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Grounding urban resilience through transdisciplinary risk mapping

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Abstract

During 2015, three key global agreements were established which converged on enhancing resilience as an overall strategy towards sustainable development. This paper builds an argument and a structured process for future research and practice that succinctly links urban resilience enhancement with the transdisciplinary development of risk maps. Risk maps are highlighted as useful tools improving a shared understanding of risk, raising awareness, and effectively guiding land use planning and zoning towards enhanced urban resilience. Building codes incorporating past and recent disaster experiences, and multi-hazard maps with high quality data for different performance levels, should be the foundation of transdisciplinary risk mapping.

Keywords: Building codes, Climate change, Food systems, Resilience, Risk reduction, Risk-maps, Sustainability, Transdisciplinary, Urban

Policy and practice recommendations

- Develop a long-term vision for better guidance of innovative actions in response to global challenges
- Make more substantial investments in prevention efforts supported by robust risk reduction strategies
- Encourage transdisciplinary development of risk maps to enhance the effectiveness of risk reduction strategies
- Ensure more frequent updating of building codes underpinning risk maps

Science highlights

- Enhancing urban resilience is a central strategy to face multiple global sustainability challenges
- Risk reduction related to natural hazards and climate impacts is a priority for enhancing resilience
- Risk maps integrating building codes support consistent agency towards enhancing resilience
- Transdisciplinary development of risk maps generates effective communication of resilience-enhancing actions

Introduction

Our planet is confronting numerous challenges particularly affecting the poorest and more vulnerable communities, the Least Developed Countries and Small Island Developing States. Climate change, urban migration and concentration, and high levels of inequity have been identified as major global sustainability challenges (Briceño 2018). Multiple linkages exist among these global challenges. Climate change, for instance, is an important and growing threat to the infrastructure sector (UNEP 2006), to the global food systems and a significant "hunger-risk-multiplier" (FAO 2016, Porter et al. 2014, Reardon and Zilberman 2018), hence aggravating inequality and poverty. Furthermore, increasingly unpredictable and extreme weather events related to climate change can force populations to migrate without a plan thus exacerbating inequalities and creating conditions for social unrest and conflict. On the other hand, the concentration of people in urban areas without developing adequate risk reduction measures (e.g. land use planning and zoning, early warning systems) can also result in unnecessary loss of lives, property damage, and leaving thousands of people inevitably vulnerable. For example, in 1999 Vargas state - Venezuela was faced with exceptionally intense rainfall, during a short period of time, creating massive landslides that left around 120,000 victims (Larsen et al. 2001). Recurrent events remain a threat in Vargas if no remedial actions are taken. Furthermore, the possibility for events of similar magnitude exists in other parts of the world where extensive urban development has taken place on alluvial fans (e.g. Los Angeles, Salt Lake City and Denver in the US, and Naples in Italy) (Larsen et al. 2001). Another example comes from Chennai in southern India during the winter of 2015 when more than 500 people were killed and over 1.8 million were displaced due to floods also from heavy rainfall. This event was categorized as a "man-made disaster" by the Comptroller and Auditor General of India (CAG) in July 2018 (Government of Tamil Nadu 2017).

The complexities and interdependencies that characterize global challenges demand new approaches that encourage integrative agency to guide innovative policies and practices (Bendito and Barrios 2016). Risk mapping has been largely conducted through modeling approaches based on secondary data (e.g. HAZUS, Capra, SELENA, RADIUS) (Bendito et al. 2014; Cardona et al. 2012), and through community-based risk-mapping methodologies that combine local perceptions about vulnerability with current and historical hazard data (Rambaldi 2010; Sugathapala and Munasinghe 2006; The Power of Maps 2016). There is a growing consensus that a transdisciplinary approach is required to effectively integrate efforts from the social, economic and environmental dimensions of sustainability (Lang et al. 2012; McGregor 2004; Miller et al. 2010; Scholz 2000; Scholz et al. 2006; Scholz and Steiner 2015a) and build on previous efforts to develop risk reduction measures.

This paper explores a research and policy agenda that can contribute to reduce the current emphasis on reactive approaches and rather promotes strategic and preventative approaches to face key global challenges to our existence in the planet. To this end, it develops a useful argument for future practice and a structured process that succinctly links urban resilience enhancement with the need to create spaces for transdisciplinary engagement, learning and agency. Here, risk maps firmly rooted on building codes, are proposed as suitable boundary objects to facilitate transdisciplinary processes during the co-development of possible options to building urban resilience in different contexts. Boundary objects are considered in this paper "as collaborative products such as reports, models, maps, or standards that are both adaptable to different viewpoints and robust enough to maintain identity across them" (Clark et al. 2011).

Reducing vulnerability and building resilience

During 2015, three key global agreements were established: the overarching Sustainable Development Goals (SDGs) (UNISDR 2015), the Sendai Framework for Disaster Risk Reduction 2015–2030 (SFDRR) (UN 2015), and the Paris Agreement for Climate Change (UNFCCC 2015). The converging goal of these three international agreements was to find ways to maintain or even increase levels of economic growth in a sustainable manner, hence without irreversibly damaging the planet and negatively affecting human livelihoods. It is increasingly clear, that these global ambitions share the common challenge of strengthening resilience, in its many dimensions (UNFCCC 2017).

Nevertheless, we cannot build resilience without reducing vulnerability as they are intrinsically interdependent (UNFCCC 2017). Resilience is considered here as "the ability of a system to absorb shocks, to avoid crossing a threshold into an alternate and possibly irreversible new state, and to regenerate after disturbance" (Resilience Alliance 2009) and vulnerability as "the characteristic and circumstance of a community, system or asset that make it susceptible to the damaging effect of a hazard" (UNISDR 2009).

How to eat a chocolate elephant?

Complexity, metaphorically "eating a chocolate elephant", is usually a deterrent to action. It is unquestionable the need to build a step by step process (i.e. one bite at a time), as proposed in this paper and synthesized in Fig. 1 to effectively support a long-

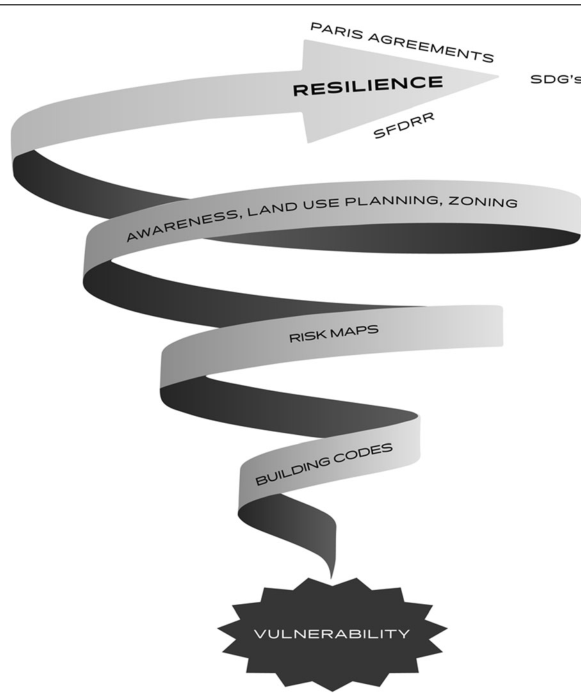

Fig. 1 Enhancing resilience through the transdisciplinary development of risk maps that are firmly rooted on building codes

term vision and strategy that can guide the transition towards a society that is less vulnerable and hence more resilient to major global challenges.

The fact is that most disasters are actually preventable if a robust risk reduction strategy is in place and everyone benefits when money is saved and losses are avoided. From 1991 to 2010 the international community committed over USD 3.03 trillion in aid. However, only 13% of that amount was committed to risk reduction, while 65% corresponded to emergency response, and 22% for reconstruction and rehabilitation. Furthermore, "… many high-risk countries have received negligible levels of financing for risk reduction compared with emergency response, 17 of the top 20 recipients of response funding received less than 4% of their disaster-related aid as risk reduction …" (Kellet and Caravani 2013).

There is increasing evidence that early actions and resilience-building interventions better protect development growth and are significantly more cost-effective than emergency actions. For example, there is a global estimate that risk reduction saves $7 for every $1 invested (DFID 2004). This calculation is consistent with the 2017 Interim Report released by the US Federal Emergency Management Agency (FEMA) indicating that, on average, mitigation grants funded through select federal government agencies can save the nation $6 in future disaster costs for every $1 spent on hazard mitigation". Nevertheless, even though the benefits of an ex-ante risk reduction strategy are recognized in the international policy guidelines, most governments are still devoting most expenditure and effort to emergency management (Briceño 2018, Oliver-Smith et al. 2016).

Creating space for transdisciplinary processes

Enabling a transdisciplinary approach requires the use of participatory methods involving relevant stakeholders (e.g. local communities, local and federal government, development organizations, national environmental and socio-economic research, academia, NGOs and private sector) to facilitate knowledge sharing and co-created innovations that integrate ideas and efforts of multiple sectors in a "fertile middle ground" (Bendito and Barrios 2016; McGregor 2004). In contrast, the lack of integration of different sectors to address complex problems can have devastating consequences as it has been seen during and after several contemporary disasters. For example, one of Japan's approaches to prepare for tsunamis consisted of planting coastal areas with pines. Thereafter, during the tsunami caused by the Great East Japan Earthquake in 2011, these trees became the first debris to damage houses and other buildings (Renaud and Murti 2013). The selection of pines was probably an inadequate choice given that pines are shallow rooting trees (Canadell et al. 1996) and highlights the importance of ensuring broad and inclusive consultation processes - both nationally and among countries facing similar challenges - to identify suitable risk management options. Another example, following the Indian Ocean and Samoan Tsunamis, showed that when community members were not involved in the planning of relocation activities this led to illegal returns to their original land thus leaving them vulnerable again (Kennedy et al. 2008).

Transdisciplinary approaches, however, have their own challenges. For example, the management of stakeholder engagement, the co-creation and sharing of knowledge, and linking knowledge to action during transdisciplinary processes is intricate and nonlinear due to differences among sectors and stakeholders (McGregor 2004; Miller et al. 2010). This involves the need to devote considerable time and effort to collection, consolidation and joint interpretation of data from different sectors, as well as consensus building processes, which can limit the capacity to adapt to rapidly changing new scenarios if not properly managed. In a review of 41 mid- and large-scale studies that engaged in transdisciplinary processes, Scholz and Steiner (2015b) highlighted differences in knowledge background, discourse, dialects, normative perspectives, and timeframes of each sector involved among the key challenges faced.

The use of boundary objects, however, constitutes an important tool to facilitate transdisciplinary processes (Clark et al. 2011). Boundary objects help creating spaces for innovation and participatory decision-making that contribute to build the relevance, credibility and legitimacy of co-developed options to multiple audiences (Cash et al. 2006). Also, boundary objects can help creating better understanding, coordination, and coherence as they enable enhanced convening, interpretation and mediation functions. Risk maps built through a transdisciplinary process constitute an excellent example of a boundary object that could be central in facilitating the implementation of sustainable risk reduction measures.

Fostering sustainable risk reduction

Risk has been generally defined as the combination of hazard and vulnerability affecting any particular community or context (Briceño 2018). Even though it is important to know and understand natural hazards, little can be done to prevent them from occurring. It is possible, however, to identify measures to reduce vulnerabilities, of people, processes (e.g. responsible for food loss and waste), and properties (e.g. hospitals, roads and other public infrastructure) in the short, medium and long-term. Suggested measures include developing a better understanding of vulnerability, improving risk awareness raising and fostering risk-smart education (Bendito and Barrios 2016).

Understanding of vulnerability

Several factors can contribute to a hazard becoming a disaster, but some factors are less obvious than others. For instance, immediate causes of a building collapse may be a landslide due to poor urban planning that allowed building in a highly vulnerable location and/or the lack of building codes and guidelines. A detailed assessment, however, may reveal that the root cause involved local communities cutting down the natural vegetation to produce charcoal and denuded hillsides resulted in increased sediment flows during landslides (FAO 2010). Effective prevention measures are therefore not always evident, and hence the need of a transdisciplinary approach for a more holistic vulnerability assessment, in order to understand risks at different spatial and temporal scales, understand the environmental implications of adaptation efforts, and the importance of the social-ecological context to be able to address the root causes. Prevention measures, more focused on understanding "the characteristics of a person or group in terms of their capacity to anticipate, cope with, resist and recovery from the impact of a natural hazard" - i.e. social vulnerability (Blaikie et al. 2004) should be a fundamental component of the strategy to build resilience.

Improving risk awareness raising and fostering risk-smart education

Frequently heard myths can contribute to inaccurate perceptions that need to be confronted with effective awareness-raising campaigns that deliver accurate and up-to-date knowledge and information. The notion that "natural" disasters represent manifestations of God's will, or that "fate is written" and human beings cannot do anything, favors a surrendering attitude that ultimately leads to greater pain as it discourages facing the problem. In reality, human behavior transforms natural hazards into what should really be called "unnatural disasters". It is thus urgent to replace the use of the term natural disasters with that of "natural hazards" to accurately communicate this phenomenon to society (Briceño 2015; Oliver-Smith et al. 2016; World Bank and The United Nations 2010). Building a risk-smart culture through awareness raising and education at different levels can encourage communities to engage and incorporate risk reduction measures into their lives.

Commonly, the main priority for people is to improve their quality of life (e.g. health, food security, better homes) and following risk reduction measures is not on the top of their list. It is necessary to help communities understand that risk reduction is associated with vulnerability reduction and improved livelihoods. Experience shows that preventing self-construction is not viable, hence building awareness through user-friendly guidelines that include basic rules of building design, orientation, construction materials and maintenance issues (Bendito and Twomlow 2014) can significantly improve knowledge on self-construction, and help construction workers to understand basic rules that are often bypassed (e.g. ensuring the continuous load path on a building so that the structure can resist the different loads acting on a building). Additionally, empowering communities on the use of new technologies (e.g. smart phones) could help provide monitoring and early warning services that anticipate necessary actions for future disasters. Empowered community members could also contribute to data collection using a common methodology and develop high quality databases, the absence of which currently represents one of the main obstacles to developing risk maps in many areas of the developing world. For instance, a similar community-empowerment approach has significantly helped the government of Bangladesh to better understand urban dynamics and migration patterns (Flowminder.org 2018).

Building robust evidence to support risk-smart education and knowledge transfer to communities, governments, and other stakeholders is essential to help in the enforcement, implementation and dissemination of building codes as a strategic normative tool to reduce risk. The new generation of professionals should be equipped with transdisciplinary skills to be able to think globally while acting locally. Higher education curricula should be updated to integrate transdisciplinary approaches to better face the constraints and opportunities emerging from present and future global challenges. For example, engineering curricula needs to incorporate ecological knowledge and insights so that engineers can benefit from better understanding synergies, complementarities and trade-offs between green and blue, grey, and hybrid approaches (Bendito and Barrios 2016).

The grounding effect of building codes

Building codes consolidate in a synthetic way the most credible and robust evidence to support actions that lead to good, desirable or permissible outcomes. As defined by

UNISDR (2009) "building codes constitute a set of ordinances or regulations and associated standards intended to control aspects of the design, construction, materials, alteration and occupancy of structures that are necessary to ensure human safety and welfare, including resistance to collapse and damage".

The dramatic contrast between the impacts of the 2010 earthquakes in Haiti and Chile is an excellent example to show why building codes are so important. While the earthquake in Chile released 1000 times more energy than in Haiti, the earthquake in Haiti resulted in 1000 times more deaths. This was largely the result of updated building codes in Chile incorporating lessons learned from past earthquake events, and the lack of codes in Haiti (Bendito and Gutiérrez 2015).

A study conducted by UNEP (2006) recognized the infrastructure sector, which includes buildings, as one of the most climate-sensitive. New infrastructure should be better adapted to the probability of natural hazards and integrate climate-related hazards that are expected to intensify in frequency and/or intensity. This means that the return period of the hazard, in most cases, could be reduced. Therefore, building codes should be updated following more comprehensive procedures that include information on multiple hazards at a given spatial scale, and different stages of expected damage to the building structures (i.e. performance levels), that are correlated to the probabilities and frequencies of the hazard levels (i.e. return period). Along this line of thought, Heather et al. (2010) proposed to include a regional "climate change adaptation factor" as a possible way to update building codes that internalize climate-related hazards. Furthermore, building codes should take advantage of new technologies for data generation and management (e.g. cell-phones, drones, satellites, crowd-sourcing, big data) to update current hazard maps with real-time and spatially explicit data (e.g. including local climate data). In order to create multi-hazard maps, different hazard maps should be overlaid for different structural performance levels or goals using Geographic Information System (GIS).

Currently, most building codes are developed with minimum design requirements that allow significant levels of damage to the structure to ensure the safety of occupants during a specific design event, but not to preserve the functionality and continued availability of services. Building codes should not only protect the lives of occupants, they should also protect the building structure, architectural components and facades, mechanical/electrical/plumbing equipment after a natural hazard occurs (Bendito et al. 2014; REDI 2013), in order to be more resilient and support faster recovery processes following a disaster.

Building codes can also directly influence food security and nutrition. For instance, reducing food loss and waste through adequate post-harvest facilities can positively influence the four dimensions of food security: availability, utilization, access and stability (FAO 2015). At present it is estimated that more than a third of all food that is produced is lost before it reaches the market or is wasted by households (Gustavsson et al. 2011). Recent publications recognize that sub-optimal post-harvest facilities are main drivers of food loss and waste (Global Panel on Agriculture and Food Systems for Nutrition 2018, Vermeulen et al. 2012). In Rwanda, for example, none of the post-harvest facilities evaluated by an International Fund for Agricultural Development (IFAD) funded project were constructed following building codes or even designed considering emerging climate change challenges (Bendito and Twomlow 2014). This resulted in higher potential for food losses due to diseases, pest and rodent infestations (i.e. reducing availability and utilization) given the lack of adequate storage, as well as lower profitability to farmers because they could not protect their produce while waiting for optimal market prices (i.e. reducing access and stability).

Some green infrastructures should also be guided by building codes. The implementation of green roofs is a growing trend since the 1960s. After gaining popularity in Europe, most of the world is now familiar with green infrastructure as part of the sustainable design of buildings (Semaan and Pearc 2016). While there are undoubtedly many benefits derived from green roofs (e.g. contributing to food security and nutrition, carbon sequestration, and a greener environment while reducing heat, and filtering smog and dust) (Semaan and Pearc 2016), it is necessary to ensure that the additional forces exerted on the building are not enhancing vulnerability.

For instance, when green building efforts involve adding unplanned weight into the design loads, which are not accounted in the building codes, the potential for structural collapse increases. For example, adding moist soil to create a garden at the corner of a building's roof can create unplanned forces to the structural elements of the building. The reported collapse of a green roof in November 2013, in Riga, Latvia, resulted in 54 fatalities and 41 casualties, and alluded to the incorrect estimations of maximum roof loads and faulty connections (BBC News 2013).

Lessons learned from past disaster experiences highlight the need to improve current regulations and to encourage a people-centered approach, where communities are part of the implementation and dissemination of the codes and are empowered to proactively protect themselves against natural hazards by adapting their behavior and becoming more resilient and thus preventing unnatural disasters (UNISDR 2015).

The central role played by risk maps

The transdisciplinary development of risk maps generates a very useful tool to explicitly identify and effectively communicate vulnerability-reducing actions. Such risk maps provide communities and governments with synthetic understanding of the spatial and temporal impacts of potential natural hazards and climate change impacts on people, food systems, infrastructure, and ecosystem services while highlighting areas of high, medium and low risk.

Risk maps developed through a transdisciplinary process provide the opportunity to build an inclusive decision-making space for the co-creation and sharing of knowledge that can enhance ownership and facilitate agreements at different scales of governance on priorities, challenges and opportunities, and thus guide policies and actions to increase adaptability and reduce vulnerability to global change. These risk maps can contribute to empower extension agents, NGOs, and other organizations in the field to incorporate valuable information into their awareness raising programs and hence encourage behavioral changes required to support sustainable development pathways. In a study conducted in six different rural and marginalized communities from Africa, Caribbean and the Pacific, the Technical Centre for Agricultural and Rural Cooperation (CTA) demonstrated the power of maps to help communities and governments to better understand and share knowledge on the spatial distribution of their resources, challenges and opportunities, and the impact of extreme climate events on their livelihoods (Rambaldi 2010; The Power of Maps 2016).

In order for risk maps to be most effective, they should include - multi-hazard maps derived from updated building codes, spatially explicit data on vulnerability, actual and potential provision of ecosystem services, and local knowledge and experience - all integrated using GIS. Local knowledge plays a critical role during knowledge sharing that is key to building relevance, credibility and legitimacy of risk maps as a boundary object (Bendito and Barrios 2016; Clark et al. 2011). Developing risk maps through a transdisciplinary process can also help to develop or strengthen links between different institutions (e.g. those responsible for implementation, monitoring and enforcement of building codes), and stakeholders.

Risk maps can also be used to facilitate the convergence of disaster risk reduction (DRR) and climate change adaptation (CCA) approaches. Instead of planning for DRR with traditional engineering options through structural approaches (reservoirs, dykes, sea walls, and dams), or planning CCA solutions with only Ecosystem Based Adaptation approaches, both approaches should be jointly analyzed planning future development efforts so that adaptation to climate change is conducted simultaneously while managing risk.

Conclusions

Risk maps are an essential component of the strategy to ground urban resilience. The goal of resilience enhancement demands transdisciplinary approaches to address the limitations of sectoral approaches. Given the recognized challenges faced during the convergence of different disciplines and stakeholder demands while developing risk reduction measures, the use of risk maps as a boundary object can become an effective enabling tool. Building codes are key inputs to develop effective risk maps but they should be reviewed and improved by incorporating past and recent disaster experiences, and multi-hazard maps developed with high quality data for different performance levels. Such transdisciplinary risk maps are useful tools for increasing understanding of risk, raising awareness, and effectively guiding land use planning and zoning towards enhanced resilience, which is the common desired global outcome of the SDGs, SFDRR, and the Paris Agreement as shown in Fig. 1.

Abbreviations

CCA: Climate change adaptation; CTA: Centre for Agricultural and Rural Cooperation; DRR: Disaster risk reduction; FEMA: Federal Emergency Management Agency; GIS: Geographic Information System; IFAD: International Fund for Agricultural Development; SDGs: Sustainable Development Goals; SFDRR: Sendai Framework for Disaster Risk Reduction

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References
BBC News (2013) Available via www.bbc.com/news/world-europe-25045879. Accessed 5 June 2018.

Bendito A, Barrios E. Convergent agency: encouraging transdisciplinary approaches for effective climate change adaptation and disaster risk reduction. Int J Disaster Risk Sci. 2016;7(4):430–5.

Bendito A, Gutiérrez A. Can building codes stop the vicious cycle of recurrent disaster? Open Civil Eng J. 2015;9:226–35. https://doi.org/10.2174/1874149501509010.

Bendito A, Rozelle J, Bausch D. Assessing potential earthquake loss in Mérida State, Venezuela using Hazus. Int J Disaster Risk Sci. 2014;5(3):176–91.

Bendito A, Twomlow S. Promoting climate-smart approaches to postharvest challenges in Rwanda. Int J Agric Sustain. 2014; 13(3):222–39.

Blaikie P, Cannon T, Davis I, Wisner B. At risk. Natural hazards, people's vulnerability and disasters. London: Routledge; 2004.

Briceño S. Looking back and beyond Sendai: 25 years of international policy experience on disaster risk reduction. Int J Disaster Risk Sci. 2015;6(2):202–4.

Briceño S. Lessons on risk governance from the UNISDR experience. In: Oxford research encyclopedia of natural hazard science; 2018. https://doi.org/10.1093/acrefore/9780199389407.013.311.

Canadell J, Jackson RB, Ehleringer JR, Mooney HA, Sala OE, Schulze ED. Maximum rooting depth of vegetation types at the global scale. Oecologia. 1996;108:583–95.

Cardona OD, et al. CAPRA — comprehensive approach to probabilistic risk assessment: international initiative for risk management effectiveness. In: Paper presented at the 15th world conference on earthquake engineering, Lisbon, Portugal 24-28 September 2012; 2012.

Cash DW, Borck JC, Patt AG. Countering the loading-dock approach to linking science and decision making. Sci Technol Hum Values. 2006;31(4):465–94.

Clark WC, Tomich TP, van Noordwijk M, Guston D, Catacutan D, Dickson NM, McNie E. Boundary work for sustainable development: natural resource management at the consultative group on international agricultural research (CGIAR). Proc Natl Acad Sci. 2011;113(17):4615–22.

DFID Department for International Development. Disaster risk reduction: a development concern. A scoping study on links between disaster risk reduction, poverty and development. London: DFID; 2004.

FAO Food and Agriculture Organization of the United Nations (2010) Global forest resources assessment 2010. http://www.fao.org. Accessed 3 Aug 2017.

FAO Food and Agriculture Organization of the United Nations (2015) Global initiative on food loss and waste reduction. http://www.fao.org. Accessed 26 Mar 2017.

FAO Food and Agriculture Organization of the United Nations (2016) Climate change and food security: risks and responses. http://www.fao.org. Accessed 20 May 2017.

Flowminder.org (2018) Mobile phone data to understand climate change and migration patterns in Bangladesh. Available via http://www.flowminder.org/case-studies/mobile-phone-data-to-understand-climate-change-and-migration-patterns-in-bangladesh. Accessed 28 Nov 2018.

Global Panel on Agriculture and Food Systems for Nutrition. Preventing nutrient loss and waste across the food system: policy actions for high-quality diets. Policy brief no. 12. London: Global Panel on Agriculture and Food Systems for Nutrition; 2018.

Government of Tamil Nadu (2017) Report of the comptroller and auditor general of India on performance audit of flood management and response in Chennai and its suburban areas report no. 4 of 2017.

Gustavsson J, Cederberg C, Sonesson U, Van Otterdijk R, Meybeck A. Global food losses and food waste: extent, causes and prevention. Rome: Food and Agriculture Organization of the United Nations (FAO); 2011.

Heather A, Waller J, Eng S, Klaassen J, Morris R, Fernandez S, Cheng V, MacIver D. (2010) The changing climate and national building codes and standards. Available via https://ams.confex.com/ams/pdfpapers/174517.pdf. Accessed 23 July 2019.

Kellet J, Caravani J. Financing disaster risk reduction: a 20-year story of international aid. London: Overseas Development Institute (ODI); 2013.

Kennedy J, Ashmore J, Babister E, Kelman I. The meaning of 'build back better': evidence from post-tsunami Aceh and Sri Lanka. J Conting Crisis Manage. 2008;16(1):24–36.

Lang DJ, Wiek A, Bergmann M, Stauffacher M, Martens P, Moll P, Swilling M, Thomas C. Transdisciplinary research in sustainability science: practice, principles, and challenges. Sustain Sci. 2012;7:25–43.

Larsen MC, Wieczorek GF, Eaton LS, Torres-Sierra H. Natural hazards in alluvial fans: the debris flow and flash flood disaster of December 1999, Vargas state, Venezuela. In: Paper presented at the sixth Caribbean Islands water resources congress, Mayagüez, Puerto Rico, 22-23 Feb 2001; 2001.

McGregor SLT. The nature of transdisciplinary research and practice. In: Kappa Omicron Nu human sciences working paper series; 2004. Available via http://www.kon.org/hswp/archive/transdiscipl.html. Accessed 20 May 2016.

Miller F, Osbahr H, Boyd E, Thomalla F, Bharwani S, Ziervogel G, Walker B, Birkmann J, Van der Leeuw S, Rockström J, Hinkel J, Downing T, Folke C, Nelson D. Resilience and vulnerability: complementary or conflicting concepts? Ecol Soc. 2010;15(3):11.

Oliver-Smith A, Alcantara-Ayala I, Burton I, Lavell AM. Forensic investigations of disasters (FORIN): a conceptual framework and guide to research (IRDR FORIN publication no. 2). Beijing: Integrated Research on Disaster Risk; 2016.

Porter JR, Xie L, Challinor AJ, Cochrane K, Howden SM, Iqbal MM, Lobell DB, Travasso MI. Food security and food production systems. In: IPCC. Climate change 2014: impacts, adaptation, and vulnerability. Part a: global and sectoral aspects. Contribution of working group II to the fifth assessment report of the intergovernmental panel on climate change. Cambridge: Cambridge University Press; 2014. p. 485–533.

Rambaldi G. Participatory three-dimensional modelling: guiding principles and applications. 2010 edition. Wageningen: CTA; 2010.

Reardon T, Zilberman D. Climate-smart food supply chains in developing countries in an era of rapid dual change in agrifood systems and the climate. In: Lipper L, McCarthy N, Zilberman D, Asfaw S, Branca G, editors. Climate smart agriculture: building resilience to climate change. Natural Resource Management and Policy, vol.52. Rome: Springer; 2018. p. 335–51.
REDi™ Rating System Resilience-based Earthquake Design Initiative for the Next Generation of Buildings (2013) Available via https://www.arup.com/-/media/arup/files/publications/r/redi_final-version_october-2013-arup-website.pdf. Accessed 9 May 2014.
Renaud F, Murti R (2013) Ecosystems and disaster risk reduction in the context of the great East Japan earthquake and tsunami. A scoping study. UNU-EHS Publication Series No.10 Available via https://portals.iucn.org/library/node/10373. Accessed 22 June 2014.
Resilience Alliance (2009). Assessing and managing resilience in social-ecological systems: a practitioner's workbook, version 2.0. Available via https://www.resalliance.org/files/ResilienceAssessmentV2_2.pdf. Accessed 27 July 2019.
Scholz R. Mutual learning as a basic principle of transdisciplinarity. In: Scholz RW, Haberli R, Bill A, Welti M, editors. Transdisciplinarity: joint problem-solving among science, technology and society. Workbook II: mutual learning sessions. Zurich: Haffmans Sachbuch Verlag; 2000. p. 13–9.
Scholz R, Lang D, Wiek A, Walter A, Stauffacher M. Transdisciplinary case studies as a means of sustainability learning: historical framework and theory. Int J Sustain High Educ. 2006;7(3):226–51.
Scholz R, Steiner G. The real type and ideal type of transdisciplinary processes: part I – theoretical foundations. Sustain Sci. 2015a;10:527–44.
Scholz R, Steiner G. The real type and ideal type of transdisciplinary processes: part II – what constraints and obstacles do we meet in practice. Sustain Sci. 2015b;10:653–71.
Semaan M, Pearc A. Assessment of the gains and benefits of green roofs in different climates. Elsevier Procedia Eng. 2016; 145:333–9.
Sugathapala KC, Munasinghe DS (2006) Risk mapping as a tool for disaster risk reduction in urban areas of Sri Lanka. Available via https://www.nbro.gov.lk/images/content_image/publications/.../risk_mapping.pdf. Accessed 28 July 2019.
The Power of Maps (2016). CTA Technical Centre for Agricultural and Rural Co-operation. Available via https://www.cta.int/en/event/book-launch-and-reception-for-the-power-of-maps-a-cta-publication-on-participatory-3-dimensional-modelling-p3dm-sid01ba7ddeb-d031-4287-840b-d88baec6b6e7. Accessed 22 May 2018.
UN United Nations (2015) Sustainable development goals. Available via https://sustainabledevelopment.un.org/. Accessed 27 Aug 2016.
UNEP United Nations Environment Programme. Adaptation and vulnerability to climate change: the role of the finance sector. Geneva: United Nations Environment Programme Finance Initiative (UNEP-FI); 2006.
UNFCCC United Nations Climate Change Secretariat (2017). Opportunities and options for integrating climate change adaptation with the sustainable development goals and the Sendai framework for disaster risk reduction 2015–2030.
UNFCCC United Nations Framework Convention on Climate Change (2015) Adoption of the Paris Agreement. Decision 1/CP. 21. Available via https://unfccc.int/resource/docs/2015/cop21/eng/10a01.pdf). Accessed 10 Oct 2018.
UNISDR United Nations International Strategy for Disaster Reduction (2009) Terminology. Available via https://www.unisdr.org/files/7817_UNISDRTerminologyEnglish.pdf. Accessed 8 Mar 2011.
UNISDR United Nations International Strategy for Disaster Reduction (2015) Sendai framework for disaster risk reduction 2015–2030. Available via https://www.preventionweb.net/files/43291_sendaiframeworkfordrren.pdf. Accessed 20 Mar 2016.
Vermeulen SJ, Campbell BM, Ingram J. Climate change and food systems. 2012. https://doi.org/10.1146/annurev-environ-020411-130608.
World Bank and The United Nations (2010) Natural hazards, unnatural disasters: the economics of effective prevention. Available via www.gfdrr.org/sites/default/files/publication/natural-hazards-unnatural-disasters-2010.pdf. Accessed 27 May 2012.

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