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Extending from Adaptation to Resilience Pathways: Perspectives from the Conceptual Framework to Key Insights

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Abstract

The extent and timescale of climate change impacts remain uncertain, including global temperature increase, sea level rise, and more frequent and intense extreme events. Uncertainties are compounded by cascading effects. Nevertheless, decision-makers must take action. Adaptation pathways, an approach for developing dynamic adaptive policymaking, are widely considered suitable for planning urban or regional climate change adaptation, but often lack integration of measures for disaster risk management. This article emphasizes the need to strengthen Adaptation Pathways by bringing together explicitly slow-onset impacts and sudden climate disasters within the framework of Resilience Pathways. It explores key features of Adaptation Pathways—such as thresholds, performance assessments, and visual tools—to enhance their capacity to address extreme events and foster the integration of Climate Change Adaptation and Disaster Risk Management.

Keywords Dynamic adaptive policy pathways · resilience management · climate change adaptation · disaster risk management · decision support · uncertainty

Introduction

The impacts of climate change are one of the main challenges humankind is facing. Significant variations have already been monitored in several climate indicators like temperature (Simmons et al. 2021; ECMWF 2024), sea level rise (Cazenave et al. 2014; Nicholls et al. 2021), and ice sheets (Morlighem et al. 2017; Kulp and Strauss 2019). Impacts associated with the slow-onset shifting climate have not only been simulated but are already observed in the natural environment: the decay of Australian reefs (Figueiredo et al. 2022), phenology changes (Vitasse et al. 2022), and impacts on various economic sectors (Hamilton and Tol 2007; Rapp et al. 2019) and urban areas (Lehoczky et al. 2017). These slow-onset effects are accompanied by impacts from sudden-onset extreme events or disasters, which increase in frequency and intensity with the accelerating climate change. Examples include the 2022 heatwaves in Europe (UK Meteorological Office 2022), the Central European drought in 2018–2019 (Conradt et al. 2023) and latest flood events in Valencia and Central Europe.

Climate change adaptation (CCA) is essential for addressing vulnerabilities and risks from gradual environmental changes, whereas Disaster Risk Management (DRM) handles impacts from sudden extreme events. Thus, CCA supports DRM by tackling slow-onset changes that contribute to sudden disasters. In the EU, this is particularly important in urban areas, where 72% of people live (Nabielek et al. 2016). Initiatives like C40 Cities (C40 Cities 2023) and the EU Covenant of Mayors (EU Covenant of Mayors for Climate & Energy 2023) highlight this need. This requirement for systematic CCA planning is also reflected in the development of frameworks like the Urban and Regional Adaptation Support Tool developed by the European Climate Adaptation Platform Climate-ADAPT. On the DRM side, the DRM cycle has been the fundamental framework since the 1970s (see (Coetzee and Niekerk 2012) for a discussion of the evolution and origin of the DRM cycle).

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On the other hand, the inherent complexity of urban areas and the uncertainty associated with climate change impacts limits policy making for adaptation actions. Urban areas, as complex adaptive systems (Allen 2012; de Roo et al. 2020), are characterized by interdependent components, feedback loops, and emergent behaviors that complicate linear planning approaches. Adding to this complexity is the uncertainty associated with climate change, which spans multiple dimensions—epistemic, aleatory, and ontological uncertainties (Kwakkel et al. 2010)—and reflects not only the unpredictability of future climate impacts but also limitations in knowledge, data, and institutional readiness. In particular, deep uncertainty arises when planners cannot agree on system behavior, future outcomes, or the valuation of various responses (Kwakkel et al. 2010). This concept is central to Decision Making under Deep Uncertainty (DMDU), a paradigm that supports planning under such conditions.

For example, traditional infrastructure and urban planning often assumes stationary climate conditions—a simplifying assumption that overlooks the non-linear, dynamic, and non-stationary nature of climate change impacts. This mismatch between static planning paradigms and the evolving nature of climate risks exposes urban areas to heightened vulnerabilities. The non-stationarity of climate conditions necessitates decision-making approaches that accommodate uncertainty and allow for flexibility and adaptability over time.

Recognizing these challenges, decision-oriented approaches are increasingly replacing problem oriented ones in CCA (Wise et al. 2014). This has resulted in the development of various methods and tools that support adaptation policy making under climate change uncertainty. While other methods which consider uncertainty exist (Swart et al. 2004; Harvey et al. 2012), the most recognized approaches are Adaptive Policy Making (Walker et al. 2001, 2013; Haasnoot et al. 2024), Adaptation Pathways or Dynamic Adaptive Policy Pathways (Haasnoot et al. 2012; Ranger et al. 2013), and Real Options Analysis (Linquiti and Vonortas 2012). After mapping the various existing tools and methods that support adaptation planning, Walker and co-workers (Walker et al. 2013) concluded that Adaptation Pathways, a prominent approach within the DMDU framework, is the most dynamic approach.

Adaptation Pathways are crucial for building resilience, as they allow for adjustments over time in response to evolving risks and conditions enabling more flexible policymaking. Although these tools are inherently flexible, aligning with monitor-and-adapt paradigm, and thus, support adaptive planning under uncertainty, the present work seeks to enhance their focus on resilience-oriented planning by CCA and DRM frameworks. Although resilience is increasingly recognized as the unifying concept that bridges these areas, operational integration is still limited (Venton and La Trobe 2008). For resilience to be effectively operationalized, it is crucial for policymakers, experts, and practitioners in both fields to enhance their communication and collaboration. This integration could lead to significant reductions in climate-related losses by linking DRM measures with adaptation strategies, optimizing the use of financial, human, and natural resources (Gero et al. 2011), and improving the overall effectiveness and sustainability (Forino et al. 2015) of both CCA and DRM efforts (Venton and La Trobe 2008).

Thus, this article seeks to address this gap in the operationalization of resilience by proposing ways to integrate CCA and DRM in the Adaptation Pathway methodology. In doing so, it explores the potential of Adaptation Pathways to transition into Resilience Pathways as a holistic and systematic approach for resilience policymaking.

Basis of Resilience Pathways as understood in this article is a joint CCA/DRM planning framework, the ARCH (Advancing Resilience of Historic Areas against Climate-related and other Hazards) resilience framework illustrated in Fig. 1. The ARCH framework highlights the need to switch from a reactive risk management to a proactive resilience management that addresses both slow-onset and sudden climate impacts across governance levels. It consists of ten cyclical steps spread across the three DRM phases: ‘pre-disaster,’ ‘during,’ and ‘post-disaster’, further distinguished into a ‘normal operating’ phase and an ‘emergency operation’ phase. Outside the occurrence of emergency events, decisionmakers and planners regularly run through an extended CCA planning cycle of the Urban Adaptation Support Tool (steps 1–6, skipping steps 7–10) that includes considerations for DRM. It is important to note that the steps of this sub-cycle cannot be considered completely separate from each other. Instead, it is likely that steps will overlap and that there will be the need to revisit previous steps continuously even during a cycle.

As soon a disaster is imminent, emergency response and post-disaster recovery actions (Steps 7–10) are put into motion, including an additional revision of the results from the normal operating phase as soon as the rebuilding begins. This revisiting of original actions makes it explicit that the post-disaster reconstruction phase can and should also be used as an opportunity to reassess CCA measures to support Building Back Better. The ARCH resilience framework can be employed regardless of the (dynamic or stationary) planning process that is in place or shall be implemented in the future. However, using a pathway approach for implementing and monitoring measures (steps 5 and 6) and thus address decision making under uncertainty is highly beneficial, as will be discussed in the following sections.

By incorporating these considerations, the presented research aims to answer the question: *How can we*

Fig. 1 The ARCH resilience framework

incorporate the DRM dimension in the pathway approach and advance the Adaptation Pathway towards a Resilience Pathway? In pursuit of this aim, this work analyses the adjustment of key features—tipping points and thresholds, visualization of pathways, and assessment of pathways—within the Adaptation Pathways model to ensure the effective operationalization of the Resilience Pathway. The DRM integration within the Adaptation Pathway approach would create a holistic framework capable of addressing both slow-onset impacts and sudden-onset extreme events, while enhancing flexibility for adjustments in response to social, environmental, and economic changes. Achieving this is essential for enhancing cooperation, optimizing resource efficiency, and strengthening both preparation and response strategies.

Operationalizing Key Concepts Toward Resilience Pathways

The design of Resilience Pathways involves key elements such as identifying measures, their combination alternatives and sequencing them, benchmarking the performance of these alternatives, and defining thresholds and tipping points. Thus, this section explores the operationalization of thresholds and tipping points, the simultaneous visual representation of adaptation and DRM pathways, and the assessment of resilience pathways' performance.

Thresholds and Tipping Points

A climate threshold is a critical limit at which a socio-ecological system responds drastically to external forces, resulting in a shift to a different stable state (Allan et al. 2021), i.e., they represent impacts that cannot be tolerated in a given context. A "tipping point" indicates when this threshold is crossed, leading to irreversible change. Understanding and determining thresholds are vital for assessing when a socio-ecological system faces sever climate risks (Magnan et al. 2023), and up to when it becomes ineffective or non-functional socially, environmentally, or economically. However, translating climate thresholds (e.g., 1.5 degrees Celsius warming) into socio-economic thresholds (e.g., stakeholder acceptance) is often challenging (Ahmed et al. 2018) due to the difficulties in applying quantifiable metrics (e.g., water safety standards).

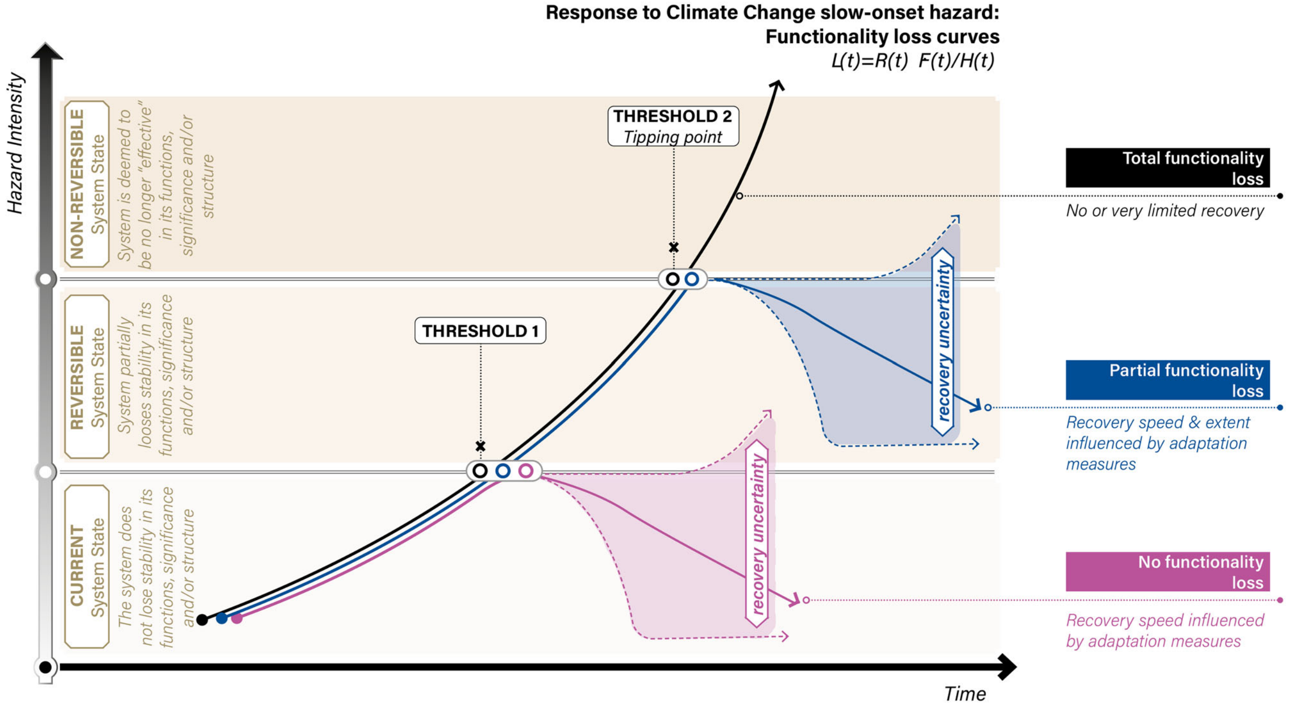

Fig. 2 The conceptualization of adaptation thresholds and tipping points considering the system's functionality loss curve as a result of the hazard intensity (slow-onset) over time while considering the influence of adaptation measures. High hazard intensity is directly associated with greater undesired impacts on the socio-ecological system, leading to a loss of functionality. The equation $[L(t)=R(t)\cdot F(t)/H(t)]$ represents the functional loss over time, where L(t) is the Functional loss at time t; F(t) is the Function performance at time t; H(t) is the Hazard intensity at time t and R(t) is a variable that encapsulates other influencing factors such as resilience measures' implementation. Functionality refers to the socio ecological system's ability to sustain and perform its essential functions and processes, maintaining the well-being of both human societies and ecological components. The functions can be ecological, social or economic in nature

Additionally, financial (e.g., cost-benefit) and societal values (van der Brugge and Roosjen 2015) play significant roles, particularly in fields like heritage conservation (Egusquiza et al. 2023). It is important to recognize that threshold determination may be expressed qualitatively when quantitative metrics are not available. For example, social and cultural functionality of the system can be represented by thresholds related to valued coping mechanisms or social norms, which reflect the identity and well-being of communities.

Since Resilience Pathways address both slow-onset climate change and sudden-onset disasters, two types of thresholds and tipping points should be simultaneously considered:

- Adaptation thresholds, as described in existing literature evaluate when a socio-ecological system begins to lose effectiveness due to slow on-set changes (Threshold 1 as illustrated in Fig. 2). Monitoring informs the necessity to deploy adaptation measures to minimize climate impacts and thus reach a threshold. If no adaptation measures are deployed, the system will continue to transition toward a non-functional state determined by a tipping point. As depicted in the Fig. 2, depending on the timing, extent and effectiveness of adaptation measures as well as evolving environmental conditions, recovery may be partial or complete until the tipping point is reached, at which point adaptation policies fail to address the system's needs regarding values, risks, and consequences of change (Lenton 2020).
- Disaster thresholds correspond when specific extreme events (and their early signals) serve as triggers for DRM measures and reinforcement of adaptation policies. The intensity of these events, illustrated in Fig. 3, determines whether the system can absorb impacts or is significantly affected. Events that do not reach this threshold, with appropriate resilience measures before and after the disaster, may restore the system's state, while those that do can lead to significant impacts and an irreversible transition to a different stable state. However, transitions that do not reach the tipping point may be partially or fully reversible, depending on the event's severity and the extent, timing and effectiveness of pre- and post-disaster measures. The system´s response to the disaster and the extent of functional recovery are not deterministic; instead, recovery speed and outcomes are subject to variability represented by doted lines shape.

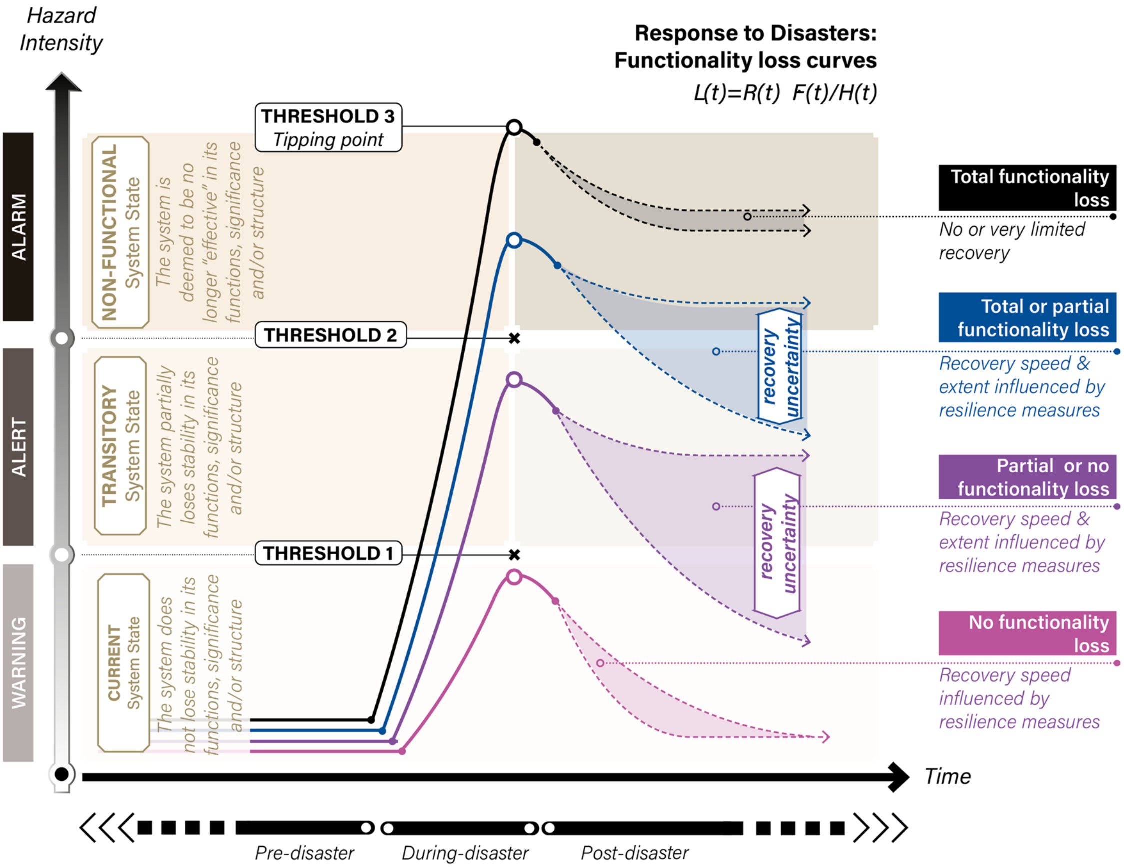

Fig. 3 The conceptualization of disaster risk thresholds and tipping points considering the system's functionality loss curves as a result of the hazard intensity (disaster) over time while considering the influence of resilience measures. High hazard intensity is directly associated with greater undesired impacts on the socio-ecological system, leading to a loss of functionality. The equation [L(t)=R(t)·F(t)/H(t)] represents the functional loss over time, where L(t) is the Functional loss at time t; F(t) is the Function performance at time t; H(t) is the Hazard intensity at time t and R(t) is a variable that encapsulates other influencing factors such as resilience measures' implementation

Several factors influence the determination of climatic tipping points. While thresholds related to sea-level rise are relatively straightforward (Kwadijk et al. 2010), thresholds associated with future scenarios involving changes in precipitation, temperature, or wind patterns, are not only more uncertain but also more complex due to limited impact modeling resources and (unreliable) data. Furthermore, the effects of climate change can exhibit time lags, meaning that the full effects may not be felt for several years or decades after the initial changes occur, complicating the analysis of potential thresholds.

Another critical factor is the complexity and interdependence of systems. Many socio-ecological systems are highly interconnected, complicating the identification of thresholds that could trigger tipping points (Werners et al. 2013). Feedback loops between different system elements can amplify small changes, making predictions difficult. Additionally, climate change impacts may be influenced by economic (Winkelmann et al., 2022), social (Winkelmann et al. 2022; Juhola et al. 2022), and political factors, further complicating threshold analyses.

Addressing knowledge gaps in defining tipping points requires a multidisciplinary approach that integrates scientific research with stakeholder engagement and knowledge co-production (Heaton et al. 2016). Participatory and integrative methods can help identify and quantify the impacts of climate change on various systems and develop effective Resilience Pathways.

Stakeholder-led approaches to identify critical factors contributing to thresholds and tipping points (van Ginkel et al., (2020)) also require further research. These approaches can facilitate the identification of early warning signals, enabling proactive measures to prevent systems from crossing thresholds. Close collaboration among stakeholders is essential for building a shared understanding of risks. Climate services[1] may be a powerful tool to facilitate shared understanding as they provide "*climate information*

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[1] The provision of climate information in such a way as to assist decision-making by individuals and organizations. The service component involves appropriate engagement, an effective access mechanism and responsiveness to user-needs The Global Framework for Climate Services | Nature Climate Change

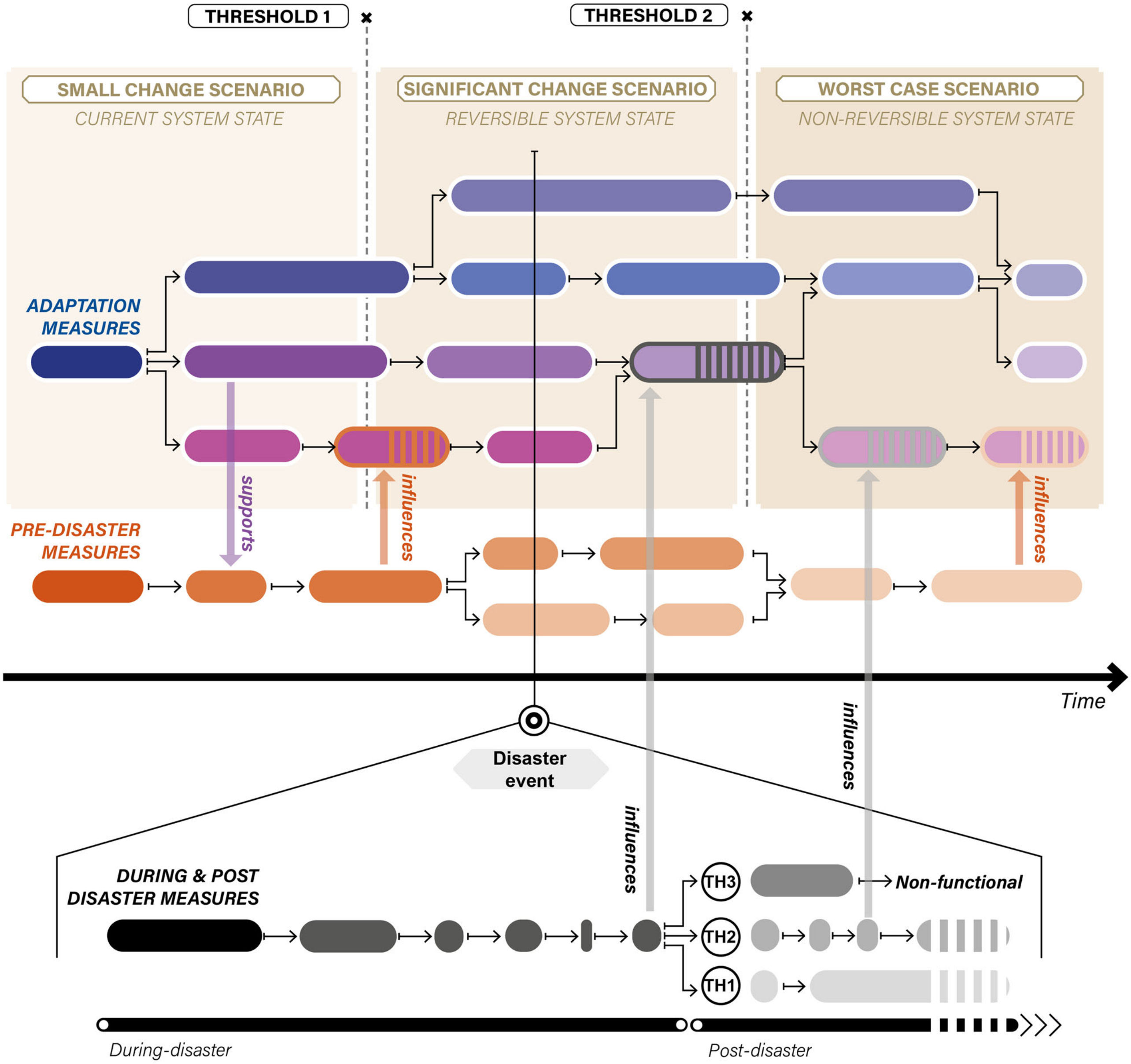

Fig. 4 Resilience pathway visualization integrating adaptation and disaster risk management measures considering adaptation and disaster risk thresholds encapsulating flexible planning in both planning approaches while understanding their interconnections.TH refers to Disaster Thresholds as present in Fig. 3

in such a way as to assist decision-making by individuals and organizations". An important part of climate services is the "*appropriate engagement, effective access mechanism and responsiveness to the user needs*" (WMO 2014).

Visual Representation

The core concept of the Adaptation Pathway visualization model centers on the idea that adaptation measures maintain effectiveness only under certain conditions, often linked to hazard intensity or other factors, including the finite duration of their efficacy. Consequently, a given set of measures may remain viable only up to a specific threshold associated to a partial functionality loss of the system (Threshold 1 from Fig. 4). Once this threshold is exceeded, a decision point is triggered, prompting to the implementation of additional or alternative measures. Although this fundamental principle applies equally to both Adaptation and Resilience Pathways, integrating resilience measures for the during and post-disaster phases into the representation of Adaptation Pathways (normal operating phase, see Fig. 1) remains unclear. The authors propose to have one dedicated visual aid for the pre-disaster/adaptation phase and a second visual aid for the during- and post-disaster phases (Fig. 4), providing an easy way for comprehending complex resilience information. This is logical as the deployment of measures, i.e., the sequence of actions for the during- and post-disaster phases, to tackle sudden-onset event impacts will only take place once the disaster takes place. Despite the event in Fig. 4 having been placed at a specific time point, the event may take place at any point, or even cascading disasters may occur or various disaster could take place over different scenarios. The essence of the representation lies in decision points as thresholds are reached that determine the gradual deployment of measures to maintain the functionality of the system. The dynamic pathway navigation has also been suggested to be influence by different factors (as future unfolds) such as financial disposition, knowledge, environmental, governance etc. (represented by various arrows departing a measure, which suggest a decision point). However, disaster thresholds may influence mainly the post-disaster path to embark in, which is linked to the efforts needed to recover to the current state. Figure 4 depicts that different pathways may be envisioned depending on the severity of the sudden-onset disaster. Depending on the disaster severity reached (associated to thresholds as seen in Fig. 3) the resilience path may imply that the recovery of the socio-ecological system is not possible or more or less efforts are needed. For simplicity, a linear sequence of resilience measures has been depicted in Fig. 4. However, it is important to note that multiple pathway alternatives, similar to those observed for normal operating phase, are likely. Additionally, pathways associated with disaster thresholds 1 and 2 are as well likely to be interconnected. The influence between adaptation and resilience pathways are represented by dashed colored items which determines the extent and duration of deployment of measures.

These visual representations provide a valuable aid to:

- Comprehend the different possible paths and recognize the relationships between resilience tipping-points, needs, actions, and objectives (Haasnoot et al. 2024).
- Enhance decision-makers' ability to evaluate dynamic responses to evolving conditions, helping to identify barriers, prioritize actions, and avoid lock-ins. These representations are especially useful for conveying complex data and multiple solutions in an accessible format (Lurie and Mason 2007).

Performance Assessment

Assessing the performance of different pathways is crucial to ensure their effectiveness in achieving goals under various scenarios. Depending on the pathway's objectives, approaches such as performance-oriented or stakeholder-led assessments can be applied (Werners et al. 2021a; Haasnoot et al. 2024).

Performance-oriented pathways prioritize quantifiable measures to evaluate the effectiveness of resilience actions in reducing risks. These assessments rely on data-driven approaches, such as models to assess the effectiveness of adaptation measures and pathways to mitigate impacts of climate change-related hazards (Mendizabal et al., 2021; Haasnoot et al., 2012; Werners et al., 2021a), indicators (Mendizabal et al. 2018; Zorita 2022), multicriteria analysis or cost-benefit analysis (Haasnoot et al. 2024). However, these methods depend on quality data availability, and require significant technical expertise and resources. Nevertheless, stakeholder engagement can be integrated in models and measures within the performance-oriented pathways.

In contrast, stakeholder-led pathways are essential for addressing complex issues where local knowledge is critical, or data on risk reduction is limited. These approaches target stakeholder engagement and participation to ensure that the assessment reflects the diverse needs and priorities. Assessing pathways in this manner often incorporates a broader range of qualitative or semi-quantitative metrics, such as community well-being, social capital or the ranking of the acceptance of the resilience measures, which complement quantitative data (Pelling and High 2005; Smit and Wandel 2006). Participatory methods like community meetings, co-production of knowledge, which can be complemented with consultation methods (e.g., focus groups, and surveys) are effective in gathering insights and developing climate adaptation or transformation narratives (Paschen and Ison 2014). These approaches can reveal how social inequalities shape vulnerability and resilience, enabling solutions tailored to marginalized or high-risk groups. They are also important when considering socio-institutional measures that contribute to resilience. These measures are critical in resilience building, as they help to address the underlying social, governance, and economic factors that contributing to vulnerability. Governance initiatives, cultural values, and the lived experiences of local populations can be integrated into pathway assessments to ensure inclusive solutions that resonate with community priorities.

Adaptation Pathways have traditionally focused on risk reduction by identifying structural measures to minimize exposure or increase adaptive capacity. While their effectiveness can be assessed through environmental and economic modeling, evaluating Resilience Pathways remains challenging, particularly due to the role of socio-institutional measures in resilience building. These measures, which include governance, policies, and social equity initiatives, are difficult to incorporate into physical models. Benchmarking diverse resilience measures, such as permeable pavement or post-event evacuation strategies, is complex and underexplored. Economic assessments, such as cost-benefit analyses, could help address this gap, despite limitations related to climate change consideration in the analysis or data availability (Robinson and Hammitt 2011; Scovronick et al. 2019). Multicriteria analysis also offers a valuable approach for evaluating Resilience Pathways, especially in scenarios involving multiple conflicting criteria (Haasnoot et al. 2024).

Future Perspectives

Despite the progress made in the conceptualization of the Adaptation Pathway approach to embed DRM, the consideration of several areas within this approach still requires further research. Key future research directions include:

- Operationalizing Climate-Resilient Development Pathways: It is necessary to further elaborate on the operationalization of Resilience Pathways and to demonstrate their implementation across diverse contexts, incorporating intersecting policies such as mitigation and sustainability. Engaging in dialogue with the broader scientific community, policy officers, and practitioners can strengthen and refine their operationalization.
- There is an urgent need to move beyond a risk-reduction perspective in CCA and address the root causes of vulnerability. This requires further research on integrating future-thinking tools into pathway approaches and establishing assessment criteria for desired changes to reshape systems, ensuring long-term climate resilience.
- Integrating Resilience Pathways into policy frameworks: There is a need to explore how Resilience Pathways can be articulated with or deployed through key policies like land use, spatial, and urban planning. That is, how they can present a coherent evolution of climate mainstreaming in those key policies that play a critical role in shaping the physical and social environment of cities and communities, as well as their vulnerability to climate change impacts. It is important to explicitly consider resilience as a key objective of planning processes, and to determine specific resilience indicators to guide and inform flexible decision-making.

Furthermore, moving forward, it will be vital to address issues such as siloed decision-making, legal frameworks, and funding models that limit the adaptability of policies in response to evolving risks. Greater collaboration between academic research and real-world applications, along with forums for exchanging practical experiences between countries, will also be essential for advancing the implementation of dynamic policy pathways and ensuring resilience at all levels of governance.

Data availability

No datasets were generated or analysed during the current study.

Author contributions SZ: Conceptualization, Methodology, Investigation, Writing – Original, Writing – review & editing & Visualization. KM: Investigation, Writing – Original, Writing – review & editing & Visualization. NP: Writing – Review & Editing, visualization. AA-S: Visualization. DL: Investigation, Writing – Original, Writing – review & editing & Visualization, Funding acquisition. EF: Writing - Review & Editing, Funding acquisition.

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Compliance with ethical standards

Conflict of interest The authors declare no competing interests.

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