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Perspective

Managing systemic risk through transformative change: Combining systemic risk analysis with knowledge co-production

Stefan Hochrainer-Stigler,[1,*] Teresa Maria Deubelli-Hwang,[1] Janne Parviainen,[2] Lydia Cumiskey,[3] Pia-Johanna Schweizer,[4] and Ulf Dieckmann[1,5,6]
[1]International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria
[2]SEI, Oxford, UK
[3]MaREI: The SFI Research Centre for Energy, Climate and Marine, Environmental Research Institute, University College Cork, Cork, Ireland
[4]Research Institute for Sustainability (RIFS), Helmholtz Centre Potsdam, Potsdam, Germany
[5]Complexity Science and Evolution Unit, Okinawa Institute of Science and Technology Graduate University (OIST), Onna, Japan
[6]Department of Evolutionary Studies of Biosystems, The Graduate University for Advanced Studies (Sokendai), Hayama, Japan
*Correspondence: hochrain@iiasa.ac.at
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SUMMARY

Increasing interconnectedness, along with the effects of climate change and other global risk drivers, has led to mounting systemic risks in the complex systems that characterize our world. Systemic risks, with their cascading impacts and long-term sustainability concerns, necessitate transformative approaches to manage their effects across system scales and dimensions. To date, however, an "operationalization gap" impedes translating between propositions for transformative change and policy options for addressing systemic risk. Here, we propose combining systemic risk analyses with local approaches, prominently including knowledge co-production, to achieve a more comprehensive understanding of complex systems. This combined approach can support stakeholders in designing transformative risk management and adaptation interventions that balance individual and higher-order interactions, incorporate diverse viewpoints, and thus manage systemic risks and leverage transformation potential more effectively. Furthermore, we suggest that a risk-layering approach can help differentiate, prioritize, and orchestrate these options for incremental and transformative changes.

INTRODUCTION

Adverse impacts of climate change and other global risk drivers observed now and expected in the future, such as biodiversity loss, are systemic due to the interactions and interdependencies among them, leading to cascading negative socio-economic impacts[1–3] and long-term sustainability concerns.[4] For example, compounding slow- and sudden-onset hazards such as those associated with droughts, sea-level rise, floods, or storm surges are expected to become more frequent and are projected to overwhelm the capacity of individuals, governments, and the private sector in many regions of the world to adapt to such hazards and to cope with losses and damages following their impacts.[5] Given this rise in global and climate-related systemic risks, there have been increasing calls for a fundamental shift toward more resilient futures through deliberate transformative approaches to both risk management and adaptation.[6–8]

However, while there is a growing acknowledgment of the need to initiate transformative change, evidence suggests a slow uptake, including an "operationalization gap" in terms of translating propositions and models for transformative change into policy options.[9] In addition, limited guidance for creating transformative adaptation and risk-management interventions and measures—particularly for managing global systemic risk—further hampers progress on transformational-change initiatives. This is especially true given the difficulties policymakers and decision-makers face in comprehending complex system dynamics with numerous path dependencies, elements at risk, and interlinkages that need to be taken into account together with uncertainties and emergent behaviors in bringing about transformative change toward system resilience.[10,11] Approaches based on natural science alone may soon not be enough to meet these challenges, as most of them neglect important characteristics of human agency[12] (e.g., the role of free will) or social processes[13] (e.g., disruptive emergent behavior). Questions about the generalizability of research on ecological tipping points to social systems arise as well, with findings suggesting that social systems do not follow universal rules and laws in the same way natural systems do, as human choices are prone to cognitive biases and social factors.[14] The described situation calls for an in-depth, iterative, and adaptive approach to the management of global and systemic risks that follows multiple lines of evidence, including regular monitoring and evaluation of current and emerging changes.

Building on recent developments in systemic risk research, we suggest that the aforementioned challenges are best addressed by a system-of-systems approach, which enables identifying

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vulnerabilities, cascading effects, and potential tipping points within and across systems. This also includes the assessment of new risks arising from climate and disaster risk management (such as maladaptation) across sectors, through time, across regions, or between impacts and responses,[15] as also emphasized in recent IPCC reports regarding adaptation and mitigation options for climate risk assessment as well as management.[16] Importantly, we argue that one method alone may not suffice to capture the full complexity of real-world systems and the diverse perspectives of stakeholders. The choice of method must also guard against potential blind spots resulting from gaps in data availability and in our understanding of complex systems, particularly regarding the interdependencies, feedback loops, and emergent behaviors that can arise within them. It is for these reasons that we propose combining system-level approaches with local approaches. Specifically, we recommend that a combination of insights from systemic risk analyses (covering system-level aspects) with knowledge co-production (covering local aspects) can help better access and integrate local knowledge, diverse expertise, and different perspectives when adopting a multiple-lines-of-evidence approach. Such an analysis needs to be conducted in an iterative manner, as ongoing system dynamics and future system changes potentially require transformative interventions. While incremental changes play a role in addressing immediate challenges and making local improvements, stakeholder engagement through knowledge co-production enables broader perspectives and facilitates identifying opportunities for fundamental system-level changes. By integrating transdisciplinary perspectives, examining individual and higher-order interactions, and exploring diverse viewpoints, transformation potentials can be identified and leveraged to manage systemic risks effectively across scales, from the local to the system level. With incremental transformations occurring locally and fundamental transformations occurring on the system level, knowledge co-production approaches can be instrumental in bridging the gap between the resultant—sometimes very divergent—perspectives and proposed solutions.

INDIVIDUAL- AND SYSTEM-LEVEL TRANSFORMATION NEEDS

The realization of systemic risk leads, by definition, to the collective loss, dysfunction, or collapse of a system or its subsystems, which can cause substantial turmoil and disruption in its aftermath.[17–19] One prominent example of a systemic risk realization is the global financial crisis that occurred in 2007/2008, which was triggered by the default of a single investment bank, propagated through the financial system, and, because of close links between the financial system and the real economy, spread quickly and triggered a global economic downturn.[20] Other examples of systemic risk realization include climate-related hazards damaging critical infrastructure like power plants and transportation networks, disrupting energy supplies and causing widespread economic losses,[21] or change-induced shifts in weather patterns causing crop failures and diminished agricultural productivity. The resultant food shortages, price surges, and potential social unrest impact not only food producers but also consumers and industries reliant on agricultural inputs.[2]

However, amid these challenges, there are also opportunities. The recognition or realization of systemic risk may lead to reorganization and, in some cases, transformative positive outcomes in the longer term.[22] When a system collapses, this signifies a breakdown or failure of the existing structures, processes, or institutions that supported the system, which can create chances for reevaluation, restructuring, and innovation of infrastructure, policies, and practices to better withstand future systemic challenges.[10] In response to the aforementioned financial crisis, new regulatory measures and options were implemented across the globe to mitigate the risks associated with an excessively strong and interlinked banking sector.[23] In the context of critical infrastructure, the recognition of their vulnerabilities to climate-related hazards may spur investments in more resilient energy systems and transportation networks, which could lead to the adoption of cleaner and more sustainable energy sources, thus contributing to efforts to mitigate climate change while enhancing resilience to its impacts. Similarly, the awareness of the risks posed by climate-induced shifts in weather patterns can prompt innovations in agricultural practices and technologies aimed at increasing productivity and resilience.[21] In this vein, systemic risk analysis focuses on the presence of interdependencies that, upon the failure of a critical element (or elements) within a system, would trigger cascading impacts. The magnitude of influence that each individual interdependent element has on the entire system thus affects the scale of systemic risk and the impact of failure.[24]

Very often, analyses of systemic risk assume the influence of elements in a system to be constant, but such constancy may be an idealization. In particular, interdependencies between the elements of a system may become stronger when the system experiences additional stress, due to either events within the system or external, sometimes even remote, events.[20,25] As a case in point, we mention three examples. First, the COVID-19 pandemic has led to large fiscal stimulus packages all around the world: by considerably increasing indebtedness levels, this has negatively influenced the financial resilience of governments in responding to natural hazard events, which implies that long-term effects and opportunity costs for governments after disasters may become more serious than before the pandemic.[26,27] Second, instruments such as the European Union Solidarity Fund designed to reduce stress levels for governments after disasters may fail exactly at the moment when they are needed the most if they are developed based on assumptions about the current system state.[28] For instance, the European Union may be affected by remote events outside of Europe, and this may be exacerbated by climate change and other global changes. Such constellations may include tropical cyclone events happening in the US or the Caribbean region that can trigger a tight insurance market in Europe, making insurance less affordable. As a result, governments may bear higher costs as insurers of last resort while also providing significant support and emergency assistance to developing countries, thus incurring substantial fiscal burdens.[29] Third, another scenario involves simultaneous bread-basket failures due to drought events, leading to food shortages, price hikes, and subsequent displacement worldwide.[30,31] Such failures may not only affect a focal system but could pose additional challenges for targeting and managing risks that lie beyond the respective system boundaries.

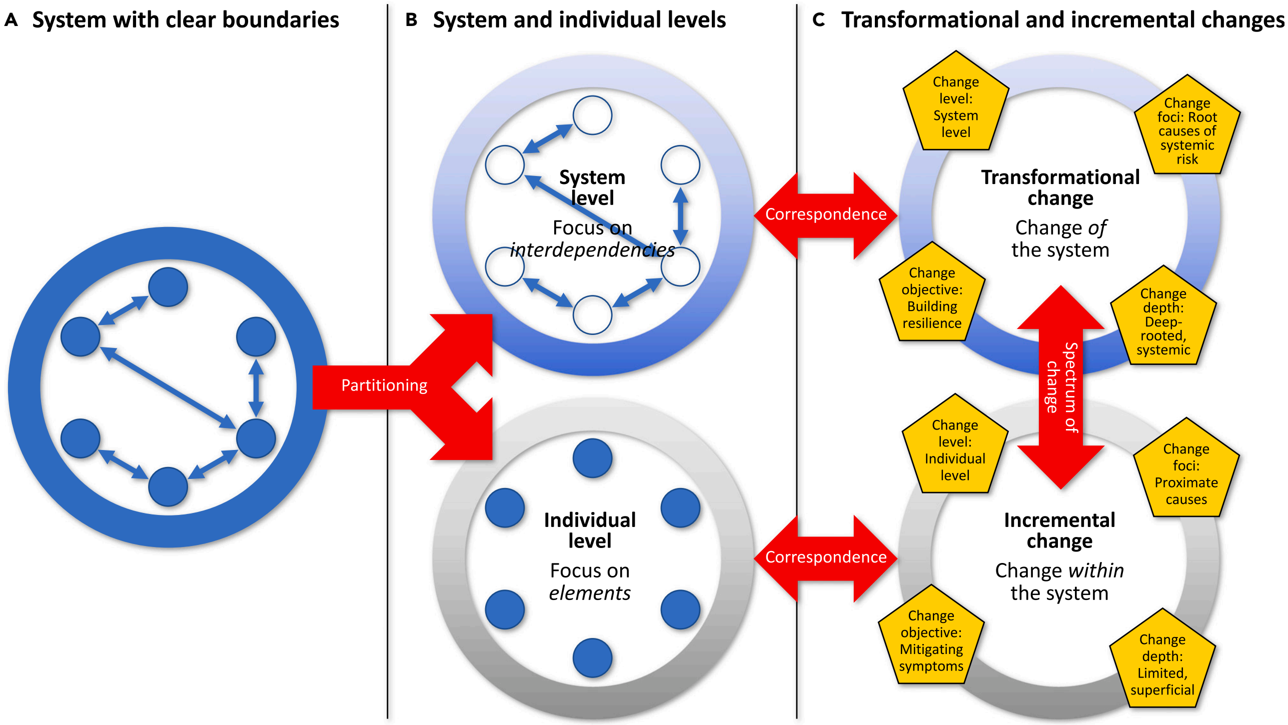

Figure 1. The spectrum of change, from incremental to transformational

(A) A system is defined as a set of partly interdependent elements with clear boundaries.

(B) The analysis of the system can be partitioned between the system level with a focus on the interdependencies (top) and the individual level with a focus on the elements (bottom).

(C) The spectrum of change ranges from transformative change (top) to incremental change (bottom). Transformative change addresses systemic risk by targeting root causes and promoting profound, sustainable shifts to resilient futures. In contrast, incremental change tackles immediate causes on a small scale within the system, providing limited and sometimes superficial symptom treatment. Source: based on and extended from Deubelli and Mechler[22] and Deubelli and Venkateswaran.[38]

These three examples highlight the fact that a system under stress may exhibit substantially more interdependencies compared to the same system in a normal situation, hence facilitating the spread of risks throughout the system.[17,18,32,33] Climate change and other global changes can be stressors, amplifying interdependencies and systemic risks in complex, non-trivial ways that demand appropriate systemic approaches for effective management. Especially, long-term stressors that are not easily identified beforehand and may differ across world regions, such as changes in the frequency and severity of drought events[2] or increases of compound events,[34] need to be carefully examined, as they could cause systemic risk to be realized, leading to phenomena like forced migration and political instability.[35]

We suggest that addressing such destructive and cascading risks that could threaten the entire future of humankind[36] requires strategies for managing systemic risks through incremental and—as systemic risks due to climate change and other global changes are putting systems under mounting pressure—increasingly also deliberate transformative approaches.[22] These risk management and adaptation strategies can be envisaged within a continuous spectrum of system-level change (Figure 1C) ranging from incremental adjustments to transformative shifts that cause deep-rooted, qualitative change toward a more resilient system state. We position these forms of transformation within a system-of-systems approach (meaning that a system's elements may also need to be understood as systems), building on system boundaries[37] as important concepts (Figure 1A). This enables complementing a focus on system elements on the individual level with a focus on system interdependencies on the system level (Figure 1B). It also enables connecting these foci through systemic risk analyses that help understand the spreading mechanisms through which individual failures may cascade into system failures.

At one end of the spectrum, incremental change occurs within existing structures and objectives, prioritizing continuity and making small, gradual adjustments to existing systems in response to identified risks and changing conditions (Figure 1C, bottom). Incremental approaches typically involve measures such as reinforcing infrastructure, improving early-warning systems (EWSs), implementing risk-reduction measures, and enhancing preparedness and response capabilities. At the other end of this spectrum, transformative change involves profound alterations that challenge the established status quo of a system in response to current and future risks and uncertainties (Figure 1C, top). Transformative approaches may involve reimagining social, economic, and environmental systems, changing policies and regulations, promoting behavioral changes, and fostering innovation and technological advancements to tackle root causes and promote sustainability

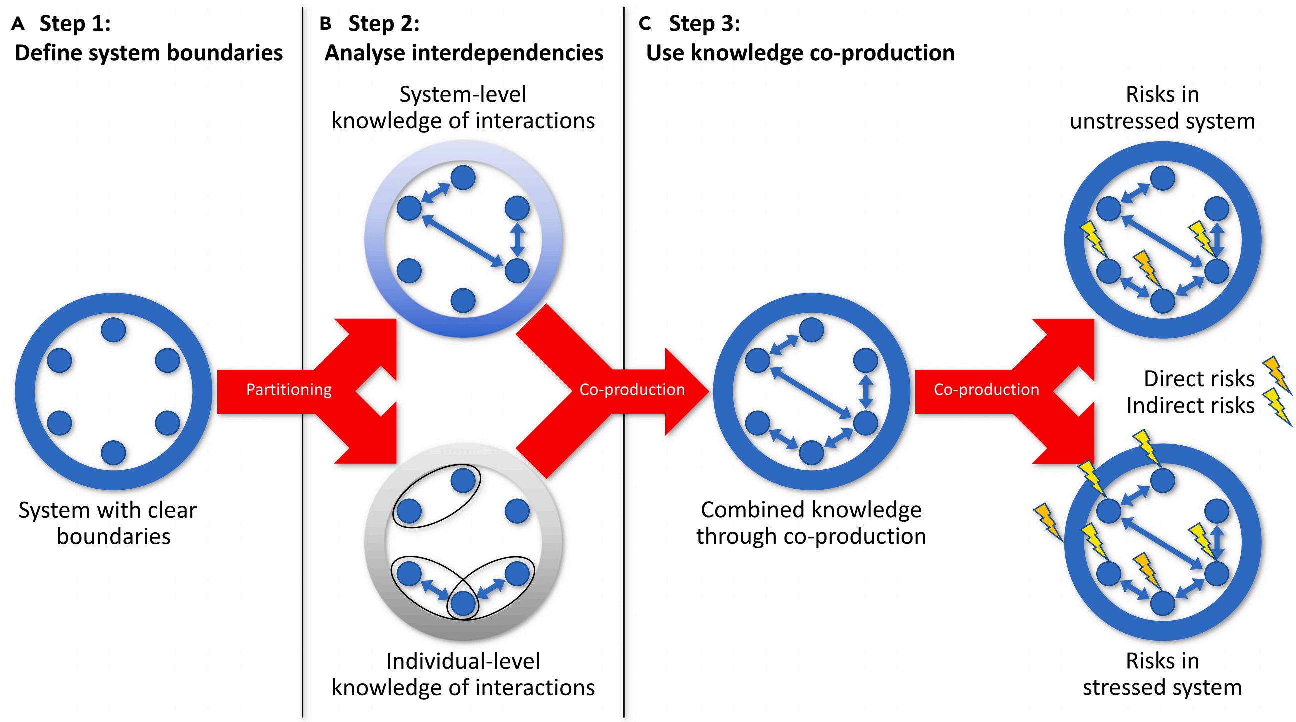

Figure 2. Process for combining systemic risk analysis with knowledge co-production
Starting from identifying a system with clear boundaries (step 1, A), systemic risk analysis based on local and system-level knowledge (step 2, B) is used for deriving a comprehensive picture through co-production (step 3, C) that helps identify systemic risk due to inside or outside events. Orange lightning bolts represent direct risks and yellow lightning bolts indirect (follow-on) risks propagated by interactions, with risk defined here purely as downside risk, e.g., in terms of potential losses occurring if the risk is realized. This information is then used within a risk-layering approach for prioritizing and orchestrating transformation options (step 4, Figure 3). This four-step process provides information for, and can thus guide, possible transformations needed for reducing systemic risk.

and equity. As highlighted by the correspondence between Figures 1B and 1C, we propose that incremental transformation is especially relevant for managing individual system elements, whereas fundamental transformation is especially relevant for managing system interdependencies within the system-of-systems perspective.

SYSTEMIC RISK RESEARCH AND KNOWLEDGE CO-PRODUCTION

While Figure 1 illustrates the rationale for combining transformative and incremental approaches to adaptation and risk management within a system-of-systems approach, implementing transformative change to enhance resilience in complex systems is a demanding endeavor that hinges on two key factors: (1) context-specific understanding of systemic risk to develop and implement solutions that address the unique challenges and opportunities within a given system and (2) a shared understanding and trust in the chosen transformative pathway to boost the potential for successful implementation.[38] We suggest that this dual challenge can best be addressed by tapping into the insights of systemic risk research in conjunction with employing knowledge co-production approaches. By helping to comprehend the intricate dynamics of complex systems and interfacing such comprehension with local knowledge, the combined approach provides avenues for bridging the operationalization gap in an informed and efficient manner while also fostering a common vision of transformation pathways.[39]

For implementing this combined approach, we recommend a four-step process, as shown in Figures 2 and 3. In step 1, the system boundaries are defined, which enables recognizing interdependencies within and across systems. In step 2, an understanding of possible interactions based on both local and system-level knowledge is established. In step 3, additional insights as well as divergent and often conflicting views on the identified interactions are brought together through a knowledge co-production process, which enables identifying how systemic risks may realize from events within as well as outside the system, including possible interrelationships between both. In step 4, a risk-layering approach is applied, which enables prioritizing and orchestrating possible transformative options through knowledge co-production, on the individual level as well as on the system level, to decrease systemic risks. Below, we discuss each step in more detail.

Step 1: Define system boundaries

Given the mounting problems arising from climate change and other global changes, developing and implementing context-specific solutions that address the unique challenges and opportunities within a given system are becoming more and more important. As transformative change takes place on the system

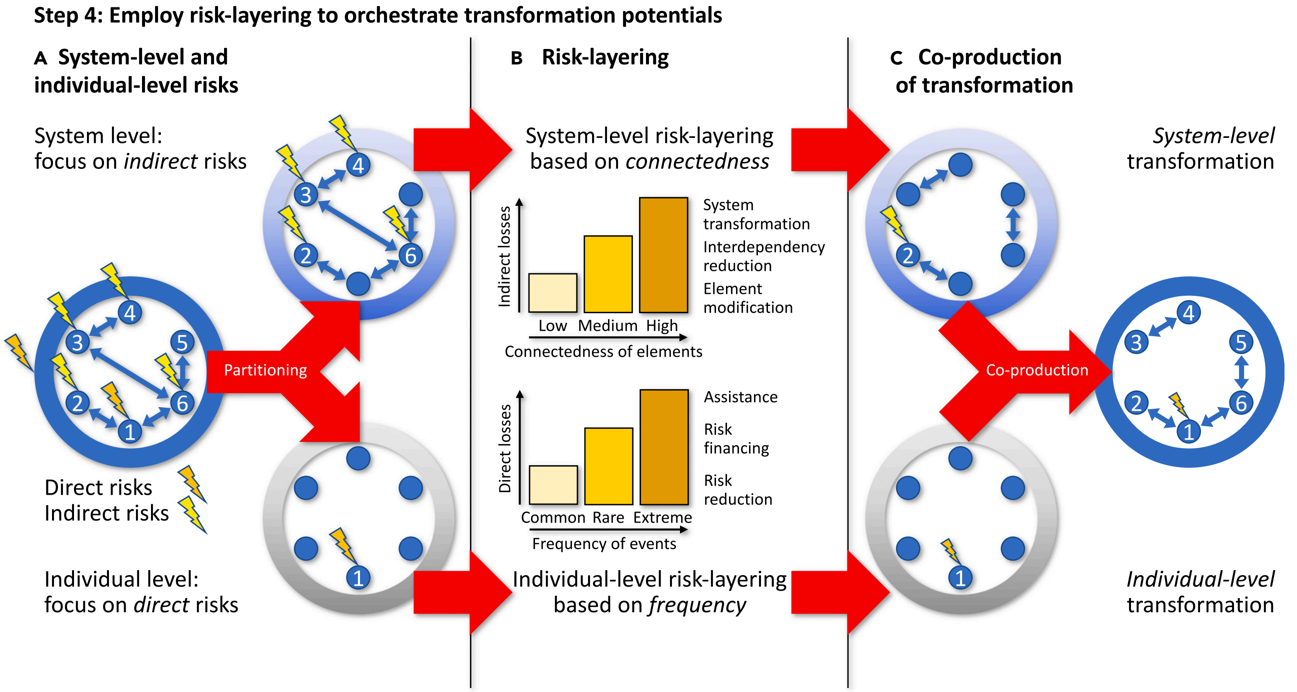

Figure 3. Risk-layering analysis (step 4) for understanding the dynamics and interactions of incremental and transformative change
Based on distinguishing system elements on the individual level from system interdependencies on the system level (A), categories based on event frequency on the individual level and element connectedness on the system level can be linked with corresponding sets of intervention options (B), which eventually are prioritized and orchestrated through co-production (C).

level and solutions must be rooted in local knowledge, adopting a system-of-systems approach based on delineating system boundaries is key for enabling interventions that help bridge this gap. It also assists in determining if stressors of the system causing increased levels of systemic risk by inducing stronger interdependencies are originating from factors inside or outside the system. System boundaries and system elements can be delineated according to geographical scales, political boundaries, or private and business-sector entities (e.g., insurance entities, governmental bodies, or civil society). Furthermore, these elements may be tangible (e.g., assets) or intangible (e.g., health effects or life satisfaction), and they may be monetarized using market-based methods (e.g., replacement value of damaged houses) or not (e.g., environmental effects or biodiversity loss).[40] These systems may overlap or can be distinct, and they can interact with each other on some scales or may be completely independent. Furthermore, the system definition may differ among different entities looking at the same threats and may also change over time.[41,42] A clear system definition is fundamental for examining a system and is key to recognizing its elements and their internal and external interdependencies (Figure 1A). This, in turn, is crucial for understanding the distinct roles of system elements and system interdependencies in causing and propagating systemic risks and driving transformative change.

Step 2: Analyze interdependencies

Systemic risk analyses provide valuable insights into the complexities resulting from interdependencies, feedback loops, and emergent behaviors within complex systems. We recommend that such an identification of systemic risks is best achieved by combining a top-down perspective with a bottom-up perspective. As indicated in Box 1, when developing systemic risk analyses, local knowledge is often limited and does not cover the full range of interdependencies (or interactions) across the considered system. The latter is better accomplished from a top-down perspective. On the other hand, a system-level perspective usually cannot uncover subtleties on the local or individual level that may be essential for systemic risk propagation and identifying transformation potentials. The latter is better accomplished from a bottom-up perspective. Combining a top-down perspective with a bottom-up perspective can thus overcome blind spots in our understanding of complex systems.

Analyses of systemic risk hence benefit from the inclusion of divergent views about what constitutes the considered system and how its elements interact.[45] For this reason, local stakeholders are increasingly recognized as resourceful agents with valuable local knowledge and insights.[46] As shown in Figure 2B, an incremental process of systemic risk analysis builds from the local level of system elements all the way up to the system level. Combining bottom-up and top-down information enables the determination of systemic risk under various circumstances. After defining system boundaries among all system elements according to a system-of-systems approach, local interactions as well as system interactions are determined and combined to reveal possible systemic risks due to events inside and outside the system. Many different quantitative as well as qualitative risk metrics for such an assessment are now

Box 1. Examples of individual-level vs. system-level interventions for addressing systemic risk

Addressing systemic risk involves interventions on the individual level and the system level, with the latter being crucial for enabling transformations that recognize the interconnectedness of systems and overcome the limitations of local individual-level actions. For example, supply chain risk is usually dealt with on the firm level (i.e., individual level), and firms are trying to reduce the risks of supply chain shortages up to their tier-two suppliers while keeping their businesses profitable. However, firms are embedded within larger supply networks, the details of which typically are, due to limited resources, unknown to the individual firms in full: therefore, a top-down (i.e., system-level) perspective is needed that takes such overall interactions into account. To reduce systemic risks, either the individual firms can be made more resilient, e.g., through having larger stocks, or the interactions between the firms can be made more robust, e.g., by identifying critical nodes and providing incentives or regulations that help avoid contagion from building up.

The relative importance of the individual-level and system-level perspectives may change in response to stressors acting on a system. One example is supply chain risk under the COVID-19 pandemic and corresponding interventions, which have elevated supply chain risks around the globe. Another example are wildfire risks under climate change: compound events, such as the simultaneous occurrence of high temperature and low rainfall, may increase the spatial correlation of wildfire risk and cause large-scale wildfire events that can no longer be dealt with on the local level. In a similar vein, management measures taken on the system level may influence systemic risk realization by altering the contagion possibilities among different wildfire areas. Also, the COVID-19 pandemic has shown how viruses quickly spreading on the global scale can be managed through system-level interventions, such as the modularization, or "lockdown", of regions to stop contagion among regions but also through individual actions, such as the use of masks to decrease contagion among individuals.

However, all these events cause additional stresses on other systems, either in the short term or long term, raising the question of how such compound events may be dealt with, especially in the case of systemic risk considerations within a transformation context. It is therefore beneficial to use knowledge co-production to identify dedicated roles for all considered interventions, both on the individual level and on the system level. Sources: Handmer et al.,[37] Colon et al.,[43] and Colon and Hochrainer-Stigler.[44]

available. For example, from a quantitative perspective, the focus can be on either risk realization of system elements through probabilistic approaches (e.g., using average losses, expected shortfalls, or loss distributions) or risk realization due to interdependencies (e.g., using too-central-to-fail measures such as DebtRank).[47] In addition, many different qualitative approaches for such an analysis are available (e.g., stakeholder mapping or focus group discussions; see Loureiro et al.[48] for a review). This helps identify strategies for transformative risk reduction and adaptation that can address the expanding scale and consequential impact of climate change and other global changes. As indicated at the beginning, this should include an analysis of changes in long-term stressors due to climate change, either in regard to the system elements (e.g., changes in compound risks[34]) or the interdependencies (e.g., changes in the frequency and severity of hazards; see Gaupp et al.[2] for the case of drought) and across different systems (e.g., from environmental to economic impacts or from forced migration to political instability). Due to the large uncertainties in regard to such long-term changes of stressors, different approaches need to be applied, ranging from traditional probabilistic assessments to more recent climate storylines[29] or transformation-oriented pathway development[49] that considers path dependencies due to past decisions reinforcing existing conditions alongside the adaptation pathways, which delineates future scenarios and alternative courses of action to address these dependencies. Scenario-based pathways planning models, such as the dynamic adaptive policy pathways approach[50] can further support decision-making under conditions of complexity and deep uncertainty as related to systemic transformative change. For various reasons, including diverse resources, objectives, and timescales, the tools and interventions available on the individual level and on the system level are—and have to be—different. Yet, they can be integrated using a knowledge co-production process, as discussed next.

Step 3: Use knowledge co-production

In step 3, the identified interactions are brought together through a knowledge co-production process. This step also includes the identification of how systemic risks may be realized from events inside as well as outside the system, or both. As Figures 2 and 3 show, knowledge co-production is an essential part operating throughout our proposed framework, and we therefore now discuss it in some detail for each of the proposed steps.

By recognizing the complex and contested nature of the notion of a system, it becomes clear that narrow disciplinary perspectives may not fully align with the ontology of systems or of systems of systems in the absence of an absolute Archimedean point. In other words, systems and especially systems of systems as well as elements within them may overlap, may have shared qualities or very divergent objectives, may be defined by different stakeholders differently, and may use different governance approaches as well as terminologies. As a result, the perception of improvement may vary depending on the chosen system boundaries, and an intervention that appears beneficial within one specific boundary may not be seen as an improvement when the boundaries are expanded or defined differently. This is particularly relevant when planning transformative interventions that target underlying drivers of risk and highlights the significance of addressing conflicts and trade-offs when seeking transformative solutions on and across different system scales.[51]

Co-production, if applied by leveraging its reflexive and transdisciplinary commitment that avoids social and techno-scientific determinism,[52] can increase the scope of knowledge regarding the system(s) under investigation, from both the individual-level

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perspective and the system-level perspective. In practice, the process—by providing a platform that facilitates and encourages knowledge integration through equal and non-hierarchical collaboration—can lead toward a strengthened understanding of systemic behavior through the transdisciplinary exploration of diverse but equally legitimate expert and non-expert viewpoints,[53,54] enabling the identification of synergies and conflicts as well as potentials for transformative and incremental changes for reducing current and emerging risks on, e.g., sustainability.[55]

For example, by engaging stakeholders and integrating diverse viewpoints through group model building,[56] the work of identifying system variables, causal relationships, parameter values, and non-linearities can become more effective. This helps navigate the complex decisions regarding entry points for transformative interventions, notably along system boundaries, and empowers both the individual-level and system-level perspectives as key inputs for developing a transformative change vision. Similarly, engaging stakeholders in participatory system dynamics modeling enables a better understanding of the interactions of policy with behavior, action, and financing or the implications of positive (reinforcing) and negative (balancing) feedback loops while helping to overcome potential blind spots in understanding complex systems by harnessing local insights.[57] Fuzzy cognitive mapping or analytic-deliberative approaches,[58] which are semi-quantitative modeling techniques, are examples of engaging stakeholders in developing (cognitive) models that incorporate diverse perspectives in an organized manner within a single model, enabling a shared vision and hence greater support and lasting buy in for the transformative steps to be taken.[59] Climate change is a particularly apt target for applying a co-production approach, given that its origins are rooted in anthropogenic stressors inseparable from their socio-political, economic, and cultural drivers. For instance, the Flood Resilience Measurement for Communities is an example of applying a co-development approach to understand local systems, possible biases, and resilience capacities with a view to design climate risk management and adaptation interventions that reflect diverse viewpoints and transformation potentials.[38,60]

Especially when chasing system transformations, there is a need to leverage methods that can examine and contest possible biases and ideologies that may limit the ability to depart from the status quo.[61] By integrating transdisciplinary perspectives from particular interactions (individuals' beliefs and ways of knowing and working) and general interactions (systemic higher-order dynamics) and by examining systems based on this information to learn about their operations,[62] it becomes possible to identify entry points for supporting transformative change. The potential effectiveness of knowledge co-production has been highlighted by many studies,[54,55,63,64] especially in terms of the capability to uncover and facilitate novel pathways toward resilience by enabling the exploration of options beyond the hegemonic ways of knowing.[54] This includes cultural change, which may be driven by different factors including individual-level incremental change as well as system-level transformative change. In addition, by widening the pool of stakeholders involved in these deliberations and deconstructing social hierarchies or disciplinary boundaries between them, governance settings designed to facilitate co-production can generate trust, improve communication, and build foundations toward improved collaboration in the longer term.[59,65] These benefits extend from synthesizing knowledge to terraforming the ways in which stakeholders organize themselves, as the latter is positively affected by the process of reasoning together toward transformations.[55]

Notably, when stakeholders are actively involved in the process of modeling a system, they develop a sense of ownership and investment in the outcomes, increasing the likelihood of stakeholder buy-in and acceptance of the model results and recommendations. This is especially important when considering that transformative risk management and adaptation approaches involve deep and fundamental changes on the system level that may be met with substantial opposition if not designed in a collaborative way that embeds local insights in the design and implementation of policies. For example, in Lusaka, Zambia, methods of co-production were leveraged to support the design and use of climate services among climate scientists, researchers, policymakers, and practitioners and to address the climate knowledge "usability gap."[66] The process-centric co-production approach fostered a transdisciplinary dialogue in efforts to deepen the understanding of local impacts of climate change, increase the ability of participants to collaborate, and integrate climate information into ongoing projects.[67] The case study demonstrated the value of co-production processes for bringing the users of climate services closer to their providers and using creative methods to co-design these to make sure available information met the needs of policy and practice while strengthening partnerships to support effective implementation. Similarly, in Peru, the non-governmental organization Practical Action harnessed co-production methods to develop a shared transformative vision for flood risk management in the Rimac and Piura watersheds, drawing on inclusive participatory governance models with bottom-up and intrinsic leadership and a collective reflection on problems and processes, all guided by a power-sensitive mindset. The outcome was the implementation of transformative resilience-building measures, prominently exemplified by the community EWS approach. This initiative gained traction at higher levels of government and expanded in 2021, now benefiting approximately 457,000 people by providing timely alerts regarding potential flooding risks. A second phase of expansion of the EWS is expected to positively impact over 9.3 million individuals residing in the Rimac watershed.[68]

When opening systemic risk research to local insights through knowledge co-production, it also becomes possible to identify opportunities for harnessing the potential of smaller incremental changes in unlocking greater transformative change. When implemented consistently and strategically, incremental changes have the potential to create cumulative effects and shape the trajectory of a system toward transformation.[22] Insights from organizational change and climate adaptation governance suggest that in-depth, large-scale, and quick changes are not always concurrently feasible,[69] making it crucial to identify specific contexts in which such changes are not suitable and adapt the design of solutions accordingly. As such, to facilitate transformative change in practice, governance systems need to provide conditions enabling and amplifying incremental changes through small in-depth wins. Such changes can then continuously accumulate to make policy progress on wicked problems like climate adaptation, by embracing complexity and energizing stakeholders to avoid paralysis and inaction.[70]

Similarly, a deeper understanding of system elements, boundaries, interdependencies, interrelationships, and causal loops within a system and across system boundaries is necessary input for predicting the potential ripple effects of actions taken by an agent (which may be an individual, a group of people, or an organization) on other agents within the same system and in interconnected systems. Depending on data availability, systemic risk models can be used to reflect on policy measures, including the identification of possible adverse snowball effects in other system dimensions.[30] Such an examination supports the development of transformative approaches by more effectively addressing the expanding scale and consequential co-evolutionary impacts between interconnected elements in a system and related systems due to climate change and other global changes.[71]

However, the co-production of knowledge toward identifying and enabling systemic transformations is not without its challenges. To begin with, much of the literature on co-production and its practical application remains aspirational, lacks empirical evidence, and often does not provide an explanation as to why such processes may underdeliver on their ambitions.[72,73] Yet, challenges may emerge, for instance, from the encounters between polycentric governance systems and the locally generated forms of self-organization occurring at the grassroot levels. Given that the latter do not lack agency or knowledge, they continue to act autonomously within the folds of complex governance arrangements (similarly lacking a distinct hierarchy), therefore rendering the pathways to shared societal transformation non-linear. This clash between the top-down and bottom-up is also embedded in the conceptual juxtaposition of co-production that simultaneously promotes local actors' engagement with, while recognizing their autonomy from, the actors above.[74]

Another source of potential failure relates to these tensions, since knowledge co-production is always a matter of power, politics, and conflict. Indeed, in the absence of mitigating measures, it is possible that more powerful actors may exert their influence over co-production interactions, thus reproducing norms and hierarchies in a manner that hinders the integration of new knowledge necessary for transformations.[72,75] The equality of participants is often not self-evident, and the inequalities often favor actors with more time, resources, knowledge, and skills to orchestrate and shape co-production contexts.[72] At their worst, these dynamics may continue reproducing and maintaining a systemic status quo, thus jeopardizing any potential for transformations.

Consequently, catalyzing broader societal transformations through knowledge co-production processes is complicated, and its outcomes remain uncertain, albeit promising. However, the existing literature suggests that there are pathways to navigate and address this complexity and potential conflicts between transdisciplinary actors. For example, it should be of the researchers' interest to identify pathways and monitor mechanisms through which these take place—especially in terms of impacts. After all, if it is assumed that transformations are the outcomes of use of knowledge, then the importance of the process associated with knowledge generation becomes evident—including the functions of trust, accountability, and legitimacy that would support collective action toward the reduction of systemic risks. Naturally, this entails conflict management among stakeholders, i.e., the exploration and addressing of politics, power, and influence that may either enable or hinder knowledge co-production (and therefore the potential for transformations to occur). While dismantling such hierarchies is among the most difficult tasks regarding co-production, it is nonetheless necessary, not only for the sake of knowledge production but also to build networks through which collective action may take place.[76] In addition, it should be clear what is meant by transformation, and pathways for achieving it should be well explored among actors at different levels.[77] One possible way forward in that regard, using a so-called risk-layering approach, is discussed next.

Step 4: Employ risk-layering to orchestrate transformation potentials

Above, we have suggested defining a system as a set of interconnected elements with clear boundaries (step 1). This enables an understanding of local and system-level interactions (step 2). We have further indicated that the combination of local and system-level knowledge through co-production processes can help build up and expand such an understanding of interactions and possible systemic risks (step 3). We now discuss how in the last step (step 4), a risk-layering approach can help differentiate, prioritize, and orchestrate options for incremental and transformative changes to decrease risks.

Building on distinguishing between the individual level focusing on the system elements and the system level focusing on the system interdependencies (Figure 3A), we apply risk-layering analyses to both levels in turn (Figure 3B), starting with the individual level. In the context of natural-hazard-induced disasters and climate change, it is common to categorize the elements within a system according to the frequency and corresponding severity of single-hazard and multi-hazard events threatening their resilience, with the associated hazards taken to be inherently random.[78] Such a categorization provides the basis for risk-layering, which not only categorizes events according to their frequencies and corresponding severities but also associates each resultant category with specific intervention options for how to increase the resilience of the system elements with respect to the considered event types. For each category, different intervention options may be prioritized, e.g., first, risk reduction for common events; second, risk financing for rare events; and third, assistance for very infrequent extreme events (Figure 3B).

Contrary to the individual level, in which risk-layering is based on the frequency and the corresponding severity of events threatening system elements, on the system level, risks should be layered according to the strength of system interdependencies and the corresponding connectedness of system elements.[79] In the case of very strong connections, a (possible transformational) change in the network structure may be needed to reduce systemic risk. However, one other possibility is to reduce system interdependencies or to strengthen the resilience of system elements, as systemic risk is only realized starting from failures of individual elements (Figure 3B). Through a co-production process, this twofold risk-layering analysis results in an orchestrated portfolio of intervention options and transformation potentials, covering incremental as well as transformative risk management and adaptation options (Figure 3C).

For example, in Figure 3A, we use the information about systemic risks identified in step 3 of Figure 2C as the starting point for the risk-layering analysis. We assume that the system is under stress due to an outside event and, in addition, that element 1 is affected by realized direct risk, e.g., due to a natural hazard event, as indicated by the orange lightning bolts in Figure 3A. This realizes indirect risks due to interactions within the system for elements 2, 3, 4, and 6, as indicated by the yellow lightning bolts in Figure 3A. In Figure 3B, on the individual level and based on the risk-layering approach, the resilience of element 1 against events has been strengthened, e.g., through risk reduction, as indicated by the shrunken orange lightning bolt in Figure 3C, and on the system level, the connections between elements 1 and 6 as well as between 3 and 6 have been weakened, as indicated by the dropped arrows in Figure 3C. When considering such interventions, it must be kept in mind, however, that the weakening of connections, as much as it may be desirable on the system level, may be seen as problematic on the individual level, as there often are specific functional reasons for strong connections. Using a knowledge co-production process, these different options and viewpoints may be analyzed together to derive a joint understanding of which interventions are deemed feasible and adequate, both on the individual level and on the system level, to decrease systemic risk. In the example illustrated in Figure 3C, this prioritization and orchestration is indicated by the reestablishment of the arrow between elements 1 and 6 enabled by the sufficient increase in the resilience of element 1 through risk financing, e.g., by using insurance instead of or in addition to risk reduction. In this way, indirect risks can be eliminated, not only for the unstressed system but even when the system is under stress (Figure 2C).

In summary, we suggest that the four-step process we have described here helps to bridge the gap between methodologies more based on natural science that provide well-established tools for systemic risk analyses accounting for event frequency and element connectedness[79,80] and methodologies more based on social science that focus on dimensions and processes related to human agency and governance. In this sense, traditional concepts like probability and utility, while still necessary, are on their own increasingly insufficient for understanding global systemic risks. Instead, there is a need for delving into understanding the critical aspects of specific global systems, in which numerous human agents interact within complex and ever-changing networks. In such systems, even the most influential agents cannot achieve better outcomes without engaging in a co-evolutionary process with other agents, creating win-win opportunities within expanding networks.

CONCLUSION

In this paper, we have argued that, by opening systemic risk analyses to local insights through knowledge co-production approaches, it becomes possible to identify opportunities for incremental and transformative change, helping to close the operationalization gap. Such an iterative multiple-lines-of-evidence approach can create cumulative effects and shape a system's trajectory toward transformation. By drawing on local insights and diverse perspectives while acknowledging the dynamic nature of systems and the need for adaptable interventions, this approach enables stakeholders to identify and harness potentials for transformative change more effectively.

We have outlined how systemic risk analysis and knowledge co-production can be combined in a four-step process. To begin, we suggest taking a system-of-systems approach to identify system boundaries distinguishing between system elements and the studied system as a whole, which serves as a foundation for assessing interdependencies within and across systems. Moving forward, we recommend analyzing these interdependencies, covering systemic risk factors stemming from internal and external events along with potential interactions among these factors. Finally, we propose that the concept of risk-layering can be leveraged to differentiate among categories based on event frequency (e.g., common, rare, and extreme) and link them with individual-risk instruments (e.g., risk reduction, risk financing, and assistance) on the individual level and, likewise, differentiate among categories based on element connectedness (e.g., weak, intermediate, and strong) and link them with systemic risk instruments (e.g., transformative network restructuring, reducing connection strength, and enhancing element resilience).

In combination with knowledge co-production approaches, risk-layering can simultaneously address individual and higher-order interactions and reveal entry points for determining transformation potentials. Naturally, the selection of metrics and approaches is contingent on the considered system scales, governance contexts, and process-related policies. Furthermore, given the difficulties in understanding systemic risk and the observed operationalization gap in bringing transformative change underway, this integrated four-step approach offers opportunities for bridging between social and natural science disciplines, recognizing that both are essential for managing systemic risks through transformation. Ultimately, co-production processes are instrumental for consolidating insights and reconciling divergent, and at times conflicting, viewpoints pertaining to implementing transformative change in any given system.

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DECLARATION OF INTERESTS

The authors declare no competing interests.

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