



The state of knowledge on disaster risk

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IRDR is an international scientific programme under co-sponsorship of the International Science Council (ISC) and United Nations Office for Disaster Risk Reduction (UNISDR) and with support from China Association for Science and Technology (CAST) and Chinese Academy of Sciences (CAS). Started in 2010, the Programme has been pioneering in the promoting international and interdisciplinary studies on DRR and has made its contributions through scientific publication and policy papers as well as dialogue toward shaping international agenda in the understanding disaster risks, bridging science and policy gaps and promoting knowledge for actions, all required in the Sendai Framework for Disaster Risk Reduction 2015-2030 (SFDRR) and its top priorities. Over time, the scientific agenda of IRDR has attracted many international renowned expertise and institutions. IRDR community is now, institutionally speaking, characterized by its strong Scientific Committee and six thematic working groups, thirteen IRDR national committees (IRDR NCs) and one regional committee (IRDR RC), sixteen international centres of excellence (IRDR ICoEs), a group of some one hundred fifty Young Scientists (IRDR YS) and a broad partnership with national, regional and international institutions working for SFDRR.

This Working Paper Series is thus specially made to facilitate the dissemination of the work of IRDR NCs, ICoEs, YS and institutions and individual experts that IRDR considers relevant to its mission and research agenda, and of important values for much broader range of audience working in DRR domains. As one will notice, all working papers in this series has anchored their relevance and contributions of their work toward SFDRR, IRDR, SDGs and Paris Agreement on climate change. It is the hope of the authors of the working papers and IRDR that this working paper series will not only bring new knowledge, experience and information toward disaster risk reduction, but also helped build better coherence of DRR with the mainstream agenda of UN today toward inclusive, resilient and sustainable human societies.

Team of IRDR-IPO

The state of knowledge on disaster risk

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Published in 2022 by Integrated Research on Disaster Risk (IRDR), an interdisciplinary body of the International Science Council (ISC).

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Cover photo: https://unsplash.com/photos/2jW-z_DQDpQ

Design: Fang LIAN

Edit: Qunli HAN, Fang LIAN

Printed by IRDR

Printed in Beijing, China

Citation of this publication: Tran, M. and Boyland, M. (2022). The State of Knowledge on Disaster Risk. *IRDR Working Paper Series*, 24 pages. doi: 10.24948/2021.10

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1 Introduction

Disasters have been studied for centuries, but ‘modern’ disasters studies have arguably developed over the past half century or so. For instance, the journal *Disasters* began publication in 1977. During this period, disaster knowledge and practices have evolved from an emergency management framing to a broader perspective encapsulated by ‘disaster risk reduction (DRR)’ (Davis 2019). Priority and focus have shifted from responding to disaster events (i.e. an ex-post approach) to proactively managing and reducing risks (i.e. an ex-ante focus). Risk is widely accepted as a function of hazards, exposure and vulnerability. Such a framing is foundational to how disaster processes are conceptualized, particularly in Western scholarship.

Global policy developments in disasters (including emergency preparedness, disaster management, and DRR) can be traced from the 1990s UN International Decade for Natural Disaster Reduction, to the Yokohama Strategy for a Safer World adopted at the first World Conference on Natural Disasters in 1994, to the Hyogo Framework for Action (2005-2015) adopted at the second World Conference on Disaster Reduction in 2005, and currently to the Sendai Framework for Disaster Risk Reduction (2015-2030), adopted at the third World Conference on Disaster Risk Reduction in 2015. The names of these events and processes alone suggest a shift in thinking of disasters as natural events (or ‘acts of God’) to acceptance that man-made risk- and development-related decisions and actions determine the disaster impact. This shift has enabled the imperative to reduce risk to grow in priority on global policy fronts - not least in relation to climate change.

Crucial to progress in understanding and managing disaster risk is ‘disaster science’, which spans both natural and social sciences, and cuts across various disciplines, including environmental, earth, economics, geography, engineering, sustainability, ecology, sociology, political science, law, education, health, anthropology and other sciences, as well as their specific branches. As science and research in these areas continue to grow, multiple agendas, coalitions and processes have emerged from global to local levels, around which researchers coalesce with a hope to inform policies.

Recognizing the knowledge and impact of existing networks and programmes, the Integrated Research on Disaster Risk (IRDR) programme seeks to establish a new research agenda to guide the development of disaster science in the coming decade. In the face of growing risks, the agenda will facilitate inter- and trans-disciplinary knowledge production, and contribute to the transition to a peaceful, safe, equitable and sustainable world within the context of DRR.

As part of the development process for this new research agenda, this paper provides context, baseline information and a ‘state of knowledge’ on disaster risk science. Specifically, this paper aims to i) trace the development and evolution of relevant concepts and frameworks, ii) outline the application of relevant methods, tools and approaches, and iii) highlight emerging gaps in data, information, and knowledge.

2 Methods

The methodology for this paper is two-fold. Firstly, an online survey was designed and disseminated across IRDR networks (i.e. Science Committee members, International Centres of Excellence, and National Committees) and members of the Research Agenda Core Group to gather recommended literature. The survey received 15 responses with a total of approximately 200 (excluding duplicates) journal papers, edited books and grey literature reports recommended for inclusion in this review.

Secondly, literature was gathered and reviewed from online sources, using the Scopus database, accessed through Chulalongkorn University, Thailand. The following ‘Title-Abstract-Keyword’ search string was used to search for relevant literature in the advanced search function of Scopus:

TITLE-ABS-KEY ((disaster OR emergency OR emergencies OR crisis OR crises OR hazard*) AND (resilien* OR vulnerab* OR adapt* OR mitigat* OR prevent* OR prepar* OR recover* OR reduction OR respond OR response* OR sustainability OR sustainable))*

Limiting the results to publications from the past 50 years, i.e. 1970-2020 (inclusive), the search returned over 542,632 results. The search was further narrowed down by excluding publications from the subject area of ‘Medicine’ which reduced the number of results to 301,333. By way of comparison, an earlier review of disaster science literature found over 27,000 papers published between 2012 and 2016 (Elsevier, 2017).

Figure 1 below shows how the number of academic publications has accelerated in recent years. For instance, there are 30,579 results for 2020 alone - more than the results for 1970-1997 combined (29,362 results in 28 years).

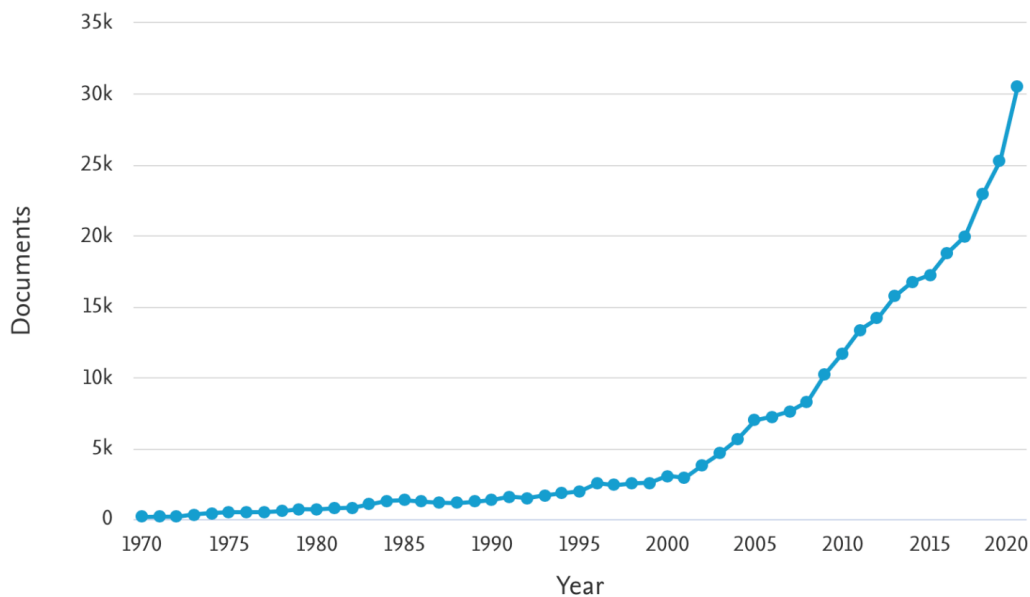


Figure 1. Literature search results per year (1970-2020).

Given the large number of results and non-specificity of the search string, it is also interesting to note the scientific disciplines from which the results are derived. Figure 2 shows the top three to be Engineering (17%), Social Sciences (12%), and Environmental Science (12%). It is noted that scientific discipline categorization is according to Scopus literature results tagging.

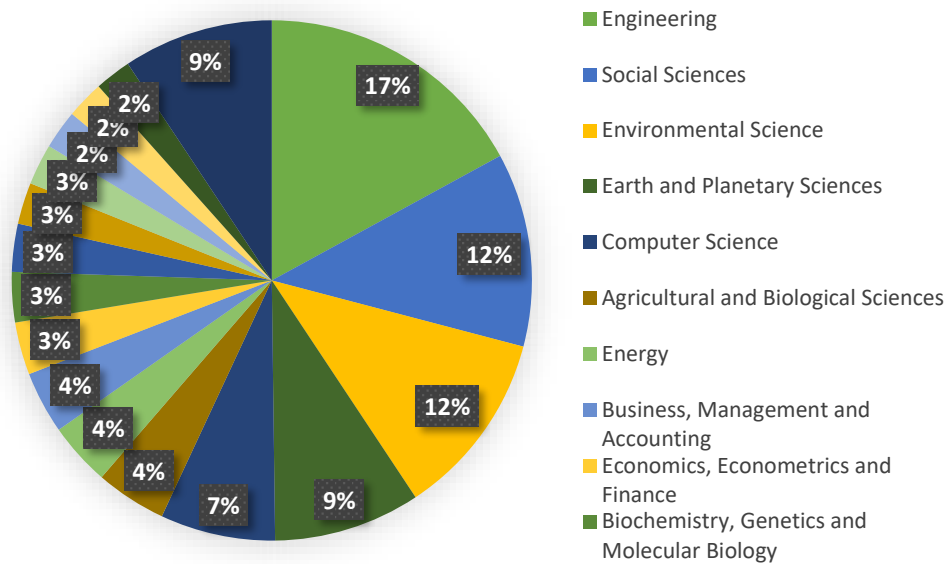


Figure 2. Literature search results by scientific discipline (1970-2020, excluding 'Medicine').

Results by region, as shown in Figure 3 below, given an indication of where scientific publications are coming from. The headline finding is that there is a relatively even split between Asia-Pacific (31%), Europe (31%) and the Americas (28%), but only 3% of results are from Africa. Three countries dominate the publication of literature - United States (21.8%), China (9.8%) and United Kingdom (6.4%).

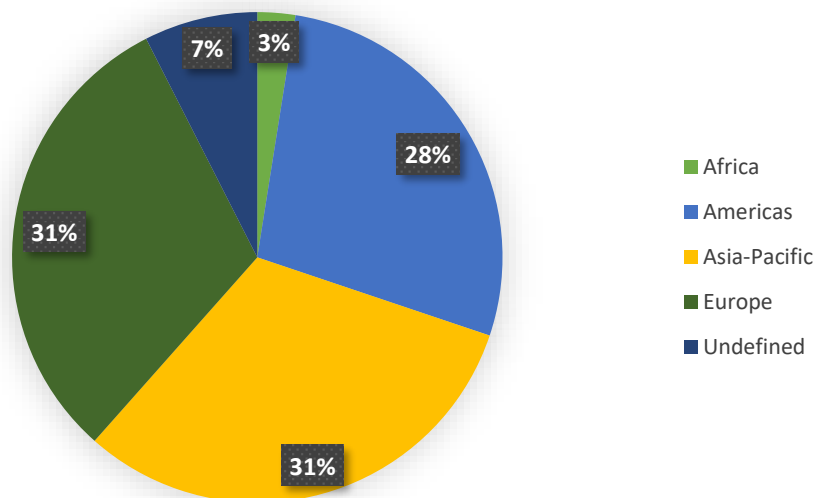


Figure 3. Literature search results by region of origin (1970-2020, excluding 'Medicine').

As demonstrated by the large number of results and their disciplinary origins (e.g. biochemistry, chemistry), it is clear that not all results are relevant for the aims of the paper, and the wider research agenda. Therefore, results were further restricted to 2010-2020, to align with the period of the IRDR, which produced a total of 206,515 items.

Results were then sorted by ‘most cited’ in order to prioritize, and titles and abstracts were screened to produce the top 150 relevant results, which were the basis for this review. These results were supplemented by both the survey results and an additional search in Google Scholar and Google for existing systematic literature reviews of DRR and related themes (i.e. resilience, climate change adaptation and sustainable development).

This paper is not without methodological limitations. The scope is English-language publications only, therefore the paper is based on predominantly Western scholarship. It was also not in the scope of this paper to systematically review all bodies of literature relevant to disaster risk science. Rather, the paper synthesizes and assesses the current state of knowledge around key themes and concepts related to disaster risk science (and DRR more broadly), as well as adaptation, resilience and sustainability. Findings from the review will be used to develop recommendations for future research, policy and implementation.

3 Concepts and frameworks

This section traces the development and evolution of key concepts in disaster studies in three groups, following Solecki et al. (2011). The first group includes the concepts of hazard, exposure, and risk, generally concerning the likelihood of a disaster event. The second includes impact parameters - resilience, vulnerability, and justice - which reflect and inform how social groups experience the impacts and outcomes of a disaster. Lastly, societal responses are reviewed, including disaster governance, adaptation and its integration with DRR, and transformation. These concepts and grouping are not comprehensive, and the review does not attempt to capture their entire history. Rather, the aim is to provide an overview of key concepts in the collected literature and how their evolution is shaping trends in disaster studies.

3.1 Hazard, Exposure and Risk

The word ‘risk’ in disaster studies necessitates enquiry into the broader context of disaster (i.e. risk without disaster) and underlying causes. Research increasingly recognizes disaster risk as a process rather than an event or outcome (Davis 2019). It is a function of hazard, exposure and vulnerability. This formulation promotes interdisciplinary analysis of the natural (i.e. hazards, environment) and the social (i.e. vulnerability, capacity) dimensions of risk (Wisner 2004). As shown below, knowledge on the more ‘natural’ dimension of risk has evolved to not only reflect the multiplicity and systems characteristic of risk drivers and how they interact, but also recognize the important and inseparable role of social processes.

3.1.1 Hazard and exposure

Research on both hazard and exposure has increasingly recognized that these are not static, linear conditions or measures. Rather, they involve complex processes intertwined with multiple natural and social systems. Early definitions of hazard, for instance, were limited to events and phenomena that are well defined temporally and spatially, overlooking processes such as creeping environmental changes (Kelman 2018). Over time, disaster scholars have come to realize the complex, dynamic nature as well as the social construction of hazards. Human activities can contribute to both the creation of hazard and how it is experienced (Wisner 2004). Hazard is now generally defined as processes, phenomena and human activities that have harmful impacts on health, life, property and social, economic and environmental conditions (UNDRR and ISC 2020).

Yet, despite the recognition of its complexity, much emphasis remains on more quantifiable and less complex hazards. Seeking to clarify the scope of all hazards, a recent study classifies a total of 302 hazards into eight clusters: meteorological and hydrological hazards, extra-terrestrial hazards, geohazards, environmental hazards, chemical hazards, biological hazards, technological hazards, and societal hazards (UNDRR and ISC 2020). The study acknowledges the exclusion of “complex human activities and processes where it was difficult to identify a single or limited set of hazards, compound and cascading hazards, and underlying disaster risk drivers (such as climate change)” (UNDRR and ISC 2020, p.9). This points to the need for further research and different ways of studying hazards without reducing them to simple natural phenomena.

In places that are prone to hazards, the presence of people and assets gives rise to exposure. A major driver of exposure are existing social institutions and development processes, which influence where communities settle and infrastructures are developed (Cardona et al. 2012). The notion of ‘multiple exposure’ expands the scope of susceptibility, emphasizing the potential impacts of various ongoing challenges, such as climate change, globalization, poverty, epidemic, earthquakes, landslides and more (Kelman et al. 2015).

3.1.2 Risk

Research on risk also recognizes the connected and complex social-ecological systems within which risks are created and manifest - something which has been recently recognized outside of academia, such as in the Global Assessment Reports on DRR (UNDRR 2019). Numerous concepts have emerged as alternative framings to capture the dynamic nature of risks in ‘modern’ systems, such as compound risk, interacting risk, systemic risk, cascading risk, ‘Natech’ risk, and Anthropocene risk, among others.

One definition of disaster risk is the “potential loss of life, injury, or destroyed or damaged assets which could occur to a system, society or a community in a specific period of time, determined probabilistically as a function of hazard, exposure, vulnerability and capacity” (UNDRR 2017). Disaster risk results from the interplay between the human society and the natural environment, or the intricate relationship between natural events and people’s susceptibility to its harmful impacts (Wisner et al. 2012). Risk is also used as a

synonym for both the probability of harmful effect or the magnitude of expected undesirable consequence (UNDRR 2019).

The notions of systemic risk and Anthropocene risk focus on interdependency as a driver of risks. Adopted from the financial management field, systemic risks are those rooted in interconnected components of a whole; poor understanding of their interactions may result in the collapse of the total system. Systemic risks tend to be global, non-linear, inter-connected and stochastic in nature (Lucas et al. 2018; Renn 2020). Anthropocene risk relates the human-environment interactions that inform systemic risks. Anthropocene risk accounts for how anthropogenic changes, cross-scale linkages and global tele-coupling processes interact with traditional risks (Keys et al. 2019). As a conceptual tool, it highlights the need for a new governance architecture that better addresses challenges that are unique to the Anthropocene (Keys et al. 2019).

Not only are risks intertwined with larger systems, they also interact and collide. There are four types of risk based on the domain in which interactions take place: compound risk, interacting risk, interconnected risk and cascading risk (Pescaroli and Alexander 2018). Alternatively, when classifying by the nature of the interactions between hazards, four different typologies of compound events are identified, i.e. preconditioned events, multivariate events, temporally compounding events and spatially compounding events (Zscheischler et al. 2020).

Furthermore, understanding risk also requires considering the social, political and cultural construction of risk. According to Thomalla et al. (2015), worldviews and values, informed by socio-cultural contexts, influence people's behavior and practice in response to hazard and thus their level of risk (Thomalla et al. 2015). Yet, risk may also be framed as processes where people deal with uncertainty. Responses to risk depend on how people interpret uncertainties, and this interpretation is mediated by cognitive heuristics, experience, learning, and trust (Eiser et al. 2012).

3.2 Resilience, Vulnerability, and Justice

The concepts of resilience, vulnerability and justice concern the 'social' dimension of risk, shaping the extent to which communities are susceptible and how they cope with and respond to disasters. The literature documents how these concepts have emerged and or evolved through debates and critics over time. Increasingly, disaster scholarship has directed its attention to what *underlies* the factors determining who is resilient, vulnerable or prone to injustices in the first place.

3.2.1 Resilience

While many resilience definitions exist and the word has a long history (see Alexander 2013; Manyena 2006; Zhou et al. 2010), Holling's (1973) definition is often credited as one of the earliest and most influential for the study of disasters. It characterizes resilience as "a measure of the ability of ecological systems to absorb changes of state variables, driving variables, and parameters, and still persist" (Holling 1973, p. 18). Coming from the field of ecology, Holling's work first related resilience to a systems theory approach.

Tiernan et al. (2019) summarize resilience to refer to system attributes i) maintaining stability, ii) recovering, and iii) adapting. Overall, many consider it a ‘chapeau’ or ‘umbrella’ term which refers to different system responses to stresses, shocks and changing conditions (Tiernan et al. 2019).

While a popular concept and framework in disasters and related themes, critics argue that resilience is now serving more as a ‘policy buzzword’ than a science or paradigm (Comfort et al. 2001; Reghezza-Zitt et al. 2012). It does not necessarily challenge the status quo and advance our understanding of issues related to risk, vulnerability, poverty and marginalization (Alexander 2013). The term has been critiqued for overlooking power asymmetries and assuming the existence of a desired resilient state (Brown 2014; Gaillard 2010). In response, the ‘equitable resilience’ framing, among others, has emerged, emphasizing social and power relations (Matin et al. 2018).

3.2.2 Vulnerability

Vulnerability has evolved as a complex concept in disaster risk science, also with varying definitions and uses (Cutter 2003). By one definition, it is “*the predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm or damage, and lack of capacity to cope and adapt*” (IPCC, 2014, p.128). By another, vulnerability refers to “the conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards” (UNDRR 2017). With the UNDRR’s definition putting more weight on societal factors, the IPCC’s definition is critiqued for a rather narrow view that fails to address root causes of vulnerability (Hore et al. 2018).

Vulnerability, however, must also be understood as a process, shaped by related relationships and temporal dimensions (Kelman 2018). Multiple definitions of and strands of research on vulnerability, beyond UN glossaries, recognize the social processes that influence vulnerability via the capacities to cope or protect oneself, the situations of vulnerability that people move into and out of over time, and the social construction of vulnerability (Wisner 2004). Wisner et al. (2012) use “the progression of vulnerability” as a framework to explain vulnerability in the context of disaster risk by relating root causes, dynamic pressures, fragile livelihoods, unsafe locations and hazards.

3.2.3 Disaster justice

An expansion of the concept of justice, along with environmental justice and climate justice, disaster justice concerns social inequality, power distribution, rights, fairness, and humans’ impact on the environment. Disaster justice is about fairness in policies addressing catastrophic hazards and disasters (Verchick 2012), and “a moral claim on governance” (Douglass and Miller 2018). It is distinctly shaped by i) a moral obligation in the context of the Anthropocene, ii) the political nature of disaster governance, iii) everyday inequality that informs vulnerability, and iv) the role of recognition and empowerment in disaster governance (Lukasiewicz 2020). Disaster justice foregrounds the importance of participatory and inclusive modes of disaster governance, collective

agency and just distribution of resources that address underlying causes of vulnerability (Douglass and Miller 2018). Uncertainties and compound disaster risks, as well as failure to adopt nuanced perspective on resilience, can further vulnerability and constitute a justice issue, which must be understood in the context of power relations (Parthasarathy 2018).

3.3 Societal responses to risk

This section discusses societal responses to risk, namely: disaster risk governance, adaptation and its integration with DRR, and transformation.

3.3.1 Disaster risk governance

Disaster risk governance concerns the engagement of actors outside the government in DRR, particularly local and marginalized groups across different scales (Gall et al. 2014a). Their roles are especially important when governmental efforts are not enough to respond to disasters or reduce risk. Central to disaster governance are the principles of accountability and transparency, highlighting a rights-based perspective to disaster- and risk-related decision-making (Gall et al. 2014a).

The evolution of how we understand risk and its interconnected nature has also prompted new approaches to risk governance. For instance, governance cannot be understood without the context of globally networked environmental risks. The interconnected nature of risk means that disaster risk governance is also shaped by international institutions, international norms and legal mechanisms, transboundary and cross-sectoral institutions, as well as innovation and legitimacy issues (Galaz et al. 2017). Developed from socio-ecological systems thinking, adaptive governance offers an alternative model for managing complex socio-environmental issues such as disasters through multi-stakeholder platforms, with a focus on collaboration, participation, learning and self-organisation (Djalante 2012). In addition, scholars have increasingly advocated for integrating disaster governance with climate change adaptation and sustainable development (Gall et al. 2014a).

3.3.2 Adaptation

The climate change adaptation (CCA) literature is rooted in the body of research on responses to environmental change and has evolved as a key concept in risk and hazard studies (Bassett and Fogelman 2013; Owen 2020). Similar to disaster studies, however, the adaptation literature covers a wide range of disciplines and fields, from tourism to urban planning, with diverse traditions and methodologies (Berrang-Ford et al. 2015).

While the term is widely used, scholars emphasize the multiplicity of ways in which adaptation is conceptualized, operationalized and monitored. Its understanding is contingent on “the multiple and intersecting ways in which people know, experience and deal with climate change” (Owen 2020, p.2). Attempts to measure progress or track adaptation outcomes also prove difficult because of the different ways that adaptation is conceptualized and operationalized (Klöß and Nunn 2019).

Within the literature reviewed, several papers explicitly define adaptation. The definitions, listed in table 1 below, vary in their framing, from capability (focusing on human agency) and action (focusing on intentional responses) to systems (focusing on larger systems). The list of definitions is in no way comprehensive. Rather, it exemplifies the wide range of framing approaches to adaptation.

As suggested by Owen (2020), adaptation can only be meaningful as a concept when its definition is well defined, articulated and contextualized in the specificities of each case and initiative. Reversely, interpretation of any adaptation analysis needs to be grounded by the specific conceptualization of the term.

Orientation	Definition	Source	Used in
Capability oriented	“The ability to respond to challenges through learning, managing risk and impacts, developing new knowledge and devising effective approaches”	International Union for Conservation of Nature (IUCN)	Shaffril, Krauss, and Samsuddin (2018)
Action oriented	“Intentional responses to a climate change impact with a view to reducing an actor’s vulnerability and increasing their resilience”	Eisenack and Stecker (2012)	Klöck and Nunn (2019); Lwasa (2015)
Systems oriented	“Adjusting behaviors, actions, and decisions within biological, social, and built systems in response to climatic changes”	Smit and Pilifosova (2003)	Owen (2020)
	“Human-driven adjustments in ecological, social or economic systems or policy processes, in response to actual or expected climate stimuli and their effects or impacts”	United Nations Framework Convention on Climate Change (UNFCCC) (2014)	
	“The process of adjustment to actual	Agard et al. (2014)	

	<p>or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects”</p>		
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3.3.3 DRR-CCA integration

As both DRR and CCA are concerned with questions of vulnerability, resilience, risks, hazards, and uncertainties, integrating DRR and CCA has been gaining ground in research and policy (Hore et al. 2018; Islam et al. 2020; Kelman 2015).

Climate change and disasters are interlinked: Climate change can drive or diminish hazards while also influencing vulnerability (Hore et al. 2018; Kelman 2015). Climate change mitigation and adaptation initiatives themselves influence disaster risk (Hore et al. 2018). Reasons for integrating CCA and DRR include sharing resources and data, avoiding duplicated efforts and missed opportunities as well as complementing sustainable development efforts (Birkmann and von Teichman 2010; Hore et al. 2018; Kelman 2015). Moreover, as DRR has a longer history of being embedded within development and evolving from the hazard paradigm to the vulnerability paradigm, failure to integrate and encompass DRR knowledge and practice in CCA has led to CCA being a scapegoat for DRR and developmental failures (Hore et al. 2018).

The siloed characteristics of disaster and climate change prevail (Birkmann and von Teichman 2010; Hore et al. 2018; Islam et al. 2020). For example, while both DRR and CCA seeks to reduce vulnerability, the two fields have not converged on a mutual definition of the term. Demarcations have been ingrained through long-term processes and political debates, hence the separate agreements of 2015 that render merging them undesirable (Kelman 2015). Moreover, differences in governance, scales, knowledge and norms as well as the lack of funding coordination and political influence present great challenges against DRR-CCA integration (Birkmann and von Teichman 2010; Islam et al. 2020).

In order to increase synergistic effort, the research community has pushed for the conceptual integration of CCA as a part of DRR within the larger context of sustainable development (Birkmann and von Teichman 2010; Hore et al. 2018; Kelman et al. 2015). Birkmann and von Teichman (2010) suggest integrating CCA into each DRR cycle of mitigation, preparedness, response and recovery and reconstruction. Furthermore,

scholars have also explored DRR-CCA integration from a governance perspective, through which Forino et al. (2015) propose a conceptual framework linking social, market and state actors through co-management, public-private partnership and private-social partnership. Alternatively, Linnerooth-Bayer and Hochrainer-Stigler (2015) adopt the financing lens and argue that risk financing and risk reduction, as subsets of disaster risk management, can target different layers of risk, thus contributing to and complementing CCA.

3.3.4 Transformation

Transformation is a relatively new concept in disaster studies, having received more attention in the climate change literature. Transformation is defined by the IPCC as “a change in the fundamental attributes of natural and human systems” (IPCC 2014) but remains absent from UNDRR terminology. Within disaster studies, transformation is gaining popularity as it problematizes the relationship between DRR and development and explores the ability of DRR to alter development trajectories (Thomalla et al. 2018). By addressing root causes of vulnerability, transformative DRR is a pathway towards sustainable development. A review of the transformative DRR literature identifies three clusters of transformation research, namely i) drivers of transformation, ii) technical and adaptive elements of social learning, and iii) case study of transitions (Gall et al. 2014b). Here, resilience and adaptivity are drivers of transformation.

In addition to transformation through DRR, the literature has also explored transformation *of* DRR. For example, eco-DRR transforms DRR efforts by capitalizing on the synergy between biodiversity conservation and DRR (Monty et al. 2016). Research and knowledge production has also received attention from transformation scholars, who advocate for fundamentally altering sustainability science towards a truly transdisciplinary field and change co-creation (Shrivastava et al. 2020).

4 Relevant methods, tools and approaches

This section highlights emerging trends in methodologies and tools that support the studies and assessment of hazard, exposure and risk, as well as frameworks and approaches to analyze vulnerability, resilience and justice. It also includes a discussion on the science and technology literature within disaster studies and DRR.

4.1 Hazard, Exposure and Risk

In large part, efforts to measure and assess risk have narrowly focused on physical hazards and economic impacts (Aitsi-Selmi et al. 2016; Rahman and Fang 2019). Hazard analysis and assessment are often subject to a “still widespread reductionist approach” (Fakhruddin et al. 2020, p.226), overlooking the complex and dynamic nature of hazard as processes. Given recent shifts in the definition and framing of risk and hazard, as outlined above, scholars have applied and promoted new tools and methods to assess and analyze systemic or compound risk and hazard.

Approaches that account for the complex nature of hazards and risks and social dimensions of vulnerability are only emerging and still need more attention (Aitsi-Selmi et al. 2016; Rahman and Fang 2019). This research highlights three approaches in risk assessment that are shifting away from the conventional focus on physical hazard and economic impact assessment: i) approaches that address compound risks and multiple drivers of risk, ii) scenario modeling methods that account for socio-economic factors, and iii) alternatives to probabilistic modelling in the context of uncertainties.

First, evolving understanding of the interconnected, systemic and compound characteristics requires a shift in how risk is assessed. For example, Zscheischler et al. (2018) call for new assessment and attribution frameworks that explicitly address compound events using an impact-centric perspective and bottom-up methodology in order to identify underlying drivers and processes. Leonard et al. (2014) similarly highlight the need for a comprehensive approach to modelling compound events, which engages diverse stakeholders, the nature and amount of physical variables, spatial and temporal scales as well as the strength of dependence.

Second, methods for futures study and scenario modeling have also contributed to enhanced disaster risk science by incorporating social and economic scenarios. Dottori et al. (2018) use a multi-model framework to estimate human losses, direct and indirect economic damages and welfare losses from river flooding under different temperature and socio-economic scenarios. A total of 108 scenarios of environmental change, taking into account two socio-economic scenarios were used to quantify future flood losses in 136 major cities by 2050 and estimate the required defence standard to address increased risk (Hallegatte et al. 2013).

Third, traditional risk assessment approaches, for instance in climate science, largely avoid the discussion of low likelihood events, which are by their very nature deeply uncertain, yet could bear the highest risks and impacts. Probabilistic analysis of physical hazards is challenged by human impact on climate and deep uncertainties. Event-based storylines, which are physically self-consistent unfolding of past events, or of plausible future events, have been proposed as a way of articulating the risk perspective in such cases, with an emphasis on plausibility rather than probability (Hazeleger et al. 2015; Shepherd et al. 2018). This concept links directly to common practices in DRR using “stress-testing” for disaster preparedness based on events that are conditional on specific (plausible) assumptions.

4.2 Resilience, Vulnerability, and Justice

Methods to study resilience, vulnerability and justice highlight the importance of scale, particularly the role of socio-economic systems and different actors at different scales of governance. At the community level, various frameworks and tools have been developed to assess community resilience. Two prominent and well-cited frameworks include Norris et al. (2008) model of four components of resilience - economic development, social capital, information and communication and community competence. The second one is the Disaster Resilience of Place (DROP) model (Cutter et al. 2008). The DROP model

integrates system attributes with inherent community resilience and vulnerability and enables the consideration of infrastructure, institutional and ecological components. The DROP model was later expanded with a series of indicators for assessing community resilience - social, infrastructure, institutional, economic, and community resilience (Cutter et al. 2010). The thinking behind this model has subsequently been built upon and expanded in several studies, such as one on the connection between wellbeing and resilience to drought in Southern African countries, which used a capacity approach with more weight on the social dimension of community resilience (Brown 2014).

For vulnerability analysis, Birkmann et al. (2015) call for the need and potential to link global and local scenario building for better vulnerability analysis. Qualitative scenario assessment using the global WorldRisk Index and local participatory scenario development at the community level demonstrates how vulnerability trends and patterns can be identified and analyzed at different scales and through different lenses for complementary outcomes (Birkmann et al. 2015).

Justice research often adopts the human capabilities and governance approaches. In the context of disaster, Amartya Sen's human capabilities approach highlights the link between natural hazards and socio-economic conditions, the importance of democratic values, and community's social, built and natural infrastructures (Verchick 2012). Meanwhile, framing disaster justice as a governance question highlights procedural justice and the roles of different actors in disaster decision making from a longitudinal and multi-scalar perspective (Douglass and Miller 2018).

4.3 Science and Technology

Given the increasing complexity around risk, hazard and vulnerability, as well as depth of knowledge and understanding around risk reduction, science and technology will be essential to informed decision making and innovative solutions to critical challenges. While it is imperative to harness the power of science and technology in all forms, ensuring no one is left behind in the process will be crucial to long-term sustainability.

Science and technology play an important role in DRR. It has supported the development and implementation of major global frameworks and initiatives and will continue to do so, as recognized in the Sendai Framework for DRR 2015-2030 as well as the Science and Technology Conference on the Implementation for the Sendai Framework (Aitsi-Selmi et al. 2016). The science and technology community has expanded and shifted from operating as a closed group to playing a more collaborative, co-productive role along with other sectors and in multi- and trans-disciplinary arenas (Shaw 2020).

Six scientific functions have been identified in the context of DRR: assessment of data and knowledge, synthesis of evidence, scientific advice to decision makers, monitoring and review of new information, communication and engagement across sectors, and capacity development for using scientific information (Aitsi-Selmi et al. 2016). Relatively, Priority 1 of the Sendai Framework in understanding risk sees the highest level of engagement and

largest role for science and technology compared to the four remaining priority areas (Shaw et al. 2016).

A technology-driven approach to DRR has seen an increase in the use of drones, artificial intelligence, robotics, 3D printing, virtual reality and other advanced technologies in both practice and research, such as loss estimation, emergency data management, search and rescue operations, and research and education (Shaw 2020). Remotely sensed data, real time digital data as well as geo-information tools and techniques offer rich inputs for improving the assessment and understanding of complex risks (Rahman and Fang 2019). GPS, GIS and hand-held portable devices are some of the tools available to complement crowd-sourced data (Aitsi-Selmi et al. 2016).

5 Emerging gaps in disaster risk science

This section discusses emerging gaps in disaster risk science, which can be taken up in DRR research and action, along three distinct strands: i) equity and diversity in DRR knowledge production; ii) social justice in DRR; and iii) data, tools and approaches for DRR.

5.1 Equity and diversity in DRR knowledge production

The formulation of risk as a function of hazard, exposure and vulnerability is influential and widely accepted in disaster studies. However, this and many other dominant risk framings are derived from Western scholarship and ontologies. In a global sense, there is no single view of what risk is and how it is formulated. More diverse epistemologies and ontologies in understanding risk are needed (see Gaillard, 2019).

To fill this gap, more diverse voices from different geographical regions and local knowledge need to be included to capture the diverse epistemologies and ontologies related to risk. Participatory, locally-led research initiatives as well as indigenous, traditional, bottom-up knowledge and practices will be critical to ensure that science is grounded on lived experiences and tailored to actionable change (Fatorić and Seekamp 2017; Gaillard 2019; Kamara et al. 2018). Further effort is needed to empower local researchers, concepts and methodologies and challenge the hegemonic Western scholarship over disaster science (Gaillard 2019). Recognizing and contextualizing risks in everyday cultural, political and social experience should be a priority in future research endeavors.

The literature reviewed covers diverse geographical regions. However, there appears to be a geographical imbalance in terms of both where data are collected and where research outputs are produced. An earlier review of disaster science literature published from 2012-16 found that China, USA and Japan are by far the most prolific countries for publishing scholarly literature (Elsevier 2017). There may be some correlation between scientific output and disaster loss, as research tends to focus on major disaster events and risks with high relevance for the context (e.g. earthquakes and tsunamis in Japan; floods and droughts in China). However, there may still be a disconnect between where

disaster impacts are felt and where research is conducted, particular in low and middle income countries (LMICs) (Elsevier 2017).

Besides research that has a clear regional or geographical focus, there is also an imbalance in terms of thematic focus. For example, most works on cultural heritage adaptation as well as on climate justice are from scholars in Europe and North America (Alves and Mariano 2018; Fatorić and Seekamp 2017). More research on adaptation effectiveness focuses on Asia (dominated by studies on China) and North America (dominated by studies on the U.S.) (Owen 2020). Meanwhile, research in small island developing states (SIDS) tends to focus on Pacific, core and near core islands (Klöck and Nunn 2019).

Similarly, a review of CCA-DRR integration research notes limited geographical range targeting key knowledge gap, i.e. policy integration studies are limited to few countries such as Australia, Thailand, Zambia and Indonesia (Islam et al. 2020). There is not yet substantial research testing different integration frameworks in various contexts and their comparative analysis (Islam et al. 2020).

Furthermore, while science and technology continue to advance and influence DRR, traditional and Indigenous knowledge will remain relevant and critical (Shaw, 2020). It is thus important that the science and technology community collaborates with local communities early on through processes of co-design and co-delivery to ensure the effectiveness, relevance and applicability of outcomes (Shaw 2020). Similarly, it is important to ensure that data collected using advanced technologies and the technologies themselves are accessible to relevant stakeholders and young researchers (Rahman and Fang 2019).

Overall, more research and knowledge production in, on and from developing and underdeveloped countries are needed. While one of the reasons for the imbalance may be the lack of data in remote and under-resourced areas, in every region there appears room for different thematic focuses to grow in the future.

5.2 Social justice in DRR

Social justice and equity remain an understudied area within the literature. Disaster justice is only emerging as a distinctive concept and framing for DRR stakeholders and audiences. Research in this area must not be siloed away from critical thinking in other disciplines; multidisciplinary scholarship is needed in order to generate evidence and affect change (Douglass and Miller 2018). A recent review of climate justice literature emphasizes room for improvement in the definition of climate justice and expansion of the research theme (Alves and Mariano 2018).

Drawing from research on procedural, distributive and interactional justice, Lukasiwicz and Baldwin (2020) propose future research on disaster justice to focus on i) understanding vulnerability and resilience of groups that might not be obviously or visibly vulnerable, ii) tackle rights, responsibilities, accountabilities, values and expectations around disaster management, iii) account for everyday injustices as well as justice issues

across the different phases of DRR, and iv) interrogate the connections between procedural, distributive and interactional justice.

The literature also highlights several areas for future research within adaptation justice. For example, more work needs to be done on political freedoms and transparency guarantees, as well as on the relationship between gender equality, women's freedoms and adaptation (Alves and Mariano 2018). There is also a need for research that analyses justice issues at the regional, national and more micro level as well as cross-scale analysis of justice (Alves and Mariano 2018). Regarding adaptation effectiveness, Owen (2020) finds a big gap in the literature addressing power relations in the distribution of benefits, adaptation process and knowledge production.

5.3 Data, tools and approaches for DRR

Further research is still needed to understand, articulate, and analyze risk in all its complexity and uncertainty. Appropriate indices and metrics are critical to capture the dynamic nature of and interactions among hazard and vulnerability elements (Fakhrudin et al. 2020; Gallina et al. 2016). There are existing tools to identify and aggregate multiple natural hazard types and assess the vulnerability of multiple targets to a specific natural hazard. However, they do not yet account for other climate change impacts, climate-induced hazards, or other types of hazards (Gallina et al. 2016). Fakhrudin et al. (2020) highlight the need to shift towards dynamic vulnerability analysis that accounts for cascading impacts, the temporality of vulnerability, and the complex interplay between coping capacity and sensitivity. Science and technology also need to take into account the complexity of hazards and their interactions (Aitsi-Selmi et al. 2016; Shaw 2020).

More research integrating human behavior, social norms and networks is needed, particularly in risk perception and risk assessment (Eiser et al. 2012). Eiser et al. argue that the role of behavioral science in DRR has received increasing recognition, yet research investigating determinants of human behavior within and across social groups remains superficial. More research on how warning systems and policies are perceived and what makes them effective is also needed. In the same vein, reviewing the literature on global governance in the context of globally networked risks, Galaz et al. (2017) suggest that the current debate on global risk governance overlooks legitimacy, or people's normative evaluation of international decision making. Whether institutional arrangements are deemed legitimate by the public is critical to their effectiveness.

Finally, a gap exists between conceptual studies at the abstract level and research on implementation and outcomes. On increasing coherence between DRR and CCA, for instance, Islam et al. (2020) suggest more research should explore decision-making and policy processes with an emphasis on the role of stakeholders and their power dynamics. More qualitative research using participatory, bottom-up and interdisciplinary approach would also enrich existing knowledge on adaptation interventions and decision-making processes (Fatorić and Seekamp 2017; Shaffril et al. 2018). Further analysis of adaptation finance, implementation action and outcomes (Ford et al. 2011; Klöck and Nunn 2019; Lwasa 2015) is needed.

Overall, while DRR literature is abundant in disciplinary and multidisciplinary works, the complex interplay among risk factors and systemic risks require more co-produced, transdisciplinary knowledge production (Ismail-Zadeh et al. 2017). In addition, DRR research would also benefit from more systematic, longitudinal data on implementation and monitoring, as well as research on the sustainability, longevity and suitability of risk management approaches in each context over the long term. Data on long-term resilience and vulnerability is another gap (Alves and Mariano 2018; Fatorić and Seekamp 2017; Klöck and Nunn 2019; Owen 2020).

6 Conclusions

In this paper, we have provided an overview of the state of current knowledge on disaster risk, covering the framings, approaches, tools, and knowledge and data gaps. Disaster risk science is constantly evolving, its concepts and framings refined, contested, and redefined across diverse and inter-related disciplines. In the context of increased global connectedness, the evolution of risk understanding from ‘natural’ to ‘systemic’ is apparent. It is central to the framings of risk, hazard, vulnerability, resilience, and adaptation, among others, and their cascading, compound, and interacting impacts, which are at the core of this review. The increasing role of the social dimensions of risk and vulnerability has foregrounded local, traditional, and Indigenous knowledges and methodologies as critical components of disaster risk science.

Innovations in scientific methods and technologies have enabled new ways of knowing, understanding, measuring, and assessing. More than ever before, the confluence of these trends and progress calls for meaningful and inclusive collaboration across scales, geographies, and disciplines and progressive governance approaches to risk reduction and management.

Through this exercise, gaps and priorities are emerging with implications for future research. First and foremost, a growing disconnect between knowledge and action is becoming apparent. The desired shift to ex-ante from ex-post approaches to risk management, for example, has not mirrored equally between disaster risk science development and policy and practice. One reason may be the lag between conceptual and theoretical advances and grounded knowledge and empirical data; another the lack of effective science to policy communication. Second, a holistic understanding of risk is lacking. While there is a plethora of quantitative and qualitative approaches to understand the manifestation, perception of and responses to risk, there is yet no integration of approaches that also account for diverse, place-based ontologies and epistemologies. Third, across scales and between regions and nations, knowledge production suffers from significant imbalance and disparities. A future research agenda needs to be conscious of power relations informing and informed by disaster risk science and make space for subaltern studies and locally-produced knowledge to drive progress.

7 References

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