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

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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. 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 SFDRR. How could they be used? Abstract lacks description of findings. Too much an introduction, too little a summary.

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

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 [1]. However, the complexity of networked society and the uncertainties inherent in emerging 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 that was previously supposed, and that this requires us to develop a new understanding of their drivers [2]. 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 [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 [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 [7].

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 [8]. Notwithstanding the rise of three factors--multi-hazard approaches, multidisciplinary integrations and holistic knowledge sharing [1]--there are persistent gaps in the research and they need to be addressed.

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 the complementarities and differences inherent in compound, interconnected, interacting and cascading risks. First, this comment focuses on compound events, which have been associated mostly with natural events and climate change. Secondly, it approaches the fundamentals of 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 structured approach and in particular must distinguish the social domain from the failure of critical infrastructure. The concluding section of this paper 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. 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 [12] 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” [12]. 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.

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 modelling 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 [9]. Indeed, climate change could increase the complexity of the system and the possible sources of non-stationarity 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 [9].

A slightly different point of view is reported in the SFDRR [8], in which compounding drivers are associated with both the creation of new disaster risk and the need to reduce both exposure and vulnerability. 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, 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) [cite Santella, N., L.J. Steinberg and G.A. Aguirra 2011. Empirical estimation of the conditional probability of natech events within the United States. *Risk Analysis* 31(6): 951-968. or other natech paper]. 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 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 research on risk factors in health [17]. 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 [18]. 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 SFDRR [8] 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 analysed in their temporal and spatial domains, including reciprocal influences between different factors and coincidences among environmental drivers [19]. Empirical studies have elucidated the relationships between primary hazardous events and secondary natural hazards of the same category or different categories [20]. 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 [11]. For example, Gill and Malamud [21] 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 [22].

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 [23]. In other words, risk can be understood as the result of interaction between changing physical systems and society, which also evolves over time [24]. In various studies, Helbing [6,25] analysed 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 (for example, a landslide triggered by an earthquake), the build environment (for instance, critical infrastructure) and people (hence, behaviour). 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 towards 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 [13]. Networks have different levels of interaction and interconnection, perhaps with multiple sources of disruption and systemic failure [26]. 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 [27].

Interacting and interconnected risk tend to overlap with cascading risk. First, interactions among hazards have been associated with the domino effect, by which we mean a chain of hazardous events in which one manifestation triggers another, as when a storm causes a flood [21,22]. Secondly, interconnected and interacting risks can be seen as precursors of the appearance of cascading effects and disasters [6,25,26]. 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' [28]. 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 [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

Among the phenomena analysed in this article, cascading risk is the broadest. For many years, it was referred to vaguely as 'uncontrolled chain losses', while the literature used as synonyms “cascading failures” and “cascading effects” [citation needed]. 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 [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' [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 [34,35]. This idea has been integrated into the early literature on NaTech disasters, interacting risk, and cascading events [36,37], but recently it has been pointed out that it could be an oversimplification and it could also decontextualise the problem [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], how one can study the processes that could cause blackouts and trigger cross-scale failures in power grids [39].

Networked infrastructure was portrayed in both its functional and social domains, including hardware, services, and the secondary and tertiary effects of disruption [40]. 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 [37].

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 [41]. In political analyses, although the presence of cascading effects was seen as a driver that could explain the scale of crises, but it remained marginal to any broader considerations of resilience to extreme events with cross-border dimensions [3,42]. The ecological debate focused on the implications of cascading risk for climate by associating it with complex causal chains, non-linear changes and recombination potential. The question of how to manage such crises was not solved [4].

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 [38,43]. 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 towards 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 [44–46]. Improved technology stimulated a new phase in modelling 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 [47,48]. In order to understand both random failures and terrorist attacks on lifelines, critical factors began to be ranked [32,49]. Attempts were made to assess cascading disruptions on a cross-national basis [31,50]. 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 adopted a more practical approach [51]. A few of the official scenarios tackled the loss of power supply caused by non-conventional triggers such as solar storms, but, in everyday reality, practice was still distinguished by a lack of buffering strategies and well-codified contingency plans [52].

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, decentralisation and greater empowerment were sought [52]. However, guidelines for the adoption of coherent mitigation actions are still not available. In this sense, the Sendai Framework for Disaster Risk Reduction can be regarded as a first step [8]. 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 the Seventh Framework Programme and Horizon 2020, other drivers of research have emerged. A couple of citations possible? Assessment and modelling of cascading failures in networks have been complemented by greater attention to the strategies that are required when disruption happens. In particular, it has been proposed that 'cascading risk' should distinguish between 'cascading effects' and 'cascading disasters', considering that, as time progresses, non-linear escalation of a secondary emergency could become the main centre of crisis [10].

This approach has shifted the focus of interest to the wider context of policy making and emergency management. First, it has begun to merge the literature on the loss of services with that on other possible drivers of escalation such as NaTech events, considering that up to 5 per cent of industrial accidents are caused by natural triggers that involve hazardous facilities [53]. In practice, this has been shown up by gaps in 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 [54]. Secondly, in order to increase the effectiveness of deployment and the organization of procurement in disaster relief, new datasets are needed. The analysis of different case studies suggests that the disruption of critical infrastructure can impact the logistics of emergency relief [46]. It also has the potential to orient international aid in order to rectify a shortfall of emergency goods and expertise caused by the disruption [55]. Finally, it has been pointed out that cascading risk may require a change in methods of scenario building and contingency planning. The flexibility of response can be increased by considering possible escalation paths that are common to different categories of triggering event [56]. This approach is complementary to the perspective of broad impact-tree analysis [57]. Shifting from a focus on hazards to one on vulnerability assessment enables one to recognise 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 [58]. 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 and scenario building [59]. 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

This paper has given a brief overview of compound, interacting, interconnected and cascading risks, and has defined their most important differences and complementarities. These relationships are shown in Figure 1, which is intended as a synthetic framework for use in future studies.

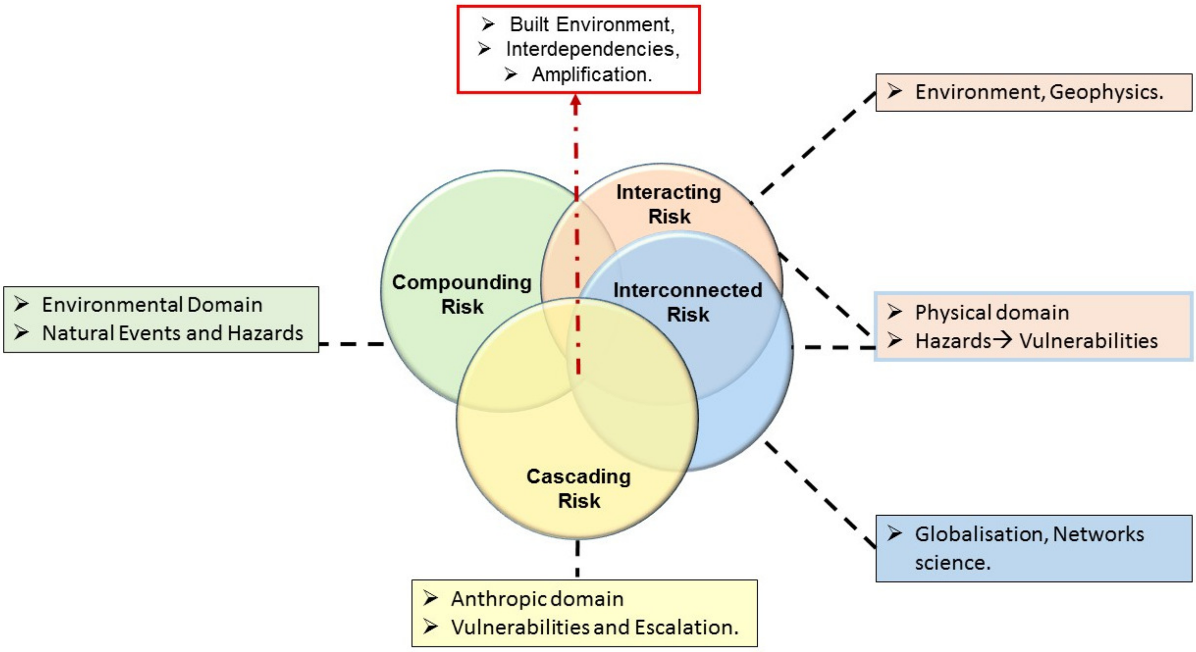

Figure 1. A framework for compound, interacting, interconnected and cascading risks

The overlapping areas described in this paper are shown in the top box of the figure. In other words, the framework has the following attributes:-

- *It includes a reference to the built environment*. This point could be referred the flexible use of existing definitions, such as in case of compounding risk where the strict definition by IPCC [12] has not always been adopted. This sentence seems out of place and does not have adequate meaning. There is a vagueness in the early use of concepts such as 'cascading risk'. There is also a lack of inter-agency agreements [37]. 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.

It includes elements of interdependencies. On the one hand, this leads to problems such as the oversimplifying of ideas such as the "toppling dominoes" metaphor [10]. On the other, it makes some progress towards integrating multi-disciplinary research on the anthropogenic dimension of disasters [13,18,24,25].

It points 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 [2,6,56]. The identification of amplification dynamics may reflect the cross-disciplinary manifestation of increased complexity at the system level.

In relation to the literature discussed in the previous sections, Figure 1 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 and casual chains. They focus on the area in which hazard

interacts with vulnerability to create disaster risk. Interacting risk may refer rather more to the environment and to disciplines such as geophysics, while interconnected risk tends to be used more often in network science and in studies of global interlinkages.

- *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 Figure 1. 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 [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" [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 cascading effects on society were subject to non-linear 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 the 11th March 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 [10,61]. First, an earthquake that triggered a tsunami represented interacting risk, which affected highly coupled infrastructure (interconnected risk), and provoked a wide range of non-linear secondary emergencies, such as the extensive loss of vital services and the creation of NaTech events (cascading risk). Secondly, the earthquake triggered a small and localised landslide (interacting risk) that cut off the Fukushima power plant from the main electric grid (interconnected risk), exacerbated existing vulnerabilities at the site and led to a full-blown nuclear meltdown (cascading risk). In both cases, the disruption of critical infrastructure orientated the progress of emergency relief towards mitigating the escalation of secondary emergencies [55], 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 [61].

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 [56,62]. 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 29th October 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 US 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 non-linear manner. While the emergency responders had to tackle leaks from refineries and chemical plants, or fires in houses, the President of the USA 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 [63] attributed around 50 deaths to the joint effect of extended power outages and cold weather (interaction of compounding and cascading risk).

6. Conclusion

In conclusion, it is hoped that the adoption of a common framework for compound, interacting, interconnected and cascading risk may support a better visualization and understanding of high-impact events. This 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 [1,6,7,23,52,59]. 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.

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. 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 such as scenario building and the broadening of impact trees. 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 need to be addressed in the furtherance of disaster risk reduction.

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