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Perspective

Understanding Compound, Interconnected, Interacting, and Cascading Risks: A Holistic Framework

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In recent years, there has been a gradual increase in research literature on the challenges of interconnected, compound, interacting, and cascading risks. These concepts are becoming ever more central to the resilience debate. They aggregate elements of climate change adaptation, critical infrastructure protection, and societal resilience in the face of complex, high-impact events. However, despite the potential of these concepts to link together diverse disciplines, scholars and practitioners need to avoid treating them in a superficial or ambiguous manner. Overlapping uses and definitions could generate confusion and lead to the duplication of research effort. This article gives an overview of the state of the art regarding compound, interconnected, interacting, and cascading risks. It is intended to help build a coherent basis for the implementation of the Sendai Framework for Disaster Risk Reduction (SFDRR). The main objective is to propose a holistic framework that highlights the complementarities of the four kinds of complex risk in a manner that is designed to support the work of researchers and policymakers. This article suggests how compound, interconnected, interacting, and cascading risks could be used, with little or no redundancy, as inputs to new analyses and decisional tools designed to support the implementation of the SFDRR. The findings can be used to improve policy recommendations and support tools for emergency and crisis management, such as scenario building and impact trees, thus contributing to the achievement of a system-wide approach to resilience.

KEY WORDS: Cascading risk; compounding risk; critical infrastructure; interacting risk; interconnected risk; Sendai Framework for Disaster Risk Reduction; societal resilience

1. INTRODUCTION

The development of concepts that describe compound, interconnected, interacting, and cascading risks is part of the process of creating new knowledge in order to increase societal resilience. Since the 1990s and the International Decade for Natural Disaster Reduction, our understanding of risk in the community has been influenced by the evolving role of science and technology (Aitsi-Selmi et al., 2016). Different perspectives from disciplines such as engineering and social sciences were merged together to provide a coherent approach to risk analysis, using a basis of knowledge about system performance and uncertainty assessments (Aven & Kristensen, 2005). Events such as the 2004 Indian Ocean Tsunami led to the development of the Hyogo Framework for Action, which provided an international plan endorsed by the United Nations to reduce disaster losses and build resilience between 2005 and 2015. According to the U.N. Office for Disaster Risk Reduction (UNISDR), disaster risk can be defined as: "The potential loss of life, injury, or destroyed or damaged assets which could occur to a system, society or a community in a specific period of time, determined probabilistically as a function of hazard, exposure, vulnerability

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and capacity" (www.preventionweb.net, updated February 2, 2017). Here, vulnerability is defined as those "conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards" (www.preventionweb.net, updated February 2, 2017).

The main consequence of this is a degree of circularity, in which the vulnerability of a system makes it more sensitive to risk, reflecting the complexity of socioeconomic factors that interact with the physical aspects of hazard (Alexander, 1993; Intergovernmental Panel on Climate Change, 2012; UNISDR, 2015). The work of the Society for Risk Analysis has highlighted the existence of other multidisciplinary aspects that have been used for models and theoretical frameworks, recommending a broad qualitative definition of risk and considering different types of ways of describing risk (Aven, 2010, 2016). At the same time, it has been suggested that there is a tendency in the engineering community to associate the definition of risk with the quantification of probabilities, but in order to be effective, the analysis of systemic accidents and unexpected events must address also uncertainties and their root causes (Aven, 2010). However, the literature suggests that further development is needed, "especially in relation to situations of large or deep uncertainty and emerging risk" (Aven, 2016).The complexity of networked society and the uncertainties inherent in threats, such as geomagnetic storms, challenge our approach to crisis management. After a long debate on unknown, low-probability, and high-impact events, it has been suggested that extreme scenarios could be more common than was previously supposed, and that this requires us to develop a new understanding of their drivers (Sornette, 2009).

The problem involves the whole anthropogenic domain. It cannot be limited to the analysis of hazards and must combine different human and natural factors that affect the magnitude of risks. It has also been shown that crises challenge the process of governance. They cross borders and involve many different aspects of society and the environment (Ansell, Boin, & Keller, 2010; Boin, Rhinard, & Ekengren, 2014; Galaz, Moberg, Olsson, Paglia, & Parker, 2011). On the other hand, global networks are becoming more interdependent and it is becoming harder to understand their vulnerabilities. In approaching safety issues and risk analysis strategies, a paradigm shift is required (Helbing, 2013). There is a need for a system-wide approach to resilience that is capable of employing penetrating analyses, innovative methods, and new tools in order to improve the operational management of complexity (Linkov et al., 2014).

In this context, in 2015, the U.N. member states adopted the Sendai Framework for Disaster Risk Reduction (SFDRR), which was designed to improve upon the Hyogo Framework for Action. This document identifies seven targets and four priorities areas to "prevent new and reduce existing disaster risk," including better action to reduce exposure and vulnerabilities. The SFDRR defines "the need for improved understanding of disaster risk in all its dimensions of exposure, vulnerability and hazard characteristics." The strategy for implementing the SFDRR requires innovation in this field and highlights the need to create policies on key topics such as the security of critical infrastructure and the mitigation of contextual factors in crisis situations (UNISDR, 2015).

Notwithstanding the rise of three- factor multihazard approaches, multidisciplinary integrations, and holistic knowledge sharing (Aitsi-Selmi et al., 2016), there are persistent gaps in the research and they need to be addressed. Our limited background knowledge of emerging risks suggests the need to improve assessment tools, and to achieve an adaptive balance between different strategies and mitigation measures (Aven, 2016). The fragmentation of the literature on compound, interconnected, interacting, and cascading risks can be seen as a part of this challenge, and obstacles must be overcome as the field develops (Kappes, Keiler, von Elverfeldt, & Glade, 2012; Leonard et al., 2014; Pescaroli & Alexander, 2015). Although concepts are very different in their possible applications, there is a tendency to use them as synonyms, which tends to cause redundancy and confusion.

This article aims to highlight the complementarities and differences inherent in compound, interconnected, interacting, and cascading risks. It aims to be compatible with the implementation of the SFDRR by supporting a better understanding of disaster risk and clarifying the underlying risk drivers. New forms of risk are still addressed generically in the framework and more clarity and precision are needed. Indeed, as noted in the literature, "the way we understand and describe risk strongly influences the way risk is analyzed and hence it may have serious implications for risk management and decision making" (Aven, 2016). Our aim is to produce a holistic framework that can support focused actions and research that will help reduce exposure and vulnerability and increase possible complementarities instead of duplicating efforts in research and practice. This is essential in order to maximize the impact and effectiveness of new political and practical recommendations that are steps in the implementation of SFDRR as shown in the recently published Words into Action Guidelines on National Disaster Risk Assessment where all the relevant elements are included (UNISDR, 2017). In other words, the scope of this article is to help scholars and practitioners to distinguish the different components of complex events that tend to overlap, supporting more focused actions in terms of measures for operational resilience and risk modeling.

To begin with, this article focuses on compound events, which have been associated mostly with natural hazards and climate change. Second, it approaches the fundamentals of interconnected and interacting risks, in which the environmental and human drivers overlap. Third, cascading risk is explained, distinguishing the complementarities of the social domain from the failure of critical infrastructure. The concluding section of this article presents a holistic framework that can be used to maximize the impact of future research and policies.

2. COMPOUND RISK

Compound risk is a well-known topic of discussion by scholars and practitioners who are interested in climate change. It involves both physical components, such as the understanding of environmental trends, and statistical ones, such as the implications of concurrence in forecasting and modeling. In contrast to interconnected and cascading risks, compound risks and disasters have been defined in official documentation as a clear area of competence. For example, the 2012 Special Report of the Intergovernmental Panel on Climate Change (Intergovernmental Panel on Climate Change, 2012) reported compounding drivers to be the possible sources of extreme impacts and associated them very clearly with the hazard component of crisis management. In other words, compound risk has been referred to as "a special category of climate extremes, which result from the combination of two or more events, and which are again 'extreme' either from a statistical perspective or associated with a specific threshold" (Intergovernmental Panel on Climate Change, 2012). The concept is fully explained in a section of the work in which its correspondence with the idea of "multiple" events is pointed out. Compound events could be: (1) extremes that occur simultaneously or successively; (2) extremes combined with background conditions that amplify their overall impact; or (3) extremes that result from combinations of "average" events. The examples reported include high sea-level rise coincident with tropical cyclones, or the impact of heat waves on wildfires. First, compounding events such as flooding that occurs in saturated soils may impact the physical environment. Second, health issues due to particular environmental conditions such as humidity can affect human systems.

Although compound risk can involve events that are not causally correlated, some exceptions have to be made for common driving forces, such as different phenomena that interact during El Niño, or when system-wide feedbacks between different components strengthen each other, as when drought and heat waves occur in regions that oscillate between dry and wet conditions. Understanding and assessing this level of interaction presents different challenges in relation to the forecasting and modeling of such phenomena. It has been suggested that, because of its implications in terms of discrete classes and artificial boundaries, the IPCC definition may be problematic for the quantification of risk. It could be better to promote a more general approach in which compound events are intended as extremes derived statistically from drivers with multiple dependencies (Leonard et al., 2014). Indeed, climate change could increase the complexity of the system and the possible sources of nonstationarity in the distribution of extremes, such as variable and dynamic combinations. With regard to impacts and dependencies between systems, these may need to be considered in a multidisciplinary way (Leonard et al., 2014).

A slightly different point of view is reported in the SFDRR (UNISDR, 2015), in which compounding drivers are associated with both the creation of new disaster risk and the need to reduce both exposure and vulnerability. This seems to contextualize cascading risk more than separate it completely from what was explained earlier. The Words into Action Guidelines on National Disaster Risk Assessment (UNISDR, 2017) refer to compounding factors as part of "underlying risk drivers," such as climate change or urbanization, but the use of the term "compound effects" in two different chapters intends that it mostly be employed in line with the IPCC definition of concurrence and combined extreme events (e.g., riverine floods and coastal storms surges).

The next section will explain better the areas of convergence and complementarities with interacting and interconnecting risk. It will also discuss the causal background of cascades.

3. INTERACTING AND INTERCONNECTED RISK

The literature on interacting and interconnected risk focuses on how physical dynamics develop through the existence of a widespread network of causes and effects. Although the two concepts are intuitively very similar, interacting risks have been studied more in the context of earth sciences, while interconnected risks have generally been tackled under the headings of globalization and systems theory. The literature associated with this field has two main foci. It tends to overlap with compound risk in the hazard domain, and with cascading risk in the social and technological domains. A similar terminology is used in research on risk factors in health (Price & Macnicoll, 2015). Overall, the topic has particular implications for disaster risk reduction, complexity science, and emergency management. Common ground for improving the understanding of the composite nature of disasters has been a relevant part of disaster management and hazard assessment processes since the 1980s, for example, with respect to earthquake-induced landsliding (Alexander, 1993). However, events such as the 2011 tsunami, and the storm surge triggered by Hurricane Sandy, have increased the need to improve forecasting strategies and early warning methods by those public and private stakeholders who are in charge of critical infrastructure protection. Although the SF-DRR (UNISDR, 2015) does not refer directly to interacting or interconnected risk, it refers to the need to strengthen capacity to assess "sequential effects" on ecosystems.

In the case of interacting risks, the mechanisms and combinations of hazards have been analyzed in their temporal and spatial domains, including reciprocal influences between different factors and coincidences among environmental drivers (Tarvainen, Jarva, & Greiving, 2006). Empirical studies have elucidated the relationships between primary hazardous events and secondary natural hazards of the same category or different categories (Marzocchi et al., 2009). Progress in this sector requires both risk assessment strategies and understanding of the components of earth systems and their multiple-hazard perspectives to be improved (Kappes et al., 2012). For example, Gill and Malamud (2014) studied systematically interactions between 21 natural hazards. They found that geophysical and hydrological hazards are receptors that can be triggered by most of the other types of hazard, while geophysical and atmospheric causes are the most common triggers. The results of such studies support a wider understanding of complex interactions that could be integrated into early warning systems and rapid response tools. Other studies have created new models based on the analysis of trigger factors, which enables them to understand relationships among hazards that are interdependent, mutually reinforcing, acting in parallel, or acting in series (Liu, Siu, & Mitchell, 2016).

However, for multiple-risk assessment to be effective, the complex nature of interacting and interconnected relationships between different triggers needs to be integrated into a holistic framework. Some allowance must be made for the social construction of disasters in a global systems perspective, including reciprocal influences among the social sphere and the built and natural environments (Hewitt, 1995; Mileti & Noji, 1999). In other words, risk can be understood as the result of interaction between changing physical systems and society, which also evolves over time (Weichselgartner, 2001). In various studies, Helbing (Helbing, 2013; Helbing, Ammoser, & Kühnert, 2006) analyzed the "interconnected causality chains" that generate and amplify disasters, framing the impacts of triggering events on both ecosystems and anthropogenic systems. In this sense, the paths of complex risks that generate secondary events are determined by physical elements (e.g., a landslide triggered by an earthquake), the built environment (for instance, critical infrastructure), and people (hence, behavior). The level of interconnection and interdependency may be determined by interactive causality chains, which can spread out in space and time. However, improved understanding of physical interactions has tended to shift national risk assessment toward multiple-hazard approaches; further attention should be given to contemporary society and the built environment. The global interdependency of human, natural, and technological systems can produce hazards and disasters, but it is increasingly hard to comprehend and control (Perry & Quarantelli, 2005). Networks have different levels of interaction and interconnection, perhaps with multiple sources of disruption and systemic failure (World Economic Forum, 2016). When events are triggered, the pathways that determine the scale of the impacts are influenced by the interlinkages between different domains, for example, the interactions by which an earthquake leads to a tsunami, along with the climate change drivers, and the components of infrastructure such as lifelines (OECD, 2011).

As the next step toward the derivation of a holistic framework, the following section will clarify the specific features of cascading risk.

4. CASCADING RISK

Among the phenomena analyzed in this article, cascading risk is the broadest. For many years, it was referred to vaguely as "uncontrolled chain losses." Its early diffusion occurred in the 1980s, when it was used to refer to measurable links and nodes that could compromise information flows in networked systems (Millen & Schwartz, 1988). In the same period, in order to define the consequences of organizational failures that happen in tightly coupled and complex technological systems, cascades were included in the theory of "normal accidents," or "systemic accidents" (Perrow, 1999). The literature has associated cascades with the metaphor of "toppling dominoes," which since the late 1940s has been used in the chemical processing industry to refer to sequential accidents (Abdolhamidzadeh, Abbasi, Rashtchian, & Abbasi, 2011; Khan & Abbasi, 1998). This idea has been integrated into the early literature on NaTech disasters, interacting risk, and cascading events (Cruz, Steinberg, Vetere Arellano, Nordvik, & Pisano, 2004), but recently it has been pointed out that it could be an oversimplification and it could also decontextualize the problem (Pescaroli & Alexander, 2015; Van Eeten, Nieuwenhuijs, Luiijf, Klaver, & Cruz, 2011).

In the early 2000s, events such as Hurricane Katrina and the terrorist attacks on the World Trade Center shifted the focus of research on cascading risk to the protection of critical infrastructure, which is understood to be those systems or assets that are vital to the functioning of society. Millennial literature has approached cascading risk from the point of view of how one can model causal interdependencies and mitigate breakdowns (Millen & Schwartz, 1988), how one can study the processes that could cause blackouts and trigger cross-scale failures in power grids (Newman et al., 2005). Networked infrastructure was portrayed in both its functional and social domains, including hardware, services, and the secondary and tertiary effects of disruption (Little, 2002). However, cascading risk remained a fragmented subject that lacked both official definition and an intergovernmental dimension. It usually referred to a branching structure that originated with a primary trigger (May, 2007).

Although new models were used to defined thresholds and mitigation strategies, their applicability was limited by the absence of testing in real scenarios and networks (Peters, Buzna, & Helbing, 2008). In political analyses, although the presence of cascading effects was seen as a driver that could explain the scale of crises, it remained marginal to any broader considerations of resilience to extreme events with cross-border dimensions (Ansell et al., 2010; Boin & McConnell, 2007). The ecological debate focused on the implications of cascading risk for climate by associating it with complex causal chains, nonlinear changes, and recombination potential. The question of how to manage such crises was not solved (Galaz et al., 2011).

Only in the late 2000s were empirical data used to demonstrate that cascading failures are not as rare as was believed. When they were driven by disruptions to the energy, telecommunications, and Internet sectors, they were generally stopped quickly (Luiijf, Nieuwenhuijs, Klaver, Van Eeten, & Cruz, 2009; Van Eeten et al., 2011). After high-impact events such as the eruption of Eyjafjallajökull volcano (2010), the triple disaster in Japan (2011), and Hurricane Sandy (2012), the field evolved toward a greater understanding of the wider implication of cascades. A wider range of case studies provided new evidence of the disruption of social, cultural, and economic life, including cross-scale implications for global supply chains and humanitarian relief (Alexander, 2013; Berariu, Fikar, Gronalt, & Hirsch, 2015; Sharma, 2013). Improved technology stimulated a new phase in modeling the complexity of interactions and interdependencies among networked systems. It promoted a more coherent approach to climate, society, economics, the built environment, and cross-sector decision support systems (Greenberg, Lowrie, Mayer, & Altiok, 2011; Havlin et al., 2012). In order to understand both random failures and terrorist attacks on lifelines, critical factors began to be ranked (Buldyrev, Parshani, Paul, Stanley, & Havlin, 2010; Zio & Sansavini, 2011). Attempts were made to assess cascading disruptions on a cross-national basis (Galbusera, Azzini, Jonkeren, & Giannopoulos, 2016; Jonkeren, Azzini, Galbusera, Ntalampiras, & Giannopoulos, 2015). In order to assess the possible impact of cascading risk on emergency management and to translate it into generic tools that could raise awareness and information sharing in particular on electricity disruptions, the risk managers looked for practical and replicable approaches (Hogan, 2013). A few of the official scenarios tackled the loss of power supply caused by nonconventional triggers such as solar storms, but, in everyday reality, practice was still distinguished by a lack of buffering strategies and well-codified contingency plans (Pescaroli & Alexander, 2016).

The promotion of strategies designed to increase the autonomy and adaptive capacity of systems could be seen as a partial answer to these problems. In decision making and planning, decentralization and greater empowerment were sought (Helbing, 2015). However, guidelines for the adoption of coherent mitigation actions are still limited in their availability. In this sense, the SFDRR can be regarded as a first step (UNISDR, 2015). This document reflects the perception that, in order to reduce damage to critical infrastructure and loss of vital services, hardware and software are the joint adjuncts of policies and mitigation actions.

In the projects supported by the European Commission, in particular by the Seventh Framework Programmes such as FP7 FORTRESS, FP7 CASCEFF, FP7 SNOWBALL, FP7CIPRNet, or FP7 STREST, other drivers of research have emerged. Lack of awareness of critical infrastructure dependencies among planners and responders could be associated with extended impact of emergencies, requiring different levels of actions for mitigating worst-case scenarios and operational challenges (Luiijf & Klaver, 2013). Assessment and modeling of cascading failures in networks can be complemented by greater attention to the strategies that are required when disruption happens, as we suggested in some of our previous works (Nones & Pescaroli, 2016; Pescaroli & Alexander, 2015, 2016; Pescaroli et al., 2018; Pescaroli & Kelman, 2017).

In particular, our approach proposed that "cascading risk" should distinguish between "cascading effects" and "cascading disasters," considering that, as time progresses, nonlinear escalation of a secondary emergency could become the main center of crisis (Pescaroli & Alexander, 2015). This shifts significantly from the "toppling dominos metaphor," which, as suggested earlier (Boin & McConnell, 2007; Little, 2002; Newman et al., 2005; Peters et al., 2008; Van Eeten et al., 2011), has mostly been employed in the context of the process industry shifting attention to critical infrastructure, complex theory, and to the understanding of societal and organizational resilience in policy making and emergency management. Fig. 1, taken from a previous work of ours (Pescaroli & Alexander, 2016), shows that cascading events can be viewed as the manifestation of vulnerabilities accumulated at different scales, including socio-technological drivers. The possible environmental triggers, shown at the top of the figures, can be associated with compounding and interconnected risk, while critical infrastructure and complex adaptive systems may be the drivers that amplify the impacts of the cascade.

First, together with the literature on the loss of services, scholars suggested other possible drivers of escalation such as NaTech events, which considers that up to 5% of industrial accidents are caused by natural triggers that involve hazardous facilities (Krausmann, Cozzani, Salzano, & Renni, 2011). In both cases, gaps have been found in the existing legislative frameworks, where it is necessary to integrate different levels of risk and critical infrastructure mapping to increase the effectiveness of mitigation strategies for multiple-scale events (Nones & Pescaroli, 2016). Second, in order to increase the effectiveness of deployment and the organization of procurement in disaster relief, new data sets are needed. The analysis of different case studies suggests that the disruption of critical infrastructure can impact the logistics of emergency relief (Berariu et al., 2015). It also has the potential to orient international aid in order to rectify a shortfall of emergency goods and expertise caused by the disruption (Pescaroli & Kelman, 2017). Finally, it has been pointed out that cascading risk may require a change in methods of scenario building and contingency planning. Our previous work suggested that flexibility of response can be increased by considering possible escalation paths that are common to different categories of triggering event (Pescaroli & Alexander, 2016; Pescaroli et al., 2018). This approach is complementary to the perspective of broad impact-tree analysis (Macfarlane, 2015). Shifting from a focus on hazards to one on vulnerability assessment enables one to recognize the sensitive nodes that may cause secondary events to escalate. On the one hand, tipping points, or thresholds, can be associated with an increased demand for products and services during events such as blackouts. This drives the prioritization of recovery actions and introduces new questions and issues regarding coordination between public and private stakeholders (Münzberg, Wiens, & Schultmann, 2017). On the other hand, in order to consider the different components of risk in relation to one another, it is essential to introduce good practices into emergency planning

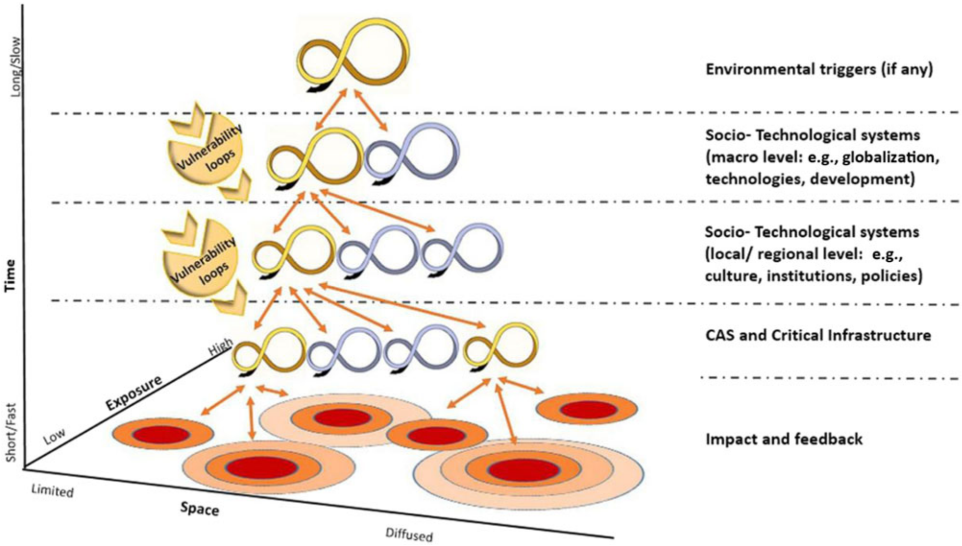

Fig. 1. Vulnerability path of cascading disasters, scale interactions, and escalations in time and space (source: Pescaroli & Alexander, 2016).

and scenario building (Alexander, 2016; Pescaroli et al., 2018). The next section will propose a holistic framework that may be used by scholars and practitioners as the basis for improved work in this field.

5. A HOLISTIC FRAMEWORK FOR COMPOUND, INTERCONNECTED, INTERACTING, AND CASCADING RISK

In order to identify complementarities and minimize the duplication of efforts in research, policies, and practices, this article has given a brief overview of compound, interacting, interconnected, and cascading risks. However, more discussion is needed to increase our understanding of areas in which the concepts overlap.

Despite the presence of a very clear definition released by the IPCC, some literature on compound risk associates or uses it interchangeably with the concepts of "interconnected" and "cascading" risks. Prior to the work of IPCC, Perry and Quarantelli (2005) referred to compound dynamics as the combination of different losses or vulnerabilities, for which the background conditions are coupled with changes in society and the built environment. In the work of Kawata (2011), compound disasters were reported as a form of amplification of sequential events, such as the 1923 great Kanto earthquake and fire, and the collapse one year later during a typhoon of some levees damaged by the earthquake. This approach was integrated by other authors to describe possible compounding features, including multiple, coincidental, and simultaneous or near simultaneous events, sequential and progressive events, random and related hazards, and infrastructure failures (Eisner, 2014). Although some parts of this description are in line with the IPCC approach on compounding risk, other elements tend to overlap with cascading and interacting risk, including their operational tools in terms of multihazard assessment, safety standards, and the redundancy of lifelines. Other literature (Liu & Huang, 2014) has used both approaches (Eisner, 2014; Kawata, 2011) in order to show that compound disasters could be a "subset of cases" in which extensive losses are associated with a compounding process that includes both physical and human factors. According to this perspective, the critical challenge for emergency management and strategic preparedness policies lies in defining the interaction between the components (Liu & Huang, 2014). However, in this case, compound risk has been associated with the linkages between natural hazards and technology without taking into account other studies, such as those that refer to technological disasters triggered by natural hazards (NATECH) (Santella, Steinberg, & Aguirra, 2011).

Interacting and interconnected risks tend to overlap with cascading risk. First, interactions among hazards have been associated with the physical and environmental domains, by which we mean a chain of hazardous events in which one manifestation triggers another, as when a storm causes a flood (Gill &

Malamud, 2014; Liu et al., 2016). This is clearly different from the use of the "toppling dominos metaphor" in the chemical industry process explained earlier (Abdolhamidzadeh et al., 2011; Cruz et al., 2004; Khan & Abbasi, 1998; May, 2007), increasing the confusion. Second, interconnected and interacting risks can be seen as precursors of the appearance of cascading effects and disasters (Helbing, 2013; Helbing et al., 2006; World Economic Forum, 2016). In interactive complex systems, the speed of cascading events (meaning their capacity to influence other components) can be the measure or manifestation of "tight coupling" (Perrow, 1999). In studies of the interdependency between critical infrastructure and the built environment, cascading risks can be seen as one of the possible categories of failure that are part of the infrastructure interdependency dimension (Rinaldi, Peerenboom, & Kelly, 2001). In other words, cascading effects can be seen as caused by dependencies and interdependencies associated with infrastructure domain (Luiijf et al., 2009; Luiijf & Klaver, 2013). In the literature on risk and resilience, this aspect has been developed for infrastructure systems and disruptions that spread out from one network to others through the many components of systems (Buldyrev et al., 2010; Galbusera et al., 2016; Guikema, Mclay, & Lambert, 2015).

The overlapping areas in the center of Fig. 2 reflect the descriptions reported in this article and have the following attributes:

- *They include a reference to the built environment*. The vagueness in the early use of concepts could be associated with duplication of efforts, for example, extending the area of interest of a certain risk (Intergovernmental Panel on Climate Change, 2012) and a common lack of interagency agreements (May, 2007). It is clear that standard definitions should be more widely adopted in order to help increase the effectiveness of research and practice, and to avoid confusion and duplication of effort in the analysis of the built environment.
- *They include elements of interdependencies*. On the one hand, this leads to problems such as the oversimplifying of ideas such as the "toppling dominoes" metaphor (Pescaroli & Alexander, 2015). On the other hand, it makes some progress toward integrating multidisciplinary research on the anthropogenic dimension of disasters (Alexander, 1993; Helbing et al., 2006; Perry & Quarantelli, 2005; Weichselgartner, 2001).
- *They point to the existence of an amplification process* that that could be associated with the higher complexity of the system and the wider impacts of possible disasters (Helbing, 2013; Pescaroli & Alexander, 2016; Sornette, 2009). The identification of amplification dynamics may reflect the cross-disciplinary manifestation of increased complexity at the system level.

They are complex risks that maintain high potential for surprise and nonlinear evolution, and this has to be considered in the assessment process. They include different levels of consequence and uncertainty (Aven & Kristensen, 2005). Due to their level of complexity, the quantification of risk and probabilistic assessment have a large degree of arbitrariness, where important drivers could have been ignored, underestimated, or are not available in the form of data sets, which would require the integration of qualitative data (Aven, 2010).These relationships are shown in Fig. 2, which is intended to be a synthetic framework for use in future studies.

Fig. 2 derives the following characteristics for each risk:

- *Compound risk* can refer to the environmental domain, or to the concurrence of natural events. Eventually, it can be correlated with different patterns of extreme impacts caused by climate change. Institutional definitions tend to focus more narrowly on the hazard component of disaster risk.
- *Interacting risk* refers to the domain of physical relations developed in the natural environment and to its casual chains. They focus on the area in which hazard interacts with vulnerability to create disaster risk. The study of interacting risk be the focus of disciplines such as geophysics and physical geography, while giving space to multiple risk assessment tools and strategies. For example, the study of the dynamics of interacting risk can be translated into simulations and models for the energy industry, thus defining better hazard maps.
- *Interconnected risk* tends to be used more often in network science and in studies of global interlinkages. It can include the complex interactions between human, environment, and technological systems, which can be translated, for

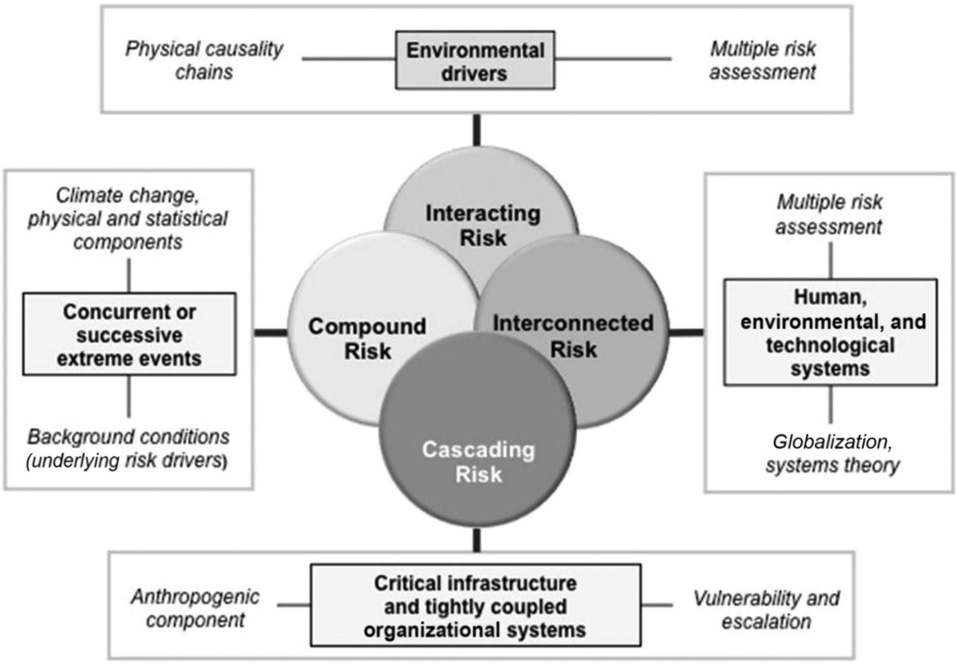

Fig. 2. A framework for compound, interacting, interconnected, and cascading risks.

example, into coherent multiple risk assessments or network analysis. Interconnected risk may be referred to as the physical interdependencies that allows societal interactions, and thus a precondition for cascading risk.

- *Cascading risk* is associated mostly with the anthropogenic domain and the vulnerability component of risk. This results in a disaster escalation process. In other words, it focuses mainly on the management of social and infrastructure nodes. With respect to triggering events, while interconnected risk can be seen as one of the preconditions for the manifestation of cascades, compound and interacting dynamics can influence its magnitude.

In the analysis of case studies, some examples will help to clarify the approach to cross-risk interaction and how to apply the framework shown in Fig. 1. This has been developed bearing in mind the needs of the SFDRR (UNISDR, 2015) and the methodologies of decision support for emergency and crisis management, such as scenario building (Macfarlane, 2015). The first event to consider is the eruption of the Icelandic volcano Eyjafjallajökull in April 2010. It demonstrates how recurrent compounding processes can have extensive impacts on the interconnected system, spreading its cascading effects to the wider cross-border scale (Alexander, 2013; Pescaroli & Alexander, 2016). The volcanic hazard itself became a problem because it was "coincident with north to north-westerly air flow between Iceland and North West Europe, which prevails for only 6 per cent of the time" (Sammonds, McGuire, & Edwards, 2011). In other words, together with the eruption, the other determining factor was weather conditions, thus creating compound risk (which was atypical but not entirely unusual). In contrast to other cases in which the impact was limited, in 2010, the ash spread out over an area with a high concentration of essential transportation system nodes. It affected global networks that are highly dependent on aviation, thus creating interconnected risk. Although the direct physical damage was limited, disruption of the infrastructure and its cascading effects on society were subject to nonlinear escalation and became the primary source of crisis that needed to be managed (i.e., cascading risk).

The second example is the triple disaster that struck Japan on March 11, 2011. In two different ways, it explains how interacting and interconnected features can overlap with social vulnerabilities and thus contribute to the cascading escalation of the event (National Diet of Japan, 2012; Pescaroli & Alexander, 2015). First, an earthquake that triggered a tsunami represented an interacting hazard, which affected highly coupled infrastructure (interconnected risk), and provoked a wide range of nonlinear secondary emergencies, such as the extensive loss of vital services and the creation of Na-Tech events (cascading risk). Second, the earthquake triggered a small and localized landslide (interacting risk) that cut off the Fukushima power plant from the main electric grid (interconnected risk), exacerbated existing vulnerabilities at the site, and leading to a full-blown nuclear meltdown (cascading risk). In both cases, the disruption of critical infrastructure orientated the progress of emergency relief toward mitigating the escalation of secondary emergencies (Pescaroli & Kelman, 2017), while the meltdown of the Fukushima Dai'ichi plant was regarded as a man-made disaster that could have been predicted and avoided were it not for the prevalence of negligence (National Diet of Japan, 2012).

Hurricane Sandy, also known as Super-Storm Sandy, is our last case. It encompasses all the possible joint effects of compounding, interacting, interconnected, and cascading risks (Kunz et al., 2013; Pescaroli & Alexander, 2016). Its relevance mainly lies in climate change scenarios, in which the primary nature of the event triggers may be subject to intensification. Hurricane Sandy made landfall in the United States on October 29, 2012. The storm winds not only wreaked direct damage, but also contributed to the generation of a storm surge that caused flood damages (interacting risk), while concurrent cold air flowing from the Arctic intensified cold weather and caused snow storms inland (compounding risk). Sandy impacted a geographical area of strategic importance to the U.S. economy. It has a dense population and a high concentration of industrial plants and financial networks, such as the New York Stock Exchange (interconnected risk).

The composite nature of the hazard and the loss of highly ranked critical infrastructure triggered a wide range of secondary crises that escalated in a nonlinear manner. While the emergency responders had to tackle leaks from refineries and chemical plants, or fires in houses, the President of the United States made a new declaration of emergency regarding the prolonged power outages and the damage to the production and distribution chain of gasoline and distillates (cascading risk). An official report (Blake, Kimberlain, & Berg, 2013) attributed around 50 deaths to the joint effect of extended power outages and cold weather (interaction of compounding and cascading risk).

However, this clarification is simply not enough to translate the conceptual framework into a tool that can be used to understand, manage, and predict events. Taking back the conceptual equation used for the definition of risk, and the complementary works cited in the introduction, it may be useful to subject Fig. 3 to further discussion.

Our review shows that the compound, interacting, interconnected, and cascading risks tend to be different components of hazards and vulnerabilities. While compound risk can be mostly associated with the physical dimension of hazards, interacting and interconnected risks gradually increase the focus on the vulnerability component. Thus, they become the center of cascading risk. The analysis of root causes and consequences uses different tools. On the one hand, the work mostly involves physical modeling and forecasting. On the other hand, it focuses on network analysis and resilience assessment in the broader sense. Those tools are complementary and can be used together, while common areas of interaction and overlapping can be identified in the built environment and in mechanisms such as early warning systems. As noted, in all of these cases, there is a common background of wide uncertainties in the environmental, physical, technological, and social dimensions, which can challenge risk assessment and management with the existence of weak background knowledge. This influences the tools that are needed, but it also affects the assessment process and the possible policy outcomes, as there may be different emphases on hazards and vulnerabilities. In order to maximize the efficiency of the process of risk analysis and risk assessment, it is essential to understand the differences and complementarities inherent in compound, interacting, interconnected, and cascading events.

6. CONCLUSION

This article has developed a common framework for compound, interacting, interconnected, and cascading risk, which aims to support a better visualization and understanding of high-impact events. It develops these ideas in line with the SDFF and characterizes complex events in a way that should support a more highly focused analysis (Aven, 2016; Greenberg et al., 2011; Linkov et al., 2014; Pescaroli & Alexander, 2016). This is in line with the perceived need for new strategies designed to integrate systemic risks in research, policies, and management that has been frequently highlighted in the literature

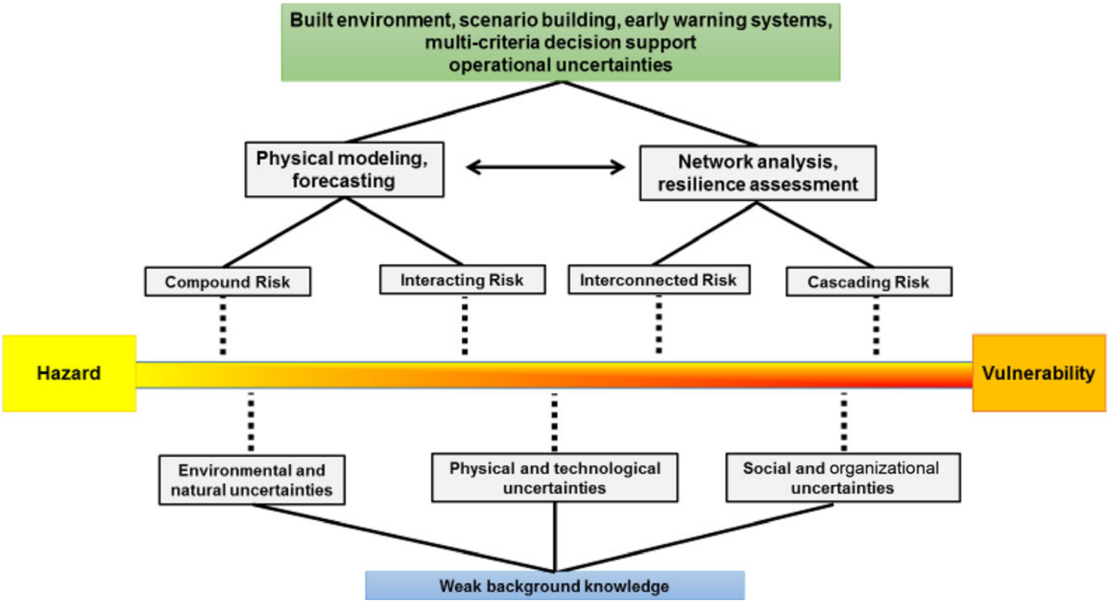

Fig. 3. Overview of the relations of compound, interacting, interconnected, and cascading risk with hazard, vulnerability, uncertainties, and analytical tools.

(Aitsi-Selmi et al., 2016; Alexander, 2016; Helbing, 2013; Helbing, 2015; Linkov et al., 2014; Mileti & Noji, 1999).

Despite a general perception of overlap between the four concepts dealt with in this article, we have shown that very specific issues have been addressed in compound, cascading, interacting, and interconnected risk. These have not always been assimilated in research and management, and this requires better coordination in order to improve the complementarities of forecasting tools, the flexibility of mitigation measures, and the ability to adapt to emergency response.

We have defined boundaries that can help to produce more focused risk estimations and better tools, which will, we trust, help stakeholders and academics to improve description, visualization, and communication, as suggested in some of the literature and in the SFDRR itself (Aven, 2016; UNISDR, 2015). There are significant limitations to this perspective that must be considered. First, the readers should note that this article does not pretend to be an exhaustive review of all the literature in the field. Instead, it provides a synthetic framework and guidelines for those readers who are interested in the topic. Although we have tried to define as much as possible the boundaries of each category, further work is needed in order to define the specific boundaries and their significance as "tipping points" for risk assessment. Future research should better consider qualitative implications for practical management of such situations in terms of scenario building and the broadening of impact trees, which must be complementary to the methodologies and tools that have already been identified in the literature (Aven, 2016; Helbing, 2013; Linkov et al., 2014; Pescaroli & Alexander, 2016). In other words, new research should be developed on *how to predict and address interdependencies*, together with advice on *what actions should be taken once interdependencies are triggered*. The translation of theoretical frameworks into practice is one of the most important challenges that needs to be addressed in the furtherance of disaster risk reduction.

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