers can design climate adaptation strategies that are not only effective in reducing physical risks but also in enhancing the resilience and prosperity of communities under various socio-economic scenarios.

Figure 2 (from O'Neill et al., 2024) illustrates the interconnected system components that influence human well-being, including both non-climate-related (e.g., urbanization, technological change, demand growth) and climate-related (e.g., droughts, floods, sea level rise) factors. Each component interacts with essential domains such as energy, water, land, and food, highlighting how systemic changes can impact health, education, living standards, and social conditions. This outcome-based approach complements traditional vulnerability and exposure assessments by framing climate risks within a broader context of societal resilience and quality of life, providing a holistic view of the drivers of human vulnerability to climate hazards.

Figure 2. System-components determining or influencing human well-being in the Shared Socioeconomic Pathways (Source: O'Neill et al., 2024)



2 Available studies, databases and approaches

2.1 Current sources and limitations

The European Environment Agency collects information on hazards, exposure, vulnerability, impacts, and policies and actions for the past and present from several sources. Information on the different elements is available through the EEA Adaptation dashboard—an integral part of the EU Mission on Adaptation to Climate Change—, JRC vulnerability index[5,6], the European Climate and Health Observatory[7], the European Climate Data Explorer (ECDE)[8], the recent interactive web report of hazard indicators carried out by the EEA (European Environment Agency, 2021) and the EUCRA viewer on

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[5] https://drmkc.jrc.ec.europa.eu/risk-data-hub#/dashboardvulnerability (assessed 8 November 2024)

[6] https://drmkc.jrc.ec.europa.eu/risk-data-hub/media/vulnerability/Indicators_and_References.pdf (assessed 8 November 2024)

[7] https://climate-adapt.eea.europa.eu/en/observatory (assessed 8 November 2024)

[8] https://climate-adapt.eea.europa.eu/en/knowledge/european-climate-data-explorer (assessed 31 October 2024)

impact drivers[9]. Within those different portals, sources of information include, among others, the Copernicus Climate Change Service (C3S) for hazard information, the Copernicus Land Monitoring Service, Eurostat and the Lancet Countdown for exposure information, the vulnerability index from the Commission's Joint Research Centre for vulnerability information, and the Risk Layer CATDAT dataset for impacts information. A latest development, released in March 2024, was the Scenario Explorer[10] based on global database extensions of adaptive capacity components recently for the SSPs.

2.1.1 Limitation of current data

Similar data sources may be also combined in different ways to further develop indicators or indices. For instance, both the index-based interactive EEA report (European Environment Agency, 2021) and the ECDE build from, among other sources, C3S. However, their use of data and purpose. The EEA 2021 report, using an index-based approach, syntheses and communicates climate risk at very high-level which can be used more readily for cross-regional or cross-sectoral analysis. ECDE instead provides access for single indicators, more useful for further analysis in specific applications. Both can (and should) be used together: the report gives a strategic overview of climate hazards, while the ECDE offers an interactive platform to explore specific data that underpins those hazards, enabling users to transition from regional understanding to localized action. This complementarity is very important, particularly in a context of rapid change and transparency for strategic decision under deep uncertainty. Here we show the example of Rohat et al. (2019), on how to build a simple, reproducible vulnerability index for future heat stress, based on single indicators.

Rohat et al. (2019) were amongst the first authors in Europe to project socioeconomic indicators for heat stress under four alternative socioeconomic and climatic scenarios at NUTS2 scale. Most current indicators still rely heavily on historical data, which may not adequately capture future risks due to changing societal and economic conditions. For example, demographic shifts like population aging, urbanization, and land-use changes can significantly alter future exposure patterns. A key challenge is incorporating these non-climatic drivers into climatic projections to understand multi-hazard and multi-vulnerability risk. A model that can reproduce all these processes to be relevant for the future any scale required does not exists. Instead, scientists and decision-makers can work synergistically by either keeping up to date with imperfect knowledge through continuous monitoring and updates of datasets or interpret and iterate knowledge through a participatory approach. Here we show how simple elicitations can provide the legitimacy and transparency to interpret, understand or construct future trends for indicators heat stress.

2.2 Approaches to assess future vulnerability and exposure

2.2.1 Overview

Socio-economic aspects can be described with non-climatic impact driver (NCID), which contribute to risks alongside climatic impact drivers (CID) or hazards. The approaches to construct relevant indicators outlined in this report are summarized in Figure 4. The single indicator approach uses a one indicator of NCID, usually describing aspects of exposure (e.g. the number of elderly people that can be exposure), and combines this with a single indicator of CID to express the hazard per exposure until (e.g. the number of elderly exposed to a certain number of tropical nights). Exposure indicators used for this often can be modelled (e.g. with population models). The index-based approach differs from this in that it combines several indicators of NCID, often these are covering aspects of both

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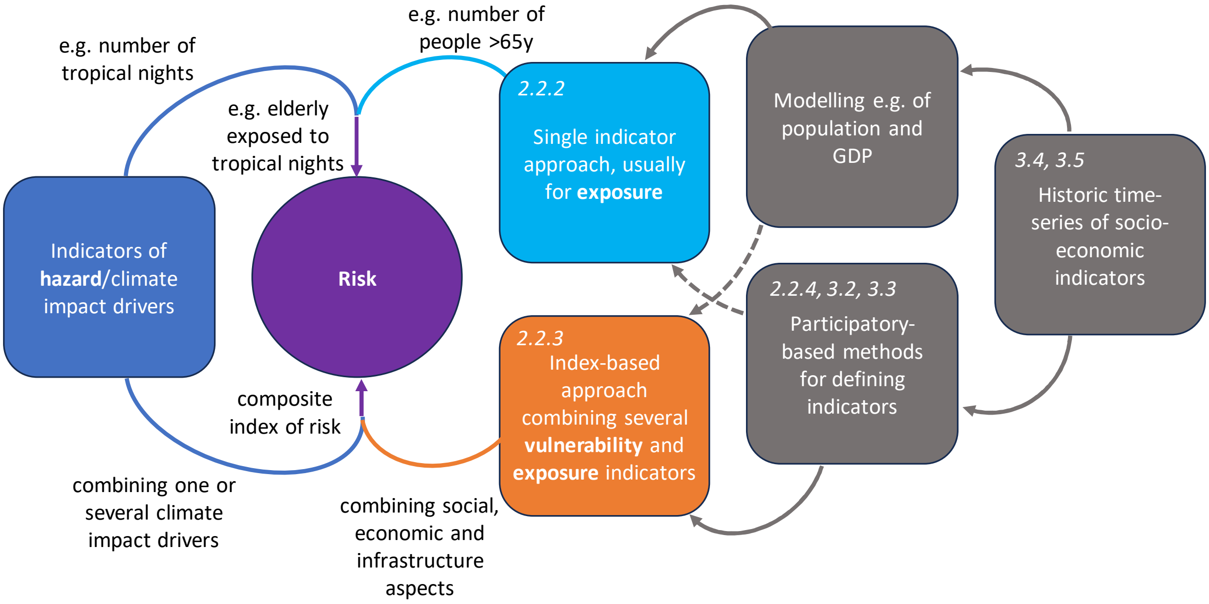
[9] https://climate-adapt.eea.europa.eu/en/eu-adaptation-policy/key-eu-actions/european-climate-risk-assessment/eucra-viewer-impact-drivers (assessed 31 October 2024)

[10] https://data.ece.iiasa.ac.at/ssp/#/workspaces (accessed 31 October 2024, SSP Scenario Explorer 3.1.0 Release July 2024).

vulnerability and exposure. Participatory-based methods can play an important role to define these indicators, and in the examples of this report we demonstrate how historic time-series of such indicators can inform the scenario quantification for future projection. Combination with indicators of CID can then be used for composite indices of risk.

Figure 3. Overview of approaches to construct indicators of exposure and vulnerability and their use to determine aspects of risk. Numbers in italic refer to relevant sections of this report.



2.2.2 Single indicator approach

The use of single indicators provides a straightforward and transparent approach to assessing vulnerability and exposure to climate risks. This approach focuses on specific variables, such as population density or the percentage of elderly residents, which are directly correlated with climate risks. Single indicators allow for clear, targeted analysis, particularly useful in cases where data availability or the need for rapid assessment limits the scope of a broader, multi-dimensional approach.

A single indicator approach can also increase comparability and usability of indicators across scales and sectors. For example, applying single indicators to complement knowledge on function-based outcomes, such as in the impact modeling of the Integrated Assessment Platform (IAP), or combining them to create a sector- and geographic-specific vulnerability index, as seen in the work of Rohat et al. (2019), enables flexible analysis across different contexts. The advantage of using single indicators lies in their transparency and ease of procedural modification, making them straightforward to update, adjust, or remove from the risk assessment as needed.

One common example of a single indicator is population density, which is often used to assess the risk of heat stress in urban areas. High population density is typically associated with increased exposure to the urban heat island effect, where built-up areas experience higher temperatures due to concrete, asphalt, and other heat-retaining materials. However, this correlation is not universally applicable; regional variations must be considered. For instance, the indicator "building density", defined as the percentage of built area or households per square kilometer, can be valuable for heat stress assessments if supported by relevant correlations (e.g., higher building density correlates with elevated temperatures and increased heat stress risk, as shown by Li et al. (2023)). However, when applied to Southern and Eastern Europe, high building density may relate to reduced heat stress

(Aleksandrowicz and Pearlmutter, 2023; Kántor et al., 2018), if building density is associated to shadowing effect at the street level (in turn, if building orientation and street configuration and morphology produce shadow).

The following examples illustrate how single indicators are utilized in different contexts and provide in-depth vulnerabilities across diverse regions and demographic groups and cohorts:

- Cumulative exposure to climate risks dependent on time of birth (Thiery et al., 2021) provide a powerful perspective on the intergenerational disparities in exposure to climate extremes. Their findings reveal that younger generations are facing a significantly increased likelihood of encountering extreme climate events within their lifetimes compared to older generations. For instance, children born in 2020 are expected to face between two to seven times the frequency of extreme events, including heatwaves, droughts, and river floods, relative to those born in 1960. By using a cohort-based approach, the study emphasizes the necessity of incorporating intergenerational equity into climate adaptation strategies, as younger people will bear a disproportionately higher burden of climate impacts.
- Elderly people exposed to heat (Falchetta et al., 2024). In regions with high levels of heat exposure, elderly populations are particularly vulnerable due to various factors, including reduced mobility, chronic health conditions, and often limited access to cooling infrastructure. Falchetta et al. (2024) underscore the increasing risk to older adults globally, showing that a large portion of this demographic will inhabit regions where extreme temperatures surpass critical thresholds. Their projections reveal a substantial increase in the number of older adults at risk by mid-century, especially in Asia and Africa, where adaptive capacity is limited.
- Population, agricultural and forest land exposed to compound climate extremes (Schillerberg and Tian, 2024). The authors highlight the escalating risks associated with compound climate extremes, such as concurrent heatwaves and flash droughts or sequential extreme precipitation followed by droughts. Their study projects that compound events will become more common under high-emission scenarios, amplifying risk exposure for sensitive sectors like agriculture and forestry. By examining shifts in exposure across different SSP scenarios (e.g., SSP1-2.6 and SSP5-8.5), they emphasize the need for targeted adaptation strategies, particularly in key agricultural regions and ecologically valuable forests. This analysis sheds light on the complexity of managing risks associated with simultaneous or sequential hazards and underscores the necessity for multi-faceted adaptation approaches.

These examples demonstrate both the utility and limits of single-based indicator approaches. While they provide insights on specific vulnerabilities across diverse regions and demographic segments that would not be detected with (high-level) index-based approaches, the complexity of climate impacts on interconnected systems and the multifaceted nature of vulnerabilities suggest that a comprehensive approach often requires moving beyond isolated indicators to address complex and compound climate risks effectively.

2.2.3 Index-based approaches

An index-based approach aggregates multiple indicators into a single composite metric, providing a broader and more holistic picture of vulnerability. By combining multiple indicators—such as income level, age distribution, population density, infrastructure resilience, and healthcare access—into one index, policymakers and researchers can gain insights into overall vulnerability patterns across regions, sectors, and population groups. This method enables the simultaneous consideration of multiple dimensions of vulnerability, which is crucial for complex, multifactorial issues like climate change. The JRC Vulnerability Index[11], developed by the Joint Research Centre of the European Commission, is an example of an index-based tool that enables users to evaluate vulnerability using multiple indicators. It offers an interactive web-based platform where users can create customized risk assessments by selecting, weighting, and combining relevant indicators to reflect the specific context of their analysis. This flexibility makes it adaptable to different geographical or sectoral contexts, allowing for a tailored assessment that aligns with regional and local characteristics.

However, while index-based approaches provide a useful overview, they also come with certain limitations. Aggregation processes can obscure underlying dynamics and patterns within individual indicators (Hinkel, 2011). For example, an index may mask the fact that while a region has high income levels, it might simultaneously have a vulnerable elderly population with limited mobility. Hinkel (2011) argues that many existing frameworks lack transparency and suffer from methodological limitations, such as failing to differentiate between sensitivity and adaptive capacity. This critique aligns with the approach advocated by Carter et al. (2016), which emphasizes the importance of allowing stakeholders to construct and adjust their own indicators to better reflect specific vulnerability profiles. Indeed, index results are often sensitive to the weights assigned to each indicator, which can introduce subjectivity. For example, placing a high weight on economic resilience might understate the vulnerability related to health risks if healthcare-related indicators are weighted less. To address the challenges associated with fixed weighting in index-based approaches, Carter et al. (2016) proposed an innovative web-tool approach that enables users to construct their own indicators[12] based on specific vulnerability and exposure factors. This tool was designed to accommodate the subjective nature of certain vulnerability components, such as the exposure and vulnerability of elderly populations to heat stress. The tool allows users to select, weight, and adjust indicators in line with the context-specific needs of the region or sector under consideration. For instance, users concerned with elderly populations can prioritize indicators related to healthcare access, social isolation, or local temperature variations, tailoring the assessment to accurately reflect the unique vulnerabilities of this group. This customizable approach provides a solution to the common criticism of aggregated indices by allowing stakeholders to define parameters that are more relevant to their specific circumstances, thus enhancing the usability and relevance of vulnerability assessments.

A novel development in index-based approaches is the integration of socioeconomic projections derived from Shared Socioeconomic Pathways (SSPs). SSPs, developed as part of the global climate change research agenda, provide multiple scenarios describing different pathways of societal development, such as sustainability-focused or fossil-fuel-driven scenarios. The adaptive capacity component of these pathways, recently developed by the International Institute for Applied Systems Analysis (IIASA), allows for the incorporation of future socioeconomic trajectories in vulnerability assessments (Andrijevic et al., 2023). By including projections of variables like population growth, urbanization, income distribution, and technological advancements, SSPs allow vulnerability indices to not only reflect current conditions but also to project how vulnerabilities may evolve under

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[11] In addition to the JRC Vulnerability Index, other tools that provide composite vulnerability assessments include the Social Vulnerability Index (SoVI) (Cutter, 2024), commonly used in the United States to assess the social dimensions of risk and preparedness in the face of hazards. The Global Climate Risk Index (developed by Germanwatch; https://www.germanwatch.org/en/cri) also operates on a similar principle, combining historical climate impact data to rank countries in terms of their vulnerability to climate risks.

[12] "Construct your own indicator"*;* see http://www.iav-mapping.net/U-C-IAV/elderly/ (assessed 1 Oct 2024)

different socioeconomic scenarios. This forward-looking approach can offer valuable insights for long-term planning and policy development.

While the integration of adaptive capacity in SSP-based indices represents a significant advancement, challenges remain. The complexity of socioeconomic systems means that future conditions are inherently uncertain, and projections may not fully capture emergent phenomena or tipping points. Additionally, the assumptions underlying SSPs, such as the rate of technological progress or shifts in governance, may not align with real-world developments, thereby impacting the accuracy of these forward-looking indices.

Similarly, the European Climate Risk Assessment (EUCRA) incorporates elements of the JRC approach by aggregating hazard, exposure, and vulnerability *impacts* indicators into a single index (clusters) to help guide EU-level climate adaptation policy. When it comes to *drivers* of impacts (climatic and non-climatic), this is based on the SSP socioeconomic scenarios adapted for Europe (Kok et al., 2019). In this sense, EUCRA follows a unique single indicator approach, similar to the individual indicators developed by Rohat et al. (2019).

2.2.4 Participatory-based methods for defining indicators

In typical vulnerability assessments, indicators often include metrics like population density, income levels, and age distribution to assess exposure and sensitivity to risks. However, integrating a well-being lens—such as health outcomes or access to resources—can make these assessments more meaningful. For example, an outcome-focused indicator like heat-related mortality rates offers greater insight into vulnerability than simply indicating that elderly populations are more susceptible to heat stress. These insights, in turn, may inform further assessments and inform policies, potentially with cascading benefits.

The diversity of climate risks across Europe means that no single set of indicators can capture all possible vulnerabilities, underscoring the need for a participatory approach. This approach is particularly valuable in contexts where values may conflict or where certain indicators, like governance-based metrics, are challenging to quantify. By involving experts and stakeholders in the process, a participatory approach enables the definition of context-specific indicators that reflect the unique challenges and characteristics of different regions.

A participatory approach, involving experts and/or stakeholders, can help define context-specific indicators also starting from top-down conceptual categories. For example, EUCRA building from STEEP (Society, Technology, Environment, Economy, Policy) categories, classifies drivers of vulnerability to create shared framings that facilitate constructive discussions towards brainstorming and consensus on characteristics of indicators. That is, their (1) importance (in Section 3.1) and (2) direction of plausible future trends in the near- and long-term future.

3 Projecting drivers of future heat-stress risk in Europe and Helsinki

3.1 Introduction

Given the diversity and complexity of climate risks across Europe and uncertainties in both climatic and non-climatic projections, it is challenging to capture all possible risks with a single set of indicators. Model-based projections provide tangible, quantitative insights, but they may obscure underlying uncertainties and relevant confounding factors. Moreover, the continuous evolution of modelled trends necessitates a deep understanding of updates and the processes explaining these trends. In a science-policy context, where transparency is essential, a participatory approach can be particularly valuable. This is especially true for complex or value-driven indicators, such as governance metrics, which are harder to quantify and often involve subjective judgments. Through collaborative engagement, a participatory approach enables the identification of indicators that reflect both current and emerging climate-related health risks, tailored to the specific context of the analysis.

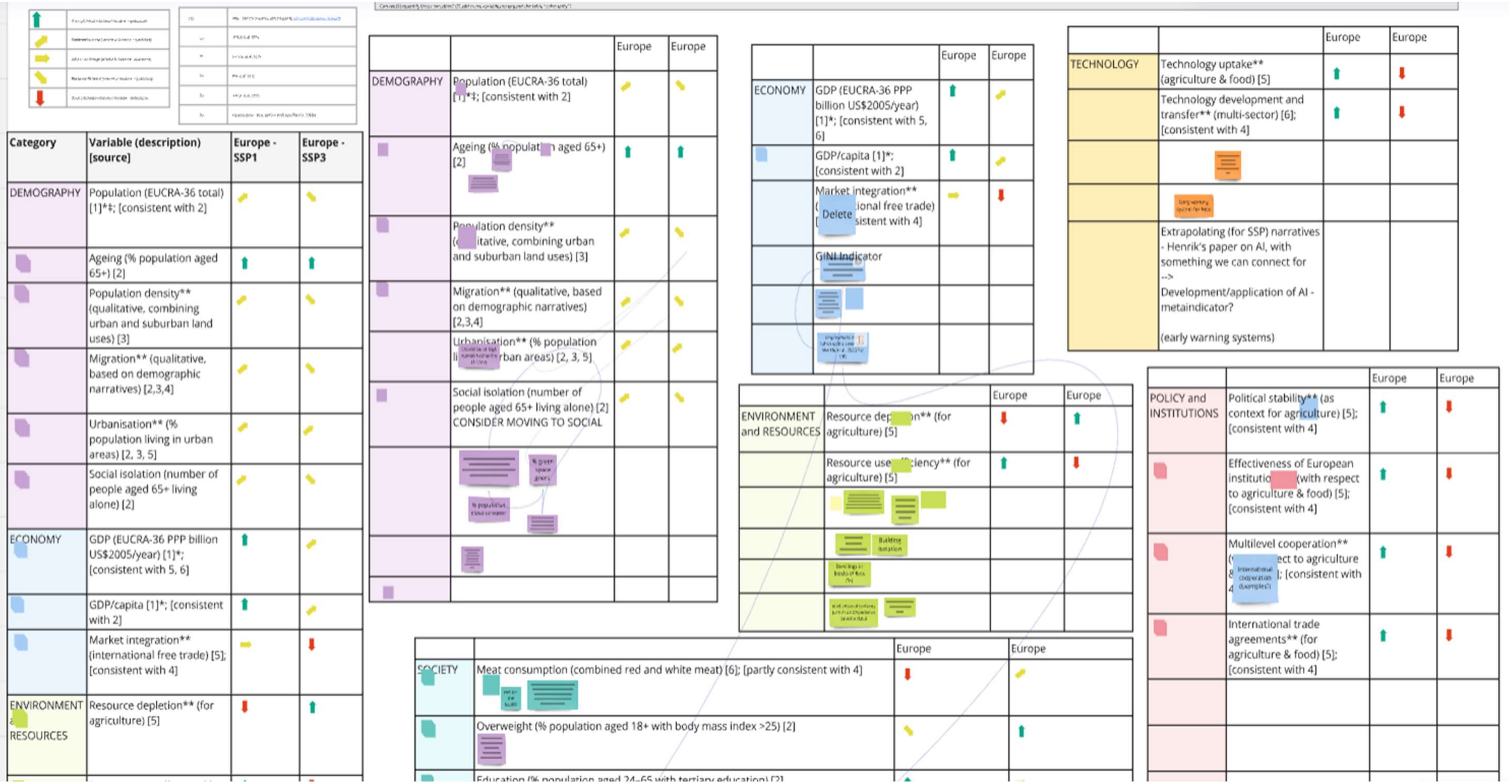
In this section, we provide an example of how a specific indicator, such as "social isolation of individuals aged 65+", can be included in a vulnerability index for a given region or country, following the methodology of Rohat et al. (2019). The challenge here is not in understanding the direct relationship between social isolation and vulnerability to heat stress—this connection is already established. Rather, the uncertainty lies in projecting how this vulnerability factor might evolve in the future, taking into account various social, demographic, and environmental changes that may influence the extent of social isolation among elderly populations.

3.2 Defining drivers of vulnerability and exposure through elicitation

Building on the participatory framework discussed in Section 2.2.2, we elicit (instead of solely desktop research) relevant indicators for vulnerability and exposure to heat stress in Europe. The full list and shortlist of relevant indicators of heat-stress vulnerability for Europe are elicited using the five STEEP categories (Society, Technology, Environment, Economy, Policy) as a starting point for the structured elicitation process that expanded and refined these dimensions for heat-stress risk assessment. This approach enabled the adaptation of broad categories of European drivers of risk into specific, context-sensitive indicators, creating a foundation for the subsequent scenario-based analysis.

Figure 3 illustrates the outcome of this elicitation process, showcasing how vulnerability drivers were grouped and categorized. The finalized list of indicators reflects a collaborative understanding of heat-stress risk, informed by both empirical evidence and stakeholder insights, and serves as the basis for projecting future vulnerability trends across Europe.

Figure 4. Cut-out raw results of the two-day elicitation process to identify drivers of vulnerability and exposure to heat stress. The colours code five different dimensions (society, technology, environment, economy, policy) that guide and organise the facilitated discussions. The outcome of this harvest is translated to the full list of indicators in the Excel (see Appendix).



Category	Variable (description) [source]	Europe - SSP1	Europe - SSP3
DEMOGRAPHY	Population (EUCRA-36 total) [1]*‡; [consistent with 2]	↗	↘
	Ageing (% population aged 65+) [2]	↑	↑
	Population density** (qualitative, combining urban and suburban land uses) [3]	↗	↘
	Migration** (qualitative, based on demographic narratives) [2,3,4]	↗	↘
	Urbanisation** (% population living in urban areas) [2, 3, 5]	↗	↗
	Social isolation (number of people aged 65+ living alone) [2]	↗	↘
ECONOMY	GDP (EUCRA-36 PPP billion US$2005/year) [1]*; [consistent with 5, 6]	↑	↗
	GDP/capita [1]*; [consistent with 2]	↑	↗
	Market integration** (international free trade) [5]; [consistent with 4]	→	↓
ENVIRONMENT & RESOURCES	Resource depletion** (for agriculture) [5]	↓	↑

		Europe	Europe
DEMOGRAPHY	Population (EUCRA-36 total) [1]*‡; [consistent with 2]	↗	↘
	Ageing (% populat n aged 65+) [2]	↑	↑
	Po ulation density** (itative, combining urban and suburban land uses) [3]	↗	↘
	Migration** (qualitative, based on demographic narratives) [2,3,4]	↗	↘
	Urbanisation** (% population li rban areas) [2, 3, 5]	↗	↗
	Social isolation (number of people aged 65+ living alone) [2] CONSIDER MOVING TO SOCIAL	↗	↘

		Europe	Europe
ECONOMY	GDP (EUCRA-36 PPP billion US$2005/year) [1]*; [consistent with 5, 6]	↑	↗
	GDP/capita [1]*; [consistent with 2]	↑	↗
	Market integration** (ional free trade) [sistent with 4]	→	↓
	~~GINI Indicator~~		

		Europe	Europe
TECHNOLOGY	Technology uptake** (agriculture & food) [5]	↑	↓
	Technology development and transfer** (multi-sector) [6]; [consistent with 4]	↑	↓
	Extrapolating (for SSP) narratives - Henrik's paper on AI, with something we can connect for --> Development/application of AI - metaindicator? (early warning systems)		

		Europe	Europe
ENVIRONMENT and RESOURCES	Resource dep n** (for agriculture) [5]	↓	↑
	Resource use ciency** (for agriculture) [5]	↑	↓

		Europe	Europe
POLICY and INSTITUTIONS	Political stability** (as context for agriculture) [5]; [consistent with 4]	↑	↓
	Effectiveness of European institutio (with respect to agriculture & food) [5]; [consistent with 4]	↑	↓
	Multilevel cooperation** (ect to agriculture &]; [consistent with 4	↑	↓
	International trade agreements** (for agriculture & food) [5]; [consistent with 4]	↑	↓

		Europe	Europe
SOCIETY	Meat consumption (combined red and white meat) [6]; [partly consistent with 4]	↓	↗
	Overweight (% population aged 18+ with body mass index >25) [2]	↘	↑
	Education (% population aged 24–65 with tertiary education) [2]		

Both the list of indicators from the elicitation process and the shortlist are reported in the attached Excel file in raw format, see Excel in Appendix. The selection of indicators is done by assessing the elicitation process against literature research. For the six categories, a minimum of 2 indicators ("Policy and Institutions") and maximum of 15 indicators ("Society") have been identified as relevant. Out of this, a total of 10 selected indicators is selected, based on considerations of feasibility.

3.3 Extrapolating future trends for Europe using a participatory scenario approach

This step involves adding a "future-oriented" dimension to the indicators identified in Section 3.2. Drawing from the shortlist of indicators established in the elicitation process, we further narrow down to two the selection to a manageable subset for this scenario-based analysis. While single indicators, such as those compiled by OECD, provide a clear, linear projection of what the future might entail for each specific variable, they risk creating a false sense of certainty about future trajectories. This can lead to underestimating the importance and impact of certain indicators, particularly if no scenario uncertainty is explicitly explored. Therefore, we embed single indicators within broader scenarios that reflect potential variability across different future contexts.

Extrapolating single indicators (which can be further combined in the form of an index) within broader scenarios can be exemplified by an SSP-based indicator composed by a simple equation like the SSP-based indicators developed Rohat et al. (2019). They combine indicators, justified by literature and data availability, such as GDP per capita, education level, artificial surfaces, social isolation based on proportion of elderly, and people with overweight condition (Rohat et al., 2019) with a simple additive approach with equal weights. In their approach, vulnerability = 1/6 * [(1-GDP_pc) + (1-Edu) + Age + Artif + Socio_iso + OverW, with:

- **GDP per capita (GDP_pc):** This indicator was derived from downscaled population and GDP projections produced by the Joint Research Center (JRC) of the European Commission. These projections are consistent with the SSPs for Europe at a 0.1° spatial resolution. From http://swicca.eu/ (not available anymore).
- **Education Level (Edu):** Education projections were sourced from the global SSP quantifications at the national level (KC and Lutz, 2017). These were first downscaled to NUTS-2 (regional) level based on existing education figures and then disaggregated further to a 0.1° spatial grid, assuming a homogeneous proportion of people with higher education within each NUTS-2 region.
- **Proportion of Elderly (Age):** Age-specific population projections were retrieved from the IMPRESSIONS project, based on Terama et al. (2019). These projections were initially available at the NUTS-2 level and were further downscaled to a 0.1° spatial resolution using current age distribution figures.
- **Artificial Surfaces (Artif):** Projections of artificial surfaces were also from the IMPRESSIONS project, specifically using data from Terama et al. (2019). These projections were made on a 10′ spatial grid (approximately 13 km x 13 km) using a regional urban growth model. The model incorporated assumptions about age group-specific residential preferences under the four SSPs for Europe.
- **Social Isolation (Socio_iso)**: This indicator refers to the proportion of elderly people living alone. Since consistent projections were unavailable, an expert-based modeling approach was used. Current figures at the NUTS-3 level were retrieved and projections were refined using expert judgments collected via an online questionnaire. This was quantified using the fuzzy

set theory approach (Pedde et al., 2019). Unlike the overweight indicator, this metric was not downscaled based on age groups or urbanization.

- **Overweight Prevalence (OverW):** Overweight prevalence projections began with current figures at the national level, which were disaggregated to NUTS-2 based on age group-specific overweight statistics. These were further downscaled to 0.1° spatial resolution using urbanization-specific overweight prevalence data. Projections were adjusted based on changes in age group structures and urbanization levels under the SSPs for Europe. Expert-based adjustments were applied using fuzzy set theory (similar to the process used for the elderly living alone indicator).

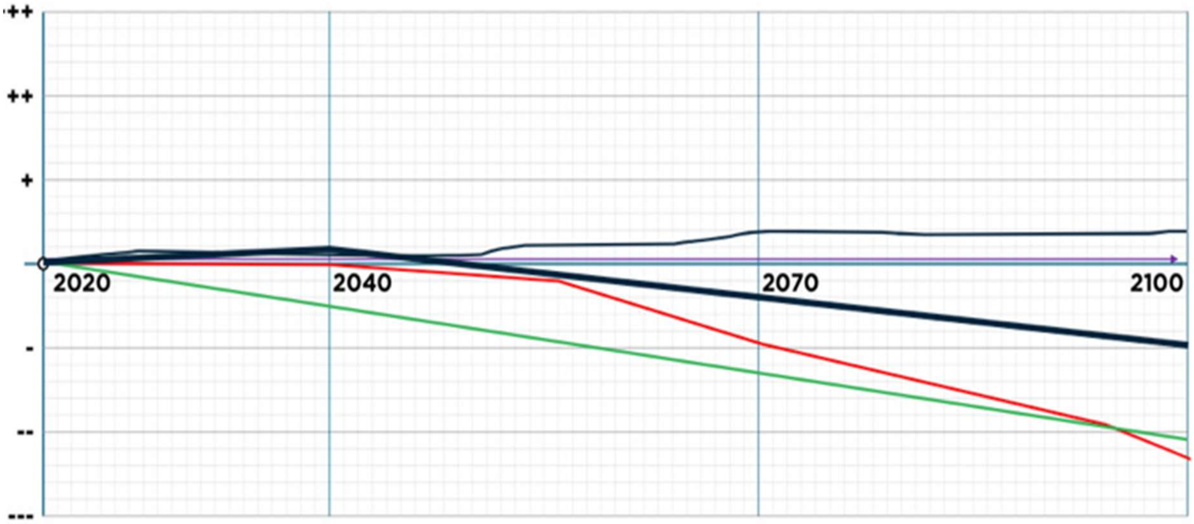
It is important to note that Rohat et al. (2019) quantified future projections from individual indicators with different methodologies. For instance, “social isolation” and “overweight” entailed a larger bottom-up component of elicitation and expert judgement than the other indicators. Different methodologies and datasets resulted in need to normalize each indicator before combining them in an index. This was done using linear min-max rescaling.

To extrapolate the quantitative trends, either bottom-up or top-down, the qualitative trends need to be fleshed out first to understand and sense-making of the quantitate trends. Individual trends are developed and justified in the broader context of future scenarios. For this purpose, similarly to Rohat et al. (2019), we have built on Pedde et al. (2019) to link qualitative and quantitative trends by adapting simplified narratives of five scenarios based on the so-called global Shared Socioeconomic Pathways (SSPs, O’Neill et al., 2017), as downscaled for Europe (Kok et al., 2019). The five SSP storylines provide alternative trajectories of high or low challenges to adaptation as follows. Like the global versions of the SSPs, the European versions (Kok et al., 2019) include:

- SSP1: a sustainable future with global cooperation and less intensive lifestyles
- SSP2: a world towards convergence, and moderate changes compared to present. (The European SSP2 was created ex-post and is unpublished, to ground the work of the United Kingdom SSPs.)
- SSP3: a future in which countries struggle to maintain living standards in a high-carbon intensive Europe
- SSP4: a world in which power becomes concentrated in a small elite and where Europe becomes an important player
- SSP5: a world where a lack of environmental concern leads to the over-exploitation of fossil fuel resources addressed by technological solutions

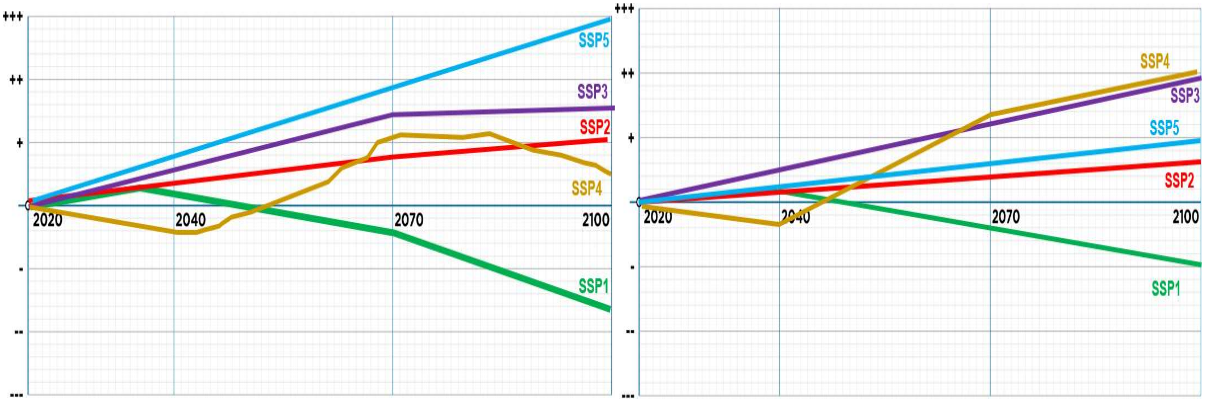
The five SSP narratives each provide a “future context” for various single indicators. The bottom-up component is provided by the view shared by each expert on what the trend for the future should entail. For example, as in Figure 4, the trend of proportion of elderly living alone in an SSP1 should generally follow a steady decrease trend. However, the strength of the decrease and in, few instances, even the direction of change (increase rather than decrease) could be different for each expert, reflecting individual interpretations and experiences.

Figure 5: Qualitative scenario trend in a sustainability scenario (SSP1) of proportion of elderly living alone as a deviation from present-day (2020) throughout the 21st century. Scenario trends were prepared individually in an elicitation by four experts (coloured lines) based on interpretation of the same storyline; the divergent individual trends are combined with a consensus process (thicker black line).



We highlight the interesting fact that, even in a very small group with similar expertise and similar background information, the trends are quite divergent (Figure 4). This suggests that correlations, even when established in literature, may still be questionable locally if driven by social or cultural norms. For this reason, a "consensus" step in the elicitation needs to follow and be facilitated for each variable in each scenario, followed by a consistency check for each scenario set. The resulting trends are the qualitative future trends for each indicator (Figure 5).

Figure 6. Qualitative scenario trends in grey surfaces that increase the urban heat island effect (left) and in the proportion of elderly living alone (right).



This section demonstrates how SSP-based projections can be quantified in the absence of model-based approaches. The basic idea here is to combine qualitative SSP-specific trends developed in the expert elicitation with observed trends of related indicators derived from official regional statistics. Two preliminary examples are shown at different scales, an analysis at NUTS2 level for European regions for a single indicator of vulnerability, and a comparable analysis at the local scale for the Helsinki metropolitan area in Finland for a related indicator.

3.4 SSP-based projections of a vulnerability indicator at NUTS2 level for Europe

The qualitative trends in Figure 4 demonstrate that future projections are highly uncertain, also considering social perception of what drives risk. This aspect needs to be maintained rather than simplified also in the quantification step presented here. One way to maintain this complexity is to present divergence of trends (for the same scenario and same variable) or variables (for the same scenario and same type of indicator).

As an example of an indicator for vulnerability to heat events at regional level across Europe, we analysed the proportion of persons at risk of poverty or social exclusion available at NUTS2 level from Eurostat (Eurostat, 2024). The indicator is available for the period 2014-2023 for some regions in Europe (Figure 7), although the time-series is complete only for a small sub-set of these. Here, we focus our analysis on regions with at least eight years of data during the 10-year period 2014-2023; these were 114 NUTS2 regions out of 258 including those that had data for a shorter period.

Building from Pedde et al. (2019) and Rohat et al. (2019), we analysed the linear trends in each region and then defined SSP-versions of extrapolating these trends into the future by:

1. defining the range of possible future changes for each country as the range of linear trends of all NUTS2 regions within one country (cf. Figure 8), and
2. assigning SSP-specific trends by selecting a trendline within this range according to the qualitative changes for each SSP that were determined in the SSP elicitation for the year 2040 as follows (see Figure 6 above):
    - For SSP4, the minimum value of the range of linear trends for all regions within one country was used to extrapolate to the year 2040.
    - For SSP3, the maximum value of the range of linear trends was used.
    - For SSP2, the average of the minimum and maximum trend was used.
    - For SSP1 and SSP5, a trend calculated as the minimum + (2/3)*(maximum-mininum) of the range of trends was used.

Figure 7. Persons at risk of poverty or social exclusion in 2022 by NUTS2 region. Note that data coverage is substantially smaller for the full period 2014-2022. Source: (Eurostat, 2024)

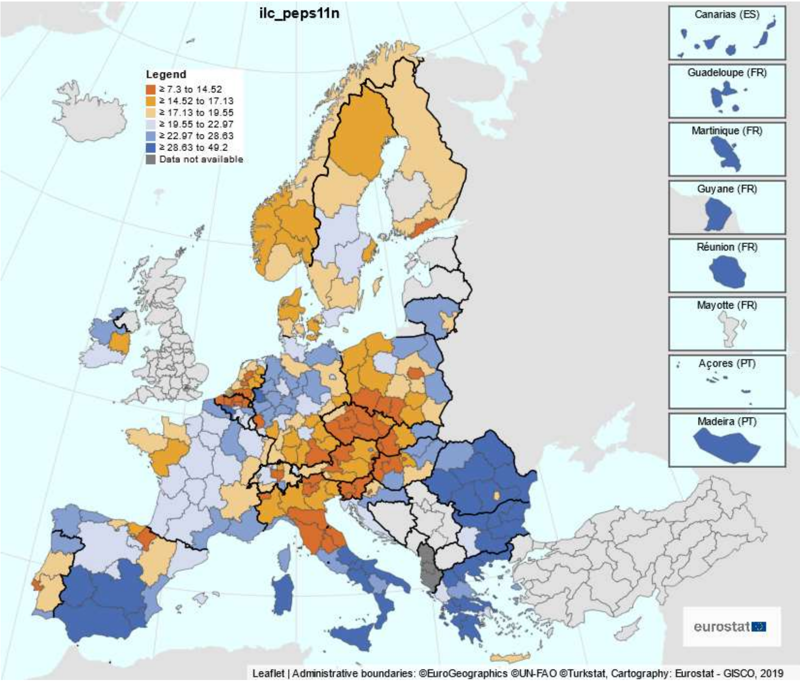
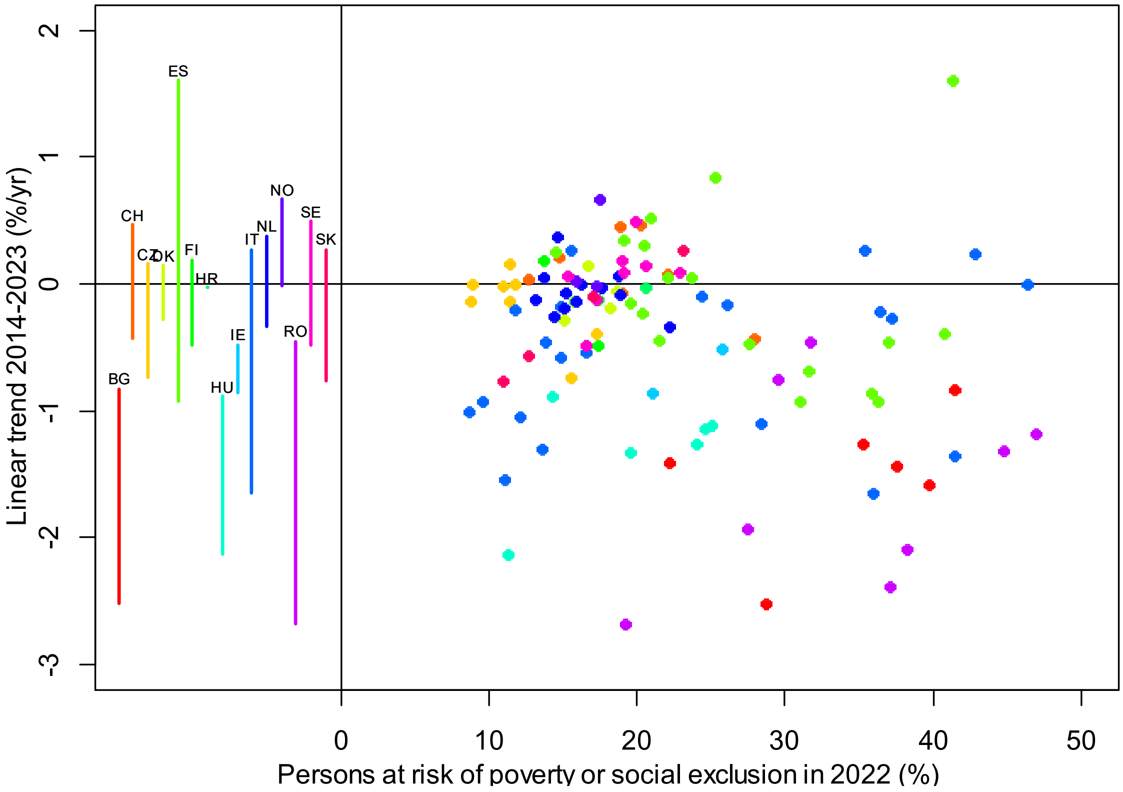
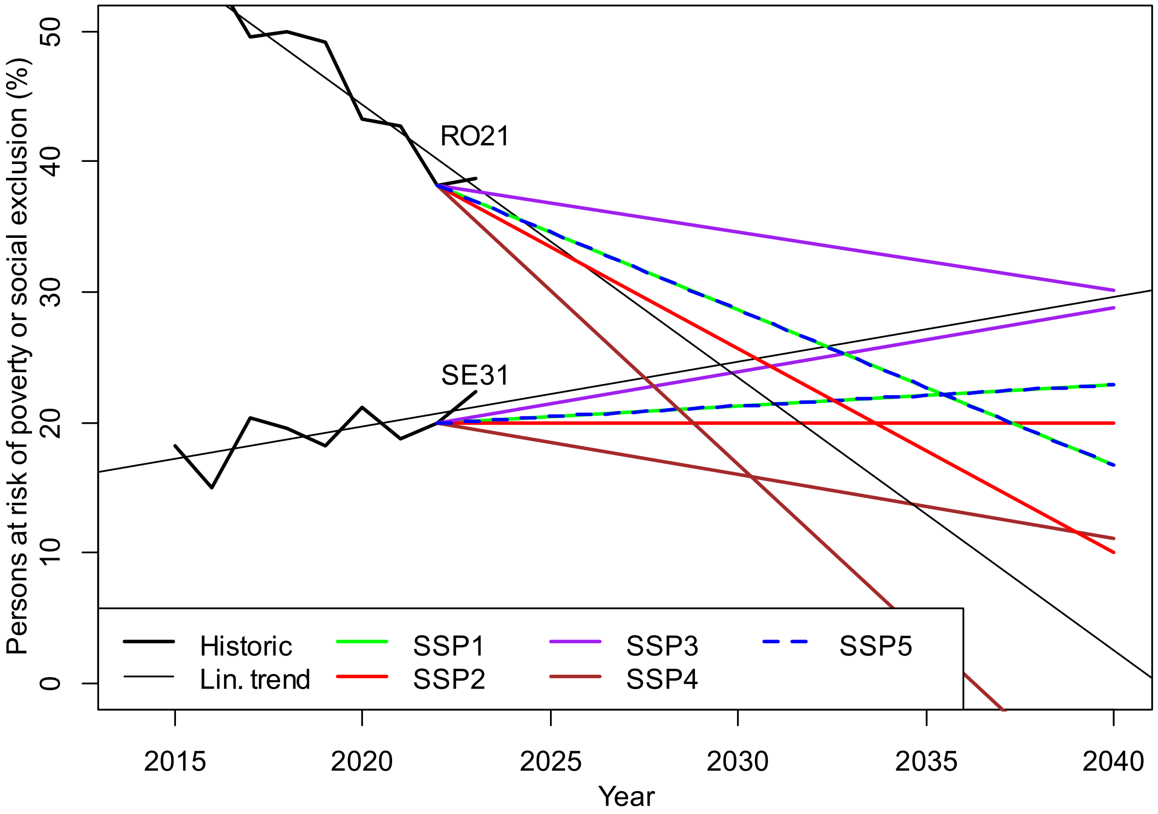


Figure 8. Persons at risk of poverty or social exclusions in 2022 for individual NUTS2 regions in Europe and their linear trend for 2014-2023 (point symbols) and the trend ranges of NUTS2 regions within a country (coloured lines on the left where the 2-character label indicates the country code). Note that data were available only for a sub-set of NUTS2 regions in Europe.



The resulting SSP-specific trend extrapolations are shown for two example regions in Romania (NUTS2 region RO21 “Nord-Est”) and Sweden (NUTS2 region SE31 “Norra Mellansverige”) in Figure 9. The region in Romania has a higher proportion of persons at risk of poverty or social exclusion than the region in Sweden but shows a strong decreasing trend over the observed time period, whereas the observed trend for the region in Sweden is increasing. Scenario projections for the Romanian region all continue this decreasing trend, but at different degrees. For the Swedish region SSP projections give a range of both increasing and decreasing trends.

Figure 9. Proportion of people at risk of poverty or social exclusion in two NUTS2 areas in Europe, Nord-Est (RO21) in Romania and Norra Mellansvergie (SE21) in Sweden, in the observed time-series 2014-2023 and for projections for the period 2023 to 2040 for five SSP-based scenarios.



The observed distribution of values for the indicator shows higher values in southern and eastern Europe for 2022 (Figure 10). The spatial patterns look slightly different for the scenarios for 2040 with increases in most regions for SSP3, decreases for SSP4, and relatively small changes for SSP2, SSP1 and SSP5.

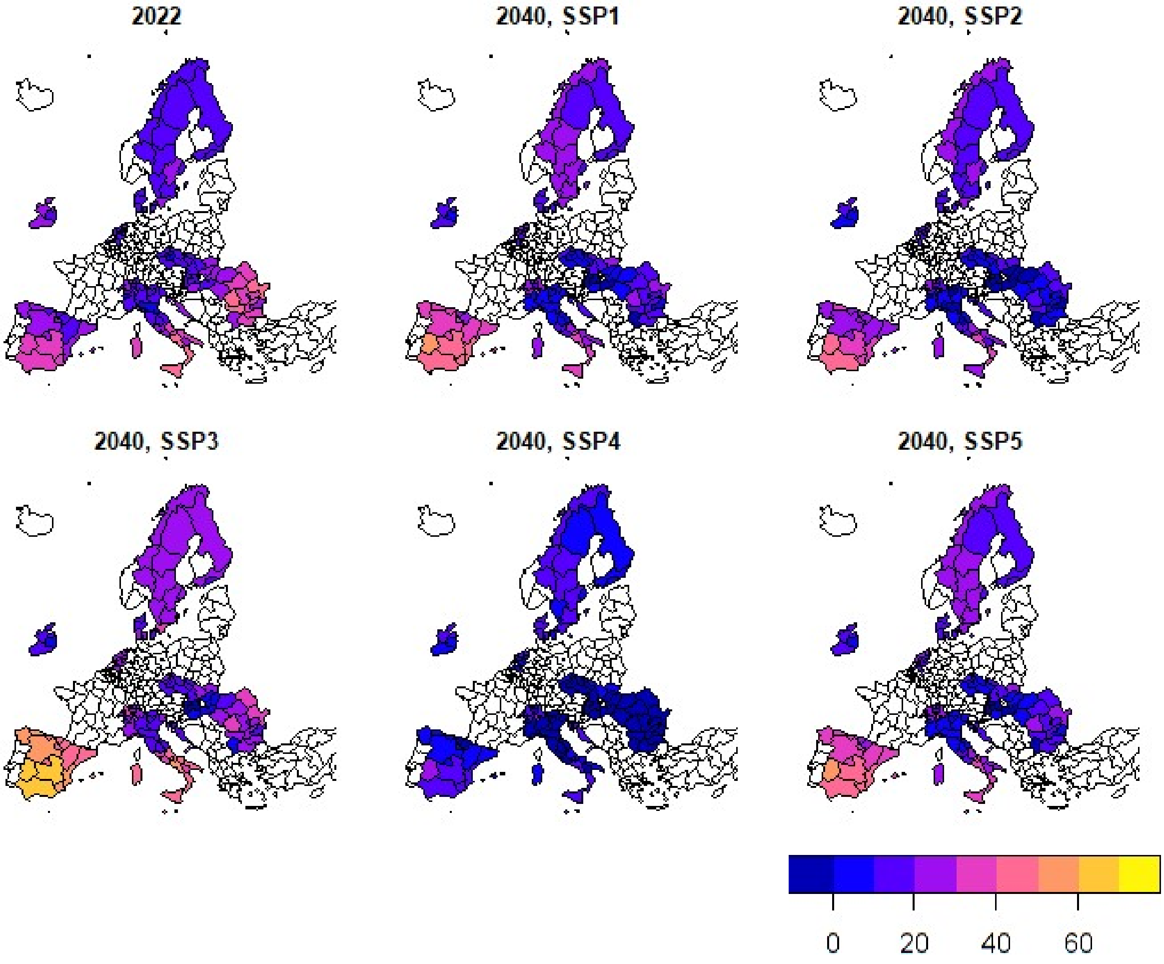
This example demonstrates a possible approach for scenario quantifications by combining qualitative scenario trends with historic data. There are several shortcomings of the analysis which should be considered when interpreting scenario results or to possibly further refine and revise these:

- The scenario values should still be carefully checked for plausibility, which is a step not done comprehensively in this example.
- The statistical data used for the analysis in this example are still incomplete and do not offer full spatial coverage across the EU as one might wish for in a European-scale analysis.
- The Eurostat indicator used here combines both economic (risk of poverty) and social (risk of social exclusion) aspects which provides ambiguity in its interpretation as an indicator for human wellbeing. It also provides a wider scope than the indicator discussed in the expert

elicitation to develop qualitative SSP trends (which was defined as the proportion of elderly living alone).

- Future trends are based on historic developments of all regions within one country. However, the range of trends within one country depends on the variability of socio-economic conditions, but can also be influenced by the number of regions within each country, which for the data presented here varies between 3 (in Finland, Norway and Ireland) and 21 (in Italy). The range of observed trends for a country with a small number of NUTS2 regions might be smaller than if a larger group of regions were considered. Alternative approaches for grouping NUTS2 regions to define ranges of trends from which SSP trends are selected could be considered.
- The linear trend extrapolation needs to be checked for plausibility, especially when applied on longer time horizons. For example, the SSP4 projection for the Romanian region (see Figure 9) falls below 0% before the year 2040, which demonstrates that linear trend extrapolation may not be sensible to be applied in all cases.

Figure 10. Proportion of people at risk of poverty or social exclusion for NUTS2 regions in Europe in official statistics for 2022 and for projections for 2040 for five SSP-based scenarios. Data are shown for regions for which time-series data were available for at least eight years in 2014-2023.



3.5 Mapping of heat risk in the Helsinki metropolitan region

In this section we illustrate the application of the results of the elicitation process conducted at European level (cf. section 3.3) in a local northern European context with an example of heat risk in the Helsinki Metropolitan region, building on earlier work and ongoing work conducted in a national project. The case study combines multiple indicators, presents results of on-going work on present-day heat risk and tests the approaches developed in this report for projecting individual indicators of heat risk into the future.

3.5.1 Mapping of present-day vulnerability, exposure and hazard to define risk

In 2015, an analysis was carried out on indicators representing various aspects of social vulnerability to climate change in the Helsinki Metropolitan Area, located in southern Finland, consisting of the four municipalities Helsinki, Vantaa, Espoo and Kauniainen. Indicators were combined into indices representing dimensions of social vulnerability to heat and flooding. In the analysis, social vulnerability was understood as an outcome of sensitivity, adaptive capacity and exposure. The purpose of the study was to enhance understanding of the spatial distribution of vulnerability to climate change within the Helsinki Metropolitan Area as observed. The analysis did not involve projecting social vulnerability into the future but provides useful information on the selection of indicators (Kazmierczak, 2015).

In the on-going analysis, risk is defined as the function of hazard, exposure and vulnerability. A set of indicators representing different aspects of heat risk were selected based on expert judgment and data availability, drawing on the identification of indicators conducted in Kazmierczak (2015). The selected indicators share similarities with the indicators reviewed in the European scale analysis of this report but differ in some respects. While in the local context the percentage of green area in a given region (as used in this example) may suffice, in coarser scale analyses where distances are long it has little meaning. There, a measure of the distance to green space might be more applicable in reflecting exposure to UHI. Due to data availability, specifically with respect to data on chronic illnesses, the analysis is conducted on the level of postal code regions extending across the Helsinki Metropolitan Area. Available data covers the period from 2000 to 2017 (for some indicators 1998-2017). Long-term means covering the period are mostly used in the analysis of observed spatial distribution of heat risk. The hazard indicator forms an exception representing the temperature surface on a single hot day (12 June 2021).

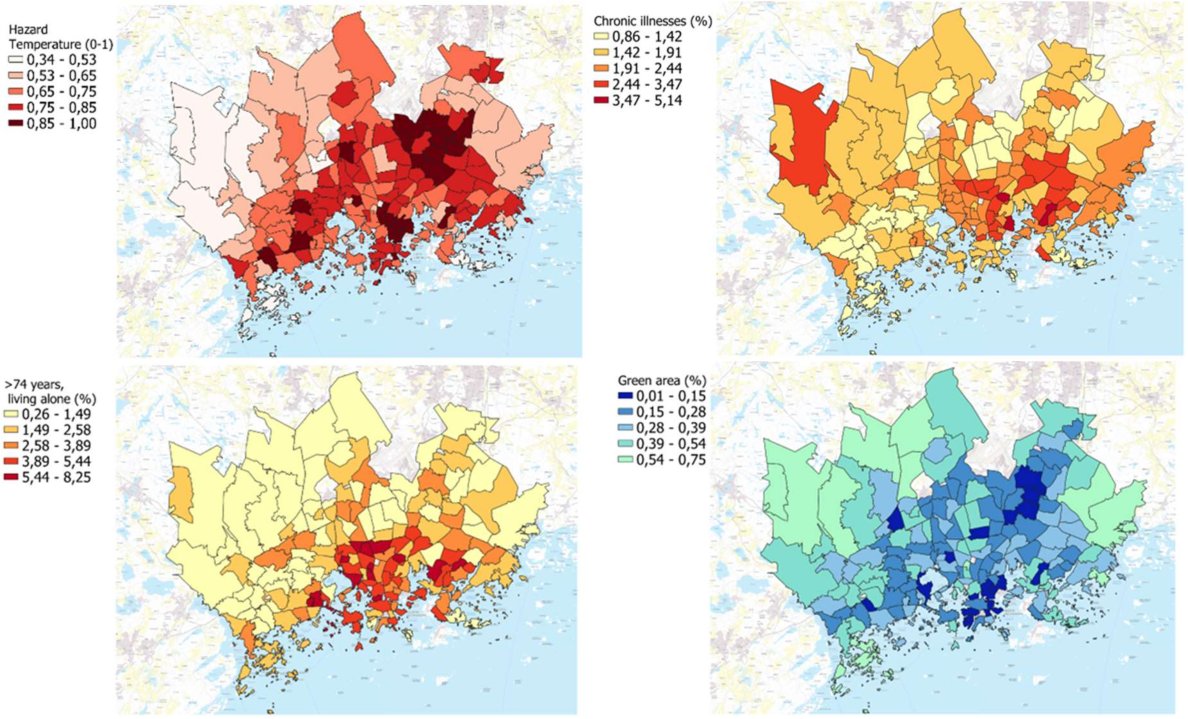
Table 1 lists the indicators included in the analysis and data sources that have been used (mostly requiring a license for accessing the data) as well as possible alternative sources publicly available. The indicator on chronic illnesses is represented by data on the visits to public specialised health care due to reasons associated with diabetes, dementia, mental disorders, renal diseases, diseases of the nervous system and cardio-vascular diseases and linked with information on the postal code area of residence.

Table 1. List of indicators selected for the analysis and the sources of data. PAAVO = Postal code area statistics, Statistics Finland.

Indicator	Aspect of vulnerability, exposure, or hazard	Risk factor	Data source used in the study	Open data source
Low income (%)	Economic status	Vulnerability	Statistics Finland, licensed data	PAAVO
Unemployed (%)	Economic status	Vulnerability	Statistics Finland, licensed data	PAAVO
Low education (%)	Information	Vulnerability	Statistics Finland, licensed data	PAAVO
Foreign language (%)	Information	Vulnerability	Statistics Finland, licensed data	
Chronic illnesses (%)	Health	Vulnerability	Statistics Finland, licensed data	
Rental housing (%)	Housing	Vulnerability	Statistics Finland, licensed data	PAAVO
> 74 years old living alone (%)	Social networks	Vulnerability	Statistics Finland, licensed data	
Green area (%) in total land area	Physical environment	Exposure	CORINE	CORINE
> 74 years old (%)	Demographic	Exposure	Statistics Finland, licensed data	PAAVO
Temperature surface 12.7.2021 (°C)	Urban heat island	Hazard	Landsat8	

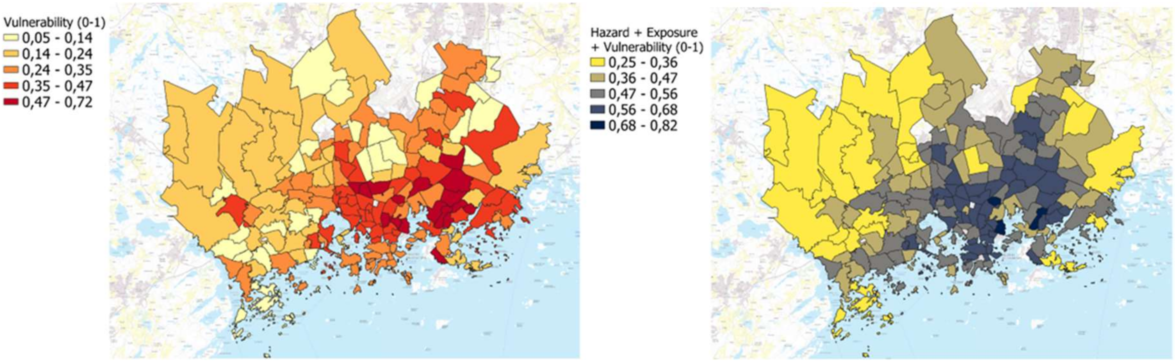
Figure 11 shows maps of selected indicators representing aspects of the hazard (temperature surface on a hot day), vulnerability (percentage of the postal code area population with chronic illnesses and percentage of population >74 years living alone) and exposure components of heat risk (percentage of green area).

Figure 11. Indicators representing aspects of the hazard (top-left: temperature surface on a hot day), vulnerability (top-right: percentage of the postal code area population with chronic illnesses; bottom-left: percentage of population >74 years living alone) and exposure components of heat risk (bottom-right: percentage of green area).



While the choice of selecting indicators most relevant in each case is ideally left to the end-user (Carter et al., 2016), in this example all indicators representing aspects of social vulnerability are merged into an index to offer an overall impression of the spatial distribution of vulnerability (Figure 12, left). Areas with highest vulnerability are largely located in the eastern and southern areas of the study region, where population density is higher than in the areas extending to the north and west. Similarly, all indicators of hazard, exposure and vulnerability (listed in Table 1) are combined into an index of heat risk (Figure 12, right), offering largely a similar overall impression of the spatial distribution as the index on social vulnerability (Figure 12, left).

Figure 12. Social vulnerability to heat (left) and heat health risk (right) in the Helsinki metropolitan area indicated by a dimensionless indicator ranging from 0 to 1 (0 indicating low and 1 high vulnerability or risk).



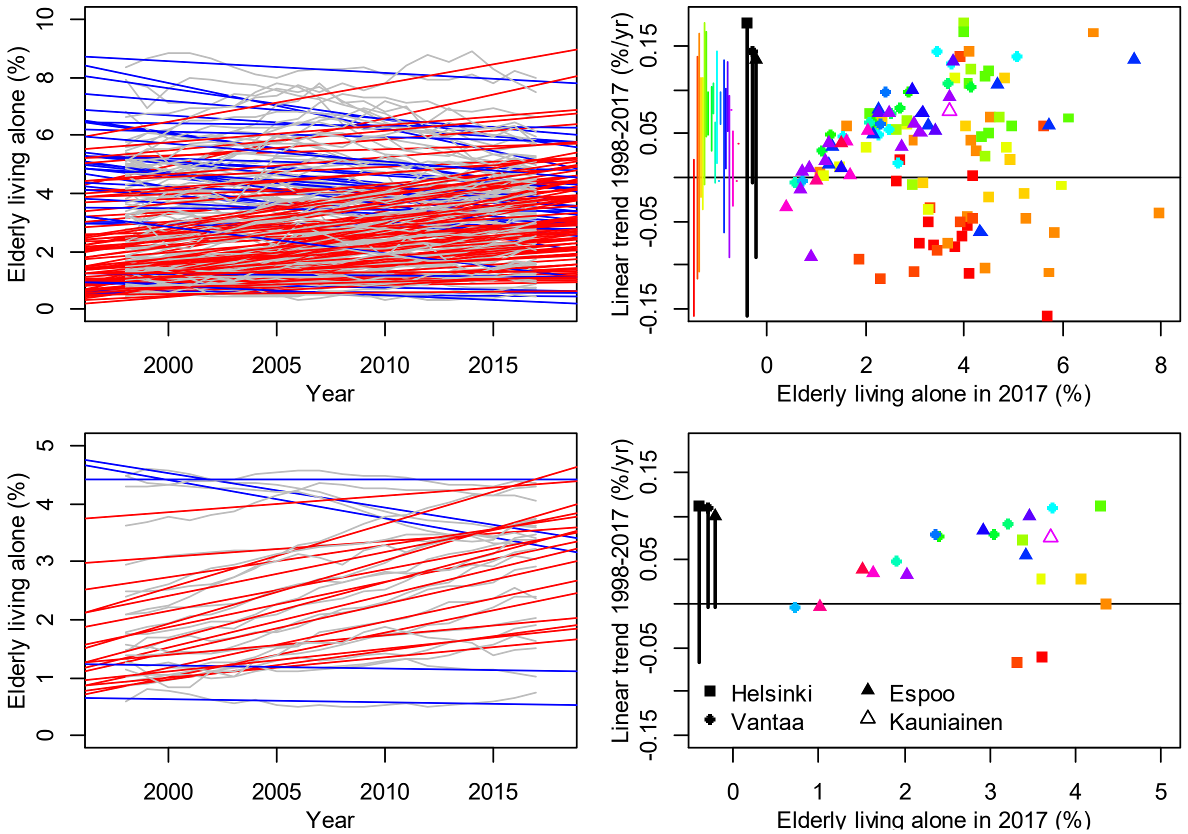
3.5.2 Future projections of elderly living alone

Examination of the observed local trends in the indicators, across the longest available time period (in this case from 1998 to 2017), provides a starting point for future projections. Analysis of observed trends links to peoples' experiences and to the understanding of the mechanisms behind the trends, and thus is an essential step when attempting to project future change, especially in a local context.

As an example of a future projection of a vulnerability indicator, we selected one of the observed indicators, the proportion of elderly (above 75 years) living alone, to develop future SSP-based projections for the year 2040 at the postal code area level that are consistent with the observed data. The principal approach used here of combining historic trends with qualitative trends defined in an expert elicitation is the same as for the European example in section 3.4 above, allowing to discuss some differences in scenario interpretation with respect to the spatial scale of the indicator.

Linear trends for the observed time-series 1998-2017 in elderly living along were calculated for each postal code area as well as for values aggregated to the next-level statistical spatial unit called "suuralue" that combines several postal code areas in one part of a municipality (Figure 13, top-left for postal code areas). The 172 postal code areas of the region are grouped in 23 "suuralue" regions.

Figure 13. Proportion of elderly living alone at postal code level (top) and "suuralue" level (bottom) as a time-series for 1998-2017 in their linear trends (left) and as a plot of the linear trend and the 2017 value (right). A "suuralue" combines several postal code areas into one statistical unit. Red (blue) lines on the left indicate increasing (decreasing) trends. The bars on the right show the ranges of trends for all postal code areas within a single "suuralue" (coloured) and municipality (black).

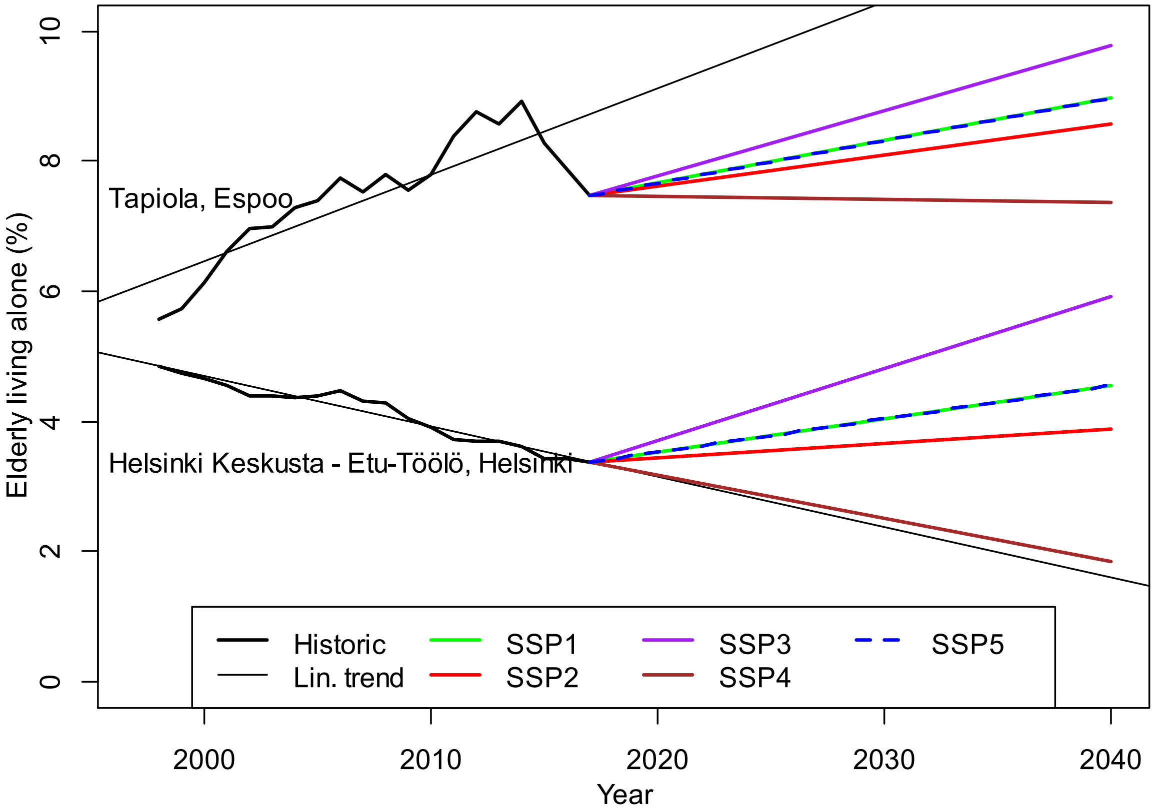


The linear trends were then used to define SSP-versions of extrapolating these into the future, following the approach used at European NUTS2 scale, by:

1. Defining the range of possible future changes for each municipality as the range of linear trends of all "suuralue" regions within one municipality (black bars in Figure 13, bottom-right). The small municipality Kauniainen, located as an "island" within the Espoo municipality and consisting of a single postal code and "suuralue" area, was treated as part of the Espoo municipality.
2. Assigning SSP-specific trends by selecting a trendline within this range according to the qualitative changes for each SSP that were determined in the SSP elicitation for the year 2040 as follows (see Figure 6 above):
    - For SSP4, the minimum value of the range of linear trends for all regions within one country was used to extrapolate to the year 2040.
    - For SSP3, the maximum value of the range of linear trends was used.
    - For SSP2, the average of the minimum and maximum trend was used.
    - For SSP1 and SSP5, a trend calculated as the minimum + (2/3)*(maximum-mininum) of the range of trends was used.

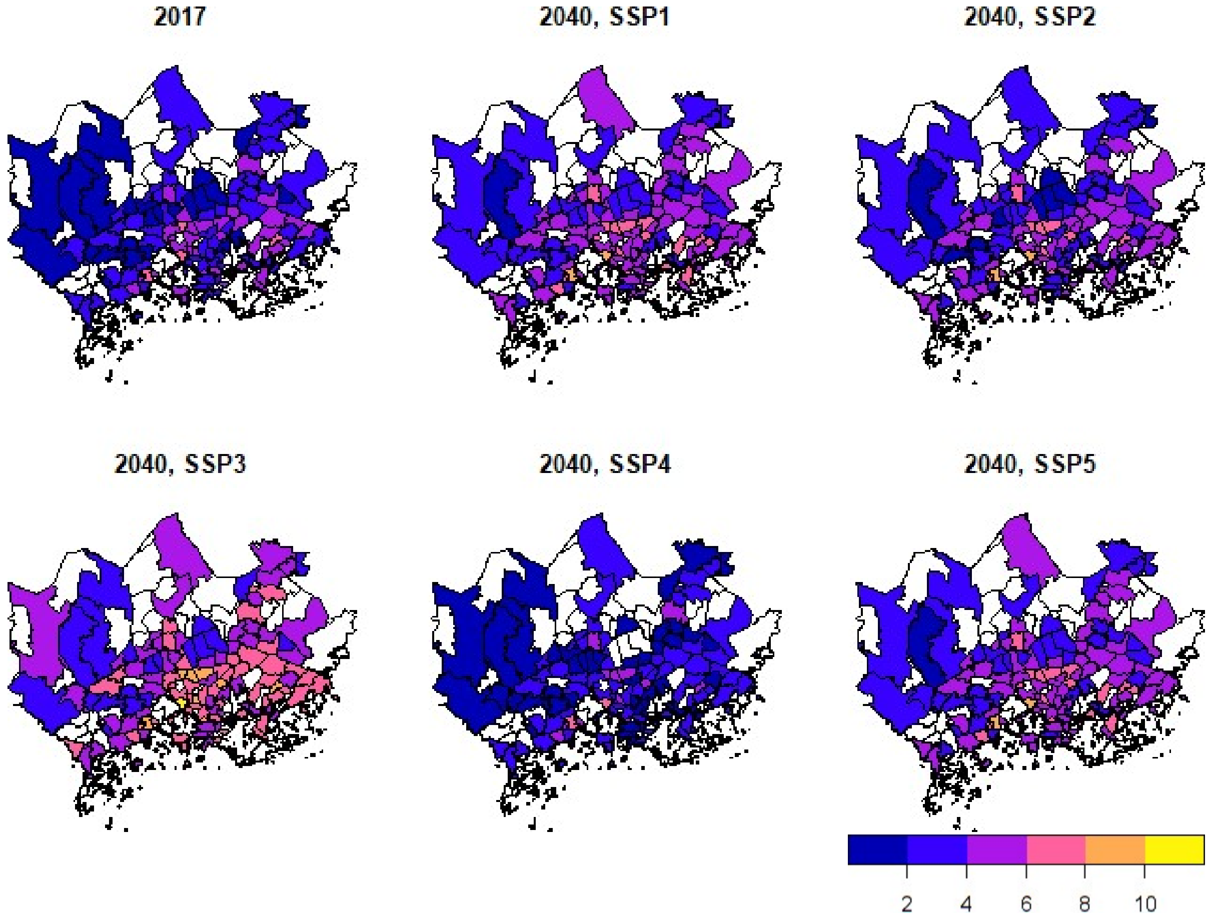
The qualitative SSP trends developed at European level in the expert elicitation are largely in line with SSP narratives developed at national scale for Finland for the health and welfare sector (Lipsanen et al., in review). The resulting ranges of trends were nearly completely above 0% for Espoo and Vantaa, but spanned a wider range with a negative value for the minimum trend in Helsinki (Figure 13, bottom-right). Consequently, changes provided by scenario estimates differ between areas in Helsinki from the other three municipalities, as illustrated in Figure 14 for the Tapiola postal code area in Espoo and the Etu-Töölö postal code area in Helsinki. The latter is one of the areas with an observed decreasing trend in the proportion of elderly living alone. Scenario values for 2040 span a wide range and in the case of Etu-Töölö reverse the observed negative trend to reach a larger value in 2040 for SSP3 than observed during the period 1998-2017.

Figure 14. Proportion of elderly >74 years living alone in two postal code areas in the Helsinki metropolitan area, Tapiola in Espoo and Etu-Töölö in Helsinki, in the observed time-series 1998-2017 and for projections for up until 2040 for five SSP-based scenarios.



The spatial patterns of the scenarios show the strongest increases in the proportion of elderly living alone under SSP3 consistently across the whole region and moderate increases for SSP2, SSP1 and SSP5 (Figure 15). The largest value for the indicator is in the Munkkiniemi postal code area in Helsinki, which increases from 8.0% in 2017 to 10.5% in 2040 under SSP3. Under SSP4, small decreases in Espoo, Kauniainen and Vantaa and larger decreases in Helsinki modify the spatial pattern for the region.

Figure 15. Proportion of elderly >74 years living alone in the Helsinki metropolitan area in official statistics for 2017 and for projections for 2040 for five SSP-based scenarios (in % per postal code area). White indicates postal code areas with missing data in 2017, the last year of the observation period, for which no scenario values were prepared.



Some of the shortcomings listed for the European NUTS2-level example above apply to a somewhat lesser degree to the Helsinki metropolitan area example here:

- The statistical data used for the analysis in this example are providing a more complete spatial and temporal coverage than in the example of the European-scale analysis. Linear trends based on a 20-year period (instead of only 10 years at NUTS2-level) are more robust and provide more confidence e.g. in statistical significance tests for the trends.
- Also, unlike the Eurostat indicator used above which combines both economic and social aspects in its definition, the indicator used in the Helsinki study has a clearer definition focusing on the social aspect and, with the elderly, on a population group that has been identified as vulnerable to heat stress. It is also better in line with the definition used in the expert elicitation to develop qualitative SSP trends for which the identical definition has been used.
- Similar to European-scale example, the linear trend extrapolation needs to be checked for plausibility, especially when applied on longer time horizons, and alternatives to purely linear trend extrapolations should be considered to avoid scenario estimates below 0%.
- As with the European-scale example, the grouping of areas to quantify ranges of trends used to select scenario trends was based on municipality which all show a large variety of socio-economic conditions.

Future work in this case study (carried out in the CHAMPS research project[13]) will address some of these issues. One idea to define more meaningful groupings of areas with similar housing structure and socio-economic conditions is to use city-scale information on the type of housing to form groups of postal code areas. Simulations with an urban development model for the region are also currently being conducted that account for expected changes in the housing structure under different scenarios of urban growth (e.g. compact vs polycentric urban development) and assign areas of new urban development in a region for which the population is projected to continue growing. Ongoing work will also expand the analysis to other indicators of exposure and vulnerability (cf. Table 1) to allow assessing future social vulnerability and heat health risks under different socio-economic and climate scenarios comparable to the maps shown in Figure 12 above for the present-day conditions.

4 Research gaps in approaches and data for exploring future exposure and vulnerability to climate change

The development and interpretation of scenarios involve inherent subjectivity, as scenarios are not meant to serve as precise predictions but rather as tools to aid decision-makers in understanding the potential impacts of their choices (IPCC, 2023). Consequently, scenario development, especially within the context of climate change adaptation, requires flexibility and careful consideration of uncertainties. The participatory approach presented in this report highlights how qualitative trends can be co-developed by experts to define plausible futures, as shown in the elicitation process. However, it is essential to recognize that the outcomes of such processes depend heavily on the composition and perspectives of the experts involved. Different expert groups might propose varying scenario elements, and even individual experts might interpret scenarios differently (as illustrated in Figure 4).

The diversity of perspectives is a strength in scenario development, as it introduces a range of plausible futures that can be considered for more comprehensive adaptation planning. However, it also creates challenges. When different stakeholders—such as policymakers, scientists, local communities, and business representatives—are involved in the scenario process, the resulting scenarios may reflect differing priorities or interpretations of drivers of risk. This divergence can complicate efforts to reach a consensus on which indicators to prioritize or how to interpret qualitative trends.

To address this, it is important to incorporate mechanisms that facilitate reconciliation of differing viewpoints. For example, conducting additional rounds of consultation or employing a structured consensus-building process can help create a more unified interpretation of future vulnerability trends. By acknowledging and valuing the range of stakeholder inputs, this approach can capture a more comprehensive view of vulnerabilities, albeit at the cost of added complexity in reaching final agreements on indicator selection and trend projections. Such an approach does not need to be more time consuming than quantitative desktop research aimed at providing state-of-the-art projections. For instance, updating datasets and projections with continuously evolving evidence and knowledge on baselines and interactions requires time and resources too, to be carried out appropriately.

The purpose of the analysis in this report is to demonstrate an approach that combines qualitative trends with quantitative scenarios to assess future climate-related vulnerabilities balancing

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[13] https://www.syke.fi/projects/champs (assessed 30 October 2024)

legitimacy, salience and credibility (Cash et al., 2002). To apply the guidelines of the present report further, in refined and expanded findings, it would be beneficial to:

- Engage a broader set of stakeholders and expand the indicator selection to have a wider diversity of perspectives which could enhance the relevance and validity of scenario-based indicators (Piemontese et al., 2022). This may also help in identifying overlooked social, cultural, or environmental factors that are crucial for robust climate resilience planning. Prioritizing the connection between stakeholder-led narratives and quantifiable trends in participatory approaches is essential to strengthen these indicators (Pedde et al., 2019) .In Section 3, we provide an example of how qualitative stakeholder inputs can be translated into quantifiable trends, building upon this necessity. .
- Facilitate consensus-building with a structured approach to integrating stakeholder feedback, such as through workshops, or iterative consultation rounds, can help reconcile differences and create a more balanced representation of future vulnerabilities. This process ensures that while diverse perspectives are incorporated, the final set of indicators or scenario elements is cohesive and actionable. The trade-off is that it is time and resource consuming.
- Include non-linear developments and surprises. While linear trend extrapolation is used here for simplicity, it has limitations, especially for long-term projections. Alternative and emerging approaches, such as non-linear modelling or machine learning-based projections (Yadav, 2022), might capture complex socio-economic dynamics more effectively and provide more accurate projections for indicators like urbanization or aging demographics. However, these projections are not yet established science, and qualitative analysis may still be necessary to complement projections. In EUCRA, for example, the concept of wildcards is used qualitatively (European Environment Agency, 2024). Social tipping points, as well as positive tipping points, with strong regional impacts may be prioritised as well in exploration of drivers of risk (Juhola et al., 2022; Tàbara et al., 2018).

4.1 Addressing uncertainties in projections

Uncertainties are an inevitable part of climate change projections, including also when integrating non-climatic factors such as social and economic dynamics (see Box 2.3 in Pedde et al., 2024). Different projection models may yield different results based on the assumptions and methodologies they employ, leading to varying interpretations of future climate risk. A critical challenge is to balance precision with policy relevance with research environments increasingly limited by time and human resources. With model resolution and accuracy constantly evolving, it is important to consider how and when to include novel datasets or updates as they become available. For instance, high-resolution downscaled datasets, such as recent SSP projections at a 1 km resolution for urban areas (Gao and Pesaresi, 2021), are becoming available increasingly faster. Resource availability for modelling single indicators and their interconnections influences the selection of projection methods. The indicators in Rohat et al. (2019) could therefore be fully or partly updated. For instance, the Terama et al. (2019) age group projections (65+, for the elderly), used in Rohat et al. (2019) could be substituted with more recent gridded population projections by Falchetta et al. (2024) combined with SSP age distribution (69+ for the elderly).

Even when resources are available, utilizing such high-resolution datasets still comes with an essential accounting of the underlying assumptions and limitations. For example, the latest urban expansion projections may not fully consider shifts in land-use policies or emerging environmental preferences, such as the trend toward coastal or green spaces, which may vary by region. European-specific dynamics, such as urban green initiatives, may need to be integrated into these projections to improve relevance and accuracy. Clear documentation of assumptions enhances transparency and allows users to understand the scope and limitations of each dataset and model.

4.2 The purpose of scenarios in climate adaptation: assumptions, not predictions

It is essential to emphasize that the purpose of scenarios is to compare coherent assumptions about potential future impacts rather than to predict the future with certainty. Scenarios enable a structured exploration of diverse possible futures based on systematic variations in underlying socio-economic and environmental conditions. For instance, fertility rates may have strong implications for demographic trends in Finland, directly influencing projections of vulnerability and exposure to climate hazards. However, as fertility rates are subject to fluctuations and policy interventions, these projections should not be regarded as fixed forecasts, but rather as conditional expectations based on specified socio-economic pathways or (temporary) baselines.

We emphasise that the assumptions underlying each scenario must be made explicit to increase transparency for users. This is a priority, with transparency taking over precision, when these criteria compete for time and resources. By doing so, stakeholders and policymakers can better understand the assumptions that underpin projected trends, which facilitates informed decision-making and scenario comparison. This transparency ultimately helps in refining assumptions or integrating new data as it becomes available, ensuring that scenarios remain relevant and reflective of emerging knowledge.

5 Conclusion

This report demonstrates that scenarios can (and should) be used to enhance policy relevance at different scales. To achieve this, the priority should lie in the careful selection of relevant indicators, with resolution assessed subsequently based on contextual needs. By employing a flexible scaling method, this report facilitates a bottom-up approach for choosing indicators that remain consistent with global datasets, yet relevant to specific applications such as those exemplified. Our approach highlights the work of Rohat et al. (2019) as a valuable example in the context of health risk. Rohat et al. (2019) demonstrate how composite indices can incorporate scenario-based single-indicators such as income, age, and social isolation combined with climate projections. Building on this foundation, this report proposes a pathway for increasing policy relevance of exposure and vulnerability projections, in a context of constant data and scenario-based insights updates.

A key component of this process is the use of participatory methods, which allow for the identification of complex, value-driven indicators—such as governance—that may be challenging to quantify through standard modelling. This inclusive approach enables the co-development of indicators that are context-sensitive and tailored to specific risks, enhancing the legitimacy and relevance of the resulting indices for diverse stakeholders.

List of abbreviations

Abbreviation	Name	Reference
EEA	European Environment Agency	www.eea.europa.eu
CID	climatic impact driver	
C3S	Copernicus Climate Change Service	https://climate.copernicus.eu
ECDE	European Climate Data Explorer	https://climate-adapt.eea.europa.eu/en/knowledge/european-climate-data-explorer
EUCRA	European Climate Risk Assessment	https://www.eea.europa.eu/publications/european-climate-risk-assessment
IPCC	Intergovernmental Panel on Climate Change	https://www.ipcc.ch
JRC	Joint Research Centre	https://joint-research-centre.ec.europa.eu
NCID	non-climatic impact driver	
SSP	Shared Socioeconomic Pathway	https://iiasa.ac.at/models-tools-data/ssp

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