



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

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

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For Peer Review

## Abstract

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. ~~The present paper synthesises and reviews the state of the art regarding compound, interconnected, interacting, and cascading risks. This paper 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 policy makers. This paper 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 could be ~~used~~ used to improve policy recommendations and ~~practical~~ support tools for emergency and crisis management, such as ~~s~~-scenario building and ~~wider~~ impact trees, thus contributing to the achievement of a system-wide approach to resilience.

**Key Words:** compounding risk, interconnected risk, interacting risk, cascading risk, societal resilience, critical infrastructure, Sendai Framework for Disaster Risk Reduction.

## 1. Introduction

55 The development of concepts that describe compound, interconnected, interacting and  
 56 cascading risks is part of the process of creating new knowledge in order to increase societal  
 57 resilience. Since the 1990s and the International Decade for Natural Disaster Reduction, our  
 58 understanding of risk in the community has been influenced by the evolving role of science  
 59 and technology (1). Different perspectives from disciplines such as engineering and social  
 60 sciences were merged together to provide a coherent approach to risk analysis, using a basis  
 61 of knowledge about system performances and uncertainty assessments (2). Events such as  
 62 the 2004 Indian Ocean Tsunami lead to the development of the Hyogo Framework for Action,  
 63 which provided an international plan endorsed by the United Nations (UN) to reduce disaster  
 64 losses and build resilience between 2005 and 2015. According to the United Nation Office for  
 65 Disaster Risk Reduction (UNISDR), disaster risk can be defined as: “The potential loss of life,  
 66 injury, or destroyed or damaged assets which could occur to a system, society or a community  
 67 in a specific period of time, determined probabilistically as a function of hazard, exposure,  
 68 vulnerability and capacity” (www. preventionweb.net, updated February 2017). In other words,  
 69 disaster risk can be expressed by the following conceptual equation:

$$70 \quad \textit{Hazard} \times \textit{Vulnerability} \times \textit{Exposure} = \textit{Risk} \rightarrow \textit{Impact}$$

71 The main consequence of this is a degree of circularity, in which the vulnerability of a system  
 72 makes it more sensitive to risk, reflecting the complexity of socio-economic factors that interact  
 73 with the physical aspects of hazard (3–5). The work of the members of the Society for Risk  
 74 Analysis has highlighted the existence of other multidisciplinary aspects that have been used  
 75 for models and theoretical frameworks. At the same time, it has been suggested that there is  
 76 a tendency in the engineering community to associate the definition of risk with the  
 77 quantification of probabilities, but in order to be effective, the analysis of systemic accidents  
 78 and unexpected events must address also uncertainties and their root causes (6).- However,  
 79 the literature suggests that further development is needed “especially in relation to situations  
 80 of large/ or deep uncertainties and emerging risks”(7).- However, the complexity of

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networked society and the uncertainties inherent in ~~erging~~ 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 (8).

-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\_(9–11)-[3–5]. 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\_(12)-[6]. 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\_(13)-[7].

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In this context, in 2015 the UN 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 priority 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 ~~Sendai Framework for Disaster Risk Reduction (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 (5) [8].

Notwithstanding the rise of three factors--multi-hazard approaches, multidisciplinary integrations and holistic knowledge sharing\_(1) [4]--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

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between different strategies and mitigation measures (7). 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 (14–16).

~~—The fragmentation of the literature on compound, interconnected, interacting and cascading risks can be seen as a part of the obstacles to overcome in the near future [9–11].~~ Although ~~these~~ 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 paper aims to ~~integrate the current state of the art in order to understand~~ 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.

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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 analysed and hence it may have serious implications for risk management and decision making” (7). 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

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research and practices. This is essential in order to maximise 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 these relevant elements are included(17). In other

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words, the scope of this paper is to help scholars and practitioners to distinguish the different components of complex events that tends to overlap, supporting more focused

actions in terms of measures for operational resilience and risk modelling.

To begin with, this paper focuses on compound events, which have been associated mostly with natural hazards and climate change. Secondly, it approaches the fundamentals of

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interconnected and interacting risks, in which the environmental and human drivers overlap. Thirdly, ~~the state of art on~~ cascading risk is explained, ~~which requires a more~~

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3 ~~structured approach and in particular must distinguish~~ distinguishing the complementarities  
4 of the social domain from the failure of critical infrastructure. The concluding section of this  
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140 research and policies.

## 2. Compound risk

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Compound risk is a well-known topic of discussion by scholars and practitioners who are interested in climate change. They involve both physical components, such as the understanding of environmental trends, and statistical ones, such as the implications of concurrence in forecasting and modelling. 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(4) [42] 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”(4) [42]. 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: (a) extremes that occur simultaneously or successively; (b) extremes combined with background conditions that amplify their overall impact; or (c) 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. Secondly, health issues due to particular environmental conditions such as humidity can affect human systems.

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3 Although compound risk can involve events that are not causally correlated, some  
4 exceptions have to be made for common driving forces, such as different phenomena that  
5 interact during El Niño, or when system-wide feedbacks between different components  
6 strengthen each other, as when drought and heat waves occur in regions that oscillate  
7 between dry and wet conditions. Understanding and assessing this level of interaction  
8 presents different challenges in relation to the forecasting and modelling of such  
9 phenomena. It has been suggested that, because of its implications in terms of discrete  
10 classes and artificial boundaries, the IPCC definition may be problematic for the  
11 quantification of risk. It could be better to promote a more general approach in which  
12 compound events are intended as extremes derived statistically from drivers with multiple  
13 dependencies (14). [9]. Indeed, climate change could increase the complexity of the  
14 system and the possible sources of non-stationarity in the distribution of extremes, such as  
15 variable and dynamic combinations. With regard to impacts and dependencies between  
16 systems, these may need to be considered in a multidisciplinary way (14). [9].

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This seems to contextualise cascading risk more than separate it completely from what explained earlier-, The Words into Action Guidelines on National Disaster Risk Assessment (17) refers to compounding factors as part of "underlying risk drivers", such as climate change or urbanisation, 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).

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~~This in line with some other literature that tends to overlap much more with the concepts of 'interconnected' and 'cascading' risks. Perry and Quarantelli [13] 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 [14], compound disasters were reported as a form of amplified sequential events,~~

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~~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, random and related hazards, and the inclusion of infrastructure failures [15]. 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 multi-hazard assessment, safety standards and the redundancy of lifelines. Other literature [16] has used both approaches [14,15] 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 [16]. 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)(17).~~ 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.

### 210 3. Interacting and interconnected risk

215 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 globalisation 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

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3 research on risk factors in health\_(18)~~[17]~~. Overall, the topic has particular implications for  
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5 disaster risk reduction, complexity science, and emergency management. Common ground  
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7 220 for improving the understanding of the composite nature of disasters has been a relevant  
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9 part of disaster management and hazard assessment processes since the 1980s, for  
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11 example with respect to earthquake-induced landsliding\_(3)~~[18]~~. However, events such as  
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13 the 2011 tsunami, and the storm surge triggered by Hurricane Sandy, have increased the  
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15 need to improve forecasting strategies and early warning methods by those public and  
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17 private stakeholders who are in charge of critical infrastructure protection. Although the  
18 225 SFDRR (5)~~[8]~~ does not refer directly to interacting or interconnected risk, it refers to the  
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20 need to strengthen capacity to assess “sequential effects” on ecosystems.  
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24 In the case of interacting risks, the mechanisms and combinations of hazards have  
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26 been analysed in their temporal and spatial domains, including reciprocal influences  
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28 230 between different factors and coincidences among environmental drivers\_(19)~~[19]~~.  
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30 Empirical studies have elucidated the relationships between primary hazardous events and  
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32 secondary natural hazards of the same category or different categories\_(20)~~[20]~~. Progress  
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34 in this sector requires both risk assessment strategies and understanding of the  
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36 components of earth systems and their multiple-hazard perspectives to be improved  
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38 235 (16)~~[14]~~. For example, Gill and Malamud (21)~~[21]~~ studied systematically interactions  
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40 between 21 natural hazards. They found that geophysical and hydrological hazards are  
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42 receptors that can be triggered by most of the other types of hazard, while geophysical and  
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44 atmospheric causes are the most common triggers. The results of such studies support a  
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46 wider understanding of complex interactions that could be integrated into early warning  
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48 systems and rapid response tools. Other studies have created new models based on the  
49 240 analysis of trigger factors, which enables them to understand relationships among hazards  
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51 that are interdependent, mutually reinforcing, acting in parallel or acting in series\_(22)~~[22]~~.  
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55 However, for multiple-risk assessment to be effective, the complex nature of interacting  
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57 and interconnected relationships between different triggers needs to be integrated into a  
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59 holistic framework. Some allowance must be made for the social construction of disasters  
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3 in a global systems perspective, including reciprocal influences among the social sphere  
4 and the built and natural environments(23)–[23]. In other words, risk can be understood as  
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7 the result of interaction between changing physical systems and society, which also  
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9 evolves over time\_(24)–[24]. In various studies, Helbing\_(12,25) [6,25]–analysed the  
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11 250 'interconnected causality chains' that generate and amplify disasters, framing the impacts  
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13 of triggering events on both ecosystems and anthropogenic systems. In this sense, the  
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15 paths of complex risks that generate secondary events are determined by physical  
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17 elements (for example, a landslide triggered by an earthquake), the build environment (for  
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19 instance, critical infrastructure) and people (hence, behaviour). The level of interconnection  
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21 and interdependency may be determined by interactive causality chains which can spread  
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23 out in space and time. However, improved understanding of physical interactions has  
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25 tended to shift national risk assessment towards multiple-hazard approaches, further  
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27 attention should be given to contemporary society and the built environment. The global  
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29 interdependency of human, natural and technological systems can produce hazards and  
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31 disasters, but it is increasingly hard to comprehend and control\_(26)–[13]. Networks have  
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33 260 different levels of interaction and interconnection, perhaps with multiple sources of  
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35 disruption and systemic failure(27)–[26]. When events are triggered, the pathways that  
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37 determine the scale of the impacts are influenced by the interlinkages between different  
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39 domains, for example the interactions by which an earthquake leads to a tsunami, along  
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41 with the climate change drivers, and the components of infrastructure such as lifelines\_(28)  
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43 265 [27].

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47 ~~Interacting and interconnected risk tend to overlap with cascading risk. First,~~  
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49 ~~interactions among hazards have been associated with the domino effect, by which we~~  
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51 ~~mean a chain of hazardous events in which one manifestation triggers another, as when a~~  
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53 ~~storm causes a flood [21,22]. Secondly, interconnected and interacting risks can be seen~~  
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55 ~~as precursors of the appearance of cascading effects and disasters [6,25,26]. In interactive~~  
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57 ~~complex systems, the speed of cascading events (meaning their capacity to influence other~~  
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59 ~~components) can be the measure or manifestation of 'tight coupling' [28]. In studies of the~~  
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~~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 [29]. 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 [30–32]. However, quantification of disruption is not the only way to approach cascading risk. As the next step towards the derivation of a holistic framework, the following section will clarify the specific features of cascading risk.~~

#### 4. Cascading risk

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Among the phenomena analysed 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(29)\_[33]. 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' (30)[28]. 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\_(31,32)\_[34,35]. This idea has been integrated into the early literature on NaTech disasters, interacting risk, and cascading events (33,34)[36,37], but recently it has been pointed out that it could be an oversimplification and it could also decontextualise the problem\_(15,35)\_[10,38].

In the early 2000s, events such as Hurricane Katrina and the terrorist attacks on the World Trade Centre 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 (29) [29], how one can study the processes that could cause blackouts and trigger cross-scale

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3 failures in power grids\_(36)–[39]. Networked infrastructure was portrayed in both its  
4 functional and social domains, including hardware, services, and the secondary and tertiary  
5 effects of disruption\_(37)–[40]. However, cascading risk remained a fragmented subject that  
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10 305 lacked both official definition and an intergovernmental dimension. It usually referred to a  
11 branching structure that originated with a primary trigger\_(34)–[37].  
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14 Although new models were used to defined thresholds and mitigation strategies, their  
15 applicability was limited by the absence of testing in real scenarios and networks\_(38)–[41].  
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18 In political analyses, although the presence of cascading effects was seen as a driver that  
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20 310 could explain the scale of crises, but it remained marginal to any broader considerations of  
21 resilience to extreme events with cross-border dimensions\_(9,39)–[3,42]. The ecological  
22 debate focused on the implications of cascading risk for climate by associating it with  
23 complex causal chains, non-linear changes and recombination potential. The question of  
24 how to manage such crises was not solved\_(10)–[4].  
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30 315 Only in the late 2000s were empirical data used to demonstrate that cascading failures  
31 are not as rare as was believed. When they were driven by disruptions to the energy,  
32 telecommunications and internet sectors, they were generally stopped quickly\_(35,40)  
33 [38,43]. After high–impact events such as the eruption of Eyjafjallajökull volcano (2010),  
34 the triple disaster in Japan (2011) and Hurricane Sandy (2012), the field evolved towards  
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41 320 a greater understanding of the wider implication of cascades. A wider range of case studies  
42 provided new evidence of the disruption of social, cultural and economic life, including  
43 cross-scale implications for global supply chains and humanitarian relief\_(41–43)–[44–46].  
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47 Improved technology stimulated a new phase in modelling the complexity of interactions  
48 and interdependencies among networked systems. It promoted a more coherent approach  
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52 325 to climate, society, economics, the built environment and cross-sector decision support  
53 systems(44,45)–[47,48]. In order to understand both random failures and terrorist attacks  
54 on lifelines, critical factors began to be ranked\_(46,47)–[32,49]. Attempts were made to  
55 assess cascading disruptions on a cross-national basis\_(48,49)–[31,50]. In order to assess  
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60 the possible impact of cascading risk on emergency management and to translate it into

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3 330 generic tools that could raise awareness and information sharing in particular on electricity  
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5 disruptions, the risk managers looked for ~~adopted a more~~ practical and repicable  
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7 approaches (50) ~~{54}~~. A few of the official scenarios tackled the loss of power supply caused  
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9 by non-conventional triggers such as solar storms, but, in everyday reality, practice was  
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11 still distinguished by a lack of buffering strategies and well-codified contingency plans(51)  
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14 335 ~~(52). {52}~~.

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16 The promotion of strategies designed to increase the autonomy and adaptive capacity  
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18 of systems could be seen as a partial answer to these problems. In decision-making and  
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20 planning, decentralisation and greater empowerment were sought ~~(52) {52}~~. However,  
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22 guidelines for the adoption of coherent mitigation actions are still ~~not~~ limited in their  
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24 340 availablitye. In this sense, the Sendai Framework for Disaster Risk Reduction can be  
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26 regarded as a first step (5) {8}. This document reflects the perception that, in order to reduce  
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28 damage to critical infrastructure and loss of vital services, hardware and software are the  
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30 joint adjuncts of policies and mitigation actions.  
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34 In the projects supported by the European Commission, in particular by the Seventh  
35 345 Framework Programmes such as FP7 FORTRESS, FP7 CASCEFF, FP7 SNOWBALL,  
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37 FP7CIPRNet, or FP7 STREST, other drivers of research have emerged. Lack of awareness  
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39 of critical infrastructure dependencies among planners and responders could be associated  
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41 with extended impact of emergencies, requiring different levels of actions for mitigating  
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43 worst case scenarios and operational challenges (53). Assessment and modelling of  
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45 350 cascading failures in networks can have been complemented by greater attention to the  
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47 strategies that are required when disruption happens, as we suggested in some of our  
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49 previous works (15,51,54–56).

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51 In particular, our approach proposed that 'cascading risk' should distinguish between  
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53 'cascading effects' and 'cascading disasters', considering that, as time progresses, non-  
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55 linear escalation of a secondary emergency could become the main centre of crisis (15)  
56 355 {10}. This shifts significantly from the "toppling dominos metaphor", which, as suggested  
57  
58 earlier (31-34) (35-39), has mostly been employed in the context of the process industry  
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shifting attention to critical infrastructure, complex theory and to the understanding of societal and organisational resilience in policy making and emergency management. Figure 1, taken from a previous work of ours (51), 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 (CAS) may be the drivers that amplify the impacts of the cascade.

, add here Pescaroli and alexander

— This approach has shifted the focus of interest to the wider context of policy making and emergency management.

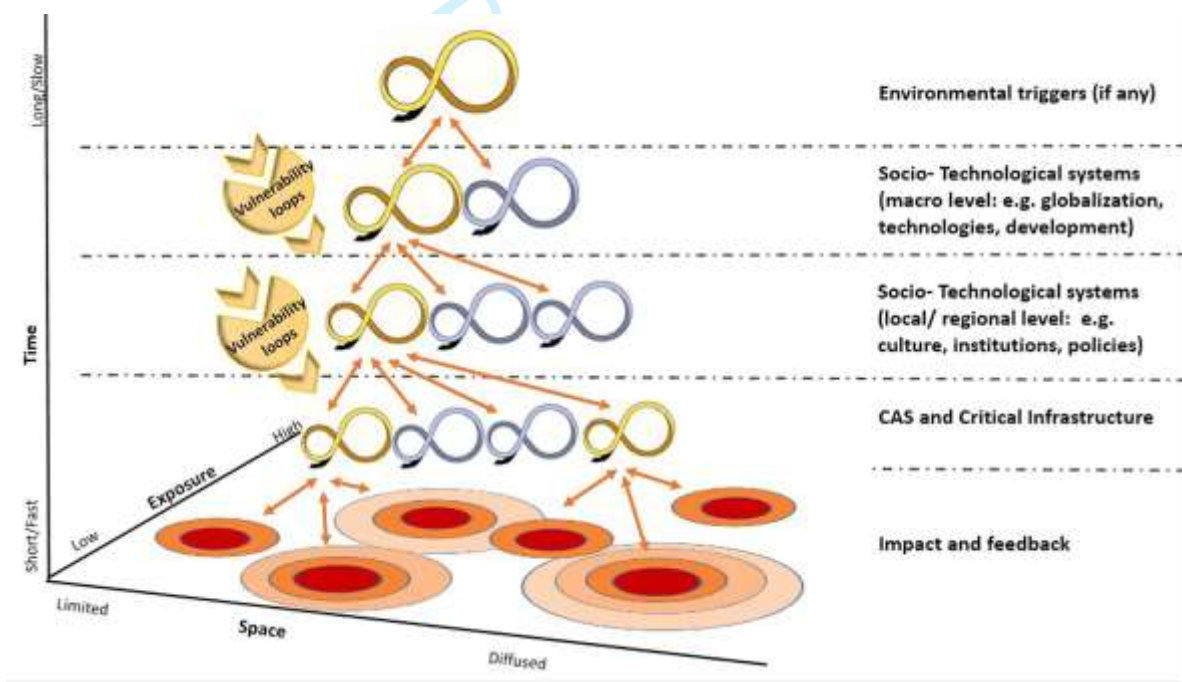


Figure 1- Vulnerability path of cascading disasters, scales interactions, escalations on time and space (Pescaroli and Alexander 2016)

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3 First, it ~~has begun to merge together~~ -the literature on the loss of services ~~there are with that~~  
4 ~~on~~ other possible drivers of escalation such as NaTech events, considering that up to 5 per  
5 cent of industrial accidents are caused by natural triggers that involve hazardous facilities  
6 (57)~~[53]~~. In practice, this has been shown up by gaps in existing legislative frameworks, where  
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11 380 it is necessary to integrate different levels of risk and critical infrastructure mapping to increase  
12  
13 the effectiveness of mitigation strategies for multiple-scale events\_(54)~~[54]~~. Secondly, in order  
14  
15 to increase the effectiveness of deployment and the organization of procurement in disaster  
16 relief, new datasets are needed. The analysis of different case studies suggests that the  
17  
18 disruption of critical infrastructure can impact the logistics of emergency relief\_(43)~~[46]~~. It also  
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22 385 has the potential to orient international aid in order to rectify a shortfall of emergency goods  
23  
24 and expertise caused by the disruption(56)~~[55]~~. Finally, it has been pointed out that cascading  
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26 risk may require a change in methods of scenario building and contingency planning. Our  
27  
28 previous work suggested that ~~The~~ flexibility of response can be increased by considering  
29  
30 possible escalation paths that are common to different categories of triggering event\_(51)~~[56]~~.  
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33 390 This approach is complementary to the perspective of broad impact-tree analysis\_(58)~~[57]~~.  
34  
35 Shifting from a focus on hazards to one on vulnerability assessment enables one to recognise  
36  
37 the sensitive nodes that may cause secondary events to escalate. On the one hand, tipping  
38  
39 points, or thresholds, can be associated with an increased demand for products and services  
40  
41 during events such as blackouts. This drives the prioritization of recovery actions and  
42  
43 395 introduces new questions and issues regarding coordination between public and private  
44  
45 stakeholders\_(59)~~[58]~~. On the other hand, in order to consider the different components of risk  
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47 in relation to one another, it is essential to introduce good practices into emergency planning  
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49 and scenario building\_(55)~~[59]~~. The next section will propose a holistic framework that may  
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51 be used by scholars and practitioners as the basis for improved work in this field.  
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## 5. A holistic framework for compound, interconnected, interacting and cascading risk

In order to identify complementarities and minimise the duplication of efforts in research, policies, and practices. ~~This~~ this paper has given a brief overview of compound, interacting, interconnected and cascading risks. ~~and has defined their most important differences and complementarities.~~ However, more discussion is needed in order 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 (26) 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(60), compound disasters were reported as a form of amplified education 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 the inclusion of infrastructure failures (61). 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 multi-hazard assessment, safety standards and the redundancy of lifelines. Other literature (62) has used both approaches (60,61) 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 (62) . However, in this case, compound risk has been associated

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3 430 with the linkages between natural hazards and technology without taking into account other  
4 studies, such as those that refer to technological disasters triggered by natural hazards  
5 (NATECH) (63).

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10 Interacting and interconnected risks tend to overlap with cascading risk. First, interactions  
11 among hazards have been associated with the , by which we mean a chain of hazardous  
12 events in which one manifestation triggers another, as when a storm causes a flood (21,22).

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14 435 This is clearly different from the use of the “toppling dominos metaphor” in the chemical  
15 industry process explained earlier (31-34), increasing the confusion. Secondly,

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23 interconnected and interacting risks can be seen as precursors of the appearance of  
cascading effects and disasters (12,25,27). ~~In interactive complex systems, the speed of~~

24 440 cascading events (meaning their capacity to influence other components) can be the measure  
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26 or manifestation of 'tight coupling' (30). In studies of the interdependency between critical  
27  
28 infrastructure and the built environment, cascading risks can be seen as one of the possible  
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30 categories of failure that are part of the infrastructure interdependency dimension(64). In other

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33 words, cascading effects can be seen as caused by dependencies and interdependencies  
34 associated with infrastructure domain (40, 53). In the literature on risk and resilience, this

35 445 aspect has been developed for infrastructure systems and disruptions that spread out from  
36  
37 one network to others through the many components of systems (47,48,65).

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41 ~~These relationships are shown in Figure 1, which is intended as a synthetic framework for use~~  
42 ~~in future studies.~~ The overlapping areas in the centre of the picture reflect the descriptions

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45 450 reported in this paper 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\_ (16), and a common lack of inter-agency agreements(34) [37].

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56 455 It is clear that standard definitions should be more widely adopted in order to help increase  
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58 the effectiveness of research and practice, and to avoid confusion and duplication of effort  
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60 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 (15)[10].

On the other, it makes some progress towards integrating multi-disciplinary research on the anthropogenic dimension of disasters (3,24–26)[13,18,24,25].

— 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 (8,12,51)[2,6,56]. The identification of amplification dynamics may reflect the cross-disciplinary manifestation of increased complexity at the system level.

— They are complex risks which maintain high potential for surprise and non-linear evolution, and this has to be considered in the assessment process. They include different levels of consequences and uncertainties (2). 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 datasets, which would require the integration of qualitative data (6).

**Figure 1. A framework for compound, interacting, interconnected and cascading risks**

These relationships are shown in Figure 2, which is intended to be a synthetic framework for use in future studies. The overlapping areas in the centre of the picture reflect the descriptions reported above. In relation to the literature discussed in the previous sections, Figure 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 and Interconnected risk* both refer 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

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3 485 risk. The study of interacting risk may be the focus of Interacting risk may refer  
4 rather more to the environment and to disciplines such as geophysics and physical  
5 geography, while giving space to multiple risk assessment tools and strategies;  
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7 For example, the study of the dynamics of interacting risk may can be translated  
8 into simulations and models for the energy industry, thus defining better hazard  
9 maps .

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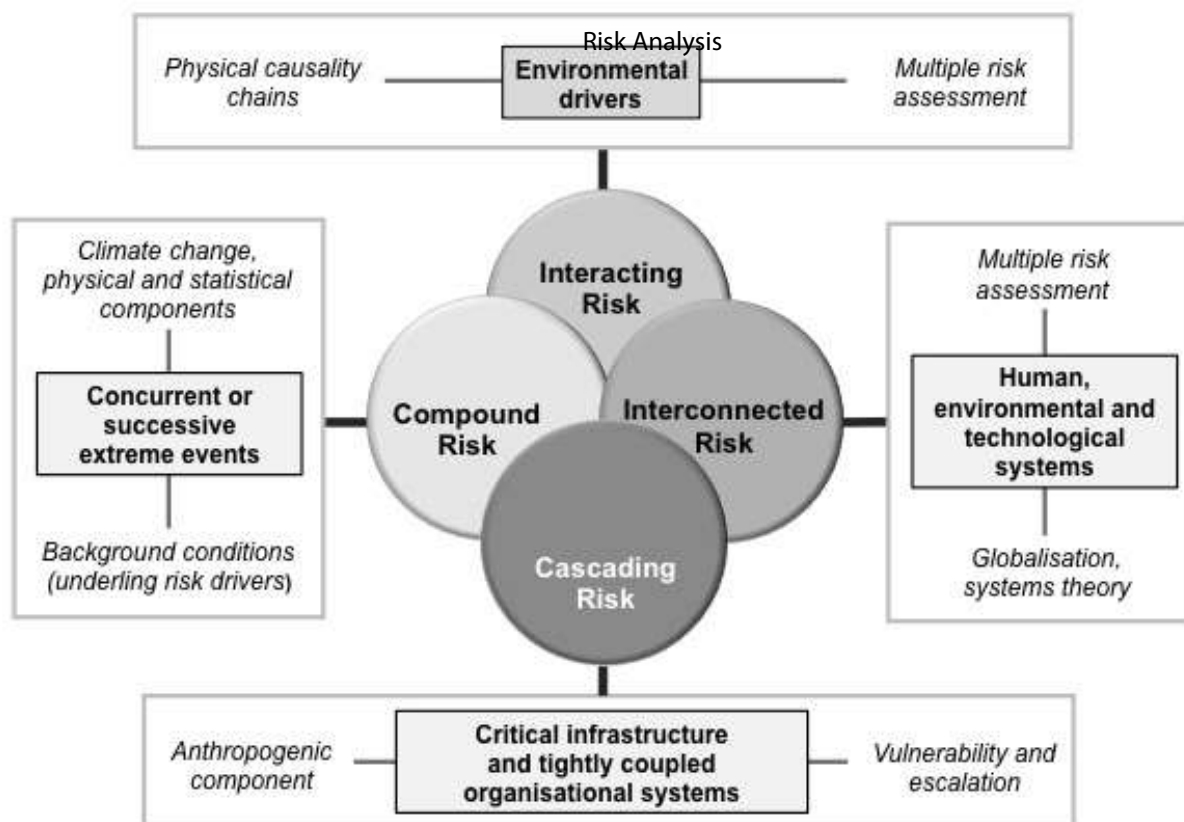
- 16 • Interconnected while interconnected risk tends to be used more often in network  
17 science and in studies of global inter-linkages. It can include the complex  
18 interactions between human, environment, and technological systems, which can  
19 be translated, for example, into coherent multiple risk assessments or network  
20 analysis. —Interconnected risk may be referred to as the physical  
21 interdependencies that allows societal interactions, and thus a pre-condition for  
22 cascading risk.

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- 30 • *Cascading risk* is associated mostly with the anthropogenic domain and the  
31 vulnerability component of risk. This results in a disaster escalation process. In  
32 other words, it focuses mainly on the management of social and infrastructure  
33 nodes. With respect to triggering events, while interconnected risk can be seen as  
34 one of the preconditions for the manifestation of cascades, compound and  
35 500 interacting dynamics can influence its magnitude.

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[Figure 2. A framework for compound, interacting, interconnected and cascading risks](#)

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 Figure 1. This has been developed bearing in mind the needs of the SFDRR(5) and the methodologies of decision support for emergency and crisis management, such as scenario building(58). 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\_(41,51) [44,56]. 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” (66)–[60]. 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

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3 525 cascading effects on society were subject to non-linear escalation and became the primary  
4 source of crisis that needed to be managed (i.e., cascading risk).  
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7 The second example is the triple disaster that struck Japan on the 11<sup>th</sup> March 2011. In  
8 two different ways it explains how interacting and interconnected features can overlap with  
9 social vulnerabilities and thus contribute to the cascading escalation of the event (15,67)  
10  
11 530 ~~[10,61]~~. First, an earthquake that triggered a tsunami represented interacting risk, which  
12 affected highly coupled infrastructure (interconnected risk), and provoked a wide range of non-  
13 linear secondary emergencies, such as the extensive loss of vital services and the creation of  
14 NaTech events (cascading risk). Secondly, the earthquake triggered a small and localised  
15 landslide (interacting risk) that cut off the Fukushima power plant from the main electric grid  
16  
17 535 (interconnected risk), exacerbated existing vulnerabilities at the site and led to a full-blown  
18 nuclear meltdown (cascading risk). In both cases, the disruption of critical infrastructure  
19 orientated the progress of emergency relief towards mitigating the escalation of secondary  
20 emergencies~~(56)-(69) [55]~~, while the meltdown of the Fukushima Dai'ichi plant was regarded  
21 as a man-made disaster that could have been predicted and avoided were it not for the  
22 prevalence of negligence (67) ~~[64]~~.  
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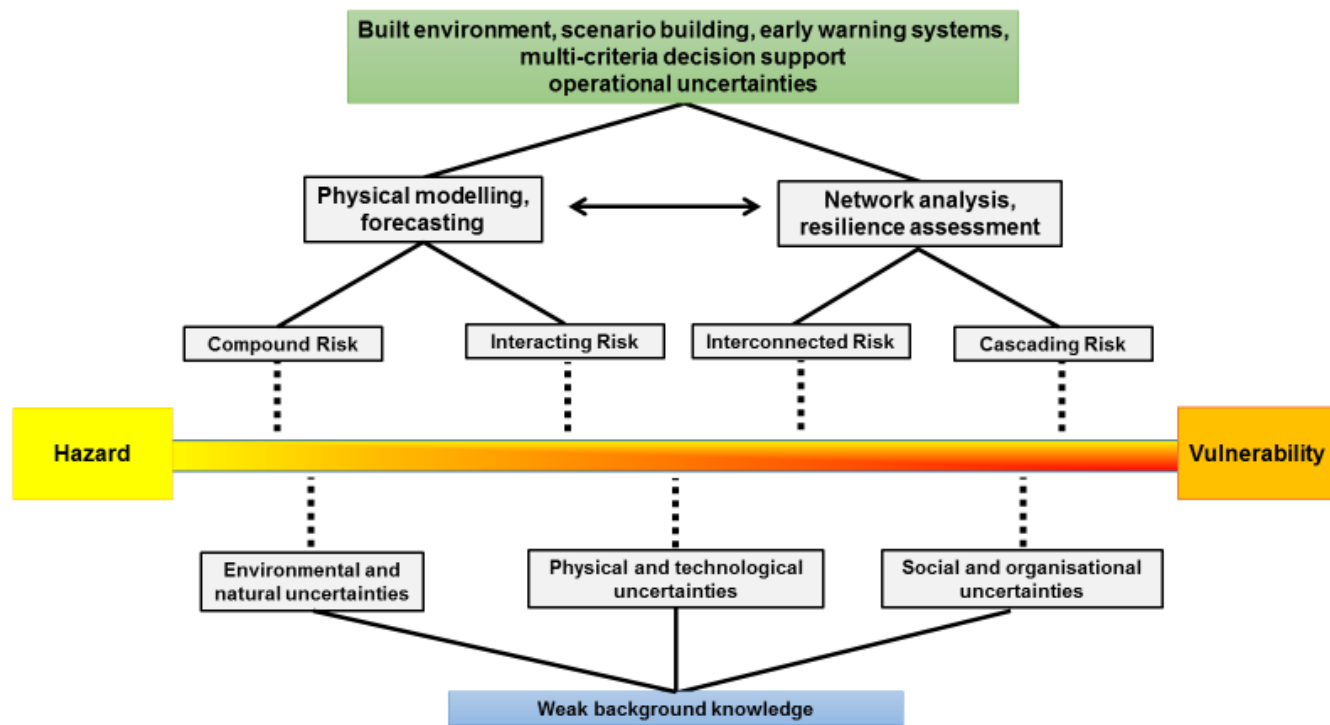
37 Hurricane Sandy, also known as Super-Storm Sandy, is our last case. It encompasses  
38 all the possible joint effects of compounding, interacting, interconnected and cascading risks  
39 (51,68) ~~[56,62]~~. Its relevance mainly lies in climate change scenarios, in which the primary  
40 nature of the event triggers may be subject to intensification. Hurricane Sandy made landfall  
41  
42 545 in the United States on 29th October 2012. The storm winds not only wreaked direct damage,  
43 but also contributed to the generation of a storm surge that caused flood damages (interacting  
44 risk), while concurrent cold air flowing from the Arctic intensified cold weather and caused  
45 snow storms inland (compounding risk). Sandy impacted a geographical area of strategic  
46 importance to the US economy. It has a dense population and a high concentration of industrial  
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56 550 plants and financial networks, such as the New York Stock Exchange (interconnected risk).  
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58 The composite nature of the hazard and the loss of highly-ranked critical infrastructure  
59 triggered a wide range of secondary crises that escalated in a non-linear manner. While the  
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3 emergency responders had to tackle leaks from refineries and chemical plants, or fires in  
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5 houses, the President of the USA made a new declaration of emergency regarding the  
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7 555 prolonged power outages and the damage to the production and distribution chain of gasoline  
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9 and distillates (cascading risk). An official report\_(69) [63]-attributed around 50 deaths to the  
10  
11 joint effect of extended power outages and cold weather (interaction of compounding and  
12  
13 cascading risk).

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16 However, this clarification is simply not enough to translate the conceptual framework into an  
17  
18 560 tool that can be used to understand, manage and predict events. Taking back the conceptual  
19  
20 equation used for the definition of risk, and the complementary works cited in the introduction,  
21  
22 it may be useful to subject Figure 3 to further discussion.

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24 Our review shows that the compound, interacting, interconnected, and cascading risk tend to  
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26 be different component of hazards and vulnerabilities. While compound risk can be mostly  
27  
28 565 associated with the physical dimension of hazards, interacting and interconnected risk  
29  
30 gradually increase the focus on the vulnerability component. Thus they become the centre of  
31  
32 cascading risk. The analysis of root causes and consequences use different tools:- On the  
33  
34 one hand the work is mostly involving physical modelling and forecasting. On the other  
35  
36 hand it focuses on network analysis and resilience assessment in the broader sense. Those  
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38 570 tools are complementary and can be used together, while common areas of interaction and  
39  
40 overlapping can be identified in the build environment and in mechanisms such as early  
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42 warning systems. As noted, in all of these cases, there is a common background of wide  
43  
44 uncertainties in the environmental, physical, technological and social dimensions, that can  
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46 challenge risk assessment and management with the existence of weak background  
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48 575 knowledges. This influence the tools that are needed, but it also affects the assessment  
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50 process and the possible policy outcomes, as there may be different emphases on hazards  
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52 and vulnerabilities.- In order to maximise the efficiency of the process of risk analysis and risk  
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54 assessment, it is essential to understand the differences and complementarities inherent in  
55  
56 compound, interacting, interconnected and cascading events. .  
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585 Figure 3- Overview of the relations of Compound, interacting, interconnected, and cascading risk with  
 590 hazard, vulnerability, uncertainties and analytical tools.

## 6. Conclusion

590 This paper has developed a common framework for compound, interacting, interconnected  
 595 and cascading risk, which aims aimed to may support a better visualization and understanding  
 of high-impact events, It develops these ideas in line with the SDFF, and that could be applied  
by decision makers in methodologies such as new scenario building, root causes analyses,  
wider impact trees characterizes complex events in a way that should support a more highly  
focused analysis (7,13,45,51). The his may result in improved tools and practices, in which  
 the holistic nature of complex risk is recognized and mitigation measures are pre-arranged in



~~such a way as to be integrated together.~~ 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\_(1,12,13,23,52,55)-[1,6,7,23,52,59]. ~~However, in the light of the SFDRR [8], further progress is urgently needed in this field in order to translate the different aspects of risk and resilience into improved effectiveness of mitigation, adaptation and response measures.~~

Despite a general perception of overlap between the four concepts dealt with in this paper, 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 some boundaries that can help to produce more focused risk estimations and better tools, which will, we trust, help stakeholders and academics to improve the description, visualization and communication, as suggested in some of the literature and in the SFDRR itself (5,7). There are significant limitations into 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.

~~———— 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, futher work is needed in order to define the specific boundaries and their significance as “tipping points” for risk assessment. In the translation of complex events into effective practices of societal resilience, new efforts are needed to define multi-criteria platforms that could support decision making. Although improvements in quantification have been one of the main attributes of the literature on compound, interacting, interconnected and cascading risk, Future research should better consider qualitative implications for practical management of such situations in terms of as scenario building and

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3 625 the broadening of impact trees, which must be complementary to the methodologies and tools  
4 that have already been identified in the literature (7,12,13,51). In other words, new research  
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7 should be developed on *how to predict and address interdependencies*, together with advice  
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9 on *what actions should be taken once interdependencies are triggered*. The translation of  
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11 theoretical frameworks into practice is one of the most important challenges that need to be  
12  
13 addressed in the furtherance of disaster risk reduction.  
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