



# Emerging regional perspectives of global climate change scenarios: a systematic review

Simona Pedde<sup>1</sup> · Kasper Kok<sup>2</sup> · Eric Kemp-Benedict<sup>3</sup> · Oliver Johnson<sup>4</sup> · Henrik Carlsen<sup>5</sup> · Carole Green<sup>6</sup> · Sara Talebian<sup>5</sup> · Stefan Fagerström<sup>7</sup> · Xiaoshi Xing<sup>8</sup>

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## Abstract

Global climate change science-policy assessments have historically relied on emissions and mitigation scenarios, with relatively limited uptake in adaptation or vulnerability research. Reframing global climate scenarios can enhance their relevance in these fields. A systematic review of 155 studies involving regional scenario development reveals five key perspectives for regionalising the global Shared Socio-economic Pathways (SSP) narratives. While top-down approaches largely dominate, multigenerational regional scenario analyses are emerging, where first-generation regional SSPs provide context for second-generation or further extensions. Participatory methods increasingly integrate bottom-up approaches, offering novel insights into cross-scale consistency. By positioning global scenarios as both boundary objects and boundary conditions, this study highlights the opportunity to expand towards more diverse regional scenarios, potentially broadening engagement with impact, adaptation, and vulnerability scholars beyond the Global North.

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✉ Simona Pedde  
simona.pedde@wur.nl

<sup>1</sup> Soil Geography and Landscape Group, Wageningen University and Research, 6700 AA, Droevendaalsesteeg 3, P.O. Box 47, Wageningen 6708PB, The Netherlands

<sup>2</sup> Earth Systems and Global Change Group, Wageningen University and Research, P.O. Box 47, Wageningen 6700 AA, The Netherlands

<sup>3</sup> Sustainability Research Institute, University of Leeds, Leeds LS2 9JT, UK

<sup>4</sup> Government Office for Science, Salford, UK

<sup>5</sup> Stockholm Environment Institute, Stockholm, Sweden

<sup>6</sup> Departments of Global Health and Environmental and Occupational Health Sciences, School of Public Health, University of Washington, Seattle, WA, USA

<sup>7</sup> Climate Solution, Finnish Environment Institute (Syke), Helsinki, Finland

<sup>8</sup> Center for International Earth Science Information Network (CIESIN), Climate School, Columbia University, New York, NY, USA

## 1 Introduction

Scenarios have long been used as tools to explore multiple plausible futures, originating from military strategy in the 1950s and later expanding into corporate and policy planning, with methodologies ranging from exploratory and normative approaches to forecasting and extrapolation techniques (Bishop et al. 2007). Climate change scenarios have been used extensively, evolving over the past three decades in climate research to explore complex and policy-relevant questions (Moss et al. 2010). Half a century after their introduction, they have shaped how global and regional futures are framed. Yet, they could more effectively integrate diverse knowledge to inform science-policy syntheses such as the Intergovernmental Panel on Climate Change (IPCC) and the Intergovernmental Platform for Biodiversity and Ecosystem Services (Pereira et al. 2020; Turnhout 2024).

The historical focus of scenarios on mitigation pathways reflects the research priorities and methodological strengths of their time, rather than an intentional bias, building on modelling advances and top-down assumptions of how societies might develop. Examples include the coupling of economic growth with high energy intensity or the deployment and effect of large-scale technologies to absorb greenhouse gas emissions (Köberle 2019; Keyßer and Lenzen 2021; Grant et al. 2022). Such progress parallels a much slower uptake and influence of bottom-up perspectives that could inform regional scenario applications such as, for example, studies aimed at climate adaptation and regional climate-resilient development (Cradock-Henry et al. 2018; Kikstra and Waidelich 2023). This dual speed is partly due to the fragmentation among different forms of knowledge used in the impact, adaptation and vulnerability (IAV) communities (Conway et al. 2019). Historically, climate change scenarios have been developed alongside climate science and coordinated Earth System Modelling efforts (Moss et al. 2010; Carter 2022). This legacy is still reflected in the current climate change scenario framework, where the Shared Socio-economic Pathways (SSPs) inform climate change scenarios and assessments, as summarised in Supplementary Information I.

Unlike its predecessors, the SSPs inform but are not formally coordinated by the IPCC. This was perceived as an advantage to foster collaboration and broader inclusion of scientific communities and perspectives, such as IAV, across regions compared to previous frameworks (Ebi et al. 2014). Without IPCC mandate, however, the trade-off was the fragmentation of scenario studies in the IPCC Sixth Assessment Report: different studies and Working Groups used a patchwork of scenario concepts and generations. This limitation could have been mitigated with more formal coordination (Pirani et al. 2024). While climate adaptation was, in theory, designed to be as relevant as climate mitigation (O'Neill et al. 2014), by 2023 the share of adaptation studies was limited to 3% of the SSP extension literature (Andrijevic et al. 2023). An evaluation of the SSP process from the First Scenario Forum in 2019 (O'Neill et al. 2020) presents both achievements and needs for the future of the SSPs. Among the achievements, the authors highlight the successful integration of climate and societal futures, and their massive uptake across diverse topics, based on a database of over 1370 SSP extensions (Green et al. 2021). A recognised need, now being addressed (see overview by Andrijevic et al. 2023), was the previous absence of relevant societal indicators for adaptation such as governance, poverty, and inequalities. Another need, still relevant to our knowledge, is to improve relevance and legitimacy of the SSPs,

by addressing low inclusion of different perspectives and methodologies, including regional perspectives (O'Neill et al. 2020; van Ruijven et al. 2022).

We assess how diverse IAV communities have responded to the original call to regionalise SSPs (O'Neill et al. 2014; Van Ruijven et al. 2014). SSPs represent illustrative global pathways, designed to be used as boundary conditions for regional extensions. Early regional applications, such as the SSPs for the US Southeast (Absar and Preston 2015), emerged before the realisation of SSP-based emission trajectories, reflecting an early interest in applying the framework to adaptation-relevant, context-specific scenarios rather than climate mitigation alone. While regional applications contextualise the specific global pathways represented by the SSPs (O'Neill et al. 2020), the ways in which they interpret, align with, or depart from the global narratives vary considerably. Different scenario processes (Elsawah et al. 2020) exhibit varying degrees of cross-scale integration (Zurek and Henrichs 2007; Conway et al. 2019; Trutnevyte et al. 2019), making them difficult to compare, translate, or appraise (van Ruijven et al. 2022). Nonetheless, they offer potentially complementary perspectives on global socio-environmental narratives (Kriegler et al. 2012).

Building on this context, we ask: 'How have scientists regionalised SSPs?' To answer this, we analyse a database of 155 studies that have extended the global SSP basic narratives published by O'Neill et al. (2014), but realised before the broader visibility of SSP-based scenarios through CMIP6 simulations and the IPCC Sixth Assessment Report in 2021 (Pirani et al. 2024). We focus on this time window, roughly concluding in 2021, beginning with the development of the global SSPs before their integration into full scenarios. We examine the use of the original SSP framework, first published in 2014, for its quality of 'broad qualitative and quantitative elements to be extended for a wide range of outcomes' (O'Neill et al. 2024). We assume that, in many IAV-focused regional extensions, global SSP narratives may be an easier starting point than fully integrated SSP-based scenarios, particularly for studies emphasising local adaptation pathways and bottom-up perspectives (Wilbanks and Ebi 2014).

## 2 Database and process to synthesise regional perspectives

### 2.1 Database generation

To identify specific regionally extended SSPs published between 2014 and 2021, we conducted a systematic review in four stages: (1) searches, (2) screening, (3) data extraction, and (4) coding. The full documentation, including methodology and complete database, is published as an open data release in the NASA Socio-economic Data and Applications Centre (SEDAC) (Pedde et al. 2023).

Additionally, while publications from 2022 to 2023 were screened for additional relevant studies, only studies published up to 2021 were systematically coded and included in the quantitative analysis presented here. Screened studies from 2022 to 2023 are archived and available (see Supplementary Data Excel File). The steps, definitions, the iterative process for selected columns, and the update procedure for the database are summarised in Supplementary Information II.

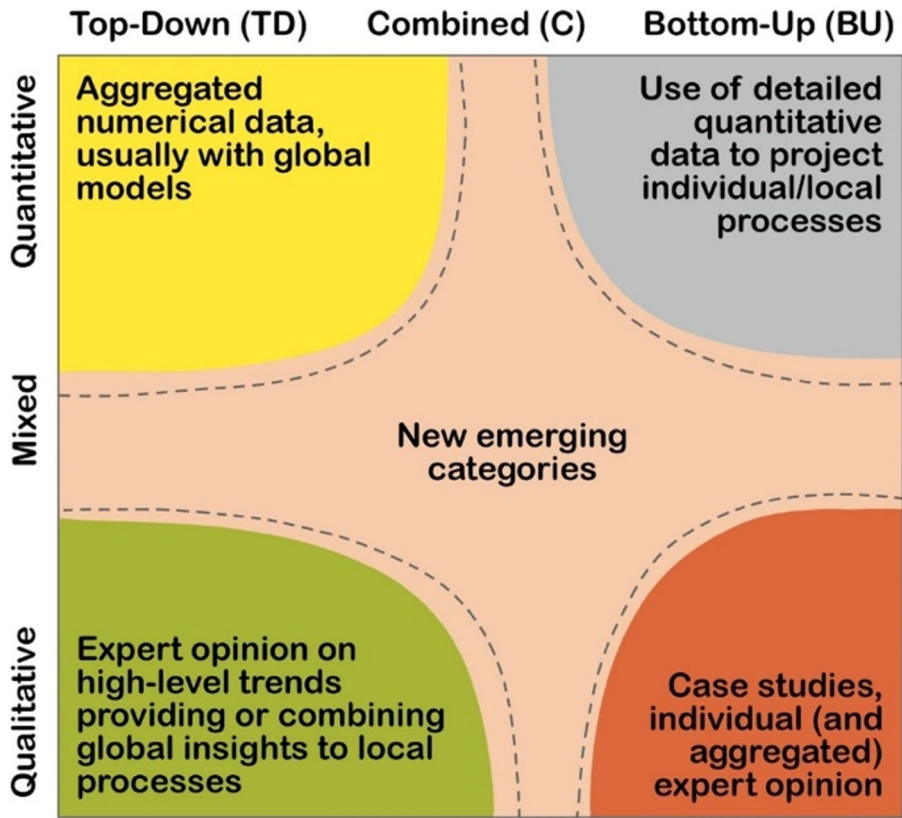
## 2.2 Process to synthesise the SSP regional perspectives

For eligibility in the screening step, studies had to meet two broad criteria: (1) add substantive knowledge about a sector or region, defined as context-specific insights grounded in empirical evidence, expert input, or participatory processes rather than replication of global narratives (Cradock-Henry and Frame, 2021a); and (2) clarify, as much as possible, how the contextualisation of the global SSP narrative(s) was performed (Van Ruijven et al. 2014). These broad criteria assume that extensions address the persistent ‘tension’ in multiscale analyses, between engaging relevant stakeholders (salience), including diverse knowledge and viewpoints (legitimacy), and maintaining scientific rigour (credibility) (Cash et al. 2002; Biggs et al. 2007). Based on the first SSP regional extensions, an array of methodologies has emerged around ‘nesting’ national and local datasets with quantitative pathways (modelled globally), often enriched with views from governance and traditions, reflecting real or perceived national and local priorities (Absar and Preston 2015; Frame et al. 2018).

Lacking further precise or standard criteria for eligibility, four heuristics were applied to form a cornerstone synthetic methodological space, visualised in Fig. 1. These heuristics, emerging during the iterative process of database generation, range across a spectrum of purely qualitative to purely quantitative methods through the top-down and bottom-up spectrum.

- Qualitative extensions integrate regional trends into the broad global socio-economic narratives of the SSPs (Zandersen et al. 2019). These extensions can range from fully bottom-up, with a strong emphasis on case studies, localised data, and participatory approaches to fully top-down, relying on broader conceptual constructs and incorporating global SSP narratives into existing local or regional scenarios (Absar and Preston 2015; Kok et al. 2019). They may also combine elements of both top-down and bottom-up approaches.
- Quantitative extensions primarily downscale SSP variables for specific sectors or regions (Sallaba et al. 2017) through statistical modelling, simulation modelling, agent-based modelling, system dynamics, or (regional) integrated assessment models (IAMs) (Brown et al. 2019). These extension may apply global SSP assumptions to regional projections (similar to ISIMIP climate impact studies) or use quantitative local data to refine assumptions. In other words, similar to qualitative extensions, they may combine elements of both top-down and bottom-up approaches.
- Mixed approaches integrate both qualitative and quantitative elements, often combining top-down and bottom-up processes. These studies often develop regional narratives with downscaled projections or sectoral analyses (Li et al. 2018) and may indicate novel, emerging approaches.
- SSPs as boundary conditions or boundary objects: SSPs can serve as ‘boundary conditions’ (Van Vuuren et al. 2014), whereby global assumptions shape regional downscaling, making regional SSPs predominantly top-down extensions. However, in other cases, SSPs serve as ‘boundary objects’ (Pereira et al. 2020), facilitating knowledge sharing and stakeholders engagement without rigid top-down enforcement.

Along these cornerstones, defining geographic and sectoral extensions of regional SSPs entails synthesising a very diverse taxonomy, ranging from environmental features, eco-



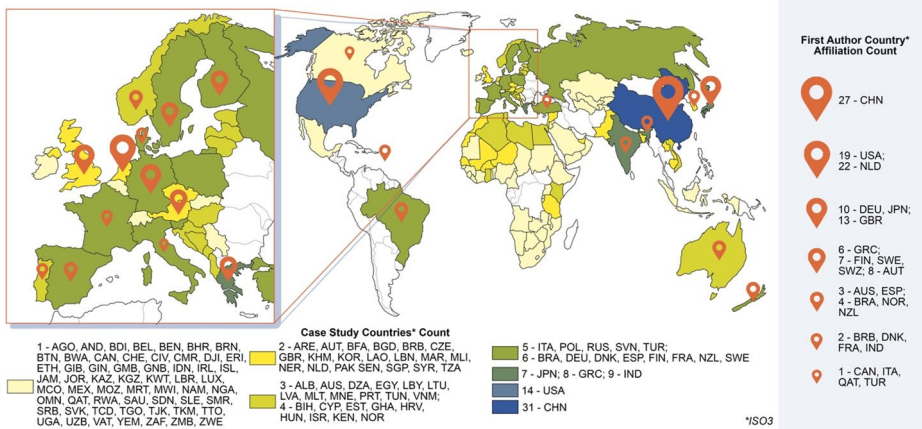
**Fig. 1** Heuristic space covering the space of contextualisation processes in regional extensions of the global SSP narratives (O'Neill et al. 2017), forming the methodological cornerstones for synthesising regional perspectives based on 155 studies, (see Supplementary Information for methods and Pedde et al. (2023) for data)

nomic and political blocs or borders, countries, and administrative, cultural or transnational regions within or across countries. The results of this process are presented in Fig. 2.

### 3 Synthesis of Shared Socio-economic Pathways regionalisation perspectives

#### 3.1 Summary of geographic extensions

The summary of data for individual columns is presented in Supplementary Information. In Fig. 2, we illustrate case study data on country coverage alongside first-author affiliation counts. About half of the countries are mapped more than twice (green and blue shades), 20 countries (dark yellow) twice, and 56 countries (light yellow) once. Japan, Greece, India, the United States, and China appear the most frequently. About one-third of the database focuses on Europe, followed by China, and North America.



**Fig. 2** Case study and first-author affiliation country counts for 155 studies extending the global Shared Socio-economic Pathways narratives (O'Neill et al. 2017; see Supplementary Information for results and Pedde et al. (2023) for data sources and definitions)

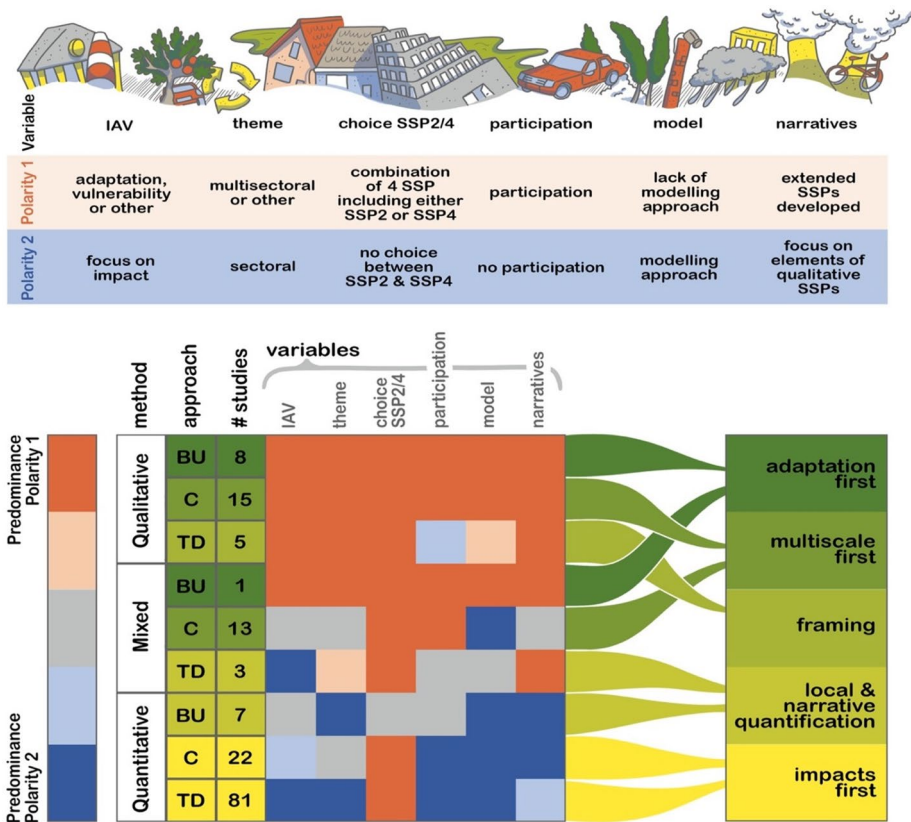
SSPs can be extended, within the same study, to very different contexts (e.g., Japan, USA, China, Middle East, and Africa), using this diversity to generalise conclusions that the future socio-economic context may affect a sector more than the climatic context (e.g., in the agricultural sector) (Yamaura et al. 2018). The presence of nine cross-regional studies suggests that SSP extensions have been implemented beyond political or biophysical borders, although this may complicate comparisons based strictly on political borders. Nevertheless, multi-context studies can be mapped within or across continents based on political country borders when country-scale data (Gross Domestic Product (GDP) and population growth for India, Bangladesh and Ghana, in this case) are explicitly designed for biophysical regions (e.g., coastal delta regions) (Kebede et al. 2018).

While the case study country count in Fig. 2 shows a global distribution of regionalisation, Western European countries, the United States, Japan, and China dominate first-author affiliations, reflecting an imbalance between the global distribution of SSP extensions and the institutions leading them. Of the studies, 68% are carried out by authors affiliated with institutions in the country of the case study. This proportion rises to 81% for studies conducted in the Global North. Notably, no African countries are represented among first-author affiliations.

### 3.2 Five perspectives on SSP regionalisation

To synthesise this heterogeneous body of literature, we avoided undertaking an overly-intricate quantitative analysis that could risk conveying a false sense of precision (Pedde et al. 2023). Instead, we chose a more transparent and descriptive approach. Drawing on six key variables (see Supplementary Table SMIII for the full list), we identified five dominant regionalisation perspectives, situated within the heuristic space illustrated in Fig. 1. These perspectives reflect recurring patterns in the literature, identified during the screening process, and are shown in Fig. 3. For instance, we examined whether the thematic focus (Column J, see all columns detailed in Supplementary Information) of bottom-up or top-down





**Fig. 3** Emerging five perspectives of regionalisation of the global Shared Socio-economic Pathways (SSP) narratives. Output approaches (yellow to green shades) result from qualitative clusters (squares in the centre) of opposing polarities for six variables characterising regionalisation, within the space delimited by the cornerstone heuristic space in Fig. 1 (bottom-up = BU; combined = C; top-down = TD). See Supplementary Information for variable definitions and data sources (Pedde et al. 2023)

studies leaned towards targeted sectoral analyses or, as observed, towards broader thematic domains. The naming of each perspective reflects qualitative judgment of the dominant patterns and features, supported by counts and descriptive statistics (see Supplementary Table SMIII). For example, in the (small) ‘adaptation first’ group, the distinguishing characteristic compared to other groups was the predominant focus on climate adaptation. In our synthesis, we have observed such leanings across six variables, each tending towards one of two opposing ‘polarities’.

The range of qualitative clusters extends from bottom-up, qualitative studies to top-down, quantitative studies (as mapped in Fig. 1). Participatory studies tend to be qualitative or mixed; quantitative studies tend to be top-down, forming about 55% of the database. However, these associations are not absolute and should be interpreted in light of additional variables. For instance, several quantitative studies in the ‘multiscale first’ and ‘impact first’ groups link directly or indirectly to studies that developed qualitative and participatory SSPs. Similarly, some mixed quantitative studies feature strong narrative components, such

as narratives developed for Western Africa based on global SSP assumptions (Palazzo et al. 2017).

Where studies explored four SSP combinations, they either excluded SSP2 or SSP4 ('choice SSP2/4' in Fig. 3), with one exception that excluded SSP5 (Drakes et al. 2020). Of the 40 studies featuring four SSP combinations, 24 included SSP4 and excluded SSP2. The exclusion of SSP2 was particularly influenced by 10 European SSP derivatives that sought to increase divergence within the SSP set (Kok et al. 2019). Quantitative studies tended to include SSP2 rather than SSP4, although no further defining attributes clearly differentiate the two groups. Both types of studies contained either extended SSP narratives or qualitative elements and engaged with sectoral or multisectoral analyses with a broad impact, adaptation, and vulnerability (IAV) focus.

### 3.2.1 Bottom-up perspectives in SSP extensions: "adaptation first"

Nine qualitative or mixed studies (about 6% of the database) follow a bottom-up approach, aligning with the bottom-right cornerstone in Fig. 1. These studies explore future socio-economic conditions underpinning societal transformation or climate adaptation.

Three sectoral (urban) studies elaborate on stakeholder perceptions of adaptation challenges for the cities of Lienz (Meyer et al. 2019), Flensburg (Reimann et al. 2021), and Tokyo (Kamei et al. 2016). Bottom-up analyses are less reliant on climatic impact assessment than top-down studies. Instead, they either extend SSP narratives to define contexts for developing adaptation pathways (Frantzeskaki et al. 2019) or use global SSP assumptions to frame, or retroactively match local or regional societal dynamics, prioritising stakeholder views in case of mismatch (Reimann et al. 2021). These perspectives are generally elicited through workshops.

Two studies involving four-scenario combinations exclude either SSP2 (Frantzeskaki et al. 2019) or SSP4 (Reimann et al. 2021). RCPs are rarely employed, with only one descriptive mention (Frantzeskaki et al. 2019). Mitigation, when addressed, is framed through its synergies with local adaptation needs (Kamei et al. 2021). All studies except one (Kamei et al. 2016) are strongly participatory. The Tokyo study relied on urbanisation theory and expert inputs. The methodology in the Tokyo study was later extended to Bhutan (Kamei et al. 2021) to incorporate normative elements, including Gross National Happiness, via workshops and literature review.

This category enriches SSPs by embedding local contextual features, such as determinants of well-being. Visioning exercises, for example, guide the objectives of adaptation pathways, with regional SSPs providing enabling and challenging conditions (Frantzeskaki et al. 2019).

While not always explicit, SSP1 (and, sometimes, SSP2) is consistently seen as representing desirable societal trajectories (Kamei et al. 2021). The local versions of SSP1 extend beyond the traditional focus on GDP to include cultural preservation, social satisfaction, and equitable development, aligning with the global SSP1 narrative. SSP1 implies decreasing inequalities between developed and less developed regions (Kamei et al. 2021). A recent study based on spatially explicit projections (Merkle et al. 2023) reinforce this pattern, showing that societal inequalities lead to greater convergence under SSP3 and SSP4 compared to SSP1 and SSP5. These findings highlight how inequality dynamics, rather than economic growth assumptions alone, drive long-term socio-economic trajectories. Urban-



rural distinctions are especially salient to capture the local scale dynamics, both in terms of determining which socio-economic indicators ought to be downscaled from the global SSPs, as well as for spatial disaggregation of projections (Reimann et al. 2021; Kamei et al. 2021).

Stakeholder preferences may guide the selection of SSPs: for instance, Flensburg stakeholders' preference for "as little change as possible" led to the rejection of SSP4 in favour of a more familiar SSP2-type of future (Reimann et al. 2021). Familiarity with utopian (SSP1) and dystopian (SSP3) archetypes was also evident in Lienz (Meyer et al. 2019), where scenarios closely matched global archetypes. Such alignment is recognised as a trade-off in stakeholder-led processes, sacrificing diversity of scenarios for resonance with local views. Quantifications, where used, are often based on national datasets, rather than ensuring strict consistency with global SSP projections.

### 3.2.2 Combined and mixed studies: "multiscale first"

Fifteen studies (about 10% of the database) combine bottom-up and top-down elements, primarily through qualitative approaches. Like 'adaptation first' studies, they are generally stakeholder-driven, but distinctively, they explicitly analyse interactions between regional developments and global dynamics described in the SSP narratives.

'Multiscale first' studies often develop full narratives (75% of cases) and universally employ participatory methods, with nine explicitly mentioning workshops. The degree of linkage to the global SSPs varies, framed using the Millennium Ecosystem Scenarios' (2007) language of 'consistency strength'. Many studies generate multigenerational SSPs: regional narratives (first generation) providing a basis for further extensions (second generation or beyond). Examples of multigenerational SSPs include regional narrative developments for Europe (2019), the Barents region (2017), New Zealand (2018) and Ocean System Pathways (Maury et al. 2017), where regional contexts serve as platforms for further scenario extensions. Unlike traditional 'Story and Simulation' studies (SAS) focused on expert-driven production of narratives for the purpose of quantitative model assumptions (Alcamo and Henrichs 2008), they facilitate contextualisation of participatory knowledge alongside basic quantifications of global SSPs. Stakeholders range more broadly, from experts to users and decision-makers, depending on the specific objectives.

Global SSPs are treated as 'boundary objects' rather than fixed 'boundary conditions'. This fosters flexibility, akin to the resilience concept in socio-ecological scholarship (Brand and Jax 2007), prioritising coherence of regional narratives over strict data equivalence. The narratives, nested between local and global scales, serve as standalone methodologies for impact assessment and land-use strategy exploration (Rakovic et al. 2020). The interpretation of SSPs as flexible pathways "to explore how different socio-economic pathways will influence future society's ability to cope with climate change" (Lino et al. 2019) distinguishes multiscale-first studies from stricter interpretations (Palazzo et al. 2017). With such interpretation, agencies in regional SSPs (Pedde et al. 2019a) are used to identify societal positive tipping points (Tàbara et al. 2018). Full contextualised narratives are developed in eleven studies, with seven studies focused on the Nordic regions in Europe. Of the two studies that cover impacts, the first focuses on agriculture and food systems in Cambodia, Laos, Vietnam (Mason-D'Croz et al. 2016) and the second focuses on urban systems, for Boston neighbourhoods' in the US (Lino et al. 2019). All five studies with four scenario combi-

nations exclude SSP2. Models were generally not used, except when applying integrated models to embed the narratives (Palazzo et al. 2017) also to “up-link” regional to global SSPs (Drakes et al. 2020).

Thirteen additional studies with more elaborated regional quantifications share similarities to these extensions and therefore belong to the multiscale first category. The main difference is that they focus on quantified impacts, either building on narratives published in a separate step (Palazzo et al. 2014), or included in the study (Talebian et al. 2021). Downscaling is more present but not prevalent, as the modelling tends to be tailored to local context. We define this overarching approach as ‘contextualised downscaling’. For example, land-use change modelling for Hungary simulates urban spatial development and regional cropping patterns. These models are not downscaled versions of global IAM, rather bottom-up models (spatial urban planning and an agent-base model) designed for local surveys, statistical downscaling of local (national) datasets and stakeholder-led SSP Hungarian narratives to identify future risk under locally specific socio-economic circumstances (Li et al. 2017, 2018). ‘Contextualised downscaling’ approaches may include regional model development (Berry et al. 2017; Nicholls et al. 2017; Drakes et al. 2020) and downscaled regionalisation (Palazzo et al. 2017; Smolenaars et al. 2021).

Both qualitative and mixed quantitative multiscale-first studies provide both climatic (e.g. based on RCPs) and non-climatic perspectives to understand the future risk resulting from climate change and challenges for local adaptation, like local risk assessments. Such approaches have enriched the socio-economic component of the SSPs, beyond simply downscaling top-down drivers. They match bottom-up local projections, either in qualitative or quantitative form with a regional-first interpretation of global assumptions developed by global IAM communities (Palazzo et al. 2017).

### 3.2.3 Qualitative and top-down: “framing”

Five studies (about 3% of the database) have developed more elaborated narrative elements of the SSPs, similar to the adaptation-first and multiscale-first approaches. However, unlike the multiscale-first approaches, these are more clearly qualitative and top-down, aligning to the bottom left corner of Fig. 1. The term emerges from their distinctive role: more than with any other group, these studies define what “top-down”, “bottom-up”, “combined” approaches mean, offering methodological insights that could be relevant for future regional extensions. While they share the thematic breadth of multiscale first studies, these studies are even more conceptual and methodologically oriented. For example, two studies strengthen, rather than extend, the European SSPs (Kok et al. 2019), the first through pairwise comparison with existing European scenarios (Rohat et al. 2018), and then second by defining the capacities of societal actors in European SSPs. While both approaches are participatory, Zandersen et al. (2019) see the extensions in Nilsson et al. (2017) as “combined” and define their own approach “top-down”. Top-down means “actively us[ing] the global SSPs and associated IIASA SSP database information to inform our expert/stakeholder group of the starting point for the regional scenarios” (Zandersen et al. 2019). In this sense, the main difference between top-down, combined, and bottom-up is the source of information used in participatory processes. While this definition is debatable case by case, it clarifies what type of stakeholder process and design can be used to extend SSP narratives. In the top-down category, and sometimes in multiscale scenarios, trade-offs between con-

sistency and stakeholder relevance— particularly in mismatching opinions of what an SSP should entail— are discussed. Both divergence and convergence (the latter also referred to as ‘equivalence’) between global and regional extensions have been observed. Convergence, in particular, is often prioritised “to maintain consistency with global developments as local and regional processes are embedded in global-scale processes” in top-down qualitative and some multiscale extensions (Reimann et al. 2018; Kok et al. 2019).

### 3.2.4 Quantitative and bottom-up: “local & narrative quantifications”

Seven studies, representing approximately 5% of the database, are bottom-up, quantitative extensions of the SSPs, primarily focused on single sectors (with only one classified as “multiple”). Owing to their methodological and thematic diversity, this group defies a unified classification, hence the long, descriptive label. These studies vary widely in theme, degree of stakeholder engagement (three include participatory workshops) and modelling approaches, which range from regression and land-use models to demographic models and fuzzy cognitive maps (FCMs). Three studies focus on quantifying dimensions of vulnerability (Diniz et al. 2015; Nikas et al. 2020; Bai et al. 2021), with one also addressing adaptation (Bai et al. 2021). Typically, these studies select and expand specific SSP components, without elaborating full narratives.

Stakeholder engagement plays a central role in several cases. In Brazil, stakeholders co-define win-wins and trade-offs on how the changes in farmers’ perceptions affect livelihoods and environmental sustainability (Diniz et al. 2015). In Central Asia, stakeholder-driven narrative elements discussed and developed during workshops are used to parameterise a global biodiversity model to explore future impacts on grasslands (Nunez et al. 2020). Workshops are combined with FCMs (Diniz et al. 2015; Nikas et al. 2020). FCMs are used to co-design risk factors for the solar energy transition. The FCMs are then used as input to business strategy and dynamic stochastic general equilibrium models to quantify the impact of different strategies (micro and macroeconomic impacts). In such an approach, the SSP global narratives guide scenario framing, including implications of policy instruments on electricity costs for end users, long-term economic growth, investment, employment, and tariff deficit.

### 3.2.5 Quantitative and combined top-down studies: “impacts first”

The category of eighty-one top-down and twenty-one combined quantitative studies together cover 103 studies, about two-thirds of the database. While eighteen of them build on regional narrative SSPs and two build further narrative elements, the dominant focus across the group is on quantitative modelling of impacts. This emphasis underpins the label “impact first”.

Fifteen studies extend SSP narratives that serve as a basis for quantifications. The original SSP-RCP matrix approach (Van Vuuren et al. 2014)— in which levels of climatic forcing are combined with different socio-economic references— is applied for different purposes: to select appropriate SSP-RCP combinations for assessing regional dynamics of socio-economic and climate change impacts on land use (Dong et al. 2018; Harrison et al. 2019), and to analyse the relative importance of socio-economic versus climatic variables in shaping climate impacts (Witmer et al. 2017; Terama et al. 2019). The assumptions developed for

the global SSPs on population, fertility, and economic growth strongly influence European regional urbanisation projections, particularly in SSP5 (Terama et al. 2019). In a comparison between the effect of climate and socio-economic context for Sub-Saharan Africa, the risk of violent conflict in the region is more closely associated with changes in political rights and (inclusive) governance than temperature anomalies (Witmer et al. 2017). Eighteen studies apply the matrix approach by extending regional SSPs. The value of quantitatively extending SSPs locally is two-fold: informing policy alternatives at the local level and identifying trade-offs and vulnerability that would be undetected at a coarser scale (Absar et al. 2021). While the approach is quantitative and top-down or combined, these studies recognise, similarly to the framing SSPs, the need to develop specific societal choices prioritising the case studies and research questions, addressing the issues of ‘consistency’ and ‘reproducibility’ across SSPs.

Among the eighty-one top-down studies, most are sectoral (only seventeen studies span across multiple themes) and have a strong focus on impacts (55 studies or 68%). Seventeen studies (about 20%) explore combinations of four SSPs, where the choice between SSP2 and SSP4 is evident for all the studies, although with no association to trends in other columns (such as predominance of specific qualitative elements associated with either SSP2 or SSP4). One study excludes SSP2 to maximise diversity in trajectories (Gomes et al. 2020). Of the nine studies with SSP4, thus excluding SSP2, six extend the European SSPs from Kok et al. (2019). Of the eight studies which include SSP2, two extend the European aquatic SSP (Pinnegar et al. 2021) and US SSPs (Absar and Preston 2015). Three studies extend the SSPs for the Baltic Sea by Zandersen et al. (2019).

Participatory elements are rare in this category. Only seven studies feature some form of participation, often loosely defined. For example, one study notes that: “the localised scenarios are developed in collaboration with the Directorate of Water, the general water managing authority for the Region of Crete”, and that “assumptions on local water demand are based on expert judgement and best reasoning” (Koutroulis et al. 2016). Even where qualitative elements are included, they typically do not evolve into full SSP narrative extensions.

## 4 Discussion and conclusions

### 4.1 SSPs as boundary objects and boundary conditions

Our analysis shows that global SSPs have been used both as boundary objects and as boundary conditions in regional extensions. The first three perspectives, e.g. adaptation first, multiscale first and framing, primarily use SSPs as boundary objects, supporting qualitative, interpretative extensions. In contrast, the impact first perspective (accounting for approximately two-thirds of the database) treats SSPs mainly as boundary conditions for top-down quantitative modelling.

Across the space defined in Fig. 1, multiscale scenarios and multigenerational SSP extensions provide a conceptual bridge between these roles, promoting coherence between qualitative and quantitative extensions. Broad regional narratives act as an integrating device, linking global assumptions with local knowledge. The dual function of SSPs extensions is particularly relevant in participatory studies, where SSPs foster cross-disciplinary commu-

nication and allow the articulation of regional perspectives, although this remains far less developed compared to other global scenario frameworks (Pereira et al. 2020).

For example, while global SSP5 anticipates rapid economic growth driven by fossil fuels, regional applications (e.g. Hungary) reveal how local stakeholders question the credibility and diverge from this pathway based on contextual realities and values (Pedde et al. 2019b).

The need to balance top-down consistency with local salience is evident throughout. This is particularly evident in studies where SSPs are used as boundary objects, not simply as predefined trajectories but as flexible tools for knowledge sharing and adaptation among diverse stakeholders. In such cases, SSPs serve as a starting point rather than a strict set of conditions, allowing alternative local interpretations of global narratives.

This dual role highlights the need for a flexible framework—one that accommodates divergent local perspectives while maintaining global coherence. A promising avenue, observed in the database, is the use of multiscale scenarios, which still operate SSPs as boundary conditions but minimise reliance on purely top-down downscaled data. Instead, they emphasise participatory processes through co-production rather than consultation (Palazzo et al. 2017; Zandersen et al. 2019). Empirically grounded approaches, such as agent-based models to explain drivers of land-use change (Li et al. 2018), and mixed methods such as Fuzzy Cognitive Mapping (Diniz et al. 2015), further reinforce this direction.

A knock-on effect could be the further diversification of SSPs and increased relevance and uptake for climate adaptation strategies, particularly when regional studies are explicitly designed to support decision-making and policy processes (Gomes et al. 2020; Carlsen et al. 2024). This evolution would allow innovation with different methods, without waiting for Integrated Assessment Models (IAMs) to integrate regionally grounded insights, which may lack the institutional prestige and influence of global modelling efforts (Turnhout, 2024).

## 4.2 Challenges in regionalising SSPs

The geographical and thematic breadth of the 155-study database echoes the successes of the SSP framework as concluded by O'Neill et al. (2020), yet also highlights the persisting limitations. The overwhelming dominance of quantitative and top-down impact-first studies underscores a lack of diversity in regionalisation perspectives. This bias in our database is particularly noticeable because of our deliberate search criteria aimed at finding bottom-up and narrative-driven extensions.

A key challenge identified across approaches is top-down standardisation of the SSP framework, which persists in both the studies analysed here and in more recent literature. While the wealth of themes and geographies could explain the challenge of classifying regional SSPs within uniform political, social or environmental boundaries, it also reflects the persisting challenge of aligning a global narrative with the diversity of plausible regional versions as discussed in Petzold et al. (2024).

Similar restrictions resulting from top-down standardisation emerge in recent SSP extensions beyond our database, such as recent SSP extensions in finance. The main limitation in this case is the assumption of economic and technological convergence, a core feature of the global SSP narratives. This leads to possible underestimation of near-term risks that are not captured in the current SSP model chain and assumptions (Kainth 2024).

Recent regional simulations reinforce, in the same tone, the need for stronger and complementary bottom-up perspectives in the SSPs, concluding that “trajectories can vary dra-

matically among local scales under the same global ‘boundary conditions’ of individual SSP scenarios” (McManamay et al. 2024).

To understand the low share of adaptation-focused (bottom-up) studies in our database, we also consider the reasons for ‘missing’ SSPs, such as cases where authors considered extending SSPs during the period covered by our database but did not do so. While in some cases resource constraints likely played a major role, in others the lack of extensions may reflect limited institutional or funding support for certain thematic areas. Nevertheless, the extension of the global SSP database, summarised in Andrijevic et al. (2020, 2023), could help fill these gaps. Examples include forest degradation (Estoque et al. 2020), Sustainable Development Framework (Ray 2020), and governance (Raudsepp-Hearne et al. 2020), which are critical for informing decision-makers.

A more challenging argument given the SSP framework design is that effective climate policies must be informed by local dynamics and stakeholder experiences (Van Vliet et al. 2020; Hewitt et al. 2021), therefore requires a bottom-up perspective. This suggests that simply adding more (top-down) datasets to global databases will not address exclusivity. The framework in its current development may reinforce “conventional worlds” (Raskin and Swart 2020) producing consistent but constrained “downscaled mini-worlds” (Cradock-Henry and Frame 2021b) limited by timing of complex and rather opaque IAM outputs (Nilsson et al. 2017; Skea et al. 2021) and by underrepresentation of developing regions, arguably due to the low influence of Global South institutions in climate science (Turnhout 2024), as evident in the distribution of first-author affiliations in our database.

#### 4.3 Path forward for inclusivity and knowledge exchange

Drawing from these findings, we outline potential pathways to enhance future regional SSP development and address current limitations.

Firstly, our synthesis highlights that, despite efforts by IAV authors to contextualise SSPs and expand SSP indicators, a critical lack of diversity of perspectives and inclusivity remains (Pereira et al. 2020; Pielke and Ritchie 2021). This is evident, for example, in the overwhelming dominance of first authors affiliated with Global North institutions (Fig. 2) and top-down analyses (Sect. 3). Addressing this imbalance will not happen by itself. It requires broader support from leading institutions and funders for context-aware methodologies that account for policy diversity and transformative societal change, issues that cannot be resolved solely through top-down economic or demographic modelling methodologies. Recognising the dominance of top-down approaches in the top-left quadrant of Fig. 1 in our findings is a necessary step toward creating a more balanced operating space across all four corners of our heuristic.

Secondly, a revival of the matrix approach, akin to the ‘SSP-lite’ recommendation made a decade ago (Wilbanks and Ebi 2014), could accommodate both roles of SSPs as boundary conditions and boundary objects. Family trees of regional SSP extensions, building from the emergence of multigenerational and multiscale regional SSPs, could be further investigated as the operational link between top-down and bottom-up for approaches.

Debates in the literature have pointed to an inadvertent cycle where funding structures may favour mitigation over adaptation, contributing to disproportionate differences in power, influence and resources among scientific communities (Wilbanks and Ebi 2014; Turnhout 2024). Overcoming this cycle is particularly timely, in light of the upcoming IPCC Seventh



Assessment Report. Strengthening the systematic use of SSP-based analyses for IAV—which was remarkably limited in the IPCC Sixth Assessment Report despite the dominance of mitigation scenarios (Pirani et al. 2024)—could mark an important shift towards more inclusive and consistent scenario development for adaptation and vulnerability research.

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**Ethical approval and consent to participate** This article does not contain any studies with human or animal participants performed by any of the authors.

**Competing interests** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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