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Invited perspectives: A research agenda towards disaster risk management pathways in multi-(hazard-)risk assessment

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Abstract. Whilst the last decades have seen a clear shift in emphasis from managing natural hazards to managing risk, the majority of natural-hazard risk research still focuses on single hazards. Internationally, there are calls for more attention for multi-hazards and multi-risks. Within the European Union (EU), the concepts of multi-hazard and multi-risk assessment and management have taken centre stage in recent years. In this perspective paper, we outline several key developments in multi-(hazard-)risk research in the last decade, with a particular focus on the EU. We present challenges for multi-(hazard-)risk management as outlined in several research projects and papers. We then present a research agenda for addressing these challenges. We argue for an approach that addresses multi-(hazard-)risk management through the lens of sustainability challenges that cut across sectors, regions, and hazards. In this approach, the starting point is a specific sustainability challenge, rather than an individual hazard or sector, and trade-offs and synergies are examined across sectors, regions, and hazards. We argue for in-depth case studies in which various approaches for multi-(hazard-)risk management are co-developed and tested in practice. Finally, we present a new pan-European research project in which our proposed research agenda will be implemented, with the goal of enabling stakeholders to develop forward-looking disaster risk management pathways that assess trade-offs and synergies of various strategies across sectors, hazards, and spatial scales.

1 From managing disasters to managing risk: a potted history

An enduring story in classical Greek mythology is the battle between the Greek hero Hercules and the river god Achelous. Hercules defeats Achelous, who has taken the form of a bull, by wrenching off one of his horns. The horn becomes the cornucopia, or horn of plenty, a symbol of abundance depicted as a large horn overflowing with produce. One of many interpretations of this myth suggests that Hercules' victory represents engineering operations, including channels, embankments, and dams, by which rivers were tamed from the vagaries of flooding to create a fertile tract of land for cultivation (Bengal, 1847). Therefore, the story can be interpreted as an early example of humans' efforts to master the natural environment. However, classic folklore and mythology also abound with examples of nature punishing humans for their treatment of the planet. Indeed, the great Roman author, philosopher, and geographer Pliny the Elder wrote in his classic *Naturalis Historia* from ca. 79 CE:

> We trace out all the veins of the earth, and yet, living upon it, undermined as it is beneath our feet, are astonished that it should occasionally cleave asunder or tremble: as though, forsooth, these signs could be any other than expressions of the indignation felt by our sacred parent! (cited in Bostock and Riley, 1857)

From the Enlightenment period, the scientific study of natural hazards moved from viewing disasters as punishments by nature or "acts of God" towards trying to explain and understand natural cause–effect relationships.

Clearly, then, there is long-standing understanding and philosophical dialogue about the role of humankind in aggravating or mitigating the impacts of natural hazards. Since the start of the industrial era, up until the 1970s, the focus of most research and practice was on managing what were long referred to as natural disasters (Burton, 2005; Peduzzi, 2019). In this worldview, humans use their know-how to design and implement measures to keep hazards at bay. Take for example Hercules' victory from the opening passage of this paper.

As our world becomes ever more populated and human settlements continue to expand at alarming rates, the impacts of natural hazards have increased sharply over the last half century (Poljanšek et al., 2017). Indeed, globalization and the concentration of population around large cities increases exposure to climate and other natural-hazard risks. Moreover, the intensity and/or frequency of many climate-related hazards is projected to increase in the 21st century (IPCC, 2022). Globally, over the last 20 years natural hazards have caused an estimated 931 000 direct fatalities (excluding heatwave deaths) and over EUR 3.87 trillion (inflation adjusted for 2021) in economic losses over the last 20 years (CATDAT, 2021) and have affected more than 200 million people per year on average (CRED, 2021). Since the 1970s, the idea that disasters are also a human construct became (slowly) accepted (Peduzzi, 2019) and is now well embedded in the literature (Kelman et al., 2016).

Accordingly, recent decades have seen a move from managing hazards to managing risks, as documented in several works. This perspective paper is not the place to review this journey: excellent histories are provided in several scholarly works, including Zentel and Glade (2013), Tozier de la Poterie and Baudoin (2015), Peduzzi (2019), and Aronsson-Storrier (2020). Suffice to say that an important point in this journey was the ratification of the Hyogo Framework for Action 2005–2015 (HFA), an outcome of the World Conference for Disaster Reduction, held in Kobe in 2005. This followed the International Decade for Natural Disaster Reduction 1990–2000 and the subsequent creation of the United Nations International Strategy for Disaster Reduction (UNISDR) in 1999 (which was subsequently renamed United Nations Office for Disaster Risk Reduction, UNDRR). The HFA is likely the most significant international document popularizing the notion of disaster risk reduction, reflecting a stronger focus on risk preparedness and prevention as opposed to the emphasis on response and recovery during the previous decades. The HFA was also the first international framework describing the detailed processes needed to reduce disaster risks across different spatial scales and sectors (Tozier de la Poterie and Baudoin, 2015).

The developments outlined above have led to a growing understanding and body of research on disaster risk. The vast majority of that research has focused on single hazards. Internationally, there is an ongoing call for more attention towards multi-(hazard-)risk. It should be noted that there are many different terminologies used in this rapidly evolving field. Whilst this paper is not the place to review this terminology, Table 1 shows several key definitions of the terms multi-hazard, multi-hazard risk, and multi-risk. For the sake of simplicity, in this paper we use the term multi-(hazard-)risk when referring to all of these different aspects collectively. For terminology related to risk in general, we follow UNDRR (2017).

Within the European Union (EU), the concept of multi-(hazard-)risk assessment and management has taken centre stage in recent years. In this perspective paper, we outline several key developments in multi-(hazard-)risk research in the last decade, with a particular focus on the EU (Sect. 2). We also present challenges for multi-(hazard-)risk management (Sect. 3) as outlined in several research projects and papers, with an emphasis on Europe. Finally, we present a research agenda that will be implemented in an upcoming project for addressing these challenges.

2 The whole is greater than the sum of its parts: from risk to multi-(hazard-)risk

The interaction of different hazards can lead to an impact that is greater than the sum of the single-hazard effects (Kappes et al., 2012; Terzi et al., 2019). Whilst Hewitt and Burton (1971) noted a half century ago the need to shift natural-hazard research from a single-hazard approach towards a systematic cross-hazard approach, concerted calls for multi-(hazard-)risk approaches only date back to the early 1990s. Agenda 21 for sustainable development (UNCED, 1992) called for a "complete multi-hazard research" approach to human settlement planning and disaster risk (Scolobig et al., 2017). This notion was taken up in the HFA and even more so takes centre stage in the Sendai Framework for Disaster Risk Reduction 2015–2030 (Sendai Framework) (UNDRR, 2015). The Sendai Framework calls to "promote investments in innovation and technology development in long-term, multi-hazard and solution-driven research in disaster risk management".

Several EU policies, strategies, and frameworks advocate for a multi-(hazard-)risk and multi-sector approach. For example, the Internal Security Strategy (SEC (2010) 1626 Final) (which evolved into the European Agenda on Security) advocates for an "all-hazard approach to threat and risk assessment"; the EU Community framework on disaster prevention point 22 underlines "the usefulness of a multi-hazard approach" in Regulation 1313/2013/EU; and the European Disaster Risk Reduction Strategy (COM 2008, 130) states the need for comprehensive approaches to disaster management (Poljanšek et al., 2017).

The move towards a multi-(hazard-)risk approach is reflected in the research agenda of the European Union, where the topic has been within its Framework Programmes (FPs) since FP4. Several major EU-funded projects are listed in Table 2. The move in science towards this approach is reflected in the creation of a subdivision on multi-hazard risk within the European Geosciences Union in 2019. The theme of multi-hazard approaches has been central to a series of conferences between the European Geosciences Union and the Asia Oceania Geosciences Society, since 2017, on "New Dimensions for Natural Hazards in Asia".

The industry and policy-driven demand for, as well as science-driven supply of, multi-(hazard-)risk knowledge has led to a proliferation of myriad approaches for multi-(hazard-)risk assessment. Several reviews of these approaches can be found in various reports and papers, including Kappes et al. (2012), Gill and Malamud (2014), Poljanšek et al. (2017), Scolobig et al. (2017), Ciurean et al. (2018), and Tilloy et al. (2019). In particular, Ciurean et al. (2018) divide these approaches into several main classes: narrative descriptions, hazard wheels, hazard matrices, network diagrams, hazard maps, hazard/risk indices, systems-based or physical modelling, and probabilistic and statistical approaches.

Moreover, recent years have seen the development of several networks focusing on various aspects of multi-hazard and multi-risk assessment and management. UNDRR launched the Global Risk Assessment Framework, with a Working Group specifically dedicated to Fostering Systems Thinking, in which risk is addressed through a multi-(hazard-)risk and multi-sector lens. Major research programmes – Future Earth, IRDR (Integrated Research on Disaster Risk), WCRP (World Climate Research Programme), and WWRP (World Weather Research Programme) – have formed an interdisciplinary network centred on systemic risk (Risk KAN; Knowledge Action Network on Emergent Risks and Extreme Events). Within the climate community, several networks have formed around the concept of compound climate extremes, including the COST (European Cooperation in Science and Technology) Action DAMOCLES (Understanding and Modeling Compound Climate and Weather Events) and the Risk KAN Working Groups on Compound Events and Impacts and on Early Warnings.

3 Challenges for multi-(hazard-)risk management

Notwithstanding the many advances made in the last decades, multi-(hazard-)risks are still not mainstreamed in disaster risk management (DRM) (Poljanšek et al., 2017; Zscheischler et al., 2018). Indeed, most research and policy still addresses risk from a single-hazard, single-sector per-

Table 1. Key definitions related to multi-(hazard-)risk.

Term	Definition	Source
Multi-hazard	"The selection of multiple major hazards that the country faces, and the specific contexts where hazardous events may occur simultaneously, cascadingly or cumulatively over time, and taking into account the potential interrelated effects"	UNDRR (2017)
Multi-hazard risk	Risk generated from multiple hazards and the interrelationships between these hazards (but not considering interrelationships on the vulnerability level)	Zschau (2017)
Multi-risk	Risk generated from multiple hazards and the interrelationships between these hazards (and considering interrelationships on the vulnerability level)	Zschau (2017)
Multi-(hazard-)risk	Used in this paper when collectively referring to all of the above	n/a

n/a stands for not applicable.

Table 2. Selected major European-funded multi-(hazard-)risk projects.

Project	Name	Period
TIGRA	The Integrated Geological Risk Assessment	1996–1997
TEMRAP	The European Multi-Hazard Risk Assessment Project	1998–2000
Na.R.AS.	Natural risks assessment harmonisation of procedures, quantification and information	2004–2006
ARMONIA	Applied Multi-Risk Mapping of Natural Hazards for Impact Assessment	2004–2007
MATRIX	New Multi-Hazard and Multi-Risk Assessment Methods for Europe	2010–2013
ENHANCE	Enhancing Risk Management Partnerships for Catastrophic Natural Disasters in Europe	2012–2016
STREST	Harmonized Approach to Stress Tests for Critical Infrastructures against Low-Probability High-Impact Natural Hazards	2013–2016
ASAMPSA_E	Advanced Safety Assessment Methodologies	2013–2016
FORTRESS	Foresight Tools for Responding to Cascading Effects in a Crisis	2014–2017
NARSIS	New Approach to Reactor Safety Improvements	2017–2022
ARISTOTLE-eENHSP	All Risk Integrated System TOwards Trans-boundary hoListic Early-warning – enhanced European Natural Hazards Scientific Partnership	2020–2023

spective. This presents challenges for addressing real-world challenges faced by risk managers and other decision makers. Firstly, multi-hazards can interrelate, and this can contribute to changes in risk. For example, an earthquake could trigger a landslide; dry conditions could amplify the likelihood of forest fires; a combination of rainfall and storm surge could cause compound flooding; or a region could face several consecutive hazards, with changes in exposure and/or vulnerability between these. How can risk be better managed by considering these interrelated effects? Secondly, DRM measures taken to reduce risk from one hazard may increase risk from another hazard. For example, wood-frame buildings may perform well in earthquakes but could sustain high damages during flooding (and fires). How can we better account for these dynamic feedbacks between hazard, exposure, and vulnerability? Thirdly, these interrelated effects have impacts across sectors and regions. For example, there are trade-offs and synergies between maintaining the sustainable use of our land and marine regions while meeting increasing demand for sustainable energy and food and reducing natural-hazard risks. How can we account for these trade-offs and synergies across sectors, regions, and hazards?

The aforementioned challenges exist within the context of an increasingly interconnected world, increased pressure for space, and climate change, in which the magnitude and frequency of single and multi-hazards are changing at an unprecedented rate (Vogel et al., 2019). Transboundary risk assessment and management for multi-(hazard-)risks across countries (e.g. the 2002 flood events in eastern Europe or the heatwave in 2003) is still lacking but very much needed in this increasingly interconnected world. As has been seen with the financial crisis in 2007/08, even in the case that individuals behave rationally in their own way (e.g. making profit) the systemic risk that they were creating together led to the near collapse of the system. The interconnectedness of hazards and risks need to be explicitly taken into account, both from the individual and system (e.g. country/-transboundary) perspective, whether in relation to the economic or social or ecological system at hand, so that individual DRM measures do not produce systemic risks on other spatial scales/sectors in the future.

A paradigm shift is needed in disaster risk management to successfully address these complex questions and challenges, in which science and practice move from a single-hazard, single-sector risk perspective towards a multi-(hazard-)risk, multi-sector, systemic approach. This approach should embrace risk-aware sustainable development, which acknowledges that sustainable development goals are endangered by multi-(hazard-)risk but at the same time can contribute strongly to systemic resilience (Reichstein et al., 2021). The COVID-19 situation lays bare the interconnections between sectors, regions, and hazards, as its impacts propagated geographically and across sectors (López Prol and O, 2020; OECD, 2020) which highlights the need for a more systemic approach to reducing risk. Several concrete challenges hindering the movement towards this approach relate to existing knowledge gaps in multi-(hazard-)risk assessment and management, such as those described in recent reviews by Ciurean et al. (2018) and Tilloy et al. (2019). Here, we give a brief overview of several of these key challenges.

Diverse language on multi-(hazard-)risk and a lack of overview of existing methods and tools. Existing reviews of multi-(hazard-)risk approaches have shown diverse and conflicting language used to characterize multi-(hazard-)risk (Kappes et al., 2012; Gallina et al., 2016; Ciurean et al., 2018; Tilloy et al., 2019). Table 1 shows several definitions used in this paper, but these (and others) are often used interchangeably in the literature. The inclusion of a definition of "multi-hazard" in the UNDRR terminology (UNDRR, 2017) may help bring clarity to this term, but there is still a lack of consensus within and between research, industry, and policy communities around the varied terminology. Moreover, whilst there are myriad qualitative and quantitative methods (i.e. ways, techniques, or processes of/for doing something) and tools (i.e. a resource to help you meet an objective or to generate new knowledge or information) to support multi-(hazard-)risk assessment (Sperotto et al., 2017; Ciurean et al., 2018; Terzi et al., 2019; Tilloy et al., 2019), they are highly dispersed through different scientific communities, often across multiple languages, disciplines, and publication types (Ciurean et al., 2018).

Lack of a clear framework and guidelines for multi-(hazard-)risk assessment and management. Conventional risk assessment and management usually consider different hazards and risks as independent from each other (Scolobig et al., 2017; De Ruiter et al., 2020). In this classic approach, individual hazards and sectors are the point of departure. In the case of multi-(hazard-)risk situations, various methodologies are now suggested that focus on specific aspects, including compound events, cascading effects, or systemic risks (Tilloy et al., 2019). These different aspects are usually treated separately within such assessments. The separation of the analysis of multi-(hazard-)risk into different compartments is not a coincidence; indeed multi-(hazard-)risk assessment and management is complex. Whilst a framework for multi-(hazard-)risk governance has been developed in the MATRIX project (Scolobig et al., 2017), an overall framework for multi-(hazard-)risk assessment and management is missing. Moreover, according to interviews conducted with risk managers within MATRIX, many of them miss criteria or guidelines that would help them to carry out a multi-(hazard-)risk assessment. Many of them mentioned that current multi-(hazard-)risk assessment methods required a large degree of expertise and that many of the available tools are not user-friendly (Poljanšek et al., 2017).

Poor understanding of dynamic feedbacks between hazard, exposure, and vulnerability (Gill and Malamud, 2014, 2016). Databases such as the GED4ALL Global Exposure Database for Multi-Hazard Risk Analysis (Silva et al., 2018) and the multiple-hazard data scheme as proposed by Murnane et al. (2019) allow for cross-hazard comparisons of risk but do not account for dynamics and feedback loops between the different components of risk. Risk models have been developed to assess changes in risk in the past and future due to changes in hazard, exposure, and (to a much lesser extent) vulnerability (Ward et al., 2020a). Also, studies have examined long-term trends in reported losses and damages (Bouwer, 2018; Paprotny et al., 2018). However, they examine long-term trends, assuming no interactions between hazard, exposure, and vulnerability. Changes in exposure and/or vulnerability can influence the occurrence of multi-(hazard-)risk events. For example, change in agricultural practice change, vegetation removal, surface and subsurface construction, quarrying, and so forth can trigger natural hazards or amplify multi-hazard interrelationships (Gill et al., 2021). Conversely, progression through a multi-hazard event can result in changes to exposure and/or vulnerability (De Ruiter et al., 2020), such as changes to exposure when community members are relocated after a volcanic eruption. New dynamic modelling approaches need to be developed that can tackle indirect and emergent risks which materialize through the interaction of physical and ecological systems and several societal actors (Reichstein et al., 2020, 2021)

Focus of many past multi-(hazard-)risk projects and accompanying software on multiple single hazards under current conditions without focusing on multi-(hazard-)risk interactions or future scenarios (Gallina et al., 2016). Large-scale multi-(hazard-)risk studies have primarily assessed the risk from each hazard individually (Koks et al., 2019), without considering interrelations. Only at local scales have complex impacts resulting from multi-hazard interactions been assessed. For example, a recent case study for the north of the Netherlands examined potential structural damage to masonry housing due to sequences of earthquakes and earthquake-triggered floods (Korswagen et al., 2019). However, such approaches are rare. In the context of future scenarios, different development trajectories may change multi-(hazard-)risk. For example, in the context of urbanization and urban expansion, future or "potential risk" depends on unbuilt infrastructure, unknown socio-economic characteristics, and unmade decisions (Galasso et al., 2021).

Assessment of only a few studies on the effectiveness of DRM measures across hazards, sectors, and time horizons. From an engineering perspective, some knowledge exists about the (a)synergies of different building practices (Zaghi et al., 2016). The Building Back Better (Hallegatte et al., 2018) research focuses mainly on critical infrastructure (e.g. bridges, schools, and hospitals) (Li et al., 2012). Nonetheless, trade-offs and synergies of DRM measures are not commonly quantified in risk assessments, which can lead to maladaptation (Liu et al., 2014; De Ruiter et al., 2021a). Moreover, these trade-offs and synergies exist over different time horizons. Long-term plans and strategic decisions need to be based on highly uncertain risk information (Peduzzi, 2019). Ignoring uncertainty could mean that we limit our ability to adapt and can result in missed chances and opportunities. Multi-(hazard-)risk and cross-sectoral trade-offs and synergies increase the complexity of these strategic planning challenges. The Dynamic Adaptation Policy Pathways (DAPP) approach has been developed to support decision-making under deep uncertainty (Haasnoot et al., 2019) and has been successfully applied in several single-hazard decision-making contexts related to climate change (e.g. Thames Estuary 2100 project, UK, Ranger et al., 2013; Delta Programme, Netherlands, Bloemen et al., 2018). However, the approach lacks guidance for use in a multi-(hazard-)risk setting. This deep understanding of multi-(hazard-)risk settings and their uncertainties is also key for shaping economic systems towards sustainability and climate change resilience. As multi-(hazard-)risk settings are systematically weakly internalized in long-term asset management and valuation, this can lead to insurance gaps and potentially misleading decisions in capital markets and government planning.

Distinct lack of in-depth case-studies on multi-(hazard-)risk assessment and management. Recent years have seen an increase in communities working on different aspects of multi-hazards (e.g. triggering relationships, Gill et al., 2020; compound events, Zscheischler et al., 2018; and consecutive events, De Ruiter et al., 2020). However, most past multi-(hazard-)risk case studies are still limited to one or two specific hazards at a given site (Ciurean et al., 2018), whilst real-life situations involve multiple hazard types and interrelated effects across various spatial and temporal scales (Tilloy et al., 2019; Ward et al., 2020b). Theoretical multi-(hazard-)risk approaches are often based on hypothetical data and focus on simulating hazard time series without addressing the impacts of spatiotemporal interactions between hazards (Mignan et al., 2014). When multi-hazard scenarios have been used to assess risk, this has focused on local-scale impacts and specific sectors (Tilloy et al., 2019).

4 A research agenda: sustainable DRM pathways through challenge-based research in real-world settings

The challenges outlined above demonstrate that there is a long way to go before the much lauded multi-(hazard-)risk setting approach is mainstreamed in decision-making. We argue for an approach that addresses multi-(hazard-)risk management through the lens of sustainability challenges that cut across sectors, regions, and hazards. In this approach, the starting point is a specific sustainability challenge, rather than an individual hazard or sector, and trade-offs and synergies are examined across sectors, regions, and hazards. Where typical risk assessments try to address questions such as "What is the risk to sector X of hazard Y in region Z, and what DRM measures can be taken to reduce that risk?", this approach requires questions such as "What DRM pathways are available to develop a sustainable future in region Z that account for trade-offs, synergies, and interactions across relevant hazards and sectors and consider inter-regional linkages?". This requires a much more explicit link between the goals of the Sendai Framework and those associated with other policy goals and frameworks such as the Sustainable Development Goals and the Paris Agreement on climate change.

We present a research agenda to help us move towards this approach in which multi-(hazard-)risk management is addressed through the lens of sustainability challenges that cut across sectors, regions, and hazards. This agenda will be implemented in the EU Horizon 2020 project MYRIAD-EU (Multi-hazard and sYstemic framework for enhancing Risk-Informed mAnagement and Decision-making in the EU). The overall aim of MYRIAD-EU is that by its completion, policymakers, decision makers, and practitioners will be able to develop forward-looking DRM pathways that assess trade-offs and synergies of various strategies across sectors, hazards, and spatial scales. The research agenda, which explicitly addresses the challenges mentioned in Sect. 3, is presented below.

Establishing a set of common multi-(hazard-)risk definitions and concepts and an overview of existing methods and tools. Improving consensus around definitions and providing a clear overview of existing concepts, methods, and tools would help to improve communication and ensure that multi-(hazard-)risk management approaches meet the expectations of the Sendai Framework. Indeed, recommendation 3 of the recent UNDRR Technical Working Group on the Hazard

Definition Classification Review is "Engaging with users and sectors for greater alignment and consistency of hazard definitions" (UNDRR, 2020). To address this part of our agenda, we will develop a handbook of multi-(hazard-)risk concepts, definitions, and indicators; a wiki-style online crowdsourcing platform of examples of qualitative and quantitative multi-(hazard-)risk methods and tools; and an overview of existing policies relating to multi-(hazard-)risk management at diverse spatial scales.

Co-developing a framework for multi-(hazard-)risk assessment and management. We propose a framework that addresses future sustainability challenges (e.g. spatial planning on land or in the sea), rather than the classic approach where individual hazards/sectors are the point of departure. The framework will be co-developed within the project between the consortium and our stakeholders in the pilot regions, which will involve an iterative process of framework development, testing, feedback, and updating. The framework is intended to provide a set of practical guidelines for carrying out a multi-(hazard-)risk assessment. We explicitly do not aim to develop a unified method or model for navigating the framework, as it is our conviction that there is no one-size-fits-all model for addressing multi-(hazard-)risk management and that continuous learning across projects and disciplines is needed to break the silos in which natural-hazard risk science operates. Instead, we see the need for a user-friendly web-based dashboard that provides access to a myriad of state-of-the-art multi-(hazard-)risk products and services from across the multi-(hazard-)risk community.

Increasing understanding of dynamic feedbacks between hazard, exposure, and vulnerability. We propose an online database of empirical evidence of multi-(hazard-)risk dynamics, which can be used to develop functions to represent these dynamics in multi-(hazard-)risk models. By modelling exposure and vulnerability profiles dynamically, DRM actions can be assessed that consider where development occurs and how this can be changed to reduce future losses. This can support demonstrating the effectiveness of land use planning and risk-sensitive developments as a DRM action. Moreover, serious games, such as *Breaking the Silos* (De Ruiter et al., 2021b), can help support stakeholders in understanding the complexities of feedbacks between different DRM measures in a multi-(hazard-)risk setting.

Developing future scenarios of plausible multi-(hazard-)risk. Datasets and time series of current and future scenarios of individual hazards have been developed in many past studies. We see the need for user-friendly software to allow users to generate realistic multi-hazard stochastic event sets at subnational to European scales that include different multi-hazard interrelationships (triggering, amplifying, compound, and consecutive). For example, this could be achieved by combining existing single-hazard data and scenarios with state-of-the-art statistical methods (e.g. multivariate methods like copulas, Markov chains, and Bayesian belief networks) (e.g. Schäfer and Wenzel, 2017; Ward et al., 2018; Tilloy et al., 2019). Such a software package should be open-source and open-access and allow for interoperability with other software packages, datasets, and models.

Assessing the effectiveness of DRM measures across hazards, sectors, and time horizons. The pathways approach to adaptation planning has been applied in many single-hazard contexts and proven its usefulness for planning under deep uncertainty. Extending the current DAPP approach to be fit for use in a multi-(hazard-)risk, multi-sector settings would ensure that the decision context and processes that govern multi-(hazard-)risk are considered throughout the whole process, from problem setting to risk assessment and decision-making. This will allow for the assessment of whether (and what) different decisions would be taken when adopting a multi-(hazard-)risk and multi-sector lens, regarding trade-offs and synergies between hazards, sectors, regions, time horizons, and decision and policy goals, compared to a single-hazard and single-sector lens.

Testing of approaches in in-depth case studies on multi-(hazard-)risk assessment and management. We see the need for in-depth case studies in which our framework and the various approaches for multi-(hazard-)risk assessment and management are tested in practice. The MYRIAD-EU approach aims to achieve this by co-developing the framework and products and services that can be used to operationalize the framework, with stakeholders in five multi-scale pilots: North Sea, Canary Islands, Scandinavia, Danube, and Veneto (Fig. 1). The pilots focus on forward-looking DRM solutions to real-world sustainability challenges, such as the following. How can spatial planning at the interface of the land and sea environments be optimized in the face of increasing and interrelated risk? How can we maintain healthy ecosystems while meeting increasing demand for energy, food, and ecosystem services? How can we increase resilience to multi-hazards that impact interconnected countries with strong macro-economic relations? They assess a spread of different hazards (meteorological, geological, biological, and hydrological) as well as multi-hazard interrelationships (triggering, amplifying, consecutive, and compound). Each pilot focuses on (interlinkages between) several key economic sectors: infrastructure and transport, food and agriculture, ecosystems and forestry, energy, finance, and tourism. For each pilot, we examine multi-(hazard-)risk within the pilot region, as well as indirect, cross-sectoral, and interregional risks throughout the rest of Europe.

Through the MYRIAD-EU project, we intend to contribute to the proposed research agenda. From our perspective, an indicator of success will be if the policymakers, decision makers, and practitioners with whom we collaborate in the five pilots have been able to develop forward-looking DRM pathways for their region that assess trade-offs and synergies of various strategies across sectors, hazards, and spatial scales. The multi-(hazard-)risk framework, methods developed, and knowledge generated should also be suitable for use in case studies throughout Europe and elsewhere. An-

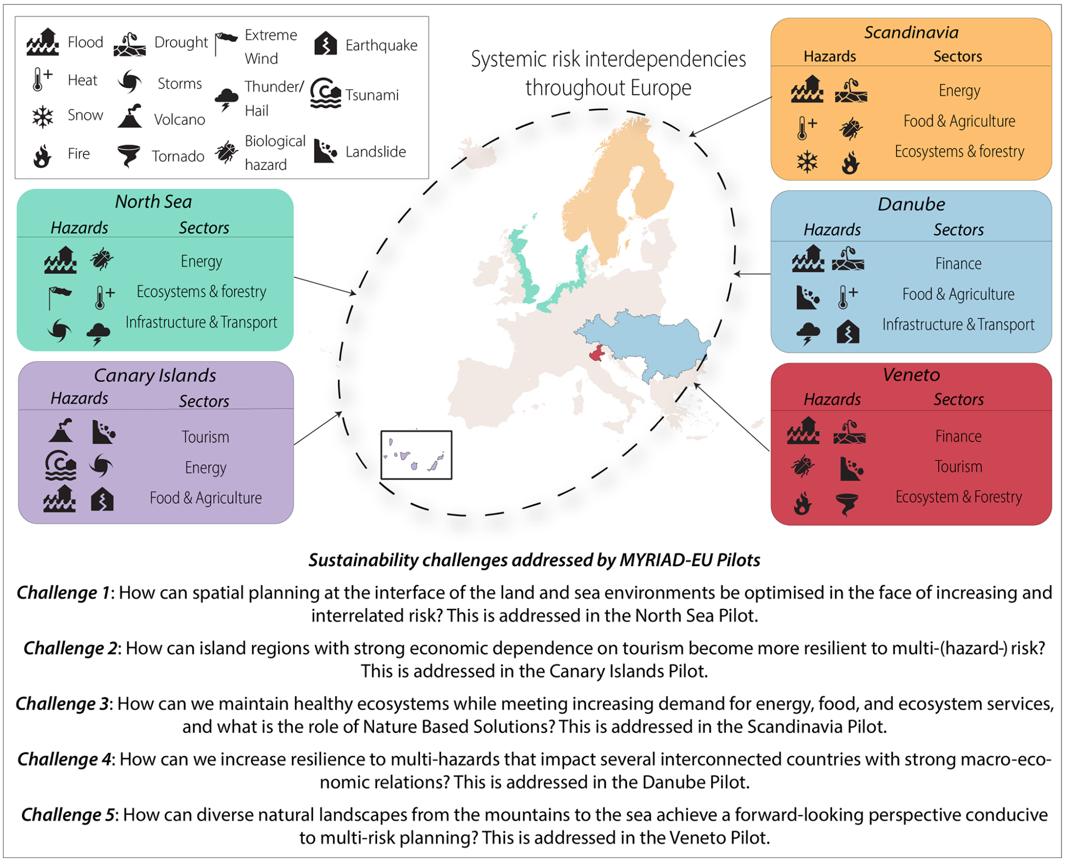

Figure 1. Overview of sustainability challenges to be addressed in the MYRIAD-EU project.

other indicator of success is therefore their uptake within wider DRM projects, networks, and dialogues. Of course, this research agenda is no panacea. Just as our contextualization of disasters, hazards, and risks has evolved throughout history, DRM practice must continue to evolve as society's understanding of risk improves and the nature of the risks it faces changes.

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