BRIEFING NOTE

SYSTEMIC RISK

REVIEW AND OPPORTUNITIES FOR RESEARCH, POLICY AND PRACTICE FROM THE PERSPECTIVE OF CLIMATE, ENVIRONMENTAL AND DISASTER RISK SCIENCE AND MANAGEMENT

International Science Council
The global voice for science

UNDRR
UN Office for Disaster Risk Reduction

RISKKAN
Knowledge Action Network

AUTHORS AND AFFILIATIONS

Jana Sillmann, University of Hamburg, CEN, Research Unit for Sustainability and Climate Risks, Hamburg, Germany; Center for International Climate Research, Oslo, Norway

Ingrid Christensen, Center for International Climate Research, Oslo, Norway

Stefan Hochrainer-Stigler, International Institute for Applied Systems Analysis (IIASA), Vienna, Austria

Jo-Ting Huang-Lachmann, Climate Service Center Germany (GERICS), Helmholtz-Zentrum Hereon, Hamburg, Germany

Sirkku Juhola, Ecosystems and Environment Research Programme, University of Helsinki, Helsinki, Finland

Kai Kornhuber, The Earth Institute, Columbia University, New York, NY, USA

Miguel D. Mahecha, Remote Sensing Centre for Earth System Research, Leipzig University and Helmholtz Centre for Environmental Research - UFZ, Leipzig, Germany

Reinhard Mechler, International Institute for Applied Systems Analysis (IIASA), Vienna, Austria

Markus Reichstein, Max-Planck-Institute for Biogeochemistry, Jena, Germany

Alex C. Ruane, NASA Goddard Institute for Space Studies, New York, NY, USA

Pia-Johanna Schweizer, Institute for Advanced Sustainability Studies (IASS), Potsdam, Germany

Scott Williams, United Nations Development Programme, New York, NY, USA

ACKNOWLEDGEMENTS

The authors acknowledge the careful review and valuable input of Karen O'Brien, Alik Ismail Zadeh, Alonso Brenes Torres and Melody Brown Burkins on the final draft and the comments received from Adam Fysh, John Handmer, Jenty Kirsch-Wood, Allan Lavell and Anne-Sophie Stevance at all stages of conceiving and writing this Briefing Note. The authors further thank all the members of the Risk KAN, IRDR and UNDRR that reviewed earlier versions of the Briefing Note as well as those who contributed to Annex I, available at: https://council.science/wp-content/uploads/2020/06/Systemic-risk-briefing-note-Annex-1_List-of-current-definitions.pdf. The authors also thank the participants of the initial workshop (as listed in Annex II, available at: https://council.science/wp-content/uploads/2020/06/Systemic-risk-briefing-note-Annex-2-list-of-workshop-participants.pdf) for their expert insights that shaped this Briefing Note. The authors would like to thank Subhra Bhattacharjee, Kazi Shahidur Rahman and Andrew Colin Spezowka for their support in the selection of the case study in Bangladesh, providing materials and giving their valuable feedback for revisions for the anticipatory action pilot in Bangladesh. Furthermore, the authors would like to thank Arturo Balderas Torres for his valuable feedback for revisions for the case study in Mexico. Jana Sillmann and Ingrid Christensen were supported through the CICERO Strategic Project on Climate Change Risk (no. 160015/F40), funded by the Research Council Norway. Alex C. Ruane received support from the NASA Earth Science Division via the GISS Climate Impacts Group and NASA Community Service funds. Miguel D. Mahecha was supported by the Helmholtz Association of German Research Centres project Coping Capacity of nations facing systemic crisis, COCAP.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

Systemic risk is associated with cascading impacts that spread within and across systems and sectors (e.g. ecosystems, health, infrastructure and the food sector) via the movements of people, goods, capital and information within and across boundaries (e.g. regions, countries and continents). The spread of these impacts can lead to potentially existential consequences and system collapse across a range of time horizons. Globalization contributes to systemic risk affecting people worldwide. The impacts of climate change or COVID-19 show how the challenges of addressing systemic risk go beyond conventional risk management and governance. Critical system interdependencies, amplified by underlying vulnerabilities, highlight that there is a growing need to better understand cascading impacts, systemic risks and the possible political (governance) and societal responses. This includes improving our understanding of the root causes of systemic risk, both biophysical and socio-economic, and related information needs. Addressing contemporary challenges in terms of systemic risk requires integrating different systems perspectives and fostering system thinking, while implementing key intergovernmental agendas, such as the Paris Agreement, the Sendai Framework for Disaster Risk Reduction and the Sustainable Development Goals.

This Briefing Note represents an integrated perspective of climate, environmental and disaster risk science and practice regarding systemic risk. It provides an overview of the concepts of systemic risk that have evolved over time and identifies commonalities across terminologies and perspectives associated with systemic risk used in different contexts. Key attributes of systemic risk are outlined without prescribing a single definition, and information and data requirements that are essential for a better and more actionable understanding of the systemic nature of risk are discussed. Finally, the opportunities to connect research and policy for addressing systemic risk are highlighted, followed by recommendations for future work in science, policy and practice on systemic risk. The Briefing Note is based on insights and knowledge gained from an expert workshop, literature review and expert elicitation.

1 SYSTEMIC RISK: WHY DO WE NEED TO CARE?

Understanding and managing systemic risk is more important than ever due to our immense global connectivity, whether between sectors, such as food–health–water–energy, countries and continents, or even between individuals (Gaupp, 2020). Although the notion of systemic risk is several decades old (Faulhaber et al., 1990), the term is used in diverse ways across different disciplines (e.g. financial systems, medicine, Earth system sciences, disaster risk research and climate science). Triggered by the repercussions of the global financial crisis of the late 2000s, and more recently the COVID-19 pandemic, which are clear realizations of systemic risk, the perception of systemic risk has often focused on global and catastrophic or even existential risks (e.g. Helbing, 2013; World Economic Forum, 2021). Systemic risk, however, can be seen as a feature of systems at all possible scales – global, national, regional and local – with system boundaries varying depending on the context.

The systemic nature of risk (or systemic risk) is based on the notion that risk, for instance arising from a policy, response action or a hazard event (for definitions see Murray et al., 2021), depends on how the elements of the affected systems interact with each other. These interactions either aggravate or contain the overall effect of the constituent parts, creating the potential for cascading impacts on system elements far from the first impact. Interactions occur through positive or negative feedback processes that can lead to system malfunction or even collapse. Systemic risk is different from conventional risk and thus challenges well-established approaches to risk analysis and risk governance that seek to analyse and manage by addressing individual elements of a system or sub-systems as though they are or act in isolation (Cutter et al., 2015).

Systems can be affected by critical events or shocks (see examples in Figure 1) that occur outside or within the system. Furthermore, the design and evolution of systems, like the financial or food system, can create risks as well as opportunities that make elements of the system more resilient towards external shocks. For example, the pursuit of ever more efficient food systems has resulted in greater reliance on trade to compensate for local or national production gaps or to absorb over-supply (Otto et al., 2017; UNDRR, 2019). This so-called efficiency of the system (often eliminating the contexts relevant to the functioning of the system) contributed to reduced grain storage and thus to a reduced buffer against unplanned outcomes, which likely contributed to price spikes and cascading risk throughout and beyond the food system in 2008–2012 (Puma et al., 2015; Laio et al., 2016; Schewe et al., 2017).

Recognizing its relevance to many current challenges, a wealth of recent publications has picked up on the topic of systemic risk. For instance, the *Global Assessment Report on Disaster Risk Reduction* (UNDRR, 2019), as well as the International Council of Risk Governance (Florin and Nursimulu, 2018), take a close look at the drivers of systemic risk, its governance and the future emergence of such risks (see also Centeno et al., 2015). The Intergovernmental Panel on Climate Change (IPCC) is moving from what could be characterized as a static framing of risk as a function of hazard, exposure and vulnerability to a more dynamic characterization where responses to risks with potential side effects, and interactions between risks, are more strongly considered (Reisinger et al., 2020; IPCC, 2022). The Integrated Research on Disaster Risk programme has compiled the comprehensive *Framework for Global Science in Support of Risk-informed Sustainable Development and Planetary Health* (ISC-UNDRR-IRDR, 2021) that focuses on complex impacts and systemic risk from a multi-hazard and disaster risk perspective. Furthermore, the United Nations Development Programme (UNDP) is considering systemic risk from a social construction perspective (Maskrey et al., 2021). In the context of climate change,

BOX 1
COVID-19 and climate change as systemic risks: Learning from EU CASCADES and RECEIPTS projects
(Van den Hurk et al., 2020)

What do the COVID-19 pandemic and climate change have in common? Both can disrupt societal systems and global networks and can have amplifying effects through systems. On the one hand, COVID-19 has highlighted the ability and willingness of different stakeholder groups, such as governments, experts and the public, to respond rapidly and substantially to a global and local crisis, and how recovery measures could contribute to future resilience and socio-economic sustainability. On the other hand, the shock to national, regional and global economies from COVID-19 hampers investments and development aid that are needed to increase societal resilience against impacts from climate change.

Debt levels are likely to increase, particularly in countries facing the double effects of COVID-19-related lockdowns and declining export revenues. COVID-19 raised the awareness of our reliance on international networks to exchange goods, services and capital. It encouraged political leaders challenged by globalization to rethink the balance between local and global action. It also reminded us of the importance of well-functioning systems, such as supply chains, health care, food, social security and education.

Most climate risk assessments and adaptation strategies focus on nations and sectors, addressing clearly identified risks, actors and options to reduce risk. However, the systemic and transboundary nature of many climate change drivers requires system transformation and better preparation for cascading risk from climate change leading to systemic impact. Governments, public and private sectors as well as civil society organizations trying to anticipate future disruption must take a systemic perspective when designing policies or measures to reduce and manage these risks. By putting emphasis on the implementation of the Sustainable Development Goals, especially in lower- and middle-income countries, and hence reducing key underlying vulnerabilities, the world would be in a better position to respond to and reduce systemic risks, such as those that can be triggered by climate change impacts and pandemics.

for instance, it can be misleading to describe climate and weather extremes as the cause of disasters (e.g. Ismail-Zadeh, 2021). Given that disasters are caused by pre-existing fragilities and inequalities on the ground, place-based vulnerabilities and their socio-political causes need to be dealt with in order to understand and manage systemic risks (Lahsen and Ribot, 2021). A systemic risk perspective will also be key for ensuring sustainable and resilient future development (Reichstein et al., 2021), which has been the focus of three major global agreements adopted in 2015: the Sendai Framework, the Sustainable Development Goals and the Paris Agreement (cf. Handmer et al., 2019).

Contemporary challenges, such as climate change, biodiversity loss or the COVID-19 pandemic, are all interconnected, interdependent and rooted in patterns of thinking that struggle to internalize complexity and uncertainty (see e.g. Box 1). This requires a fundamental change of the underlying narrative from, for example, 'Problems are to be solved by suppressing complexity and eliminating inconvenient contexts', to 'Problems are paradoxes to be mutually understood and addressed holding trans-contextual perceptions' (Bateson, 2016). In this context, current scientific and societal endeavours to address complex problems, such as the climate crisis, draw attention to the interacting domains of transformation to sustainability, which encompass the practical, political and personal spheres of transformation (O'Brien and Sygna, 2013; O'Brien, 2018).

From the perspective of climate, environmental and disaster risk science and practice on systemic risk, this Briefing Note provides in the following sections a review and discussion of the attributes of systemic risk, information needs for understanding and modelling systemic risk, opportunities for research and governance of systemic risk, and future perspectives. The Briefing Note reflects expert elicitation from the global networks represented by members of the Knowledge Action Network for Emergent Risks and Extreme Events (Risk KAN), which is a joint initiative of the World Climate Research Programme (WCRP), the World Weather Research Programme (WWRP), Future Earth and Integrated Research on Disaster Risk (IRDR), as well as the Global Risk Assessment Framework (GRAF) working groups of the United Nations Office for Disaster Risk Reduction (UNDRR) and the Society of Risk Analysis (SRA).

2

ATTRIBUTES OF SYSTEMIC RISK

2.1 Evolution of the debate on systemic risk

Research on systemic risk originally emerged within complexity science. This began in the early 1950s, making great progress over time (see, for example, the review by Castellani, 2018). What set complexity science apart was that it did not belong to one specific field. Instead, it was developed by and across different scientific disciplines, with important contributions from cybernetics (e.g. Wiener, 2019), biology (e.g. Varela et al., 1974), ecology (e.g. Holling, 2001), sociology (e.g. Luhmann, 1995) and economics (e.g. Haldane and May, 2011), to name but a few (see Figure 1).

At first, systemic risk was conceptualized in the context of network dynamics. The approaches ranged from purely mathematical models that were assuming a specific network structure, through to agent-based models that depicted network structures by means of individual agents (the network structure is itself an emergent phenomenon). The application of these models to real-world problems was limited, focusing on pandemic outbreaks (Epstein, 2009) or fishery or ecological aspects. Such risk models were largely used to model impact, such as epidemiological models capable of showing the spread of a virus with certain characteristics within a specific environment. However, these models were not designed to model the systemic nature of risk, or the anticipation of systemic risks. The concept of systemic risk and its application to 'wicked problems' (Rittel and Webber, 1973) has gained more attention in the 2000s. This is probably attributable to events such as the financial crisis in 2007/08 and climate-related impacts. These events increased awareness of how specific events (such as physical hazards, or economic or geopolitical events) have knock-on effects across regions and sectors through interconnected and interdependent systems, causing unmodelled losses and potentially systemic collapse. Yet risk analysis and risk modelling have been largely unconcerned with these relational and procedural aspects of risk that cause cascading failure.

Figure 1 provides an overview of the continuously evolving debate from research and policy-making perspectives. The graphical representation is based on expert input from the Risk KAN and SRA. It is indicative of discursive developments in science and policy-making and does not imply an exact or proportional representation in terms of the number of publications or exact timing of the science emerging from different disciplines.

In 2003, the Organisation for Economic Co-operation and Development (OECD) began using the category of systemic risks to account for risks that threaten society's essential systems, such as infrastructure, health care and telecommunications (OECD, 2003). This was a major milestone because the concept consequently became visible outside academia and gained traction in policy-making. Another seminal work was published in 2003 on systemic risks in banking, stressing the importance of knock-on effects caused by systemic interdependencies, leading to breakdowns of entire systems that could happen at a national or transnational scale (Kaufman and Scott, 2003, p. 372). However, systemic risks manifest at all scales. Therefore, scholars (Aven and Renn, 2020) suggest that systemic risks have to be differentiated at the regional, national and global level (Centeno et al., 2015; Aven and Renn, 2020). Thus, research has often been targeted towards

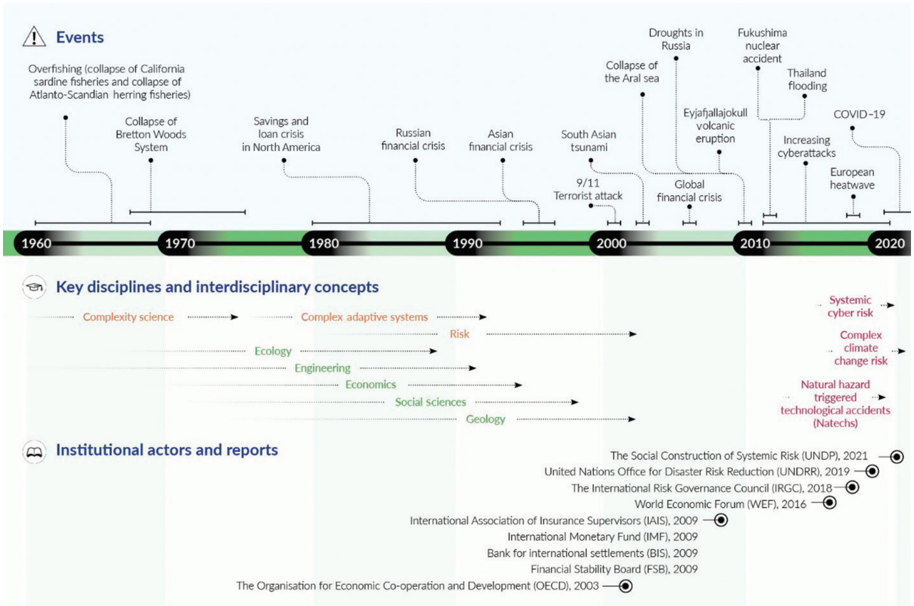

FIGURE 1: Overview of the evolving debate on systemic risks, including a selection of major events that triggered research on aspects of systemic risk, the disciplines in which systemic risk is covered or mentioned, and institutional actors and reports driving research agendas on the topic of systemic risk (based on a non-exhaustive literature review (see also Annex I) and expert elicitation).

systems failure and breakdowns as well as towards systemic interdependencies leading to knock-on effects. Systemic risks may spread from one sector or dimension, such as public health, to another, such as economy and finance, to others still. These cascading effects can be channelled through different transmission pathways (Naqvi et al., 2020), raising the question of how these transmission pathways can be identified and controlled.

2.2 Characteristics of systemic risk

Scholars have provided a detailed discussion on the broad-based features of systemic risk (Schweizer and Renn, 2019; Renn et al., 2020; Schweizer, 2021). Figure 2 builds on this work with a synthesis of the existing terminology for key attributes of systemic risk. These can be broadly categorized under five themes relating to the scale of the system, the level of system understanding, the relationship of the elements within a system, transboundary effects and the outcomes of systemic risk. This categorization of key attributes is based on the review of current available definitions of systemic risk (see Annex I). Different wordings have been used for the attributes depending on scientific discipline and/or target group(s).

A key attribute of systemic risk is that it can transgress spatial and sectoral boundaries with other systems, sectors and geographical regions, thus leading to cascading effects (Schweizer and Renn, 2019; Renn et al., 2020; Schweizer, 2021). Furthermore, systemic

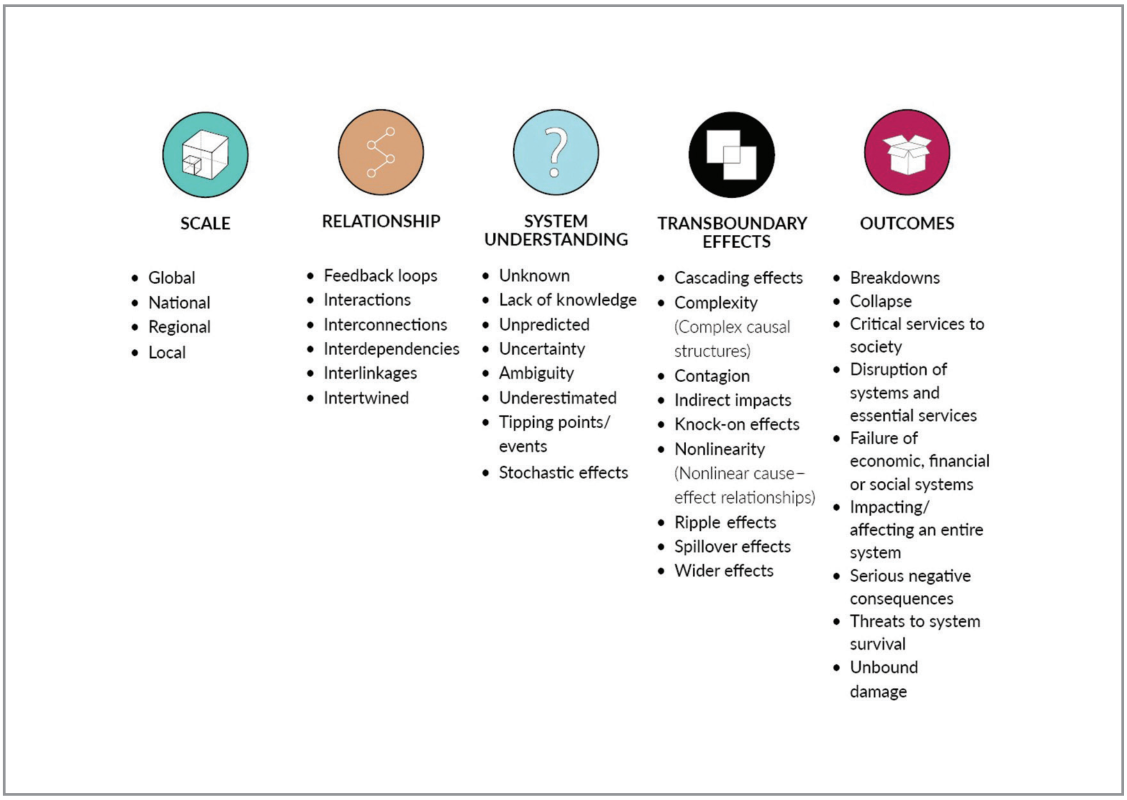

FIGURE 2: Synthesis of definitions concerning systemic risk based on the literature compiled in Annex I. Below each key attribute is a non-exhaustive list of terms/words used to describe or refer to the overarching theme in the reviewed literature (see Annex I).

risks tend to be attenuated rather than amplified in public perception due to various factors, such as risk perception not being linearly calibrated to the seriousness of the risk due to lags in cause and effect (Schweizer et al., 2021). This factor seems particularly prominent in the climate change discourse between emitters of greenhouse gases and places where the impacts of climate change are most acutely felt (see Box 2). Systemic risks are caused by interdependencies in complex coupled systems. In most cases, these interdependencies cannot be discovered directly by people's day-to-day experiences. For instance, communities that have directly experienced damages from weather extremes are more prone to invest in climate change adaptation than communities that have not been affected (Amundsen and Dannevig, 2021). Even more difficult for many people to grasp are consequences of remote weather extremes that are transmitted through the system. An example of this would be a drought affecting crop yields in some regions and leading to increases in food prices or food shortages in other areas, that in turn can trigger social unrest and challenge local or national policy interventions (Gaupp, 2020).

Without day-to-day experiences as a guiding yardstick, risk perception is influenced by trust in science and other institutions, such as government and regulation. In the case of systemic risks, causality is obscured by the multitude of intermediary factors and increasing lack of predictability in their relationships. Together with the increasing fragility of public trust in institutions, these unpredictable and counter-intuitive relationships often lead to the social attenuation of systemic risks. This reflects society's tendency to underestimate systemic risk rather than to reduce the force, effect or value of it (Schweizer et al., 2021). For instance, scientific evidence pointing towards the systemic risks of climate change have been available since the 1970s. However, even now that social mobilization has resulted in a broader acknowledgement of climate change as a severe threat (as shown by campaign groups like Fridays4Future, Extinction Rebellion), currently-implemented climate change mitigation policies are still insufficient to meet the goals of the Paris Agreement (IPCC, 2018, 2021; Lenton et al., 2019). Scholars claim that the characteristics of systemic risk, such as the transgression of geopolitical boundaries and an emphasis on the interconnectedness of system elements (Figure 2), set systemic risks apart from other risks and challenge established governance arrangements (Frank et al., 2014; Renn et al., 2020).

Therefore, a major challenge when analysing systemic risks is the issue of focus. As systemic risk speaks to cross-systems and transboundary drivers and impacts, it is crucial to be specific about the systems under consideration and what they incorporate (including what is unclear or unknown about a system) and its boundaries or transboundary effects.

BOX 2
Case study: Addressing global and systemic risk with local climate planning in Mexico (based on Torres et al., 2021)

Mexico loses more than USD 2 billion per year due to climate-related disasters but has put forward one of the least ambitious Nationally Determined Contributions (NDCs) among G20 nations (Government of the Republic of Mexico, 2015).

Mountainous areas, which are home to nearly a billion people globally and cover one-quarter of the global landmass, are particularly vulnerable to a range of climate-related risks, including more frequent and intense flooding. These risks can compound existing vulnerabilities, especially in urban areas, putting development needs in jeopardy. Recognizing the global and systemic nature of these risks, the city of Xalapa, in a mountainous region of southern Mexico, was one of the first places in Latin America to prepare a local climate action plan back in 2010. The city developed alternative approaches to urban development, including ‘green’ and ‘blue’ ecosystem or nature-based solutions in place of conventional ‘grey’ infrastructure. Projects and policies include solutions based on green infrastructure and nature-based solutions (silvo–pastoral food production and forest conservation, urban food gardens, infiltration pathways, natural wetland recovery), ‘light grey’ infrastructure (rainwater collection), changes in governance and institutional arrangements (such as urban planning regulations), and the promotion of new community-based approaches (the deployment of small-scale water collection tanks). By implementing this diverse set of adaptation strategies, Xalapa shows how the institutionalization of local climate policies can foster incrementally more ambitious action over time and a wider range of social and environmental benefits. By recognizing the global and systemic nature of the challenges related to climate change, and with the support of forward-looking policies, stakeholders can play a key role in helping communities reduce local vulnerabilities while transitioning to a zero carbon resilient future.

It is also important to reflect on these assumptions. These considerations are important for creating an analytical focus on the type and number of variables and degrees of freedom for the analysis. However, the analytical focus and the boundaries of analysis change as research progresses and/or the systemic risk evolves. The boundaries can be, for instance, spatial or political (e.g. regions, countries) or sectoral (e.g. economic sector). As discussed by Aven and Renn (2020) as well as Hochrainer-Stigler et al. (2020), the system itself can be of any type and at all possible scales, from local to global. Therefore, an integrated approach towards risk management that pays attention to the interconnectivity of risk and particularly its transboundary effects merits consideration (see also Figure 2).

The complexity of the major challenges we as society face, such as environmental degradation, climate change and financial crises, are often downplayed or ignored, and technical solutions are often preferred over more complex ones including behavioural changes (O'Brien, 2018). To successfully address systemic risks, however, requires a systems approach that identifies effective places to intervene in systems to reduce risks, also known as key leverage points. Interventions may include a willingness and capacity to examine the underlying assumptions and premises regarding how societies relate to and transform systemic risk. Transformability, as defined by Westley et al. (2011), is: 'the capacity to create untried beginnings from which to evolve a fundamentally new way of living when existing ecological, economic and social conditions make the current system untenable.' O'Brien and Sygna (2013) argue that, to achieve sustainable systems in the context of systemic risk, the three related and interacting 'spheres' of transformation – the practical, political and personal – must be considered and simultaneously addressed (see Figure 3).

The practical sphere most often involves largely 'technical responses': enhancing knowledge and expertise, promoting innovation, improving management and changing behaviour. The political sphere consists of systems, structures and processes (e.g. social and cultural norms, rules, regulations, incentives and infrastructure) that reflect how society is organized, how systems function and how systemic risks are managed or addressed. The political sphere is where collective action and political processes can challenge the vested interests and power relations that maintain systems and structures intact. Inertia in this sphere may also be caused by sticking to solutions that have functioned well earlier in other contexts but that are no longer pertinent to current challenges. The personal sphere includes the individual and shared beliefs, values, worldviews and paradigms that influence attitudes and actions. These shape individual and collective views of the systems as well as perceptions and attitudes associated with systemic risks, which in combination can often explain preferred strategies for practical transformations (O'Brien and Sygna, 2013). Therefore, it is in the practical sphere where we tend to observe and measure whether systemic risk is reduced. But whether those actions are the right actions, and whether they succeed, depends on what happens in the political and personal spheres. Addressing systemic risk in only one or two of the spheres will likely not result in transformative change towards reducing systemic risks. Considering all three spheres in conjunction affects how we perceive and recognize the different elements of the system and how we design and communicate solutions for reducing systemic risks.

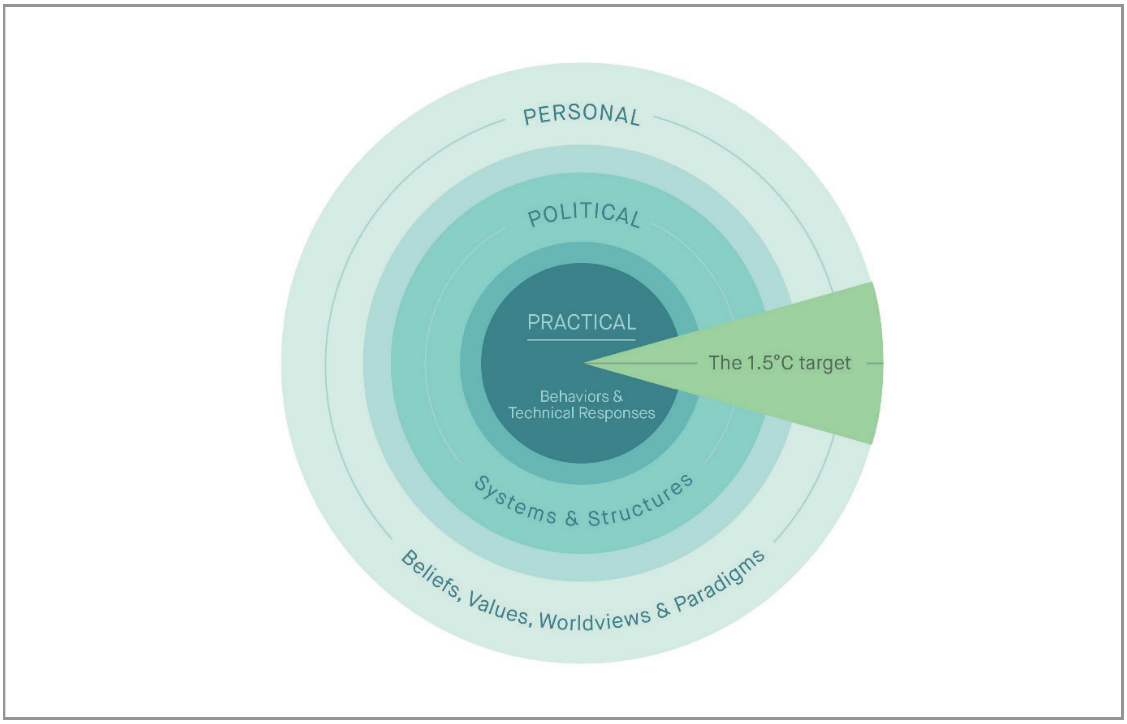

FIGURE 3: Three spheres of transformation (from O'Brien and Sygna, 2013).

3

INFORMATION NEEDS: WHAT DO WE NEED TO KNOW ABOUT A SYSTEM?

3.1 System elements and boundaries

Systems include different sub-systems, components, elements or actors with diverse interactions and relationships between them. Setting system boundaries and defining what is considered inside or outside a system depends, for instance, on the scientific, decision-making or governance context, and is often needed to reduce complexity and enable us to describe and model a system. As illustrated in Figure 4, a system is generally assessed according to its elements within defined system boundaries (endogenous system components) and elements outside the system boundaries (exogenous system components) that can either directly or indirectly affect elements within the system. For instance, a simple model of the global food system would consist of production, storage, consumers and a trade network. Not all system elements may be known or can be measured and modelled. This is particularly true for the trans-contextual relationships between the elements or actors in the system, such as the interaction and behavioural patterns and norms of local farmers and other actors or stakeholders (e.g. Aaheim et al., 2022; Franzke et al., 2022).

When trying to model a system, it is crucial to have knowledge and data about the elements and a definition of the system boundaries for the purposes of the analysis. If boundaries are drawn too narrowly, important feedback loops or cascading effects can be missed, thereby underrepresenting systemic risks. This is schematically shown in Figure 4, where, for instance, important elements within system boundary 2 are ignored if the model only operates within system boundary 1. A real-world example of a complex system, discussed in Nagabhatla et al. (2021), is the shrinking of Lake Chad Basin. This has had multifaceted consequences both directly and indirectly, including forced displacement, violent conflicts and political instability across the Sahel. The water–migration–conflict and climate change impacts are influencing regional governance strategies, particularly those related to cross-border agendas of water management, governance operations and water sharing. Empirical data collection has brought insights into the multifaceted spill-over effects of conflict and migration in a complex sociocultural context. A better understanding of the cross-boundary effects as well as state and customary water-sharing norms are now guiding the current and future regional discourse on hydro-diplomacy in the region.

In general, broader system boundaries can capture more interactions and better characterize systemic risk, but also increase complexity and uncertainties when trying to model the system. In this context it is important to note that the definition of system boundaries either follows certain assumptions and perceptions about the system and its elements, or is tailored with respect to the complexity of the research question. However, as these decisions can affect the results of modelling, they need to be thoroughly documented and motivated.

Given the uncertainties and complexity involved in identifying and then analysing systemic risks, no streamlined approach will capture its complexity (Page, 2015). A trans-contextual perception is necessary, accepting (rather than suppressing) all contexts, and can be

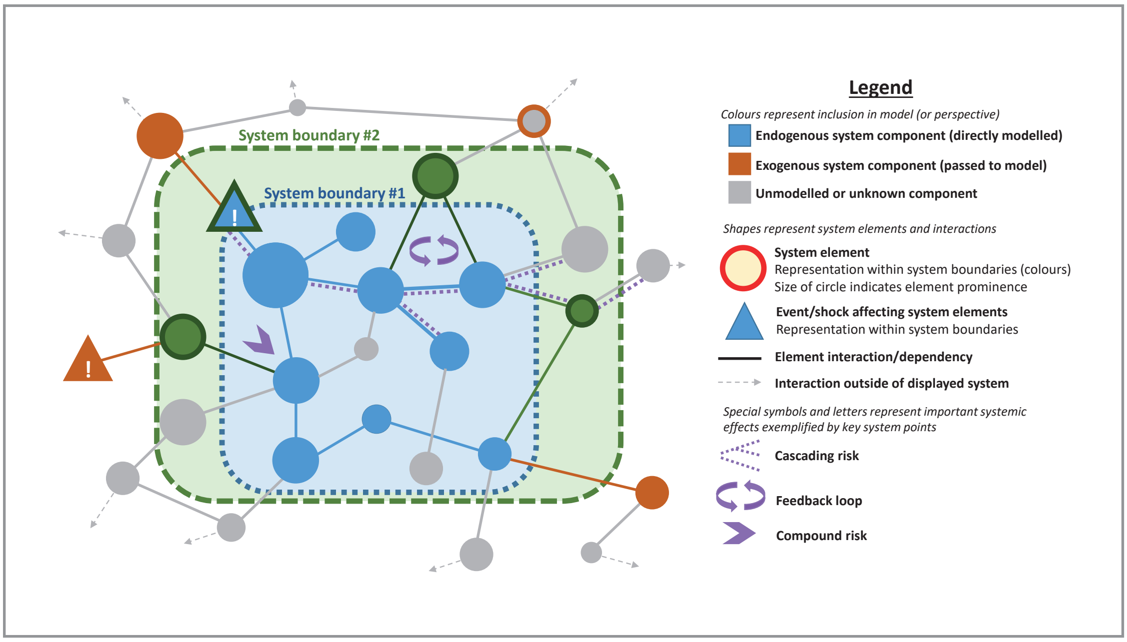

FIGURE 4: Illustration of the nature of systemic risk and how it can be captured in model approaches. All models of systemic risk explicitly represent only a sub-system of a larger and complex interconnected system (displayed here as endogenous components and interactions in blue), with simulations additionally driven by assumptions (exogenous elements and interactions in orange) that indicate the responses of components not directly modelled. Systems extend beyond components, and interactions not explicitly modelled or considered (e.g. unknown or trans-contextual information) are typically assumed to be non-responsive (in grey) in the model. A key challenge for systems planning is to determine which elements must be represented, whether explicitly or via scenario assumptions, and which can be practically assumed to be non-responsive. Expanding from a narrower perspective (system #1) to a more expansive perspective (system #2) allows for the representation of potentially important key system risks icluding cascading risks, compound risks and feedback loops. Shocks or events affecting system elements can be endogenous or exogenous to the system or system boundaries considered.

built in an open and inclusive process of widening perception by including a broad set of stakeholders (e.g. when developing national risk assessments) that can in turn increase trust and buy-in by decision-makers. This will only be achievable over time and in an iterative process that essentially constitutes an adaptive and integrative approach using multiple lines of evidence and models. Toolbox approaches, comprising a range of methods and different types of quantitative and qualitative information, may be promising in that they typically link methods and models in a way that highlights the essential complex nature of systemic risk analysis, especially the emphasis on multiple entry points. A toolbox approach may shift the emphasis from a single means of analysis to an understanding that systemic risk problems are essentially multifaceted and require a multitude of approaches and methodologies.

3.2 The role of quantitative data and models

Quantitative information is central for developing a better understanding of systemic risk. It can be in the form of data that can describe multiple dimensions of hazards, exposure and vulnerabilities, but also general societal and environmental conditions as well as factors in space and time. Such understanding is necessary for an informed identification, prevention, preparedness and reduction of associated harm, for instance by developing novel preventive risk management approaches, establishing early warning systems, forecast-based financing and emergency plans (Merz et al., 2020). Recognizing that there are considerable differences in the nature and availability of quantitative data for hazards, exposure and vulnerabilities, the value of quantitative data can be described as follows:

- First, these data can be explored to improve the understanding of past hazard or impact events and quantify how a certain risk has materialized in actual damage or loss (i.e. building empirical evidence for systemic risk and its consequences);
- Second, availability of calibrated socio-economic vulnerability data (e.g. gender, age) and sources of structural inequality can provide insights into the root causes of systemic risk;
- Third, quantitative data can be used to calibrate models, which are deduced from existing theory;
- Fourth, as well as underpinning early warning and forecasting tools, data also help model proactive and reactive interventions, which allow adaptation, risk reduction and resilience strategies to be identified and informed (see Box 3).

Data-driven or empirical approaches are important to build coherent and robust theory; however, a lack of data and theory makes model development challenging. In the context of systemic risk, a shift in perception from elements to patterns, and from interconnectivity to interdependence, is necessary. This requires a shift in what data are considered relevant to support modelling systems. Modern statistical inference and machine learning, for instance, only yield generalizable results when sufficient data have been collected under a variety of conditions and are most reliable when the system in question exhibits a certain degree of stationarity, effectively ignoring the dynamic nature of systems. Statistical models must be calibrated to multiple environments and validated against independent data samples when their aim is to generalize their application. Statistical models are constrained by the degree to which the relationship between different elements can be statistically described and they require a sufficient overlap between the range of the training data and the intended application; thus their applicability might be limited. However, depending on the application, mechanistic models may help to reduce the risk of wrong statistical inferences, as their internal causal structure is predefined according to our physical understanding that is valid even under altered conditions such as a warmer climate (Reichstein et al., 2019).

Finally, approaches that require configuring, to realistically represent a system within a model, and parameterizing, to represent relevant processes in dynamical models, are likewise data-intensive. For instance, no epidemiological model, no matter how detailed the underlying theory is, can be applied without proper calibration against field data and representation of the existing populations. In other words: data scarcity, in terms of availability, accessibility and level of necessary detail, limits both empirical and theory-guided model development for representing systemic risk. Even if data have been collected for relevant hazards, exposure and vulnerability within the defined system boundaries, their comparability and interoperability is typically limited. Further, regions that are most vulnerable to climate-related hazards, for example, often lack the infrastructure necessary for reliable data collection and maintenance (Sillmann et al., 2018; Harrington and Otto, 2020).

While quantitative data plays a crucial role in development of models and theories, it will never be enough to understand the full extent and complexity of systemic risk (see also the role of trans-contextual information, below), so models and theories ultimately will need be modified to accommodate new data and information as it becomes available. Meanwhile, there are quantitative methods allowing the use of scattered (incomplete) data and uncertainties in risk assessments, and they can assist in policy-making by highlighting basic features of systemic risks when sub-systems data are incomplete (e.g. Behrens et al., 2021; Moe et al., 2021).

3.3 Model and data needs for different applications

Advanced statistical tools can be useful to model systems and infer causal structures across variables if large datasets are available (for instance, from Earth system models). Multivariate statistical tools are particularly important to identify significant relationships among variables (such as through Copula models) (Naqvi et al., 2020). Novel causality methods have been introduced recently and allow for distinguishing common and indirect drivers and are useful for hypothesis testing (Pearl, 2000; Peters et al., 2017; Runge et al., 2019). Going beyond classical correlation analysis, they provide strength, direction and lead–lag information on relationships when provided with time series of suitable resolution. However, causal inference methods can also be used to quantify complex relations when confounding factors, such as socio-economic conditions, vary in space. In the context of early warning systems, such inferences will increasingly play a role in determining reactive and proactive responses. However, these advanced statistical models will only be as good as the data and knowledge that goes into the models, given that some elements or relationships cannot be captured and that the system boundaries are subjectively drawn.

Model approaches can also be used to forecast and project hazard conditions that trigger cascading impacts and systemic risk. Examples of modelling domino effects are:

1. Modelling disruptions causing secondary effects in urban guided transport systems faced by flood hazards (Gonzva et al., 2017);

2. Domino effects triggered by natural hazards, such as the 2007 Texas liquid petroleum gas fire (Naderpour and Khakzad, 2018);

3. Vulnerability of the oil and gas sector to climate change and extreme weather events (Cruz and Krausmann, 2013);

4. Extreme weather impacts on freight railways in Europe (Ludvigsen and Klæboe, 2014).

Building, verifying and validating an accurate model for predicting an extreme weather event will require data with specific temporal and spatial resolutions describing the state of the Earth system, such as the atmospheric profile and circulation characteristics of the weather hazard (Marotzke et al., 2017). Accurately modelling its impact on society relies on data describing the exposed and vulnerable societal systems. This can be expressed as, for instance, demographic statistics, tolerance stability of a dam and other data from civil engineering, insurance systems or availability of health services (Raymond et al., 2020; Simpson et al., 2021). For impact modelling, diverse perspectives are required to ensure that no impact is underrepresented, as risks and impacts can be heterogeneously distributed (e.g. on different vulnerable populations) (DeFries et al., 2019).

In situations with many potential outcomes, for instance if climate models disagree on the signal of climate change in a specific region (e.g. West Africa getting wetter or drier) due to large uncertainties in representing climate variability, the mean response might not be a reliable quantity for risk assessment as it tends to underestimate the associated risk (Hazeleger et al., 2015). Storyline approaches have proven useful in such situations as they permit scenarios about unlikely but plausible outcomes and allow a system to be 'stress-tested' by considering a particular set of assumptions regarding the hazard, exposure and vulnerability of its elements and relevant relationships among them (Raymond et al. 2020, Sillmann et al., 2021; Young et al., 2021). A similar approach is the use of 'war games', which are based on systems and game theory and constitute a method of scenario planning. War games anticipate decision-making under stressful conditions that may drive system responses beyond traditional management expectations. They were most prominently used by military strategists during nuclear strike exercises, executed under the premise of 'thinking the unthinkable' (Kahn, 1962). Models are only able to capture system connections and responses that are directly represented or result from well-configured interactions; however, simulations of grand challenges, such as climate change, are often constrained by limitations in process representation and scenario components (DeFries et al., 2019).

3.4 The need for trans-contextual information complementing data and modelling

For each 'risk decision' and 'risk decision-maker', it is the existence of implicit, unconscious, inflexible and largely invisible habits that reinforces a worldview of 'solving and fixing' and 'separating and controlling'. These habits that all people use to make sense of their world actually constrain the possibilities for a wider perception and a better understanding of the systemic nature of risk, and therefore our ability to transform systems. This fundamental challenge of the limitations of perception cannot be addressed directly by quantitative data (Bateson, 2016). Locally varying societal value and belief systems, as well as objects and locations with religious, spiritual, cultural or emotional value, can trigger conflicts and motivate decisions that might not seem reasonable according to available data (e.g. people deciding not to migrate out of an area facing increasing flood risk). Thus, relational and trans-contextual information is needed to understand the personal and political spheres within a system (e.g. Nagabhatla et al., 2021) and a dynamic interaction between 'spheres of transformation' seems to be essential in reducing systemic risk (cf. Figure 3). Relational and trans-contextual information is described as 'a specific kind of information about the way parts of a complex system (e.g. members of a family, organisms in the oceans, institutions in a society or departments of an organization) come together to give vitality to that system' (UNDRR, 2019). By contrast, data – as usually considered for the purposes of modelling and described in the previous parts of section 3 – will describe only the parts. The relational and trans-contextual information describes their interplay in context, illustrating and explicitly considering the vital and dynamic relationships among the parts of a system.

The value of trans-contextual information, in the process of identifying and responding to the systemic nature of risks, is that it allows for an educated interpretation of all available information while considering aspects that are challenging or impossible to quantify. In addition, it is crucial to move from response thinking to system thinking, including relational and contextual information. As with all risks, cultural and social contexts matter. Risk perceptions can be amplified or attenuated due to a variety of factors such as perceived distress, familiarity or lack of controllability (Slovic, 1987; Renn et al., 1992; Breakwell, 2014; Siegrist and Árvai, 2020). These qualitative risk factors, i.e. attributes that people associate with risks, may lead in combination with intuitive heuristics, biases and social communication to a disconnect between people's concern and perception about risks and the actual risk in terms of impact measured or measurable by statistical or experimental analysis (Renn, 2005; Ropeik, 2010; Raue and Scholl, 2018; Siegrist and Árvai, 2020). The ultimate goal should be to bring these different elements of information together (as illustrated in Figure 3).

It is critical now to find new strategies that enable better understanding of the systemic nature of risk within dynamic societal and environmental contexts. Complex decision-making environments require the ability to allow all, or as many as possible, of the different contexts to be perceived. Not just those that are convenient to expedite a decision, such as only focusing on the economic outcomes (e.g. gross domestic product as a proxy for socio-economic wellbeing). Due to the comparatively rigid nature of our habits within a scientific worldview, decisions routinely exclude or eliminate various contexts. The challenge then is how to break free from dualistic decision-making approaches and become accustomed to examining our habits.

There is a range of emerging practices exploring how to better understand and navigate the shifting contexts of the systems in which risk management decisions must be made. These emerging practices are focused on generating spaces for challenging hard-wired habits and building new approaches to address risks. By holding spaces to relinquish certainties that are constrained by experience, and by shifting perceptions, new ways of learning and knowing about the systemic nature of risk become available.

Examples of these inclusive, collaborative approaches already exist in different regions and contexts, where a trans-contextual format is used to explore complex problems and to generate the potential to understand systemic patterns through mutual learning (e.g. Kontar et al., 2021). This approach could usefully be combined with a data-driven approach that provides opportunities from retrospective to prospective, such as learning what will prevent systemic risk from being constructed or created before an event, as done for instance in collaborative 'hackathons' to co-produce knowledge on local climate adaptation governance (Kvamsås et al., 2021) (see also Box 3).

4 OPPORTUNITIES FOR RESEARCH AND GOVERNANCE OF SYSTEMIC RISK

Governance and management of systemic risk differs significantly from the traditional approach of risk management, which is generally sector-focused and response-oriented (Frank et al., 2014). Given its nature, the governance of systemic risk inherently requires inter- and transdisciplinary approaches and trans-contextual perception in identifying the drivers and the involvement of a wider sets of stakeholders to address them (Schweizer, 2021). Opportunities to address systemic risk require connecting research, policy and action under consideration of the three spheres of transformation: the practical, political and personal spheres, as illustrated in Figure 3. This section discusses the opportunities to address systemic risk through the prism of three interconnected themes: the data–policy gap, activation of the policy field, and multiple resilience dividends from addressing systemic risk.

4.1 Bridging the data–policy gap

Below are several issues which affect the data–policy gap, highlighting the need to engage in transdisciplinary activities to generate data and translate that data into knowledge for decision-making. It is important to consider that there are few studies that consider the use of data with regards to systemic risk.

Data interoperability is one of the challenges in risk reduction, acknowledging that while there is a proliferation of data and it offers many opportunities, the availability of data itself does not ensure its use (Migliorini et al., 2019). Interoperability here refers to fundamental differences in data collection methods, datasets and information sources, based on the methodologies of different disciplines and their use in assessing risk. For example, the CODATA initiative (Migliorini et al., 2019) has identified four reasons why data interoperability remains a challenge in disaster risk reduction. First, there are many actors involved, which means that there are multiple languages, perspectives and systems that need to work together. Second, there is a need to link policy goals with specific sets of data and analysis. The third factor relates to the process of data collection and data quality assessment, acknowledging what type of data can be obtained, issues related to its reliability and completeness, use and application (see section 3). The fourth issue relates to the temporal nature of emergency relief and longer-term disaster risk reduction. Given the differences in the timeline of activities, there is a need for different types of data and for this data to be linked to forecasting capacities and disaster recovery (see Figure 7 and Box 3). With regards to systemic risk, all these four issues may become even more complex, as systemic risk can span geographical, sectoral or other boundaries (e.g. Figure 4), introducing challenges not only in data collection but also in policies addressing it.

BOX 3

Case study: Anticipatory action before the tipping point in Bangladesh (OCHA, UNRCO (Bangladesh), Anticipatory Action Pilot, 2020)

The example of anticipatory action in Bangladesh illustrates how local interventions could be designed to predict the probability of breakdowns at one leverage point of a system to mitigate systemic risk. Bangladesh is one of the most vulnerable countries to climate-related disasters, especially monsoon flooding from March to September. The risks, ranging from natural hazards such as floods to damages to farms and the food system, are spread across sectors and different levels of society in Bangladesh, from the poverty line of individuals to households' economic situations to the overall development of the nation. How can interventions be set up to mitigate systemic risks? The key is to be prepared through early engagement across scales and sectors, such as forecasting technology, early warning systems, intervention selection and design, and to engage local communities across social groups and partnerships to coordinate the forecast-based early intervention to mitigate systemic risks using anticipatory action.

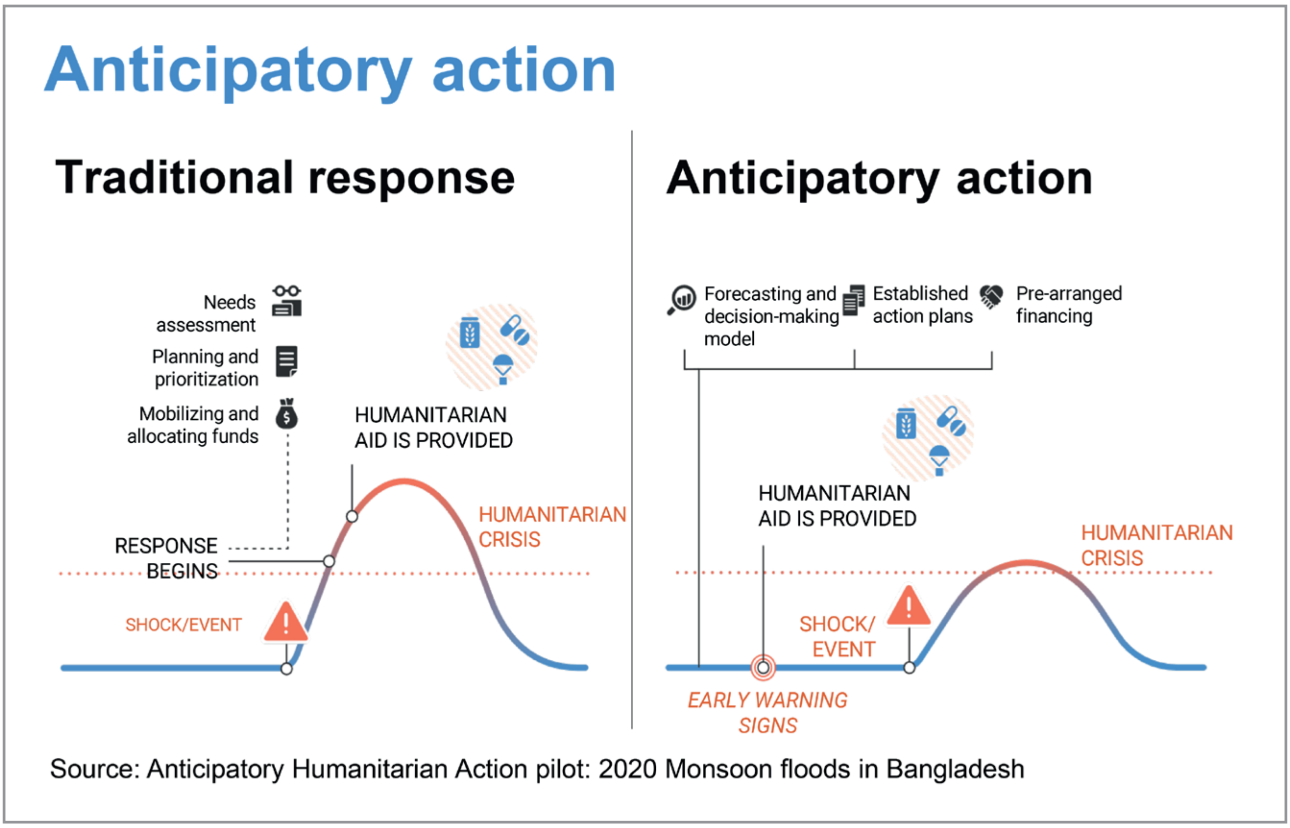

FIGURE 5: Example of moving from a traditional response to anticipatory action using available information from forecasting and decision-making models based on qualitative and quantitative data to avoid ripple effects in the humanitarian sphere.

BOX 3 Continued...

One concrete intervention was the forecast-based financing for rapid disbursement of funding for anticipatory actions, as shown in Figure 5. This is designed to reach people before flooding and reduce systemic risk. Targeting the most vulnerable in areas affected by floods, where millions of people are living at or below global poverty levels, the Central Emergency Response Fund set aside up to USD 5.2 million to be released in two tranches to incentivize anticipatory action for monsoon-related flooding, with a first pre-activation (or readiness) trigger with a 10-day lead time to cover essential readiness activities, and a second stage of activation trigger when the water level is forecast to reach government-defined danger level within 5 days. In 2020, forecast-based anticipatory humanitarian action was piloted to address the cascading impacts of flooding. On 4 July 2020, severe floods were forecasted from 18 July and anticipatory actions were triggered. Extensive learning and evaluations from the anticipatory actions before the first peak of the 2020 monsoon flood builds a basis for the improvement of the learning process. The learning process is illustrated in Figure 6 and this feedback loop could be applied on different scales.

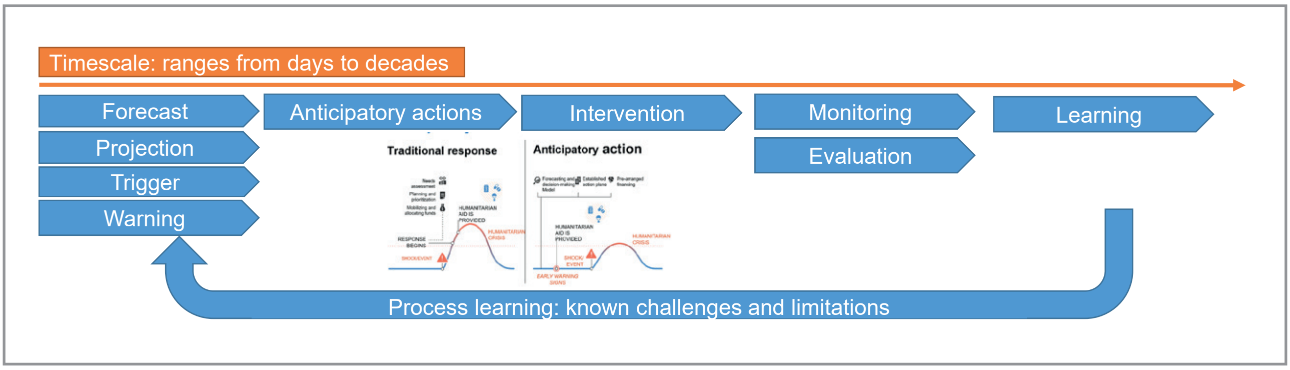

FIGURE 6: The iterative learning process for mitigating systemic risks.

The emergence of the co-design of research and practice, as well as the use of citizen science (engaging citizens in data collection), have become more common. Low-cost and robust technologies enable the collection of extensive and often real-time information for risk management (Paul et al., 2017; Yao et al., 2021). These approaches work best when their purpose and the motivations of all partners are clearly defined, as suggested by Mercer et al. (2008). Engaging citizens in this way has the potential to enhance knowledge creation, as well as analysis and interpretation of information, leading to education and empowerment of communities, which are often ignored in traditional knowledge generation (Paul et al., 2018).

When engaging with stakeholders across different levels, it is important to recognize that there are fundamental ethical issues around data ownership which need to be addressed. This ownership issue is important when considering what types of data count, given the multi-epistemic nature of systemic risk. It is also important to account for epistemic justice and data sovereignty (Walter, 2021), as in: ‘who owns data and can give permission for the data to be used?’; ‘who ultimately owns the results?’; and ‘how can one ensure the socially beneficial uses of data?’ A key activity in engaging stakeholders is to build data literacy in different types of action learning environments and train data translators for specific contexts, recognizing that there are always context-specific issues that need to be considered.

4.2 Activating the policy field: governance of systemic risk

Given the systemic nature of risk, it is imperative that governance approaches are receptive to innovative analytical methods that engage a broad range of stakeholders. Addressing systemic risks through principled policies and instruments is challenging, as current risk governance systems are not designed to deal with these non-conventional problems that require a more future-oriented exploration than that achieved with regular planning timeframes. Moreover, they require a broader framing of risk and a wider perception beyond conventional systems boundaries.

To address systemic risk through policy and governance, there is a need to foster system thinking and to engage a wide variety of stakeholders in the efforts to map risk, as well as in identifying policy measures to deal with systemic risk in an anticipatory way to avoid realization of risk (e.g. Box 3). These processes can be advanced through education and continued emphasis on connectedness and interrelations. As mentioned above, storylines or storytelling approaches are increasingly being tested and enhanced to include stakeholders and explore the option space for decision-making (e.g. Sillmann et al., 2021). There are numerous research methods, including causal loop modelling, which can be used to highlight the complexities of systemic risk to illustrate emerging issues (Groundstroem and Juhola, 2021).

For example, the International Risk Governance Centre (IRGC) (Florin and Nursimulu, 2018) devised a structured process for exploration, envisioning the co-development of management strategies for systemic risk based on iterative learning organized around seven steps (see Figure 7). Step one includes exploring the system to define its boundaries and dynamics. The second step involves the development of scenarios to identify possible ongoing and future transitions. Step three consists of determining goals and the level of tolerability for risk and uncertainty that is acceptable for the stakeholders. In step four, stakeholders can be involved in co-developing and assessing management strategies dealing with each scenario. Step five allows stakeholders to address unanticipated barriers and sudden critical shifts that may arise when dealing with systemic risk. Steps six and seven include deciding, testing and implementing strategies as well as monitoring them in order to learn to review and adapt again. Stakeholder engagement is a key element throughout the governance process (IRGC, 2020) (see Figure 7).

FIGURE 7: IRGC's guidance for the governance of systemic risks, comprising seven interlinked steps (Florin and Nursimulu, 2018).

4.3 Decision-making: multiple resilience dividends from addressing systemic risk

The identification of co-benefits that may emerge from different policy fields can strengthen the ability of society to withstand shocks emerging from systemic risk. Motivating increasing investments in resilience has been very difficult. The perceived trade-offs can be partially overcome if multiple benefits are considered.

Various approaches have been proposed that consider multiple resilience dividends and thus go beyond the standard rationale of reducing downside risk only (Mechler and Hochrainer-Stigler, 2019). One such example, the ‘triple disaster resilience dividend’ approach (Surminski and Tanner, 2016), suggests that risk and investment policy should focus on deriving dividends as follows:

1. Avoiding and reducing direct and indirect downside risk;

2. Unlocking socio-economic development through reducing background risk that impedes development (e.g. through enhanced insurance and social protection schemes);

3. Generating resilience co-benefits that generate ‘returns’ that are not dependent on the occurrence of specific shocks (e.g. building resilience in health systems).

To inform such systemic decision-making at various scales, applied decision support tools for systemic resilience capacity measurement have been proliferating. One example, the Flood Resilience Measurement for Communities framework and tool (Keating et al., 2017), is being used globally by non-governmental organizations, in conjunction with communities, to scope out a multitude of resilience benefits. Co-generating resilience in this context means studying the interaction of development and flood risk to identify resilience strengths and weaknesses, both before and after actual events. It also provides overall support for crafting solutions with communities to minimize weak links and maximize strong links in interconnected (local) systems.

5

CONCLUSIONS AND RECOMMENDATIONS

To conclude, systemic risk challenges established compartmentalized approaches to risk analysis and risk governance. It is evident that moving towards more anticipatory and inclusive approaches is essential to understand and address systemic risk. In the following, key messages from this Briefing Note and recommendations for further collaboration among research, policy and practice are organized around the main steps of a risk governance cycle.

5.1 Systemic risk analysis

1. Traditional compartmentalized approaches towards analysing and governing systemic risks as isolated components are inadequate, and need to be augmented by anticipatory approaches inspired by systems thinking to reduce adverse systemic risk outcomes.

2. Systems thinking implies embracing complexity and uncertainty, and revealing complex interconnections and relationships that recognize values, vulnerability and social justice. Systems thinking is also fundamental for understanding the dynamic, complex moving parts that make up a resilient society, including their points of intersection.

3. A major challenge for analysing systemic risks is the issue of focus. Systemic risks speak to transboundary drivers and impacts across systems. Therefore, analysts must be specific about their choices regarding the system under consideration and what it incorporates (also including what is unclear or unknown about the system), its boundaries and transboundary effects, with due reflection on methodological choices and assumptions.

4. Adaptive and integrative approaches using multiple lines of evidence can lead the way for systemic risk analysis. Integrating a range of methods and different types of quantitative and qualitative information can help highlight the essentially complex nature of systemic risk and identify multiple entry points for addressing risks. Being adaptive means instilling active learning processes such as acting early, assessing regularly and adapting continuously.

5.2 Systemic risk management

5. Current emphasis on individual hazard and risk assessment dominant in the geoscientific community needs to be shifted to a transdisciplinary system analysis with action-oriented research on disaster risk reduction, co-produced with multiple stakeholders, including policy-makers (Ismail-Zadeh et al., 2017). Decisions on risk reduction and recovery measures require trade-offs based not only on cost-effectiveness but also resilience and sustainability (Sarkis et al., 2020; Trump and Linkov, 2020). These trade-offs need to be communicated to the respective stakeholders as part of an integrative and iterative appraisal approach.

6. Locally varying societal value and belief systems, locations, or objects with religious, spiritual, cultural or emotional value can motivate decisions but also trigger conflicts. Thus, relational and trans-contextual information is needed to understand the personal and political dimensions of a systemic risk. This includes revisiting how we collect, consider and analyse data and bring in trans-contextual perceptions and information. Providing equitable access to risk knowledge is essential for fostering trust and participation as well as engaging and supporting people to understand and use risk information effectively.

5.3 Systemic risk agency

7. The governance of systemic risks requires interdisciplinary and cross-sectoral cooperation and engagement from scientists, regulators and stakeholders from private and public spheres (Renn et al., 2019; Schweizer, 2021), as well as wider considerations of intergenerational and polycultural dimensions of governance.

8. Communication and knowledge sharing with stakeholders is crucial for information generation and analysis as well as risk governance. Therefore, communication and knowledge sharing with stakeholders should be facilitated iteratively throughout the risk governance process (Kontar et al., 2021). This should be balanced by global public diversity in numeracy and in particular comfort with probability, uncertainty and risk. Problem-solving competencies should be strengthened through training and education in systems thinking (AIDR, 2021).

9. Organizations, including international institutions and donors, need to adopt systems thinking and systems approaches when working across disciplines. Systems thinking will also help such organizations engage and interact with stakeholders to advance science to better meet societal needs and global policy agendas, such as the Paris Agreement, the Sustainable Development Goals and the Sendai Framework.

It is upon us – researchers, policy-makers, societal actors and citizens of this planet – to take responsibility for implementing these points across scales, from local to global, and across the practice, political and personal spheres, to build a resilient society on a healthy planet that can manage, reduce and respond to systemic risks.

REFERENCES

Aaheim, H. A., Orlov, A. and Sillmann, J. 2022. Cross-sectoral challenges for adaptation modelling. C. Kondrup, P. Mercogliano, F. Bosello, J. Mysiak, E. Scoccimarro and A. Rizzo (eds.), *Climate Adaptation Modeling*. New York, Springer Climate.

AIDR. 2021. *Systemic Disaster Risk Handbook*, 1st edn. Melbourne, Australian Institute for Disaster Resilience. https://knowledge.aidr.org.au/resources/handbook-disaster-risk/ (Accessed 19 January 2022).

Amundsen, H. and Dannevig, H. 2021. Looking back and looking forward – adapting to extreme weather events in municipalities in western Norway. *Regional Environmental Change*, Vol. 21, No. 108. doi:10.1007/s10113-021-01834-7.

Aven, T. and Renn, O. 2020. Some foundational issues related to risk governance and different types of risks. *Journal of Risk Research*, Vol. 23. doi:10.1080/13669877.2019.1569099.

Bateson, N. 2016. *Small Arcs of Larger Circles: Framing Through Other Patterns*. Triarchy Press.

Behrens, J., Løvholt, F., Jalayer, F., Lorito, S., Salgado-Gálvez, M. A., Sørensen, M., et al. (2021). Probabilistic tsunami hazard and risk analysis: a review of research gaps. *Frontiers in Earth Science*, Vol. 9, No. 114.

Breakwell, G. M. 2014. *The Psychology of Risk*, 2nd edn. Cambridge, Cambridge University Press. doi:10.1017/CBO9781139061933.

Castellani, B. and Gerrits, L. 2021. 2021 Map of the Complexity Sciences. Durham, Durham University. http://www.art-sciencefactory.com/complexity-map_feb09.html (Accessed 19 January 2022).

Centeno, M. A., Nag, M., Patterson, T. S., Shaver, A. and Windawi, A. J. 2015. The emergence of global systemic risk. *Annual Review of Sociology*, Vol. 41, pp. 65–85. doi:10.1146/annurev-soc-073014-112317.

Cruz, A. M. and Krausmann, E. 2013. Vulnerability of the oil and gas sector to climate change and extreme weather events. *Climate Change*, Vol. 121, pp. 41–53. doi:10.1007/s10584-013-0891-4.

Cutter, S. L., Ismail-Zadeh, A., Alcántara-Ayala, I., Altan, O., Baker, D. N., Briceño, S., et al. 2015. Global risks: Pool knowledge to stem losses from disasters. *Nature*, Vol. 522, pp. 277–279. doi:10.1038/522277a.

DeFries, R., Edenhofer, O., Halliday, A., Heal, G., Lenton, T., Puma, M., et al. 2019. *The Missing Economic Risks in Assessments of Climate Change Impacts*. London, The London School of Economics and Political Science.

Epstein, J. M. 2009. Modelling to contain pandemics. *Nature*, Vol. 460. doi:10.1038/460687a.

Faulhaber, G. R., Phillips, A. and Santomero, A. M. 1990. Payment Risk, Network Risk, and the Role of the Fed. D. B. Humphrey (ed.), *The U.S. Payment System: Efficiency, Risk and the Role of the Federal Reserve*. Dordrecht, Springer Netherlands.

Florin, M. V. and Nursimulu, A. 2018. *IRGC guidelines for the governance of systemic risks*. Lausanne, International Risk Governance Council. https://www.epfl.ch/research/domains/irgc/wp-content/uploads/2019/09/IRGC-Governance-of-Systemic-Risks.pdf (Accessed 19 January 2022).

Frank, A. B., Collins, M. G., Levin, S. A., Lo, A. W., Ramo, J., Dieckmann, U., et al. 2014. Dealing with femtorisks in international relations. *PNAS*, Vol. 111, No. 49, pp. 17356–17362. doi:10.1073/pnas.1400229111.

Franzke, C. L. E., Ciullo, A., Gilmore, E. A., Matias, D. M., Nagabhatla, N., Orlov, A., et al. 2022. Perspectives on tipping points in integrated models of the natural and human Earth system: cascading effects and telecoupling. *Environmental Research Letters*, Vol. 17, 015004. doi:10.1088/1748-9326/ac42fd.

Gaupp, F. 2020. Extreme events in a globalized food system. *One Earth*, Vol. 2, pp. 518–521. doi:https://doi.org/10.1016/j.oneear.2020.06.001.

Gonzva, M., Barroca, B., Gautier, P.-É. and Diab, Y. 2017. Modeling disruptions causing domino effects in urban guided transport systems faced by flood hazards. *Natural Hazards*, Vol. 86, pp. 183–201. doi:10.1007/s11069-016-2680-7.

Government of the Republic of Mexico. 2015. *Intended Nationally Determined Contribution*. Mexico City, The Government of the Republic of Mexico. https://www.gob.mx/cms/uploads/attachment/file/162973/2015_indc_ing.pdf (Accessed 10 January 2022)].

Groundstroem, F. and Juhola, S. 2021. Using systems thinking and causal loop diagrams to identify cascading climate change impacts on bioenergy supply systems. *Mitigation and Adaptation Strategies for Global Change*, Vol. 26, No. 7. doi:10.1007/s11027-021-09967-0.

Haldane, A. G. and May, R. M. 2011. Systemic risk in banking ecosystems. *Nature*, Vol. 469, pp. 351–355. doi:10.1038/nature09659.

Handmer, J., Stevance, A.-S., Rickards, L. and Nalau, J. 2019. *Policy Brief: Achieving Risk Reduction Across Sendai, Paris and the SDGs*. Paris, International Science Council. https://council.science/wp-content/uploads/2019/05/ISC_Achieving-Risk-Reduction-Across-Sendai-Paris-and-the-SDGs_May-2019.pdf (Accessed 19 January 2022).

Harrington, L. J. and Otto, F. E. L. 2020. Reconciling theory with the reality of African heatwaves. *Nature Climate Change*, Vol. 10, pp. 796–798. doi:10.1038/s41558-020-0851-8.

Hazeleger, W., Van Den Hurk, B. J. J. M., Min, E., Van Oldenborgh, G. J., Petersen, A. C., Stainforth, D. A., et al. 2015. Tales of future weather. *Nature Climate Change*, Vol. 5, pp. 107–113. doi:10.1038/nclimate2450.

Helbing, D. 2013. Globally networked risks and how to respond. *Nature*, Vol. 497, pp. 51–59. doi:10.1038/nature12047.

Hochrainer-Stigler, S., Colon, C., Boza, G., Poledna, S., Rovenskaya, E. and Dieckmann, U. 2020. Enhancing resilience of systems to individual and systemic risk: Steps toward an integrative framework. *International Journal of Disaster Risk Reduction*, Vol. 51. doi:10.1016/j.ijdrr.2020.101868.

Holling, C. S. 2001. Understanding the complexity of economic, ecological, and social systems. *Ecosystems*, Vol. 4, pp. 390–405. doi:10.1007/s10021-001-0101-5.

IPCC. 2018. *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change*. V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, et al. (eds.). Geneva, IPCC. doi:https://www.ipcc.ch/sr15.

IPCC. 2021. Summary for Policy Makers. V. Masson-Delmotte, P. Zhai, Y. Chen, L. Goldfarb, M. I. Gomis, J. B. R. Matthews, et al. (eds.), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. www.ipcc.ch (Accessed 19 January 2022).

IPCC. 2022. Climate Change 2022: Impacts, Adaptation, and Vulnerability. H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.), *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, Cambridge University Press. In Press.

IRGC. 2020. *Involving Stakeholders in the Risk Governance Process*. Lausanne, IRGC. https://irgc.org/wp-content/uploads/2020/10/IRGC-Stakeholder-Engagement-Resource-Guide_Version2_2020-3.pdf (Accessed 29 July 2021).

ISC-UNDRR-IRDR. 2021. *A Framework for Global Science in Support of Risk-informed Sustainable Development and Planetary Health*. J. Handmer, C. Vogel, B. Payne, A.-S. Stevance, J. Kirsch-Wood, M. Boyland, Q. Han and F. Lian (eds.), Paris, France, International Science Council; Geneva, Switzerland, United Nations Office for Disaster Risk Reduction; Beijing, China, Integrated Research on Disaster Risk. doi: 10.24948/2021.07. https://www.undrr.org/publication/framework-global-science-support-risk-informed-sustainable-development-and-planetary (Accessed 19 January 2022).

Ismail-Zadeh, A. 2021. Poor planning compounded European flooding catastrophes. *Nature*, Vol. 598, p. 32. doi:10.1038/d41586-021-02712-2.

Ismail-Zadeh, A. T., Cutter, S. L., Takeuchi, K. and Paton, D. 2017. Forging a paradigm shift in disaster science. *Natural Hazards*, Vol. 86, pp. 969–988. doi:10.1007/s11069-016-2726-x.

Kahn, H. 1962. Thinking about the unthinkable. *Naval War College Review*, Vol. 15, No. 8.

Kaufman, G. G. and Scott, K. E. 2003. What is systemic risk, and do bank regulatorsretard or contribute to it? *The Independent Review*, Vol. 7, No. 3, pp. 371–391.

Keating, A., Campbell, K., Szoenyi, M., McQuistan, C., Nash, D. and Burer, M. 2017. Development and testing of a community flood resilience measurement tool. *Natural Hazards and Earth System Sciences*, Vol. 17, pp. 77–101. doi:10.5194/nhess-17-77-2017.

Kontar, Y. Y., Ismail-Zadeh, A., Berkman, P. A., Duda, P. I., Gluckman, S. P., Kelman, I., et al. 2021. Knowledge exchange through science diplomacy to assist disaster risk reduction. *Progress in Disaster Science*, Vol. 11, 100188. doi:10.1016/j.pdisas.2021.100188.

Kvamsås, H., Neby, S., Haarstad, H., Stiller-Reeve, M. and Schrage, J. 2021. Using collaborative hackathons to coproduce knowledge on local climate adaptation governance. *Current Research in Environmental Sustainability*, Vol. 3. doi:10.1016/j.crsust.2020.100023.

Lahsen, M. and Ribot, J. 2021. Politics of attributing extreme events and disasters to climate change. *WIREs Climate Change*, e750. doi:https://doi.org/10.1002/wcc.750.

Laio, F., Ridolfi, L. and D'Odorico, P. 2016. The past and future of food stocks. *Environmental Research Letters*, Vol. 11, No. 3. doi:10.1088/1748-9326/11/3/035010.

Lenton, T. M., Rockström, J., Gaffney, O., Rahmstorf, S., Richardson, K., Steffen, W., et al. 2019. Climate tipping points – too risky to bet against. *Nature*, Vol. 575. doi:10.1038/d41586-019-03595-0.

Ludvigsen, J. and Klæboe, R. 2014. Extreme weather impacts on freight railways in Europe. *Natural Hazards*, Vol. 70, No. 1. doi:10.1007/s11069-013-0851-3.

Luhmann, N. 1995. *Social Systems*. Stanford, Stanford University Press.

Marotzke, J., Jakob, C., Bony, S., Dirmeyer, P. A., O'Gorman, P. A., Hawkins, E., et al. 2017. Climate research must sharpen its view. *Nature Climate Change*, Vol. 7, pp. 89–91. doi:10.1038/nclimate3206.

Maskrey, A., Jain, G. and Laivell, A. 2021. *The Social Construction of Systemic Risk: Towards an Actionable Framework for Risk Governance*. New York, UNDP. https://www.undp.org/publications/undp-social-construction-systemic-risk-towards-actionable-framework-risk-governance (Accessed 19 January 2022).

Mechler, R. and Hochrainer-Stigler, S. 2019. *Generating Multiple Resilience Dividends from Managing Unnatural Disasters in Asia: Opportunities for Measurement and Policy*. Mandaluyong, Asian Development Bank. doi:10.22617/WPS190573-2.

Mercer, J., Kelman, I., Lloyd, K. and Suchet-Pearson, S. 2008. Reflections on use of participatory research for disaster risk reduction. *Area*, Vol. 40, pp. 172–183. doi:10.1111/j.1475-4762.2008.00797.x.

Merz, B., Kuhlicke, C., Kunz, M., Pittore, M., Babeyko, A., Bresch, D. N., et al. 2020. Impact forecasting to support emergency management of natural hazards. *Review of Geophysics*, Vol. 58. doi:10.1029/2020RG000704.

Migliorini, M., Hagen, J. S., Mihaljevic, J., Mysiak, J., Rossi, J.-L., Siegmund, A., et al. 2019. Data interoperability for disaster risk reduction in Europe. *Disaster Prevention and Management*, Vol. 28. doi:10.1108/DPM-09-2019-0291.

Moe, S. J., Carriger, J. F. and Glendell, M. 2021. Increased use of Bayesian network models has improved environmental risk assessments. *Integrated Environmental Assessment and Management*, Vol. 17, pp. 53–61. doi:10.1002/ieam.4369.

Murray, V., Abrahams, J., Abdallah, C., Ahmed, K., Angeles, L., Benouar, D., et al. 2021. *Hazard Information Profiles: Supplement to UNDRR-ISC Hazard Definition & Classification Review: Technical Report*. Geneva, UNDRR. doi:10.24948/2021.05.

Naderpour, M. and Khakzad, N. 2018. Texas LPG fire: Domino effects triggered by natural hazards. *Process Safety and Environmental Protection*, Vol. 116, pp. 354–364. doi:10.1016/j.psep.2018.03.008.

Nagabhatla, N., Cassidy-Neumiller, M., Francine, N. N. and Maatta, N. 2021. Water, conflicts and migration and the role of regional diplomacy: Lake Chad, Congo Basin, and the Mbororo pastoralist. *Environmental Science & Policy*, Vol. 122, pp. 35–48. doi:https://doi.org/10.1016/j.envsci.2021.03.019.

Naqvi, A., Gaupp, F. and Hochrainer-Stigler, S. 2020. The risk and consequences of multiple breadbasket failures: an integrated copula and multilayer agent-based modeling approach. *OR Spectrum*, Vol 42, pp. 727–754. doi:10.1007/s00291-020-00574-0.

O'Brien, K. 2018. Is the 1.5°C target possible? Exploring the three spheres of transformation. *Current Opinion in Environmental Sustainability*, Vol. 31, pp. 153–160. doi:10.1016/j.cosust.2018.04.010.

O'Brien, K. and Sygna, L. 2013. Responding to climate change: the three spheres of transformation. *Proceedings of Transformation in a Changing Climate*. Oslo, University of Oslo. http://cchange.no/wp-content/uploads/2013/12/1-Responding-to-climate-change-Three-spheres-of-transformation_OBrien-and-Sygna_webversion_FINAL.pdf (Accessed 19 January 2022).

OECD. 2003. *Emerging risks in the 21st century: An agenda for action*. Paris, Organisation for Economic Co-operation and Development (OECD). doi:10.1787/9789264101227-en.

Otto, C., Willner, S. N., Wenz, L., Frieler, K. and Levermann, A. 2017. Modeling loss-propagation in the global supply network: The dynamic agent-based model acclimate. *Journal of Economic Dynamics and Control*, Vol. 83, pp. 232–269. doi:10.1016/j.jedc.2017.08.001.

Page, S. E. 2015. What sociologists should know about complexity. *Annual Review of Sociology*, Vol. 41, pp. 21–41. doi:10.1146/annurev-soc-073014-112230.

Paul, J. D., Buytaert, W., Allen, S., Ballesteros-Cánovas, J. A., Bhusal, J., Cieslik, K., et al. 2017. Citizen science to support community-based flood early warning and resilience building. *AGU Fall Meeting Abstracts 2017*.

Paul, J. D., Buytaert, W., Allen, S., Ballesteros-Cánovas, J. A., Bhusal, J., Cieslik, K., et al. 2018. Citizen science for hydrological risk reduction and resilience building. *WIREs Water*, Vol. 5, e1262. doi:10.1002/wat2.1262.

Pearl, J. 2000. *Causality: Models, Reasoning and Inference*, 2nd edn. New York, Cambridge University Press.

Peters, J., Janzing, D. and Schölkopf, B. 2017. *Elements of Causal Inference Foundations and Learning Algorithms*. Cambridge, The MIT Press.

Puma, M. J., Bose, S., Chon, S. Y. and Cook, B. I. 2015. Assessing the evolving fragility of the global food system. *Environmental Research Letters*, Vol. 10. doi:10.1088/1748-9326/10/2/024007.

Raue, M. and Scholl, S. G. 2018. The use of heuristics in decision making under risk and uncertainty. M. Raue, E. Lermer, and B. Streicher (eds.), *Psychological Perspectives on Risk and Risk Analysis: Theory, Models, and Applications*. Cham, Springer International Publishing, pp. 153–179. doi:10.1007/978-3-319-92478-6_7.

Raymond, C., Horton, R. M., Zscheischler, J., Martius, O., AghaKouchak, A., Balch, J., et al. 2020. Understanding and managing connected extreme events. *Nature Climate Change*, Vol. 10, pp. 611–621. doi:10.1038/s41558-020-0790-4.

Reichstein, M., Camps-Valls, G., Stevens, B., Jung, M., Denzler, J., Carvalhais, N., et al. 2019. Deep learning and process understanding for data-driven Earth system science. *Nature*, Vol. 566, pp. 195–204. doi:10.1038/s41586-019-0912-1.

Reichstein, M., Riede, F. and Frank, D. 2021. More floods, fires and cyclones — plan for domino effects on sustainability goals. *Nature*, Vol. 592. doi:10.1038/d41586-021-00927-x.

Reisinger, A., Howden, M., Vera, C., Garschagen, M., Hurlbert, M., Kreibiehl, S., et al. 2020. *The concept of risk in the IPCC Sixth Assessment Report: a summary of cross-working group discussions*. https://www.ipcc.ch/site/assets/uploads/2021/01/The-concept-of-risk-in-the-IPCC-Sixth-Assessment-Report.pdf (Accessed 19 January 2022).

Renn, O. 2005. Risk perception and communication: Lessons for the food and food packaging industry. *Food Additives & Contaminants*, Vol. 22, pp. 1061–1071. doi:10.1080/02652030500227792.

Renn, O., Burns, W. J., Kasperson, J. X., Kasperson, R. E. and Slovic, P. 1992. The social amplification of risk: theoretical foundations and empirical applications. *Journal of Social Issues*, Vol. 48, pp. 137–160. doi:10.1111/j.1540-4560.1992.tb01949.x.

Renn, O., Laubichler, M., Lucas, K., Kröger, W., Schanze, J., Scholz, R. W., et al. 2020. Systemic risks from different perspectives. *Risk Analysis*. doi:10.1111/risa.13657.

Renn, O., Lucas, K., Haas, A. and Jaeger, C. 2019. Things are different today: the challenge of global systemic risks. *Journal of Risk Research*, Vol. 22, pp. 401–415. doi:10.1080/13669877.2017.1409252.

Rittel, H. W. J. and Webber, M. M. 1973. Dilemmas in a general theory of planning. *Policy Sciences*, Vol. 4, pp. 155–169. doi:10.1007/BF01405730.

Ropeik, D. 2010. *How Risky Is It, Really? Why Our Fears Don't Always Match the Facts*. New York, McGraw-Hill Education.

Runge, J., Bathiany, S., Bollt, E., Camps-Valls, G., Coumou, D., Deyle, E., et al. 2019. Inferring causation from time series in Earth system sciences. *Nature Communications*, Vol. 10. doi:10.1038/s41467-019-10105-3.

Sarkis, J., Cohen, M. J., Dewick, P. and Schröder, P. 2020. A brave new world: Lessons from the COVID-19 pandemic for transitioning to sustainable supply and production. *Resources, Conservation and Recycling*, Vol. 159. doi:10.1016/j.resconrec.2020.104894.

Schewe, J., Otto, C. and Frieler, K. 2017. The role of storage dynamics in annual wheat prices. *Environmental Research Letters*, Vol. 12. doi:10.1088/1748-9326/aa678e.

Schweizer, P.-J. 2021. Systemic risks – concepts and challenges for risk governance. *Journal of Risk Research*, Vol. 24, pp. 78-93. doi:10.1080/13669877.2019.1687574.

Schweizer, P.-J. and Renn, O. 2019. Governance of systemic risks for disaster prevention and mitigation. *Disaster Prevention and Management*, Vol. 28. doi:10.1108/DPM-09-2019-0282.

Schweizer, P.-J., Goble, R. and Renn, O. 2021. Social perception of systemic risks. *Risk Analysis*. doi:10.1111/risa.13831.

Siegrist, M. and Árvai, J. 2020. Risk perception: reflections on 40 years of research. *Risk Analysis*, Vol. 40. doi:10.1111/risa.13599.

Sillmann, J., Russo, S., Sippel, S. and Alnes, K. 2018. From hazard to risk. *Bulletin of the American Meteorological Society*, Vol. 99, pp. 1689–1693. doi:10.1175/BAMS-D-17-0327.1.

Sillmann, J., Shepherd, T. G., van den Hurk, B., Hazeleger, W., Martius, O., Slingo, J., et al. 2021. Event-Based Storylines to Address Climate Risk. *Earth's Future*, Vol. 9. doi:10.1029/2020EF001783.

Simpson, N. P., Mach, K. J., Constable, A., Hess, J., Hogarth, R., Howden, M., et al. 2021. A framework for complex climate change risk assessment. *One Earth*, Vol. 4, pp. 489–501. doi:10.1016/j.oneear.2021.03.005.

Slovic, P. 1987. Perception of risk. *Science*, Vol. 236, pp. 280–285. doi:10.1126/science.3563507.

Surminski, S. and Tanner, T. 2016. *Realising the "Triple Dividend of Resilience"*. Cham, Springer International Publishing. doi:10.1007/978-3-319-40694-7.

Torres, B., Angon, S., Colegio De Veracruz, E., Sudmant, A. and Gouldson, A. 2021. *Adapting to Climate Change in Mountain Cities: Lessons from Xalapa, Mexico*. London, The Place-based Climate Action Network (PCAN). https://www.researchgate.net/publication/349771318_Adapting_to_Climate_Change_in_Mountain_Cities_Lessons_from_Xalapa_Mexico (Accessed July 29, 2021).

Trump, B. D. and Linkov, I. 2020. Risk and resilience in the time of the COVID-19 crisis. *Environment Systems and Decisions*, Vol. 40, pp. 171–173. doi:10.1007/s10669-020-09781-0.

UN OCHA. 2021. *Anticipatory Action Framework: Bangladesh Monsoon Floods*. New York, UN OCHA. https://reliefweb.int/report/bangladesh/anticipatory-action-framework-bangladesh-monsoon-floods (Accessed 19 January 2022).

UNDRR. 2019. *Global Assessment Report on Disaster Risk Reduction*. New York, UNDRR. https://gar.undrr.org (Accessed 19 January 2022).

Van den Hurk, B., Otto, I. M., Reyer, C. P. O., Aerts, J., Benzie, M., Campiglio, E., et al. 2020. *What can COVID-19 teach us about preparing for climate risks in Europe?* Brussels, RECEIPT. https://climatestorylines.eu/wp-content/uploads/2020/12/Policy-Brief-Lessons-from-COVID.pdf (Accessed 19 January 2022).

Varela, F. G., Maturana, H. R. and Uribe, R. 1974. Autopoiesis: The organization of living systems, its characterization and a model. *Biosystems*, Vol. 5, pp. 187–196. doi:https://doi.org/10.1016/0303-2647(74)90031-8.

Walter, M., Kukutai, T., Russo Carroll, S. and Rodriguez-Lonebear, D. 2021. *Indigenous Data Sovereignty and Policy*. Abingdon and New York, Routledge and Taylor & Francis.

Westley, F., Olsson, P., Folke, C., Homer-Dixon, T., Vredenburg, H., Loorbach, D., et al. 2011. Tipping toward sustainability: emerging pathways of transformation. *AMBIO*, Vol. 40. doi:10.1007/s13280-011-0186-9.

Wiener, N. 2019. *Cybernetics or Control and Communication in the Animal and the Machine*. Cambridge, The MIT Press.

World Economic Forum. 2021. *The Global Risks Report 2021: 16th Edition*. Geneva, World Economic Forum. https://www3.weforum.org/docs/WEF_The_Global_Risks_Report_2021.pdf (Accessed 19 January 2022).

Yao, K., Yang, S. and Tang, J. 2021. Rapid assessment of seismic intensity based on Sina Weibo — A case study of the changing earthquake in Sichuan Province, China. *International Journal of Disaster Risk Reduction*, Vol. 58, 102217. doi:10.1016/j.ijdrr.2021.102217.

Young, H. R., Shepherd, T. G., Acidri, J., Cornforth, R. J., Petty, C., Seaman, J., et al. 2021. Storylines for decision-making: climate and food security in Namibia. *Climate and Development*, Vol. 13, pp. 515–528. doi:10.1080/17565529.2020.1808438.

COVER PHOTO
aydinmutlu / istock by Getty Images

SUGGESTED CITATION
Sillmann, J., Christensen, I., Hochrainer-Stigler, S., Huang-Lachmann, J., Juhola, S., Kornhuber, K., Mahecha, M., Mechler, R., Reichstein, M., Ruane, A.C., Schweizer, P.-J. and Williams, S. 2022. *ISC-UNDRR-RISK KAN Briefing note on systemic risk*, Paris, France, International Science Council, DOI: 10.24948/2022.01

International Science Council
The global voice for science

UNDRR
UN Office for Disaster Risk Reduction

RISKKAN
Knowledge Action Network