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LETTER

Understanding multiple resilience dividends and system boundaries in disaster- and climate-risk management: a systems approach for enhanced decision-making

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Abstract

Challenges in managing multi-hazards and multi-risks within complex risk landscapes—where numerous stakeholders with different priority needs and risk perceptions interact—remain unresolved. Here we suggest ways to tackle these pressing challenges in an integrated and comprehensive manner by applying key concepts from systemic risk research to triple- and multiple-dividend approaches. The central idea is that additional dividends (i.e., economic, social, and environmental co-benefits of disaster-risk reduction that go beyond loss-reduction benefits) can be related to different system boundaries (e.g., individual systems and system of systems) through their interdependencies. This approach allows for an integrated evaluation of interventions that may be more beneficial across various scales and for corresponding threats, thus increasing synergies (or co-benefits) and decreasing asynergies (or trade-offs) of disaster-risk reduction in a systemic way. Importantly, triple and multiple dividends, along with their related tools and approaches, can be seen as part of a 'dividend continuum', reflecting the varying levels of interdependencies across spatial and temporal scales within complex risk landscapes. As a consequence, dividends within and across systems can be managed simultaneously, based on determining priority needs, risk perceptions, and trade-offs involved in building resilience against current and future risks.

1. Introduction: single- and multi-hazard interventions to manage risks

Despite significant efforts (UN 2015, UNDRR 2015, UNFCCC 2016), there are mounting challenges in managing disasters induced by natural hazards. For example, the number of disasters triggered by natural phenomena continues to rise and will be further exacerbated due to climate and global changes in the future (IPCC 2022). In addition, there are indications that 'connected extremes'—multiple hazards whose occurrences and impacts overlap in space and time—are also increasing (Raymond *et al* 2020). The potential for these multiple hazards to cause impacts larger than the sum of the individual hazards is a reason for concern (Reichstein *et al* 2021). Importantly, natural hazard events and their impacts are not isolated phenomena but are influenced by various conditions that can amplify their overall effects (Ward *et al* 2022). For instance, the COVID-19 pandemic reduced the fiscal capacity to finance disaster responses, elevating fiscal risks associated with potential future events (Hochrainer-Stigler 2021). Other compounding factors, such as migration flows and armed conflicts, can further exacerbate already strained situations to an extent that may eventually lead to the realization of systemic risks (Frank *et al* 2014, Scheffran 2020, Desai *et al* 2021).

As a result, systemic perspectives—which focus on a whole system and its interrelationships (Renn *et al* 2022)—including multi-hazard and multi-risk assessments, together with the corresponding management frameworks, are gaining prominence (Ward *et al* 2022, Sillmann *et al* 2022, De Angeli *et al* 2022, Hochrainer-Stigler *et al* 2023). However, the challenges of managing single and multi-hazards, as well as single, multi-, and systemic risks simultaneously within these complex risk landscapes—where numerous stakeholders have different priority needs and risk perceptions—, alongside the need for quantitative modelling, remain unresolved (Laurien *et al* 2022, Trogrlić *et al* 2024). Building on concepts from systemic risk research (Thurner *et al* 2018) and the triple- and multiple dividend approaches described below (Surminski and Tanner 2016), we suggest a framework to reduce this complexity to manageable levels. It addresses both operationalization aspects of modelling and governance dimensions to meet these challenges.

Our main idea is that additional dividends (i.e., economic, social, and environmental co-benefits of disaster-risk reduction that go beyond loss-reduction benefits) can be related to different system boundaries (e.g., individual systems and system of systems) through their interdependencies. This enables a comprehensive evaluation of interventions, identifying those that are most beneficial on various scales and for corresponding threats, thus increasing synergies (or co-benefits) (Ward *et al* 2022) and decreasing asynergies (or trade-offs) (de Ruiter *et al* 2021, de Ruiter and Van Loon 2022) from disaster-risk reduction. Importantly, triple and multiple dividend, along with the related tools and approaches, can be seen as part of a 'dividends continuum' according to their level of interdependence across spatial and temporal scales within complex risk landscapes. Consequently, dividends within and across systems can be managed simultaneously by determining priority needs, risk perceptions, and trade-offs (Reichstein *et al* 2021, Renn *et al* 2022) involved in building resilience for current and future risks.

2. Definition of system boundaries for aiding the selection of risk-management instruments

We start our discussion by highlighting the importance of defining the boundaries of the system under consideration before determining the dividends (i.e., co-benefits) of possible interventions. Indeed, defining system boundaries has long been recognized as crucial for determining the effectiveness of a given intervention (Churchman 1971). This is because an intervention may be seen as an improvement within a narrowly defined system boundary, while it might not be seen as an improvement at all if the boundaries are expanded, or vice versa. Sometimes, determining boundaries is straightforward, with examples including political boundaries (e.g., based on countries), economic boundaries (e.g., based on economic sectors, economic agents, or insurance providers), or legislative boundaries (e.g., based on key regulations). In other cases, however, the salient system boundaries must be established by all those involved in and affected by the intervention, e.g., through rational dialogue (Ulrich 1996) or co-production processes (Midgley 2000, Turnhout *et al* 2020). Examples include vulnerability assessments and corresponding necessary interventions within socio-ecological systems (SES) for coastal deltas (Sebesvari *et al* 2016) or, more generally, human-environment coupled systems (Thurner *et al* 2018). It is worth noting that, while ecological systems cannot anticipate disturbances or disasters, humans can conceptualize such events and take action to manage them (Gunderson 2010). Boundaries may be defined differently by different stakeholders, and they can change over time. As a further complication, the salient system boundaries relevant for an intervention may fully, partially, or not overlap at all with those of other systems that are important to the stakeholders involved.

Despite these complications (and general questions concerning the ontology of a 'system'; Luhmann 2012), clear boundaries are crucial for decision-makers to categorize which elements are inside or outside the considered system. This categorization, in turn, determines which interventions can affect the system under consideration, other systems, and vice versa and in which way (van den Hurk *et al* 2023), thus influencing also the relevance of possible interventions for the decision-maker. On this basis, the costs and benefits of possible interventions can be assessed from a within-system perspective and an outside-system perspective. This distinction is central, as decision-makers selecting specific instruments are commonly focusing on within-system costs and benefits, while disregarding outside-system costs and benefits, which are known, respectively, as negative and positive externalities (see the discussion below).

Selecting the most appropriate risk management interventions (e.g., measures for disaster-risk reduction, including a variety of structural and non-structural measures) depends fundamentally on the performance metrics that decision-makers prioritize. Usually, different sets of interventions are, in principle, available, and selection among them can be based on various criteria, which can be qualitative, quantitative, or both. In the context of quantitative modelling, cost-benefit analysis and its derivatives are probably the most prominent approaches to accomplish such selection (for a review on cost-benefit analysis, see Mechler 2016), while for qualitative or combined approaches multi-criteria assessment is a common practice (for a review on multi-criteria decision analysis, see Barros *et al* 2014). When evaluating and selecting interventions, commonly the focus is on reducing expected losses associated with direct tangible risk (e.g., to decrease annual losses resulting from the direct contact of tangible assets with a natural hazard). Naturally, such assessments differ in terms of whether all actual costs and benefits are considered, the chosen performance metrics (e.g., focusing on average vs. extreme effects or on qualitative vs. quantitative impacts), and the comprehensiveness of these measurements (e.g., resulting, from broader or narrower notions of vulnerability or resilience; for a review, see Renn 2017). Irrespective of this diversity, very few assessments account for costs and benefits (i) analysed within and across systems (which includes negative and positive externalities), (ii) construed under different system perspectives (which are defined through different system boundaries), and (iii) mediated by dynamics between them (which can possibly be nonlinear). We suggest that systemic risk research can contribute to a new appreciation of these more inclusive assessments. Below, we examine this suggestion using the multiple-dividend approach as a starting point.

3. System of systems and their interdependencies

Systemic risk research focuses on interrelationships between elements of a system that could lead to the realization of systemic risks. A second focal point is on the failure of individual elements. In the past, various risk measures and management options were developed to address both, the dependencies and the failure of elements (Hochrainer-Stigler 2020). However, systemic risk is now seen in broader terms subsumed under a 'systemic perspective' that emphasizes systemic interrelationships rather than just systemic breakdowns (Renn *et al* 2022). This in turn opens the possibility of emphasizing the dynamics that occur both between and across systems. To advance this discussion, we broadly define a 'system' as a collection of elements that are, to some extent, interconnected (let us call them individual elements) within clearly defined boundaries. A system, thus, clearly delineates which elements lie within its boundaries and which do not (Handmer *et al* 2020). For example, when assessing disaster risk due to natural hazard events, one first may look at only those elements in this system that may be at risk and could experience losses in case a hazardous event occurs (figure 1). Without any interdependencies between the system's elements, any damage affecting certain individual elements cannot spread to other elements that are not directly affected by the disaster. Therefore, no indirect impacts can be caused in this case. If the individual elements are, however, to some extent interdependent and interconnected (as is usually the case in socio-economic systems), indirect and cascading effects (here called indirect risks) may realize and eventually propagate outside the system under consideration, affecting other elements which are defined as those that could be indirectly impacted by the hazards (figure 1).

The inclusion of indirect risks through the dependency concept opens the possibility not only to think about the mechanisms that lead to the spreading of risks but also to consider interventions beneficial for systems that are not directly affected (Hochrainer-Stigler and Reiter 2021). As a consequence, an analysis of different interventions for disaster-risk management (DRM) can happen within a given system's boundary but can also be done using a different-system boundary definition (e.g., those relevant to different stakeholders), as exemplified in figure 1 between the so-called disaster-related system and the more generally defined socio-economic system. Due to interdependencies between the system elements, both systems should not be looked at separately, as they influence each other. When analysed together, different costs and benefits may emerge, highlighting the need for a more comprehensive approach. This supports discussions about multiple- and triple dividend approaches for broadening the framework of cost-benefit analysis and incorporating extended benefits and adverse effects of interventions for disaster-risk and climate-risk management.

It should be noted that figure 1 conceptualizes only one example of many possible system of systems, focusing on disasters and their impacts across sectors and scales (Botzen *et al* 2019). There are many other systems which could be considered, including social-ecological systems (Gunderson 2010), social systems (Luhmann 1995), or earth systems (e.g., focusing on the geosphere or hydrosphere; see Schellnhuber 2006 in the context of climate change). All of them together can be considered as important (as evidenced by the systems approach within IPCC 2022). Irrespective of the system considered, clearly defining the boundaries of systems and their sub-systems, including possible interdependencies, allows for a structured and integrated assessment of the dividends that interventions can produce. This approach is discussed in the next section.

4. The resilience-dividend concept, from triple to multiple

The Triple Resilience Dividend (TRD) framework (Tanner *et al* 2015, Surminski and Tanner 2016) offers a comprehensive approach to understanding the net benefits of investing in resilience interventions (World Bank 2021), thus representing an opportunity to enhance resilience in diverse contexts across different spatial and governance scales, and creating a strong case for resilience investments

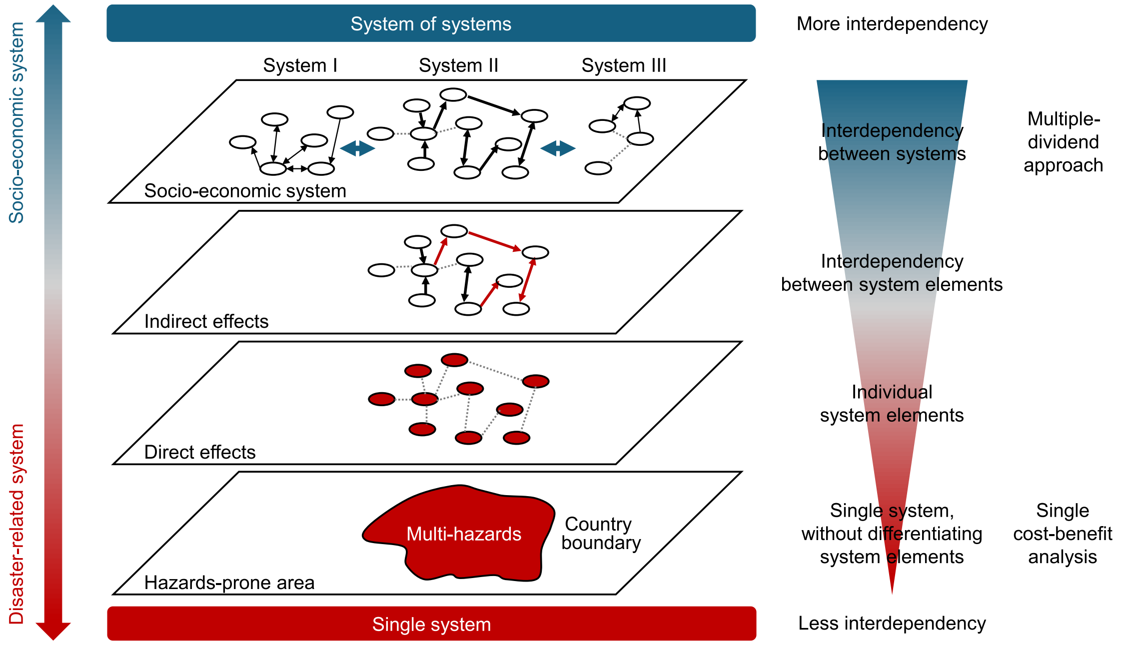

Figure 1. Example of a system-of-systems approach for the evaluation of multiple dividends based on dependencies between systems. Dependent on expanded system boundaries, one can distinguish between a disaster-related system and a socio-economic system (left-hand side). Natural hazard events that can happen in hazard-prone areas (red area at bottom) and which impact the disaster-related system elements of System II can cause direct effects (e.g., losses, red circles) which, due to dependencies, can cause additional indirect effects (e.g., production losses, red arrows). The disaster-related System II is furthermore interdependent (blue arrows) with the other, non-disaster-related Systems I and III that together represent the socio-economic system (top). With increasing inclusion of interdependencies, one moves away from a single cost-benefit analysis to a multiple-dividend approach (right-hand side). Depending on the starting point, this can happen from a disaster-related or a socio-economic perspective. *Source*: authors of this paper based on Hochrainer-Stigler *et al* (2023).

Dividends	Examples
First dividend: Avoided losses Applicable when disaster strikes	Saving lives, reducing infrastructure damage, diminishing economic losses
Second dividend: Unlocked economic potentials Appliable regardless of whether disaster strikes	Promoting entrepreneurship, encouraging building assets, stimulating investments
Third dividend: Generated co-benefits Appliable regardless of whether disaster strikes	Protecting nature, improving air quality, fostering social cohesion, enhancing food security

Figure 2. The triple-resilience-dividend framework. The three different dividends and examples of benefits are shown. While the first dividend is focusing on the disaster-related system, the second and third dividends are including non-disaster-related dimensions. *Source*: authors of this paper based on Tanner *et al* (2015), Surminski and Tanner (2016), Mechler and Hochrainer-Stigler (2019), and Heubaum *et al* (2022).

(Mechler and Hochrainer-Stigler 2019, World Bank 2021). Figure 2 summarizes the TRD framework and presents some examples for each dividend. The first dividend focuses on averting or mitigating both direct and indirect disaster risks, the second dividend entails diminishing background risks to facilitate development initiatives, and the third dividend fosters development of co-benefits that unfold irrespective of whether or not a disaster event occurs.

The Multiple Resilience Dividends (MRD) concept builds on the TRD framework by allowing for greater flexibility and adaptability to different contexts, outcomes, and needs. By eliminating the three dividend categories, the MRD concept enables a more comprehensive analysis of the wider impacts of interventions in relation to local conditions and priorities, and thus, a more nuanced understanding of their effectiveness and performance. From the MRD perspective, interventions can deliver multiple benefits in a continuum, cognizant of three aspects: (1) benefits unfold at different timescales (realization time), (2) benefits are subjective depending on who receives the effect of the intervention (receptor specificity), and (3) intervention benefits cascade across sectors, scales, and space (interconnectivity). This means that the MRD approach considers resilience-building interventions as a cross-cutting developmental aspect for system transformation, going beyond the scope of disaster-risk management. In terms of its problem domain thus far, the TRD approach has been primarily focused on disaster-risk management, while the MRD approach offers an opportunity to talk about benefits from a wider perspective of (e.g., climate) adaptation. Being more flexible than the TRD approach, the MRD approach conceives climate-adaptation measures as interventions that impact various sectors, such as food, land use, water, health, energy, and ecosystems, in different dimensions, such as social, economic, cultural, environmental, institutional, political, and technological (Rözer *et al* 2023). It is therefore more comprehensive and can be embedded within a dividend continuum using systemic risk concepts as discussed next.

5. The dividend continuum from a system-of-systems perspective

Using our systems definition, each of the three dividends can be viewed as coming from different systems, depending on the specific boundaries (e.g., sectoral, geographical, political, or based on the risk bearer). The first dividend is related to disasters (we thus call it the disaster-related system; figure 1). The second dividend is related to the development dimensions (e.g., the socio-economic system), arising indirectly through positive externalities. The third dividend pertains to general challenges that can be addressed using the same interventions as those applied to disasters, reflecting a joint perspective in both systems but with a focus on development through targeted interventions. Similarly, the multiple-dividend proposition is related to the triple dividend and spans the two extreme ends of a continuum. On one end of the continuum, DRM is approached in such a way that co-benefits are created in other policy domains (figure 3, left-hand side). This can be viewed as the perspective on elements and systems outside the disaster-related system (i.e., socio-economic system perspective). At the other end of the continuum, the approach shifts to a sectorial perspective, implying that options for DRM are integrated into development investments aimed at addressing current and future challenges (figure 3, right-hand side). Hence, it may at first treat disasters as external to the system or as only being an element of the (e.g., socio-economic) system (outside sectoral perspective). By adopting an outside-system perspective, it becomes possible to integrate disaster related dimensions into development planning, and vice versa, thus expanding the system's boundaries for a more comprehensive analysis of interventions (top of figure 3).

In this sense, the MRD approach can easily be integrated within a system-of-systems perspective, enabling analysis within and across systems through dependencies incorporation. Note that the more there are dependencies between the elements of the respective system, as well as dependencies between systems, the more suitable a multiple-dividend approach becomes for analyzing interventions (figure 1, right-hand side). Such analysis should start either with a specific system and then increase the number of systems involved or by comparing the various systems for their options to reduce risks as well as the synergies between them (figure 3, middle): independency (figure 3, bottom) allows single-risk analysis tools for evaluating dividends, while increasing dependency calls for MDR tools (figure 3, top).

Pragmatically and also in line with other approaches dealing with complexity due to interdependencies (see Schlumberger *et al* 2022 for example), the analysis starts (Step 1A) with the disaster-system perspective (i.e., comprising the elements that are exposed to hazard events) and subsequently (Step 2A) includes different sectors that can be affected (including feedback loops) due to interdependencies (Botzen *et al* 2019). This has to be done iteratively, including a knowledge co-development process that combines bottom-up (e.g., local) and top-down (e.g., system-level) knowledge (Hochrainer-Stigler *et al* 2024). In the following steps, which can also be done simultaneously with Step 1A, a sectoral perspective is taken, which does not consider disasters (Step 1B). In case there is no information available about sectoral risks, one can use the information gathered in Step 2A. In Step 2B, the dependencies between sectors are accounted for in an iterative process. Both sources of information on dependencies can be combined in Step 3, including models and approaches that are used within the respective fields and for specific purposes. For example, many disaster-related models now also include sectoral impacts, which can be used for analysing the dividends and options from a sectoral perspective (Botzen *et al* 2019).

6. Examples: from conceptual to real-world

For illustration purposes, we next describe some real-world examples for the multiple dividends to be gleaned from adopting a system-of-systems perspective. As a case in point, urban greenery and green infrastructure provide many benefits within and across several systems, such as ecosystem resilience, (coastal) flood protection, carbon storage, energy use and heat stress reduction, or water management possibilities (Choi *et al* 2021). Other studies mention that

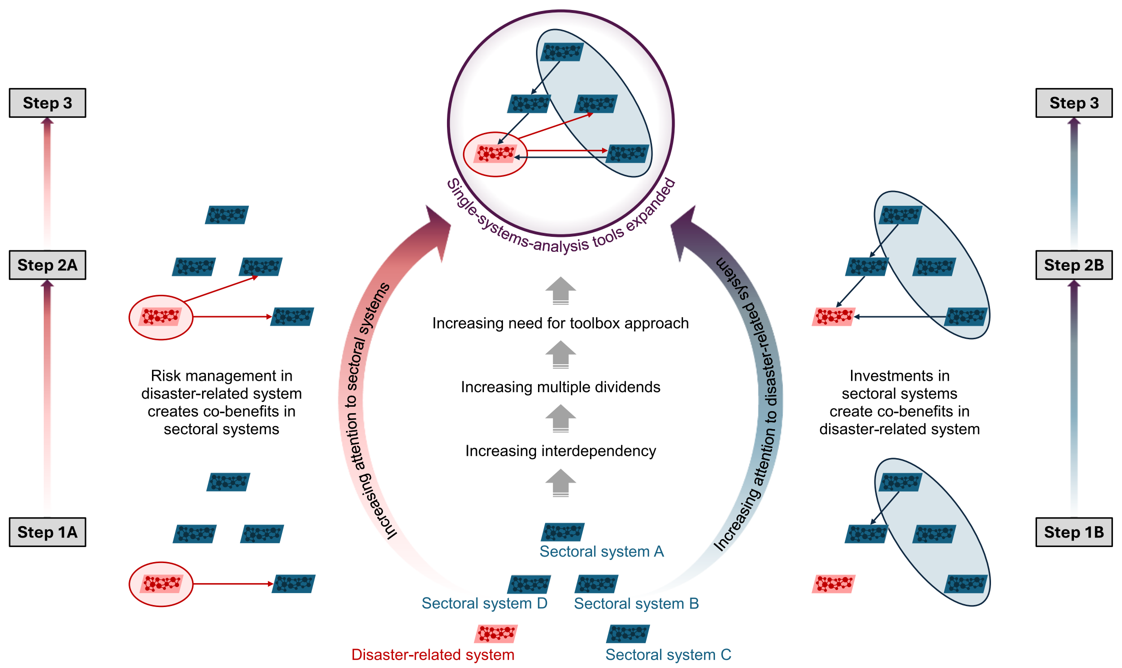

Figure 3. System of systems, dependencies, and multiple dividends across systems. Parallelograms represent systems and their boundaries (red for the disaster-related system, blue for different sectoral systems, bottom). Either starting from a disaster-centric perspective (left-hand side, Step 1A) or a sector-centric perspective (right-hand side, Step 1B) with increasing incorporation of outside dependencies, multiple-dividend analyses of increasing sophistication can be established using different tools (middle part). On the left-hand side, the disaster-centric perspective is gradually expanded to incorporate other sectoral systems through their dependencies (Step 2A). On the right-hand side, a multi-sectoral perspective is gradually expanded to other systems that can directly or indirectly affect the disaster-related system (Step 2B). By combining both perspective and expansions (Step 3), an integration of possible dividends in regard to managing risk (either from a sectoral or disaster-centric perspective) can be established, providing a holistic view (top). Note that, as dependencies are increasing, also the ways to address dividends must be modeled accordingly, which therefore necessitates a toolbox-based approach. *Source*: authors of this paper.

green spaces can ‘further support social cohesion and inclusion’ (Ommer *et al* 2022, p. 2) by providing recreational or gastronomical spaces (Raymond *et al* 2017). Another example of benefits unfolding across systems is the reduction of drought risk. For example, land use and food systems are strongly interlinked with other systems, showcasing a continuum of benefits for society. The case study of a Jamaican agriculture irrigation project described by Tanner *et al* (2016) shows that the (local) economic system heavily profited from increased productivity while social benefits (training, learning, building comradeship, recreation) and environmental benefits (wastewater treatment, maintenance of freshwater supplies, carbon sequestration, climate and water regulation) unfolded concurrently. Two case studies described by Vorhies and Wilkinson (2016) illustrate that similar nature-based solutions targeting the reduction of flood risk can provide very different benefits depending on the context of implementation. The authors explained how mangrove planting in Vietnam mainly delivered environmental and economic benefits such as carbon sequestration, nutrient retention, sediment retention, biodiversity rich habitats, flood attenuation, wastewater treatment and water supply and recharge (p. 68). The number of beneficiaries profiting from this intervention (350 000 directly and 2 million indirectly) demonstrates the opportunities for resilience dividends to unfold across scales. On the other hand, besides reducing flood risk, wetland protection and restoration in Sri Lanka delivered additional benefits by providing livelihoods and recreational areas, economic security (fishing, rice cultivation), heat mitigation (health benefits, energy savings) while contributing to the maintenance of ecosystem functioning and services (treatment of wastewater, freshwater provision, carbon sequestration, regulation of climate, water and soil, pollination and nutrient cycling). Sharifi *et al* (2021) describe a case where resilient critical infrastructure is directly connected to a better provisioning of services for the health and wellbeing of citizens. Cross-sectoral resilience dividends therefore usually come in useful to several social groups or a whole community, thus adding to their resilience. Overall, the case studies indicate that the realization of interventions (here in the context of climate adaptation) seldom unfold in only system-specific benefits but rather provide a broad portfolio of resilience dividends across systems as well as hazards (see World Bank 2021 for a quantitative assessment across sectors and systems). Further, different systems can transfer their gains in resiliency to other systems due to their strong connection. The approach presented here could clearly distinguish between systems, dividends and overlaps due to interdependencies.

The system-of-systems approach has not yet been applied within a multiple-dividend context, but similar approaches were used in the past, and one example about flood risk in Austria is briefly discussed next. In a first step, a detailed disaster-risk model for flood risk was developed that included spatially explicit information on sectoral losses for different magnitudes of flooding as well as current and future climate (Schinko *et al* 2017). This can be interpreted as Step 1A in figure 3. For analyzing indirect impacts due to such hazard events, three different highly detailed models were applied, including input-output models, general equilibrium models, and agent-based models. These help overcome some of the limitations of the other models to provide a holistic perspective of indirect impacts across sectors, scales and time (Bachner *et al* 2024). This can be interpreted as Step 2A in figure 3. In addition, a stakeholder process was started at the beginning of the analysis to include various risk bearers and decision-makers in the process of analysing interventions. Rather than focusing on disaster-specific issues, this process looked at broader challenges (Reiter *et al* 2022). This can be interpreted as Step 1B within figure 3. Information on the indirect impacts and the interrelationships between different sectors under risk was produced through workshops with stakeholders. This can be interpreted as Step 2B in figure 3. This information was combined with the models to identify interventions that are beneficial from different system perspectives (Hochrainer-Stigler *et al* 2024). This aligns with Step 3 in figure 3. For example, the finance ministry's concern with labour shortages (second dividend) was linked to the reduction of indirect impacts during the emergency phase after a disaster (first dividend). Risk-reduction and risk-financing measures proved beneficial not only for addressing disaster-related issues but also for reducing the vulnerability of exposed populations, including aspects of fairness and equity (third dividend). These dimensions were also found to be important in the context of the governance of risk (Hochrainer-Stigler *et al* 2023).

7. Operationalization aspects and available modelling tools

The detailed example above illustrates the complexity that needs to be reduced to manageable levels to effectively assess resilience dividends. It seems evident that without the explicit inclusion of interdependencies within as well as between systems, a multiple-dividend assessment would be neither possible nor needed. However, the nature of these dependencies (i.e., between system elements and system-of-systems) can vary depending on the decision makers involved and may not always align across all systems. A system may be affected by external events that it may not be able to influence directly but may still want to address in order to decrease the associated risks that could eventually stress its own stability, composition, or functioning. For example, events outside Europe, such as cyclone risks, potentially amplified by climate change across the Caribbean or South-east USA, can significantly influence the European economy, insurance pricing and EU policy tools, such as the EU Solidarity Fund (van den Hurk *et al* 2023). So-called climate storyline approaches can be used to inform contexts where outside-system events may stress a system and can have serious effects on the system that need to be treated. These storylines use counterfactual 'what-if' analyses, exploring consequences arising from shifting key climate and hazard parameters (e.g., enhanced occurrence of cyclones in the Caribbean). Often based on qualitative scenarios, climate storylines focus on scenarios that are plausible rather than on fully probabilistic assessments, due to the sheer complexity of the chains of possible interdependencies. However, costs as well as benefits of interventions can be assessed in more detail, focusing on specific performance metrics of the system and especially stress testing these. This is important as systems under a stress scenario may look very different (e.g., in terms of their interdependencies) compared to a normal situation and interventions and may fail exactly at the moment when a polycrisis (i.e. an interconnection of multiple crises) emerges (Hochrainer-Stigler *et al* 2018).

In other words, we call for a multiple-lines-of-evidence and multiple-model approach, embedded within a 'toolbox' approach that can be used for tailored specific analysis of the costs and benefits of options across systems (figure 3, middle part). For example, in economic parlance, externalities (also called spill-overs) can be considered to assess the costs (negative) or benefits (positive) not directly captured in market prices or transactions. Hence, risk-reduction benefits from project investment is related to the first dividend, with suggested extra dividends that would arise from positive externalities, such as unlocked development (second dividend), and co-benefits, e.g., investment into health systems with returns from treating disaster-affected patients and those affected by particular events, such as from disease or accidents. In our discussion, we considered as externalities the unintended positive or negative effects arising from disaster-risk-reduction investment (Harvey 1994). While externalities should be considered in standard decision-making for public-sector investment decisions, in DRM and climate adaptation they are generally not well captured, which actually gave rise to the concept of triple-dividend decision-making. It should also be noted that, while triple- and multiple-dividend decision-making has received some attention in policy and practice, evidence has remained scarce, particularly as to the second dividend (externalities).

8. Discussion and conclusion

In our interconnected world, various risks can interact across scales and sectors, forming feedback loops that entail systemic risks. The finance sector, disasters, pandemics, or conflicts are only a few of many recent examples that demonstrated this issue convincingly. It is argued that siloed risk-assessment and management approaches are no longer appropriate for dealing with these interconnected risks (Helbing 2013); instead, a systemic perspective is required (Renn *et al* 2022). Yet, the operationalization of such a paradigm shift raises significant challenges, currently subsumed under the term 'complexity' (Westra and Zscheischler 2023). Although this is not a new subject, it deserves renewed and more thorough attention. As discussed in this paper, a way to reduce complexity to manageable levels is by defining clear system boundaries, considering interdependencies, and employing a multiple-dividend approach. This makes it feasible to analyse and evaluate interventions across diverse sets of systems as well as scales. Importantly, our proposed approach can clearly delineate pros (benefits) and cons (costs) for decision-making across systems.

We have suggested focusing on the boundaries of systems and the dependencies between system elements, systems, and system of systems. In doing so, we have argued that, as the dependencies between systems increase, the use of a multiple-dividend approach may become more beneficial for understanding benefits within and across systems (see also Eker *et al* 2024 in the context of tipping points). However, it is important still to be able to operationalize the key cost and benefit dimensions, so there is a trade-off related to quantification and governance dimensions. Some of these dimensions have been discussed in relation to disaster-risk management as well as climate-change adaptation. Usually, climate change adaptation adopts a top-down perspective, while DRM often focuses on generic options. These approaches need to be complemented with bottom-up approaches that can include the local aspects (including knowledge and interventions already implemented), ideally within a co-production process (Bharwani *et al* 2024). This process can integrate these different perspectives as well as identifying necessary trade-offs to be made in a mutual reinforcing way.

We have indicated that a toolbox-based approach is necessary, as some of the systems may focus on different priority areas, e.g., extremes vs. average events, tangible vs. intangible elements, time horizons, etc. While it cannot be assumed that the delineation of the specific system boundaries will increase consensus, it can still show the way to a possible compromise between conflicting interests (Scolobig *et al* 2016). In this way, the multiple perspectives of decision makers across different systems can be acknowledged, allowing for the inclusion of both costs and benefits through quantitative and qualitative assessments.

Data availability statement

No new data were created or analysed in this study.

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