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A new dynamic framework is required to assess adaptation limits

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ABSTRACT

Anthropogenic climate change is already causing dangerous and widespread disruptions in global ecological and social systems and affects the lives of billions of people around the world. Even with scaled-up risk management and adaptation, the limits of adaptation will often be reached. Currently, very little is known about the degree to which societies can adapt to climate change, and where and when limits to adaptation will be reached. In this paper, we conceptualize adaptation limits through a novel methodological framework, assess adaptation limits along adaptation pathways, and propose a research strategy for empirical and model-based limits assessments based on biophysical and socio-economic data. Assessing limits is central to national and international adaptation policymaking. More efficient adaptation can also help climate mitigation efforts.

1. An urgent need to understand limits

Certain anthropogenic climate change pathways can become an existential threat to humans (Huggel et al., 2022, Kemp et al., 2022). Climate change is already causing dangerous and widespread disruptions in natural systems and adversely affecting the lives of billions of people around the world (Pörtner et al., 2022). Yet, it is unknown to what degree societies can adapt, and where and when limits to adaptation are reached.

There is robust evidence of adaptation limits in an increasing number of natural systems, such as for oceans, warm water coral reefs, coastal wetlands, some rainforests, some polar and mountain ecosystems and the cryosphere (Pörtner et al., 2022), including the breaching of planetary boundaries (Richardson et al., 2023). At the same time, the evidence base for limits in social systems is sparse and inconclusive (Berrang-Ford et al., 2021, Thomas et al., 2021, O'Neill et al., 2022, Berkhout and Dow, 2023).

Overall, the lack of understanding of social adaptation limits is strongly at odds with the severity of the threat of climate change. Theoretically, there is little information about at which point a social system, interacting with natural systems, can be transformed or modified. In terms of methodology, there is a lack of assessment frameworks, methods, and models for adaptation limits to be empirically applied at scale.

In this *Perspective*, we argue that research on adaptation limits, particularly for social systems, has to significantly advance theoretically, methodologically and empirically. We first present a theoretical framework to show what constitutes limits and second propose a research approach, which can be utilized to predict rapidly approaching climate adaptation limits empirically.

2. Current scholarship on limits

The current literature on social adaptation limits is dispersed and has made little progress in the last ten years (Berkhout and Dow 2023). The initial conceptualization of a limit as "the point at which an actor's objectives (or system needs) cannot be secured from intolerable risks through adaptative actions" (IPCC, 2014: p. 118) has remained largely unchallenged. Limits in the context of adaptation mean that there will be points beyond which no more adaptation will be possible.

A further distinction is made between hard and soft limits. Limits are described as "hard" if no further autonomous or planned adaptive actions are possible to avoid intolerable risks (Dow et al., 2013, Felgenhauer 2015). Evidence suggests that hard limits predominantly occur in

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ecological systems, but they also occur in social systems. For example, there are heat thresholds for human health (New et al., 2022). "Soft" limits in social systems are contemporary limits. "Soft" limits occur when planned adaptation options are currently not available due to socio-economic or cultural reasons but may be available in the foreseeable future (IPCC et al., 2014). Soft and hard limits have different temporal characteristics. Surpassing hard limits in ecological and social systems results in lost functionality at specific warming levels. Soft limits occur in social systems and these limits may develop over time. A soft limit is thus 'mutable' (Thomas et al., 2021, p. 85) and can be overcome with the help of a new technology, for example.

Recent systematic reviews done for informing IPCC's 6th assessment report demonstrate the lack of empirical literature on social limits (Berrang-Ford et al., 2021, Thomas et al., 2021; O'Neill et al., 2022). Thomas et al., (2021) found that much of the literature in their sample (n = 1682) discusses constraints to adaptation rather than limits, and only one percent of the reviewed papers provide detailed information about soft or hard limits or socio-economic or environmental change in relation to limits (Thomas et al., 2021).

Existing literature focuses on the bleaching of tropical coral reefs and species range loss in terrestrial and freshwater ecosystems around the globe (Roy et al., 2018), agricultural systems, (Harvey et al., 2014, Warner 2016), coastal systems (Karlsson and Hovelsrud 2015, Scott et al., 2020, Haasnoot et al., 2021, Mach and Siders 2021), and heat and human health (Vicedo-Cabrera et al., 2021; Muccione et al., 2024). Institutional and socio-cultural factors have also been considered as a source of soft limits to adaptation (Barnett et al., 2015, Azhoni et al., 2017, Mechler et al., 2022; Hochrainer-Stigler et al., 2023).

To advance the field, first, there must be a better understanding of what limits consists of and at which point a system must/can be transformed (Wise et al., 2014, Fedele et al., 2019, Wallimann-Helmer et al., 2019). This also includes exploration into whether our approach can create an empirically validated universal definition of limits. Second, these needs demand overcoming the current lack of assessment frameworks, methods, and models. Influential research strands, such as Integrated Assessment Modelling (IAM) for analyzing impacts, risks, and economic costs, or highly aggregated risk assessments, such as the Reasons for Concern (RFC), do not consider limits at all or only in a very generic manner (Magnan et al., 2021). Similarly, the Planetary Boundaries approach analyses planetary scale phenomena (Richardson et al., 2023) and does not account for context specificity of limits. Assessments of transformational adaptation are limited to top-down interpretation of scenarios, for example, towards projected coastal retreat (Lincke and Hinkel, 2018). Thus, there is a pressing need for more comprehensive approaches that also consider the actual dynamics of climatic and socio-economic limits drivers over time (Mach and Siders 2021, Kreibich et al., 2017).

3. A dynamic methodological framework for assessing soft adaptation limits

We propose to build on adaptation pathways that show the potential for empirical and model-based adaptation assessments focused on limits (Fig. 1). Our theoretical framework guides the identification of core metrics, which are context-specific, to connect biophysical and socio-economic information in a comprehensive model architecture. Viewing adaptation along this trajectory, it is possible to identify the conditions related to climate hazards and processes, as well as other ecological and socioeconomic drivers, under which societies adapt or are driven towards limits, both now and in the future.

This can be accomplished by combining scenarios, data on climate hazards, impacts, and risks with assessments of economic consequences and adaptation responses. *Future risks,* dependent on continued societal choices and mitigation, can be high or low, pushing the pathway towards or away from an *adaptation limit*. These future risks are strongly connected to adaptation actions, which themselves can prevent the reaching of limits. *Adaptation* here is considered along a scale from incremental adjustments to system-wide transformations. We consider limits as thresholds, where possible adaptation actions become temporarily or permanently infeasible leading to adverse outcomes in terms of large-scale losses and damages and societal disruption (as exemplified by the final column in Fig. 1). Limits are visualized as preceding adaptation actions as they are defined by increasingly tighter constraints that in interaction with adaptation options close down the adaptation space. Thus, a wide range of adaptation options is only available at low limits manifestation, and vice versa.

While the focus is on identifying limits in relation to worsening climate-related conditions (intensity, frequency and duration of climate hazard and processes), the framework is additionally informed by past and current exposure and vulnerability. In our framework, non-climate related factors, such as poverty, marginal urban settlements or adverse geographical conditions for sustained agricultural livelihoods influence adaptation limits.

3.1. Adaptation actions

Our theoretical approach to adaptation limits focuses on adaptation actions (Bisaro and Hinkel, 2016) that face multiple constraints (Juhola

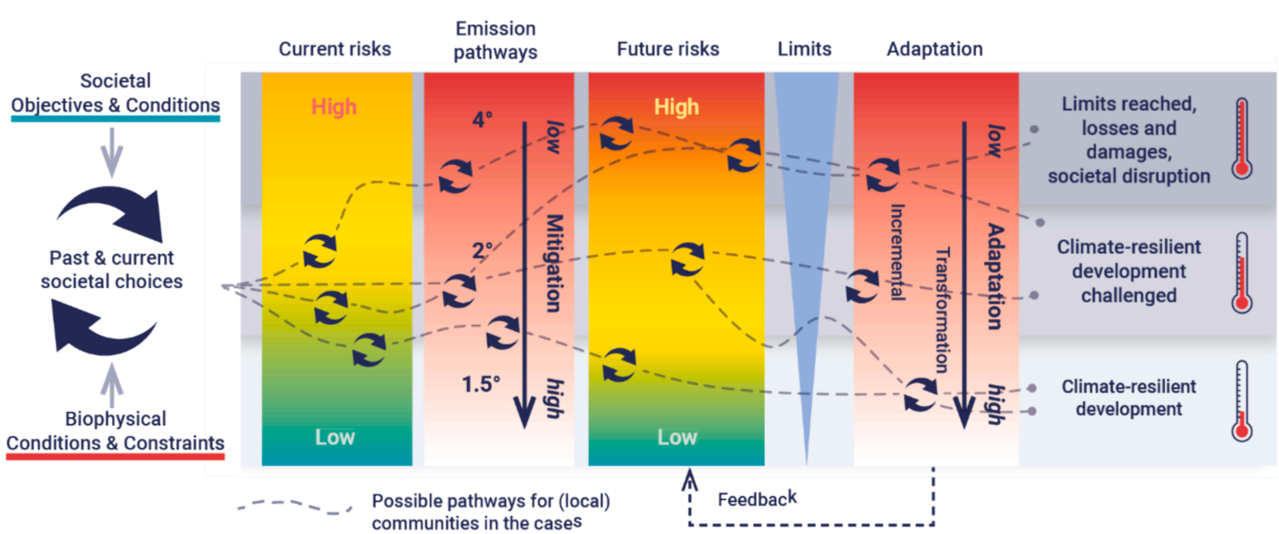

Fig. 1. Dynamic risk and adaptation limits assessment framework.

et al., 2022). These limits can be defined at actor level, i.e. lack of fulfilment of basic needs, or at the system level, in terms of ecological functions or formal institutions.

Our approach (Fig. 2) places the adaptation action (technical or policy measures, but also overall strategies) at the center. Action is made possible or constrained by the different actor or system objectives to be secured within a national context or local community. These objectives are: 1) basic needs, capabilities, human rights, and welfare (Wallimann-Helmer et al., 2021); 2) basic ecosystem functions needed for human survival; 3) financial, economic, and technological capacities for life; and 4) governance rules, including democratic governance and social justice. Adaptation actions are limited by these ecological and social characteristics. As systems are interlinked, there are likely to be hard limits set by the ecological system within which a social system is embedded, which are not yet reached but for which parameters can be identified, through bottom-up risk analysis.

In social systems, actors who plan or undertake adaptation actions have basic needs, and financial and technological capacities, which can lead to soft limits for adaptation action, depending on socio-cultural and institutional contexts. Social systems, through formal and informal institutions, also create social structures for individual actors, which may result in soft limits. It is within these interrelationships between biophysical, financial, technological, and social characteristics that indicators can be identified, and metrics proposed to show when and how adaptation limits can be reached. The outcome of tightening constraints may lead to a (local) push for further adaptation action, transformation, or collapse. Thus, in terms of dynamics, systems may transform to a different state as soon as they can no longer secure one of their objectives.

3.2. Indicators and metrics

Whether risks are tolerable or intolerable depends on the normative evaluations of those engaged in adaptation (Dow et al., 2013; Wallimann-Helmer, 2015). Thus, risks ought to be conceptualized from the perspective of ethics. By developing a social-justice oriented sufficiency scale that includes basic needs, capabilities, human rights, and welfare (c.f. Miller, 2007, Dworkin, 2000, Rawls, 2020) one can better analyze when risks become intolerable for different agents, groups and contexts. Whether intolerable risks will lead to social instability or not, depends on the available technological and financial resources and prevailing social contracts of what is considered just.

Robust and appropriate indicators for adaptation limits can be identified by connecting social system objectives with metrics based on quantitative assessment and modelling (see Table 1). The definition and scope of the indicators is guided by the system boundaries (cf Fig. 2), and hence, the indicators address system properties within these boundaries. Many indicators and related metrics may also be included in other concepts such as the Sustainable Development Goals. The indicators are introduced on a sufficiency scale based on conceptions of justice, which are then used to scope how close to limits any given society is. Drawing on ethics, the scale begins by gauging *basic needs and ecosystem functions* needed for human survival which ought to be met in any given society without leading to a limit being reached. Further along the sufficiency scale, the second (*societal well-being*) and third (*governance, effective democracy, and social justice*) system objectives illustrate how the scale encompasses both basic and complex human needs; surpassing limits can lead to degradation in these systems.

Within these system objectives, several indicators are identified which can be connected to ethics. For the *first objective*, securing basic needs requires paying attention to limits at the individual level, consisting of both physiological and social elements. This is along the lines of classical sufficietarian theories of justice, which include notions of basic needs, capabilities, human rights (sufficiency threshold for a human life in dignity, cf. Schuppert, 2011, Sen, 2000), and welfare and opportunities (specific levels of preference satisfaction, cf. Lippert-Rasmussen, 2016, Dworkin, 2000). Second, guaranteeing *ecosystem functions* requires assessing potential limits related to biophysical systems. These limits imply that past a certain threshold, ecosystem decline or even collapse may occur. This may coincide with a related decline in human wellbeing as vital ecological systems upon which humans rely degrade. Third, *technological and financial constraints* signify different types *of* social system properties, which may present soft limits for adaptation. These limits become apparent through assessments of economic considerations or technological feasibility (Tanoue et al., 2021). At national levels, a dominant societal objective has been to maximize well-being (narrowly defined by GDP or broadly defined by alternate indicators, such as human development or similar). Finally, *governance rules* work towards securing democracy and social justice for all people in society beyond sufficiency levels and help overcome inequalities in vulnerability and exposure (conditions for a just society, cf. Pettit, 2012, Scanlon, 2000), and enable actors in society to undertake adaptation measures, while the absence of functioning democratic institutions, or their misuse, may further contribute to a limit. For this, democracy

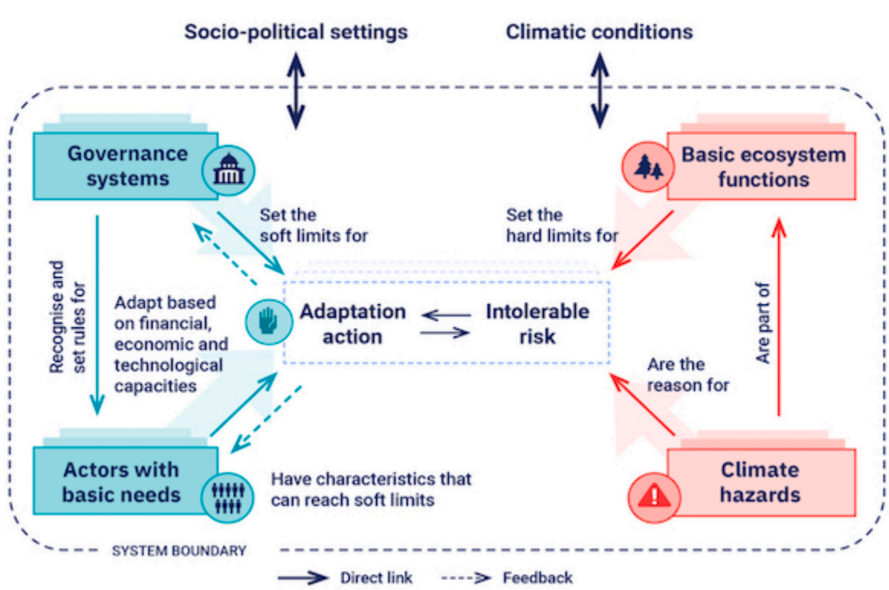

Fig. 2. Adaptation action graph.

Table 1
System objectives, metrics and parameter observations, and modelling approaches for limits assessment.

System objectives	Constraints and limits definition	Example indicators for empirical measurement of objectives	Proposed metrics and proxies for objectives achievement	Examples of assessment and modelling methods
Basic needs, capabilities, human rights, welfare	When needs, capabilities, rights or welfare cannot be secured within a tolerable range	• Shelter • Fresh water • Food • Health (life expectancy) • Education	• Living space area • Flood and landslide protection levels • Heat wave hazards • Drinking water litres per individual /year • Calories per individual /year • Medical professionals per community • Teachers per community	• Coastal erosion & land-loss (DIVA) • River flooding (GLOFRIS) • Heat occurrence from climate scenario projections • Cryosphere degradation (GLOCEM) • Flood & landslide hazards (TRIGRS, RAMMS) • Community-level resilience measurement tool (FRMC)
Functional basic ecosystem needed for human survival	When irreparable damage is caused to ecosystems, and they cease to function	• Agricultural crop and forest production • Coral reef health, eco-system services	• Crop yields • Forest production • Coral reef health/ degradation	• Agricultural production under drought conditions (WEAP, RS Minerve, GLOBIOM)
Societal well-being	When well-being is compromised as addressing of risks is limited by institutional, technological, economic & financial constraints	• Value added (national or sectoral) • Household poverty	• Monetised asset losses due to floods and landslides • Fiscal space • GDP and Genuine savings • Household poverty line	• Flood and landslide damages (Delft-FIAT) • Aggregate and fiscal risk (CATSIM model) • Micro-economic model simulations of assets and consumption pathways building on resilience measurement tool (FRMC)
Governance, effective democracy and social justice	When basic institutional and social conditions for a just society cannot be secured	• Equality & risk • Equality & status • Recognition • Procedural justice	• Distribution of adaptation measures and risks • Distribution of commodities in relation to social status • Inclusion and social disparity • Discrimination in decision-making and distribution of resources	• Models for distribution of risk between societal groups and income classes • Water resource availability and flood and landslide models combined with vulnerability and exposed wealth to detect inequalities among affected people

indicators (Boese, 2019) can be employed that focus on civil rights, political participation, free elections among others.

Several challenges are faced when operationalizing our definition. First, existing literature identifies several challenges for translating ethical concepts into quantitatively assessed metrics, including diverging and multiple definitions, selection of proxies, assigning weights to indicators and data availability issues (Tonmoy et al., 2014, Jurgilevich et al., 2017). Second, as there is no consensus on the dynamics between different limit dimensions and their thresholds, the development of robust methodological approaches is crucial. Third, there is also a need to test different indicator weighting options, with each weighting likely to yield significantly different results (Räsänen et al., 2019, Feizizadeh and Kienberger, 2017, Reckien, 2018). There is also a need to carry out uncertainty and sensitivity analyses (Saisana et al., 2005), as well as compare results from different methods, such as manual indicator removal (Mainali and Pricope, 2017). Finally, while there is value in proposing a universal definition, we acknowledge that these standards become realized under specific biophysical circumstances and according to socio-cultural, technical, and financial preferences of local stakeholders, that can be identified and typologized. Therefore, this approach would further need a robust validation process (McCallum et al., 2016).

3.3. *A flexible modelling architecture*

Our approach integrates models for the assessment of climate risks and adaptation at appropriate scale, to compute risk metrics as a basis to describe any potential limits (Fig. 3) building on existing models. The aim is to investigate a wide range of plausible futures of climate, adaptation options, including transformation (Bryant and Lempert, 2010, Kwakkel, 2017).

Plausible future climate change scenarios, focusing on warming levels of 1.5°, 2°, and 4 °C, high-resolution climate projections (Jacob et al., 2020) can be downscaled to the urban scale where needed. For future socio-economic conditions, there is a growing number of databases that successfully extend information on projected population and GDP from the global Shared Socio-economic Pathways (SSPs) to regional, sectoral, and local levels (Gao, 2019; Rohat et al., 2019). These datasets can complement bottom-up approaches of co-produced socio-economic scenarios with local stakeholders (Huggel et al., 2015; Allen et al., 2018; Motschmann et al., 2021). The outputs of this integrated effort are key risk metrics, which together with the analysis of multi-dimensional constraints, enable coherent descriptions of future limit conditions (where, when, and how).

This model architecture addresses three major gaps in current state-of-the-art risk models (Magnan et al., 2021, Simpson et al., 2021). The *first gap* is the lack of transient risk modelling that considers the dynamic nature of climatic and non-climatic drivers and human responses (Bouwer, 2022). A transient model architecture would simulate both gradual impacts, such as ecosystem degradation, and impacts from extreme weather events, such as floods and heatwaves, as well as evolving socio-economic and political conditions that determine changing exposure and vulnerability including adaptation actions. We suggest a risk modelling approach that integrates probabilistic assessment of hazard intensities and impacts, while also acknowledging the breadth and spread of system uncertainties.

The *second gap* that needs to be overcome is the challenge of modelling effects of both single and interconnected risks and how their cascading impacts on human systems may incur systemic risks or even system malfunction or collapse (Hochrainer-Stigler et al., 2020, Pescaroli and Alexander, 2018, Collins et al., 2019). This gap can be addressed through integrated risk assessments and the simultaneous analysis of different climatic hazards in multiple locations.

The *third gap* is that current state-of-the-art risk assessments mostly

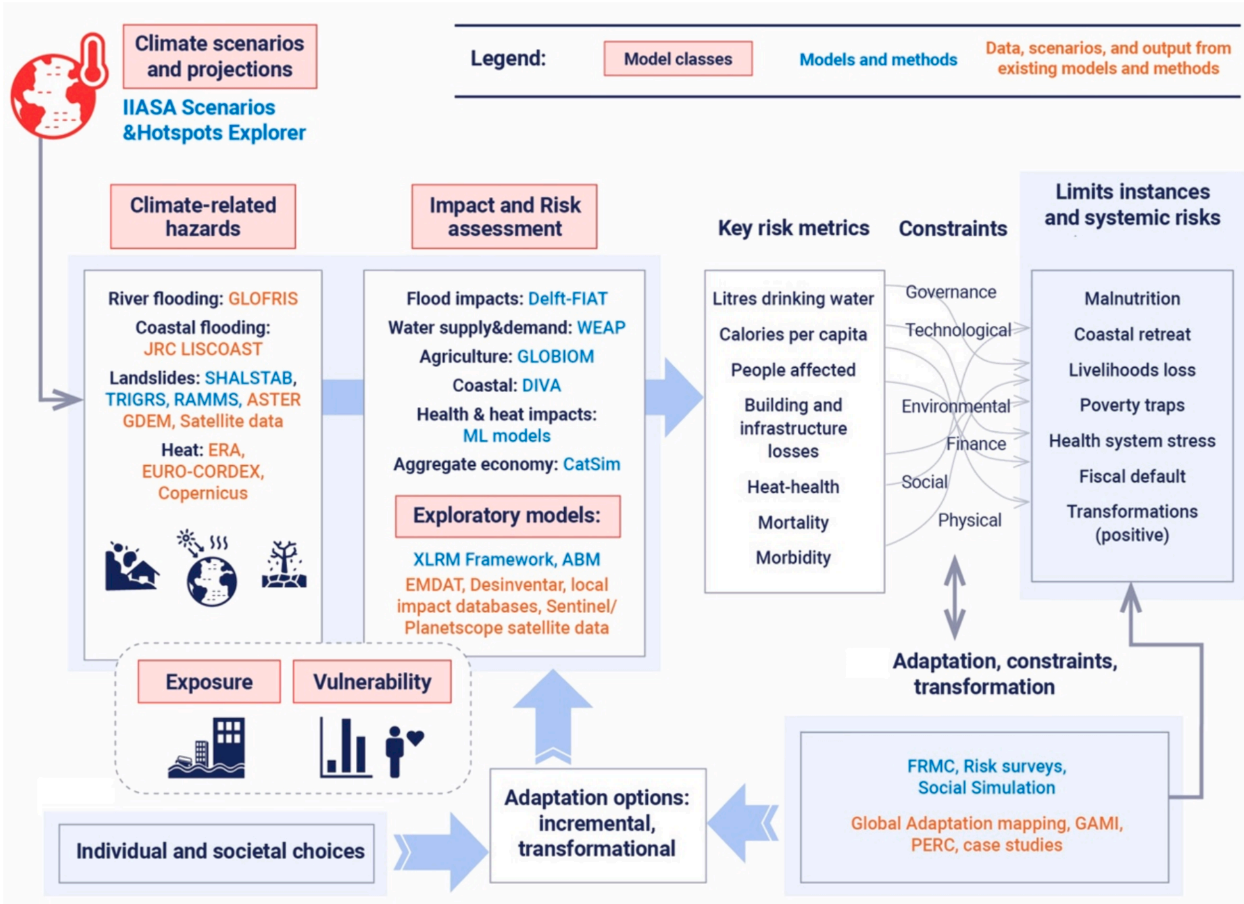

Fig. 3. Modelling architecture for adaptation limits assessment, including examples of specific models (mostly publicly available), and examples of risk metrics and limits.

continue to use a single hazard perspective (Warren et al., 2018), when multi-hazard risk simulations, which connect multiple hazards and impact types are needed. The COVID-19 pandemic and recent extreme weather events (Phillips et al., 2020, Rodríguez-Morata et al., 2019) suggest that limits are most likely reached and exceeded when multiple hazards strike in parallel or with sufficient frequency. For example, extreme floods have repeatedly pushed communities and sometimes even countries towards their limits in terms of meeting basic needs (see also Section 2), making them extremely vulnerable to consecutive or compounding events, such as water scarcity, landslides, and other natural hazards, such as earthquakes (de Ruiter et al., 2020). To comprehensively understand the latter, constraints (e.g., financial, technological, cf. Table 1) need to be integrated. Coupling of risk models with socio-economic models, such as the Catastrophe Simulation model (CATSIM) (Hochrainer-Stigler et al., 2013), enables identification of fiscal limitations, macroeconomic stress, and their dynamics.

Further, exploratory modelling approaches allow for the exploration of a broad range of uncertainties in a “what if” scenario, as opposed to a predictive logic calculation. This is particularly useful for examining impacts that are difficult to predict or quantify due to systemic complexities, limitations in scientific understanding, and range of potential human responses situated in the context of decision-making under deep uncertainty (Marchau et al., 2019). By design, exploratory modelling is reasonably flexible and can integrate new information with a strong emphasis on involving local stakeholders and experts through co-production and validation of parameters, in dialogue between stakeholders and modelers (Muccione et al., 2019; Tuler et al., 2023). For example, critical combinations of risk-response relations can signal how limits can be overcome or pushed into the future through transformations. In this approach, neither the climate models nor the socio-economic pathways are pre-assigned, and the parameters are given as plausible ranges but without probabilities to allow exploration of different futures at relatively low computational cost. For example, the XLRM exploratory modelling framework was successfully applied for adaptation of future winter tourism and for compound heat extremes (Vaghefi et al., 2021, Vaghefi et al., 2022, Muñoz et al., 2024). The exploratory modelling approach can be linked to and complemented by ’storyline approaches,’ simulating counterfactual events by modifying actual event outcomes; ‘storyline approaches; have recently emerged in climate change research (Shepherd et al., 2018; Sillmann et al., 2021).

4. Conclusion: A critical science and policy issue requiring targeted research strategies

The analysis of limits needs attention depending on current levels of evidence in certain key systems and regions urgently. The IPCC’s AR6 WG II report provides an assessment of evidence for limits and constraints in each world region and for different sectors and systems (O’Neill et al., 2022). It shows high evidence of adaptation limits within certain systems in some regions. This includes Central and South America, SIDS for terrestrial and freshwater ecosystems, poverty, well-being and food and cities. And there is low evidence for other regions, including Australasia and Asia for water, terrestrial and freshwater ecosystems. More importantly, the WG II report also provides an assessment of constraints to plan and implement human adaptation, thus making it more likely that limits will be reached (Pörtner et al., 2022, p. 77). Across different sectors, there are high constraints with limits to adaptation identified in small island developing states, Australasia, and Africa, while lower constraints are associated with limits to adaptation in Asia, Central and South America, Europe, and North America (Pörtner et al., 2022, p. 77).

This can lead to alternative research strategies. By building on an existing evidence base, the modeling of limits can be further developed and validated. For regions where there is currently limited evidence, there is a need to establish continuous assessment of limits with stakeholder collaboration, pointing to a potentially increased need for assistance with adaptation actions, for example. For those regions where the evidence base is low and adaptation is not constrained, research needs to be conducted to establish more evidence through stakeholder surveys to establish whether something is being overlooked. Finally, for those regions and systems where the evidence base is low and there are high adaptation constraints, the aim should be to conduct more rapid bottom-up, qualitative exploration to identify key variables and data to establish the current state to improve the knowledge base.

The identification and assessment of current and projected future adaptation limits is essential for improving human well-being, as it may inform appropriate and timely actions. Incidents of reaching or breaching limits are likely to become increasingly severe, widespread, and frequent, thus policy makers must pay urgent attention to addressing the challenges of limits. Limits have clear and direct implications for adaptation research; the limits approach suggests that justice-oriented adaptation requires a human well-being centric approach. Understanding when and where limits will be found requires an integrated modeling approach with information and analyses coming from multiple sources. Proactive, transformational adaptation in key locations and systems necessarily requires the building of a robust evidence base for limits. An advancement of this topic is key if human societies are to adapt to climate change appropriately and sufficiently.

CRediT authorship contribution statement

Sirkku Juhola: Writing – review & editing, Writing – original draft, Conceptualization. **Laurens M. Bouwer:** Writing – review & editing, Writing – original draft, Conceptualization. **Christian Huggel:** Writing – review & editing, Writing – original draft, Conceptualization. **Reinhard Mechler:** Writing – review & editing, Writing – original draft, Conceptualization. **Veruska Muccione:** Writing – review & editing, Writing – original draft, Conceptualization. **Ivo Wallimann-Helmer:** Writing – review & editing, Writing – original draft, Conceptualization.

Declaration of competing interest

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.

Data availability

No data was used for the research described in the article.

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