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ORIGINAL PAPER

Forging a paradigm shift in disaster science

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Abstract Despite major advancements in knowledge on disaster risks and disasters caused by natural hazards, the number and severity of disasters are increasing. Convolving natural, engineering, social and behavioral sciences and practices with policymaking should significantly reduce disaster risks caused by natural hazards. To this end, a fundamental change in scientific approaches to disaster risk reduction is needed by shifting the current emphasis on individual hazard and risk assessment dominant in the geoscientific community to a transdisciplinary system analysis with action-oriented research on disaster risk reduction co-produced with multiple stakeholders, including policymakers. This paradigm shift will allow for acquisition of policy-relevant knowledge and its immediate application to evidence-based policy and decision making for disaster risk reduction. The need for the paradigm shift is more critical now than ever before because of the increasing vulnerability

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and exposure of society to disaster risk and the need for cross-cutting actions in policy and practice related to climate change and sustainability.

Keywords Natural hazards · Risk assessment · Disaster science · Transdisciplinary · Co-productive research

1 Introduction

To develop a resilient society significantly reducing disaster risks is a passionate dream of disaster science researchers, emergency managers and policymakers. The simple fact is that disasters caused by natural hazard events continue to grow in number, intensity and impact. An exponential growth of population and associated development will increase the incidence of disasters and the consequences they create for affected populations in the years to come. In many regions, natural hazards are becoming direct threats to national security, because their impacts are amplified by rapid growth and unsustainable development practices, which increase exposure and vulnerabilities of communities and capital assets. Reducing disaster risk becomes a strategic goal for protecting national security and the foundation for sustainable development (Pelling et al. 2014). Actively pursuing risk reduction strategies can be justified on economic grounds; the interaction between more frequent and intense events, particularly from meteorological hazards, increasing as a result of climate change (IPCC 2012), and ever-increasing social development means that the costs of reacting to disasters will become progressively untenable. More attention needs to be directed to reducing this risk. While high-quality risk reduction research is being conducted, it is predominantly discipline-focused at present (Gall et al. 2015). Given the complex and multifaceted nature of disaster risk research, a more "whole-of-science" approach is needed.

Science-based approaches to disaster risk reduction management can help communities and governments become more resilient and diminish the human and economic impacts of disasters, by taking steps to reduce risk and to increase people's capacity to respond before rather than after the disaster strikes (Kundzewicz and Takeuchi 1999; Ismail-Zadeh and Takeuchi 2007; Cutter et al. 2008; Paton 2013; Paton and McClure 2013; Paton and Jang 2016). Furthermore, they are capable of doing so in ways that facilitate sustained and evolving approaches to disaster risk reduction (e.g., The National Academies 2012). Natural, engineering, social and behavioral sciences contribute to all stages of disaster risk management, including rapid scientific assessment of and provision of usable knowledge to decision makers. Scientists, meanwhile, can do more to deliver scientific knowledge on disaster risk for policymakers and society by providing and communicating robust, evidence-based frameworks and a variety of knowledge products (e.g., concepts, tools, technology, data, decision support, training) for disaster risk reduction and for social policy engagement, development and implementation. But, the knowledge required for the development of a comprehensive and inclusive understanding of disaster risk reduction and for social policy engagement, development and implementation should be inclusive of the multiple and diverse disciplinary and methodological perspectives. The latter is lacking at present. While it is a relatively straightforward task to identify the disciplines that need to be involved in this endeavor, it is less easy to mobilize them in ways required to realize the benefits of the joint creation of knowledge. This also must be done in areas ranging from research to policy evaluation, development and implementation, to name but a few.

In this article, we propose a fundamental change in scientific approaches to disaster risk reduction by shifting the emphasis from an individual hazard and risk assessment dominant in the geoscientific community today to a more comprehensive systems approach involving multiple hazards, action-oriented research on disaster risk reduction co-produced with other stakeholders including policymakers, and methods that facilitate the ability of diverse stakeholders to provide complementary perspectives. In this way, the whole becomes greater than the sum of its parts. Such a paradigm shift will allow for acquisition of basic and policy-relevant knowledge for disaster risk reduction. It will move disaster risk management from its current state of resistance (seeking to avoid impacts) and incrementalism (small improvements in existing practices and policies) to a transformative approach that is co-produced with stakeholders, beyond the extant disciplinary and multidisciplinary-based knowledge. Such an approach avoids systemic or business as usual forms of practice and policy (Matyas and Pelling 2014).

We introduce the basic types of research in Sect. 2 and the basic terms of disaster science in Appendix 1. In Sect. 3, we analyze contributions of natural and social sciences as well as engineering to disaster science and risk reduction. An integration of knowledge across different disciplines and stakeholders is discussed in Sect. 4. Integrated research cannot be formed or realized without a specific mission, specific targets and efficient management. To make disaster science needed and useful, it should proceed together with a practicing sector. And to enable scientific knowledge-based decision making, a transdisciplinary approach is required. These basic elements of the paradigm shift in disaster science are presented in Sect. 5 and conclusions in Sect. 6.

2 Basic types of research

In this paper, we refer to different types of research, which ranges from disciplinary to transdisciplinary and from pure to co-produced (see Fig. 1). The terminology used is defined in the section.

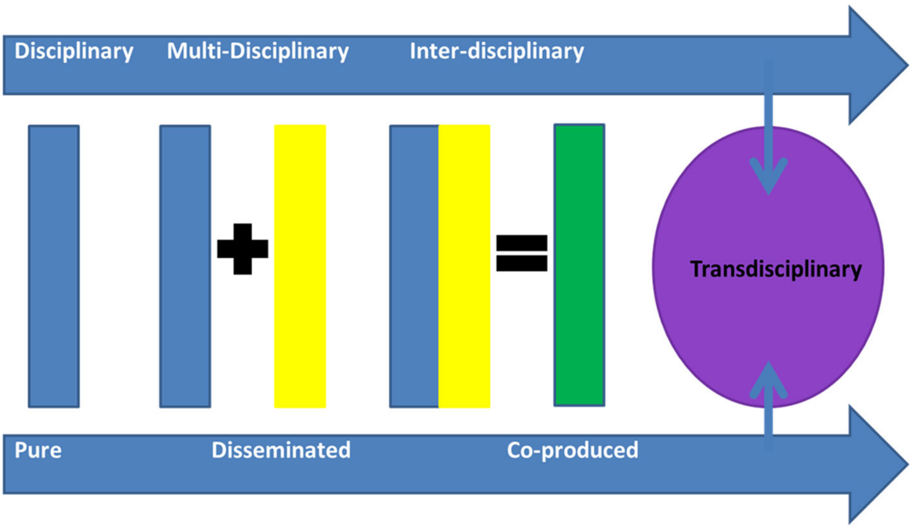

Fig. 1 Transdisciplinary science for disaster risk reduction

A *disciplinary research* is traditionally used to study nature and society, when scientists work purely inside their own discipline. This way of research has been existing since the inception of scientific investigations and has been successfully employed by scientists so far. Disciplinary research involves a cognitive process related to specific disciplinary-based questions, hypotheses, theories, models and methods.

Scientists use a *multidisciplinary approach* to unravel complex natural and/or social phenomena. Using this way of research, scientists from different disciplines determine the problem together, but work independently considering specific questions, employing the methodologies related to their individual discipline, deriving independent conclusions and disseminating their results in different professional (sometimes in multidisciplinary) journals.

Compared to multidisciplinary approach, *interdisciplinary research* allows for transferring knowledge from one discipline to another, informing each other about their work, comparing individual findings, developing common conclusions still working independently using their own methodologies, but often coming up with new problem sets and approaches. Such interdisciplinary research is co-designed and co-produced but still lacking an involvement of actors in public bodies, business and civil society into the academic research process and going beyond "the purely academic definitions, analysis and interpretation of research problems" (Aboelela et al. 2007; Hirsch Hadorn et al. 2008).

Transdisciplinary research assumes that scientists of different disciplines work together to contribute their unique expertise to the research outside their own discipline. They address a common problem and try to understand the complexities of the entire problem rather than its parts only. To achieve a common goal, scientists exchange data and information, share resources, create conceptual, phenomenological, theoretical and methodological innovations, integrate disciplines, and move beyond discipline-specific approaches. The scientists can draw on expertise gained in areas such as multiagency coordination and the development of functional disciplinary collaboration (Curnin et al. 2015a, b). Transdisciplinary research allows for (i) addressing the complexity of societal problems under study using a holistic view of the problems and the diversity of perceptions of them, (ii) involvement of actors from non-scientific fields, and (iii) implementation of research results by developing the solutions to be used in practice (Gibbons 1999; Hirsch Hadorn et al. 2008). A process of transdisciplinary research includes three main components: (1) collective framing of the problem and building a collaborative research team; (2) co-producing solution-oriented and transferable knowledge through collaborative research; and (3) integrating and applying the produced knowledge in both scientific and social practice (Lang et al. 2012).

Transdisciplinarity evolved as a critique of knowledge production in the 1970s as the anathema to science that was motivated by fundamental research questions conducted in disciplinary silos. This "normal science" (or mode 1 knowledge production) privileged detachment and aloofness in scientific inquiry and maintained the structure of academic disciplines as the status quo (Bernstein 2015). Beginning in the 1990s, a new mode of knowledge production was advanced (Nowotny et al. 2001)—one that was developed through collaborations beyond disciplines and academia more broadly focused on particular applications or problems that were more socially responsive. More than just applied science, this "post-normal science" (or mode 2 knowledge production) included human life world experiences in the problem scoping and methods involving expertise from practitioners and other stakeholders including indigenous knowledge. The co-production of knowledge did not privilege one perspective over the other, but did provide models for connecting theory to observed empirical data in an effort to predict results and solve some of the wicked problems facing society. Divergent perspectives and multiple publics are the hallmark of transdisciplinary knowledge especially with some of society's most wicked problems like climate change and its human dimensions (Castree et al. 2014).

Transdisciplinary research is developed through the application of team developmental methods that seek to first dissolve boundaries and disciplines and then synthesize them to create a cohesive transdisciplinary whole (Cronin 2008). If challenging problems are used as a catalyst for the development of transdisciplinary teams, this affords greater opportunities for introducing expertise and knowledge from external stakeholders into the team by creating an overarching or superordinate context, and conditions that can lead to the transcendent process of knowledge development and problem solving (Klein 2007). Also this affords greater opportunities for conceptualizing and managing the complex web of hazard consequences created by the diverse geophysical, geographical, social, cultural and temporal factors that accompany disasters. A transdisciplinary approach convolving diverse scientific expertise and essential contributions from diverse stakeholders (e.g., risk management agencies, community groups, businesses) also affords a more effective foundation for conceptualizing and implementing strategies such as Build Back Better (BBB) that require a comprehensive understanding of present and future social, psychological, economic, livelihood, environmental and governance process.

3 Convolving nature and society in disaster science

Natural science contribution to disaster risk reduction: successes and limitations. Basic (fundamental) research on dynamic processes in the Earth's lithosphere, hydrosphere, cryosphere, atmosphere and its environment in space is well advanced, namely real-time and long-term monitoring of active processes associated with geological (e.g., earthquakes, volcanic eruptions, lava flows, landslides, tsunamis), hydrometeorological (e.g., hurricanes, tornados, floods, droughts, wild fires) and space weather hazards (e.g., Bobrowsky 2013; Ismail-Zadeh et al. 2014; Paton 2014; Ismail-Zadeh and Cutter 2015; and references herein); hazard modeling and assessment (e.g., Todesco et al. 2002; Emanuel et al. 2006; Ismail-Zadeh et al. 2007a, b; Babayev et al. 2010; Masood and Takeuchi 2012; Ismail-Zadeh et al. 2012; Wu 2015; Korotkii et al. 2016; Tang et al. 2016); studies of predictability of extreme events (e.g., Baker et al. 2014; Gabrielov et al. 2014); and operational forecasting (e.g., Gopalakrishnan et al. 2002; Wei et al. 2014). Much is known about the physical processes and forcing mechanisms of natural hazards. The existing high level of scientific and technological competency coupled with effective communication and response capabilities has contributed to reduction in losses in some countries. For example, the emergence of groups, such as the Bushfire and Natural Hazard Cooperative Research Centre in Australia and the Joint Centre for Disaster Research in New Zealand, has led to significant changes in how knowledge is produced and used. These endeavors have contributed to creating opportunities for interdisciplinary research. There remains, however, a need to build on this foundation and to develop a transdisciplinary approach.

Despite the significant progress in understanding the geophysical processes responsible for natural hazards, there are still many challenges related to hazards science, for example hazard assessment methodology (e.g., Lin et al. 2014; Sokolov and Ismail-Zadeh 2015, 2016); local resolution of models (e.g., Stefanescu et al. 2012; Kitoh 2014); and reduction in uncertainties in forecasting of hazard events (e.g., Menz and Thieken 2009; Taylor et al. 2015; Fukutani et al. 2016). Additionally, improving the capacity of people and agencies to make informed decisions in the context of residual uncertainties in the specific timing, intensity and consequences of events presents its own challenges for an interdisciplinary approach.

For example, hazard assessments cannot provide predictive information about where or when a specific event (e.g., earthquake) will occur, how big in magnitude it will be, how long the aftershock sequence will last, etc. This unavoidable uncertainty creates problems for decision makers ranging from policymaker to planners to households. Decision experts must know of the limits of what the assessment process can produce. If those conducting hazard assessments understand the potential range of preparedness actions that would accompany the predictive information (irrespective of the uncertainty), then possible actions and their costs could be identified along with prioritizing those actions that would be timely and cost-effective in reducing disaster risk (Davis et al. 2012).

Until the end of the last century, geoscience related to individual hazards was more discipline-oriented with some cooperation across disaster risks such as between seismologists and engineers (Ghafory-Ashtiany 2014), earthquake prediction experts and water resource managers (Davis et al. 2012); volcanologists and experts in human health (Weinstein et al. 2013; Baxter et al. 2014); or hydrologists and nuclear energy experts (Teramage et al. 2014). Despite emerging interdisciplinary research in natural hazards science, scientific approaches to disaster risk still remain disciplinary and multidisciplinary (Gall et al. 2015). Many geoscientists believe that digging deeper into understanding a specific hazard and developing a physical response to that hazard will result in solving the problem of disaster risk reduction. For example, how can we better respond to drought? An answer to that question is: monitor weather patterns, rainfall estimates, water availability and agro-climatological data; develop models; pursue more research; and help in response planning for drought (e.g., water storage management, emergency extra pumping-up groundwater). Such a supply-oriented approach ignores the possibility of demand management based on the reality of human responses to drought (van Loon et al. 2016), such as reducing demand through household water conservation, shifting or substituting crops, industrial water conservation or modification of water allocation rights from low-priority use to high-priority use based on users' negotiation on emergency situation. The behavioral, social, economic and political responses to drought, and how they play interdependent roles in effective risk management, are just as important as understanding and controlling the physical event itself, with the latter often ignored by natural hazard scientists and the engineering-oriented policy community.

The major factors in escalating natural hazard losses are increasing vulnerability and exposure—more people and assets are in harm's way due to urbanization, population growth, political and economic instability, and the globalization of the economic system (e.g., Cutter et al. 2003, 2008; Peduzzi et al. 2009; Collins et al. 2015). For example, the cascading impacts of locally generated disasters can now assume global significance because of disruptions of supply chains as evidenced by the 2011 Great East Japan earthquake (e.g., Satake 2014) or the 2011 Chao Phraya floods (e.g., Koontanakulvong 2014) or airline traffic disruptions due to the 2010 Eyjafjallajökull volcanic eruption (e.g., Mazzocchi et al. 2010). Understanding the dynamic interaction of hazard, exposure and vulnerability is critical for the development of comprehensive models of risk and risk assessment.

Engineering contribution to disaster risk reduction: successes and limitations. Significant progress has been made in developing building codes to withstand earthquakes, floods and severe winds not only in the construction of new buildings, but in the retrofitting and reinforcement of existing buildings. Yet, we still witness disaster losses, mainly because of the unwillingness of some local authorities to invest in resistant construction due to various reasons including irresponsibility, ignorance, corruption (Ambraseys and Bilham 2011), the perceived requirement to balance the need for costs versus the increased costs of implementation, local politics, funding availability and other urgent and more politically competitive needs (Ismail-Zadeh and Takeuchi 2007). In order to make the building code effective, strict enforcement is necessary which becomes possible only with corruption-free, honest, serious and trusted inspectors. It is not just a matter of building code and its strict law enforcement alone but the cohesive societal formation that makes various component actions meaningful and combined actions effective.

The adoption and enforcement of building codes require social science inputs—understanding the dynamic decision making in trade-offs between long-term losses versus shorter-term expediency in construction practices as well as cost–benefit decisions in householder risk assessments. Even when regulations and laws are introduced to cover building design, we need to include complementary disaster risk reduction strategies that focus on ensuring building maintenance including facilitating building inhabitants to secure the internal living/working environment. The following example is illustrative. The 2013 Seddon, New Zealand, $M = 6.5$ earthquake resulted in no damage to recently constructed office buildings, but considerable loss and damage internally as equipment and computers, filing cabinets, were rocked by the event and fell or had contents dispersed increasing the risk of injury. People overestimate their safety based on one (substantial) mitigation action and assume that, in this case, a safe building will automatically remove the risk for its inhabitants. From earthquakes to wildfires, people are considerably more likely to undertake survival preparations (e.g., store food and water) rather than to undertake structural preparations (e.g., secure internal fixtures and fittings) and community planning preparedness activities (e.g., Paton and McClure 2013). Japan is perhaps an exception, where people know well how to protect themselves against falling furniture during an earthquake. They fix furniture to the wall using chains and tucks, or "tsuppari-bou" (stemple pole) is set between tall furniture and the ceiling to stop the furniture from falling due to strong shaking.

Social science contribution to disaster risk reduction: successes and limitations. Improvements in the science of physical and social vulnerability assessments have been made (Birkmann 2014), but there is no consistent methodology for conducting them, let alone integrating them into a broader composite assessment at regional to global scales, thus making comparisons difficult between and among places. Disaster risk data are lacking in many regions, and this is especially true for measurements of hazard, vulnerability and exposure. Good quality demographic data are particularly difficult to obtain in many regions. More fundamentally, the basic data from which we understand human losses and model societal impacts of disasters are lacking. While there are a few national and/or sub-national disaster loss and damage databases, they are not comparable at present either in terms of geographical or temporal coverage, measurement, or classification of initiating hazard or peril causing the damage. Community-based and other social learning approaches for monitoring and assessing resilience are equally important, yet there is no systematic archiving of such experiences or data (Cutter and Gall 2015). The bottom line is we do not know with any certainty the patterns and magnitudes of disaster loss in economic damage or human loss terms for individual nations or globally.

Finally, recovery after disasters—which entails the rebuilding and development of interdependent psychological, social, business, infrastructure systems—is emerging as a major theme in integrated research on disaster risk. The importance of introducing a BBB or "linking response, rehabilitation, and development" into post-event planning to build on event experience is a key component for enhancing capacity and capability for future events (e.g., UNISDR 2015; James and Paton 2016). Understanding how people interpret risks including those in the far future and their choice of mitigation or adaptive actions based on their interpretations is vital to any strategy for disaster reduction (Eiser et al. 2012). While people cannot make choices about, for example, large-scale mitigation measures such as building sea walls or levees, they can make choices, individually and collectively, about what can be done at household and neighborhood levels of analysis. People can and do make choices about levels of structural readiness in their homes, their survival readiness, and the development of functional relationships with family members, neighbors, community members and civic agencies (Paton and McClure 2013; Paton et al. 2014). Affected communities have both resilient and vulnerable groups, and it is the interaction of these two that provides the relative balance of capabilities, which govern the timing and nature of social recovery (Paton 2006). In addition, the quality and types of infrastructure and access to essential services (food, water, sanitation, shelter, and power) often differentiate the length of the recovery period, who recovers and where (Cutter et al. 2014).

As the examples in this section illustrate, understanding risk (hazard, exposure, vulnerability and coping capacity) requires such an integrated approach coupling natural science (the forcing processes), engineering (building performance and codes), and social science (adoption and implementation of codes, and perception of safety) and to do so at different levels of analysis (e.g., household versus policy levels). The development of a transdisciplinary, team-based, approach is one key way of ensuring that the respective contributions of all cognate disciplines and stakeholders are incorporated into a comprehensive risk management strategy. Including "team-based" draws attention to the need to not only identify cognate disciplines and stakeholders, but also include ways of developing their expertise into a coherent resource capable of providing comprehensive solution to problems that will only become more complex in future.

4 Integrating knowledge across disciplines and stakeholders

Disaster science aims to reduce disaster risks and losses and to create a sustainable and resilient society. However, disaster science in many cases is not yet organized in terms of targeted research and is still predominantly conducted in a traditional framework of basic geoscience. Such a framework does not require integration among wider disciplines and stakeholders. Moreover, some geoscientists as suppliers of knowledge still consider that making scientific knowledge useful and used is not their obligation nor are they responsible for translating their knowledge into potential implementation actions (for diverse stakeholders). There are many examples to illustrate this statement, but just a few. Scientists knew about historical devastating earthquakes and tsunamis, which occurred in the Indian Ocean region (e.g., a magnitude 8.7 earthquake in 1833 followed by a powerful tsunami killed 36,000 people), yet never conveyed such historical precedents to regional planners or policymakers. Scientists and engineers knew that the levees, preventing the below-sea-level city of New Orleans from flooding, were built to withstand only category 3 hurricanes, and a category 4 hurricane could cause the levees to fail. And although officials have warned for years before Hurricane Katrina hit New Orleans, no action was taken to prevent or at least mitigate an extreme event (Ismail-Zadeh and Takeuchi 2007). The geoscience perspective is that practitioners, politicians and administrators will find and use the best available knowledge, understand it and develop practical solutions based on it. So far, the advancement of disaster science is measured in terms of a disciplinary interest and novelty and not the impact to society. In other words, we have not reached the point of translating our science into practice or making the knowledge useful and used (Boaz and Hayden 2002).

A key issue is that knowing of a risk and doing something about it are very different cognitive processes (Paton and McClure 2013). This means that, for example, the value of geoscientific and other information on the action of natural processes and their hazardous consequences can be increased by linking it to social science research that offers insights into how people interpret science and scientific information. The societal value derived from public investment in research can be further enhanced by integrating, for example, policy and risk management into the mix. An example of this is outlined next.

At the stage of early warning of a hazard event, physical phenomena are observed, analyzed and forecasted followed by warnings issued under an administrative judgment. The best example is the earthquake early warning system developed in Japan to alert the public on a strong earthquake within a few minutes after the event and to help in mitigating potential damage and losses.[1] People use the alerts to escape the vulnerable places, locomotive engineers to slow down trains, and employees to stop technological process before seismic waves reach them. But in many countries, follow-up actions associated with warnings issuance still remain unresolved and could complicate real-time emergency operation. These follow-up actions include an impact assessment of false alarms; when to issue warnings to maximize compliance; ensuring that affected citizens are ready and capable of responding to warnings rather than assuming warnings are sufficient; securing and supporting reliable evacuation shelters; and emergency management responses to avoid expansion and prolongation of disaster losses (e.g., Paton and McClure 2013; Paton et al. 2015; Paton and Jang 2016). Such unresolved issues in the research and its integration into practices make warnings issuance difficult for decision makers and leaves large responsibility to administrative judgments, not science-based judgments. The above illustration demonstrates how decision in this space encompasses research into hazard processes, warning technologies, human behavior and management systems. Resolving these issues requires that interdisciplinary scientific teams play a prominent role assisting decision makers with issues related to management of complex science-related issues such as uncertainties, timing of ordering evacuation, and facilitating effective emergency responses under conditions that are always characterized by urgency and a lack of information and resources (e.g., Funtowicz and Ravetz 1993).

After a disaster happens, physical phenomena of the hazardous natural event that caused it are immediately analyzed, sometimes in exhausting detail, and engineering solutions related to damage are quickly proposed. Meanwhile, vulnerability investigations, if done at all, are conducted slowly and insufficiently and rarely done before reconstruction starts. The forensic investigations should include the analysis of why and when the people moved to the affected area and the infrastructure were developed in the damaged area; what societal changes have been taking place in the region; what human actions have been applied to the affected land in history; what preparedness actions have been exercised by the public, communities and residents; what particular decisions or actions made the disaster losses expanded or suppressed; and many other issues (Burton 2010; Oliver-Smith et al. 2016). Quite often disaster reports are merely chronicles of the flooding or earthquake or another natural hazard event. The context for the pre-impact build-up of disaster risk, the unresolved difficulties and variability in post-event recovery, and the lack of long-term

[1] http://www.data.jma.go.jp/svd/eqev/data/en/guide/info.html.

visioning and consensus building between stakeholders to foster a disaster resilient future necessitate an integrated approach to disaster risk. This is especially true in the development of strategies to cope with rare but high-impact events under changing societal conditions and to BBB (UNISDR 2015).

How can such integration take place within the broad disaster science community? Two suggestions are described below.

1. Integrated research cannot be formed or realized without a specific mission, specific targets and efficient management that agreed to a common goal. A bright example of integrated research was the Apollo project ("Man on the Moon"). This project integrated not only Earth, space and planetary science disciplines, but also other natural, social, behavioral and engineering disciplines including rocket engineering, material and fuel sciences, aerodynamics, remote sensing, health, psychology, food, sanitary engineering, political science, and also well-designed communication, mass media and administration. The project was conducted under a strong governmental leadership.

Disaster science should be developed similarly. For example, human losses due to floods were significantly reduced in Bangladesh, China and Japan, mainly because of early warning, preparedness and, especially in coastal Bangladesh, the development of evacuation shelters, which were made available by a truly integrated approach to disaster response. This approach coevolved with knowledge from geoscience (meteorology, hydrology, remote sensing), engineering (architecture, civil and structural engineering), planning (land-use planning, urban planning), psychology and political science (communities and non-governmental organizations) as well as the local knowledge about administration, organizational and institutional schemes, political leadership, budget, policymaking and news media.

Sometimes similar integrative approaches are realized in recovery or reconstruction planning stages in post-disaster cases, including the areas affected by the 2011 Great East Japan Earthquake and Tsunami (Reconstruction Design Council 2011). In Japan, at various levels, administrators and scientists work together with other stakeholders in disaster management; it is mainly done through policy-determining advisory committees organized by governments, where representatives of stakeholders are invited as members. The highest-level organization is the Central Disaster Management Council chaired by the Prime Minister consisting of all cabinet members, heads of public organizations and experts (Cabinet Office 2015). Immediately after the disaster due to the 2011 great M9 earthquake and catastrophic tsunamis, the Reconstruction Design Council in Response to the Great East Japan Earthquake was set up. The council consisted of multistakeholders appointed by the prime minister who were to provide advice on the framework for formulating guidelines on reconstruction in regions affected by the earthquake and tsunamis. The report "Towards Reconstruction—Hope beyond the Disaster" (Reconstruction Design Council 2011) was submitted to the Prime Minister of Japan in June 2011. The report included "prioritizing efforts to ensure that even if disaster strikes it will not result in the loss of human life, and also working to minimize economic damage as much as possible." It admitted also that the reconstruction will take financial resources and time, considering "an appropriate 'combination' of measures for each region, including tsunami breakwaters, coastal dikes, and setback levees, 'area-based' development including relocation to higher ground, and land use and building construction regulations". This advice led the subsequent reconstruction effort, which is both costly and taking much time. In an environment, where risk and consequences are increasing, it is important to include more anticipatory planning for mitigating future events.

2. In order to make disaster science needed and useful, it should proceed together with a practicing sector. Many individual achievements of disaster science are available, but such a piecemeal effort is not integrated for practical use. This is partly because many disasters reflect local physical, social, economic, political and other conditions, and generalized rules and tools developed at regional to global scales do not necessarily work well for specific cases. Thus, more work on generalizable theory is important (Eiser et al. 2012). The application of available knowledge, oftentimes with considerable scientific uncertainties, is left to local disaster managers who may lack the expertise and/or time to utilize the information in its present form. In other words, the science community merely creates knowledge and makes it available to all, but rarely if ever takes the next step which is to translate such knowledge into practical solutions. This is one reason why scientific knowledge on disasters has had little effect on decision-making process—decision makers do not read scientific journals, and scientists do not publish one-page briefs for practitioners. Moreover, the science, practitioner and policy stakeholders rarely ever interact prior to an event occurring.

In 1999, the UNESCO International Hydrological Program established a cross-cutting initiative “Hydrology for the Environment, Life and Policy (HELP),” where hydrological scientists, water resources managers, and water law and policy experts worked together. The initiative aimed to end the traditional separation between relevant stakeholders, when some of them are unaware of available technical alternatives, and others, including scientists, are not realizing what is exactly required for research. The aim was to co-design a research agenda and to enable free flow of information for use in management and policymaking (HELP Task Force 2001). Although the initiative was successful in general, an issue was the time lag between the research agenda identified, solutions sought and found, and the implementation of the solutions. If implementation is a focus, the time lag should be short, and one of the ways to shorten it is co-implementation of common targets with the best science already available.

Hypotheses put forward by disaster science should be verified in practice. In geoscience, hypothesis testing is normally conducted in laboratories or in geological fields. But in disaster science, the target is not nature (e.g., a fault, river or volcano), but society; thus, the required experiments are social. In some cases, evidence for hypothesis testing in disaster science could be found in historical experiences of society (e.g., based on forensic investigations of disasters). The deployment of hindcast models based on the known historical experiences could go a long way in improving our understanding of the driving factors of risk production. Such hindcasting would enhance understanding of past events and risk drivers, but the non-stationary processes of global change preclude this approach for present and future analyses. An additional social perspective is introduced here in that it is important to ensure that hindcasting is seen as a development tool and not one in which political (e.g., blaming about poor response) or economic (e.g., litigation) goals undermine its utility as a vital tool for understanding complex and infrequent events about which learning opportunities must be capitalized on.

The verification of hypothesis testing is significantly limited because of the complex and changing nature of society—its coevolving technological and socioeconomic functioning systems and their interactions with the natural systems. It is difficult to model all components of such complex systems, especially how they change over time and across space placing enormous challenges for the disaster science research community. Greater efforts are needed to communicate different knowledge on disaster risks and disasters, science-based disaster risk assessments, socioeconomic impacts, evaluations of mechanisms for risk reduction, and prescriptive options for translating scientific findings to practice. Periodic scientific assessments of disaster risk can contribute to the significant enhancement of knowledge on specific risks (Cutter et al. 2015). The assessments could identify where the science is lacking and where improvements in the knowledge base are needed, and provide the baseline for evaluating the effectiveness of future risk reduction measures, including those proposed under the Sendai Framework for Disaster Risk Reduction 2015–2030 (UNISDR 2015).

Finally, the integration across stakeholders is not as simple as might be realized. There is a fundamental behavioral issue related to a mental model of stakeholders (i.e., an abstract mental representation of the objects, events and relationships that comprise a reality; Paton and McClure 2013). When dealing with the uncertainty associated with infrequently occurring, complex and multifaceted natural hazard events, the gap between the mental models of each profession will differ, introducing problems regarding their ability to cooperate. In the absence of regular hazard experience or large-scale real-time simulations, each stakeholder will develop plans based on their role in isolation and may not appreciate how and why collaboration is required to define complex evolving problems and to develop cohesive, multiagency responses to complex, multifaceted response issues.

Stakeholders also prescribe different weighting to disaster components. For example, geoscientists are likely to give the highest weighting to hazard data, whereas risk managers may place greater emphasis on political and economic criteria as, for example, they attempt to reconcile hazard data with the pragmatics of budgetary constraints. Differences in relative foci of interest between groups can create considerable scope for differences in interpretation and misinterpretation among different stakeholders. Therefore, regular joint stakeholder exercises using various disaster scenarios, modern scientific tools and knowledge should enhance collaboration by developing coordinated approaches, planning, making decisions about, and developing the policy and management capability to enact the outcomes of these collaborative exercises, where possible, as then use the generated information as inputs into future strategic disaster risk reduction.

Some of the ethical issues in transdisciplinary work involve the power differential between researchers who value objectivity over experience and ultimately dismiss the role of practitioner or indigenous knowledge within the research group. Another ethical consideration is determining how and when to engage stakeholders and support their involvement in the research process. While scientific members of a transdisciplinary team will understand the uncertainties inherent in any endeavor involving uncertain natural process, the expectations of other stakeholders, particularly those such as government and community group representative, need to be considered to ensure they enter the process aware of the risks involved, the time frames over which intervention may be required, and the commitments required of them and so on. This is particularly difficult in the initial problem definition phase of research where conflict and tensions may be at their highest levels and trust between the communities has not been well established. Team development processes, of necessity, require that conflict is created and is used functionally to break down barriers, build relationships and create the kinds of superordinate or transcendent goals for the success of a transdisciplinary approach. Accommodating some of these ethical issues may be achieved by using techniques such as the Delphi method (Dalkey and Helmer 1963) and scenario planning and development phase.

5 Paradigm shift

Disaster risks can be reduced significantly by the efforts of disaster science community (McNutt 2015) including geoscientists working in an integrated way with other stakeholders and policymakers. For this paradigm shift to happen, the following elements are needed.

Natural hazard analysis should be considered holistically and conducted on a common interdisciplinary stage. In spite of differences in origin and nature of hazards and differences in scientific approaches to hazards in terms of research tools and the maturity of relevant knowledge, there are shared features across the hazard fields (e.g., nonlinear behavior of extreme hazard events; self-organized criticality of hazard-related physical systems and their predictability; common metrics; observations; analytical and numerical techniques; standards of evidence and practice). These properties bind research on natural hazards together and help to understand the major feature of "unexpected" events leading in some cases to disasters.

Assuming that a natural hazard event happened, *exposure and vulnerability are the key determinants of disaster risk and the main drivers of disaster loss*. For example, considering various scenarios of earthquakes, Babayev et al. (2010) and Baker (2013) showed that disaster risk depends essentially on vulnerability of exposed values (e.g., economic loss from building damage). The dynamic variability in exposure and vulnerability is well documented in the research literature (Wisner et al. 2004) as is the understanding of differences—geographically between and within regions but also among sectors and social groups (Birkmann 2014). This is one of the most urgent and difficult areas that scientists and practitioners should work together and co-produce for disaster risk reduction actions.

Disaster is not a natural but a social phenomenon representing "a serious disruption of the normal functioning of a community or a society causing widespread human, material, economic or environmental losses which exceed the ability of the affected community/society to cope using its own resources" (UNISDR 2009). A disaster associated with natural event(s) results from the combination of natural hazards, conditions of social and physical vulnerabilities, and insufficient capacity or measures or even interest to reduce the potential negative consequences of risk, and exposure. This simple proposition has been known for nearly half a century, yet disaster scientists and practitioners still insist on viewing them as "natural" which results in risk management actions that are more techno-centric and controlling of nature, rather than eco-centric where human and physical systems adjust and coexist.

An outstanding knowledge of disaster risks itself is a little help in reducing risks and disasters unless the knowledge is implemented into the practice. Many governments and societies respond to disasters, but not so much to disaster risk. Scientists should develop a new approach to bridge the best science on disasters with the best practices in the sustained reduction in disaster risks. If the comprehensive knowledge is implemented into effective strategies and designs for hazard mitigation and disaster management, this, in turn, may lead to disaster risk reduction in many populated hazard-prone areas of the world.

Although the "digging deeper" of geophysical phenomena will improve the knowledge on natural hazard events, *unconsolidated scientific efforts* ("I dig my own field to find the Holy Grail") *will not contribute significantly to risk reduction without an integrated, co-designed and co-produced approach to disaster risk research and implementation*. For example, how can this knowledge translate into greater understanding of potential consequences for built and social environments, which is what people and societies may have to contend with in the future? The knowledge gained in natural sciences combined with that gained from the social sciences and other fields (e.g., engineering and public health) aimed at reducing vulnerability to hazards helps in overall assessments of potential disaster risks.

As an example of integrated research, let us consider the work on the project on wildfire disaster risk reduction in Portugal.[2] The project research team is comprised of

[2] http://www.firextr.pt/.

representatives of disciplines selected to cover all aspects of cause and consequences of wildfires as well as implementation of wildfire disaster risk reduction (e.g., ecology, forestry, anthropology, economics, political science, psychology, geography). The program is set up not to look at wildfire disaster risk reduction, but to understand people's relationships with land and fire and to develop a comprehensive approach to coexisting with fire. The interdisciplinary element lies with setting up a goal whose achievement requires complementary (rather than parallel) inputs, in which all participants to construct together a model of how people, communities, societal agencies, environment, etc. play interdependent roles in developing, enacting and sustaining disaster risk reduction outcomes. A pivotal issue is to create a superordinate goal and to get team members to work together on understanding and developing how they each contribute complementary perspectives to defining and achieving this goal.

An alternative approach can develop from drawing on experience in another hazard-related area, emergency management. Emergency management practice often faces a need to integrate the perspectives and contributions of different professions. Researchers could draw on expertise gained in areas such as multiagency coordination and the development of swift trust (Curnin et al. 2015a, b). The swift trust concept is intended to create functional disciplinary collaboration in crisis conditions, where professions need to develop and contribute to shared goals in the short time frames and high-risk crisis response settings. The principles could be used to facilitate research relationships where disciplines only come together to work on a specific project.

The reality of conducting research in this way, however, has several challenges. One is the time that needs to be invested in developing commitment to the overall goal, and this occurs prior to any research taking place. This time is required to allow for team members to understand how their disciplinary perspective complements those of others but also ensuring a commonality of definitions and understanding of diverse methods. This draws attention to the role of the team leader. They must be knowledgeable about the respective contributions of each discipline and invest in, and be able facilitating the development of the collective understanding and goal. This must be maintained over time.

The capacity of stakeholders to achieve their goals, even if opposed by others, is another challenge (Pohl et al. 2010). In this regard, it is important to prevent the situation when a few stakeholders involved in the co-production of knowledge impose their vision as the only valid one (Wiggins et al. 2004). Co-production requires that contributions from some stakeholders are not privileged over what other stakeholders contribute (McFarlane 2006). Moreover, a "thought style" of different stakeholders, who may belong to different social groups and have a different level of education and training, can generate difficulties in co-produced research (e.g., Cohen and Schnelle 1986). Another challenge of co-produced research is to interrelate epistemological, conceptual and practical elements of the knowledge from various stakeholders and their "thought styles" in a coherent practical research on disaster risk reduction (e.g., Cash et al. 2003; Pohl et al. 2010). In addition, many scientists prefer their disciplinary work compared to co-produced research, preferring to remain "objective" and not get involved in translating knowledge to practical use (Martin 2010).

A way to achieve the paradigm shift is through integration and co-production in disaster risk research and the maturation of disaster science. Such maturation will occur through transdisciplinary research (Fig. 1) and implementation of co-produced recommendations for actions to reduce risks and to improve the resilience of society. Such transdisciplinary approaches offer a practice- and policy-oriented knowledge to mitigate or to prevent potential disasters (Hirsch Hadorn et al. 2008).

6 Conclusion

The basic science is steadily advancing and improving our knowledge of the natural world. Meanwhile, challenging problems of society urge scientists to cope with uncertainties in policy issues, e.g., in climate change, disaster risk reduction and sustainability. To understand the complex socio-natural system, like disaster risk, reductionism, which requires a system to be divided into smaller elements to study each of them, must be replaced by a holistic approach, where research is integrated across domains and involves multiple stakeholders in the process.

Education in science and relevant risk-associated practice fields can be improved by introducing the transdisciplinary approach. Such training and education within science as well as practice domains can, through co-engagement and co-production of knowledge, enhance our understanding of vulnerable regions and populations. This training can draw upon work in team development, functioning and coordination to create the conditions in which disciplinary representatives collaborate to pursue superordinate goals that integrate their respective areas of experience, expertise and knowledge into a coherent system that increases the likelihood that risk reduction strategies are comprehensive and accepted and acted upon.

Facilitating preparedness involves not only making sound scientific and practical information and resources available to people but also developing the psychological and social capital and capacity required to interpret and use information and resources in ways that accommodate diverse and unique local needs and expectations. Managing future risk will increasingly require community engagement strategies that enhance the capacity of civil agencies and communities to have shared responsibility in disaster risk management.

Disaster events will continue to grow, if exposure and vulnerability are not reduced. Economic impacts of disasters will far exceed the cost of mitigation and preparedness by orders of magnitude (Ismail-Zadeh and Takeuchi 2007). More timely interventions and sustained multiyear efforts to support disaster risk management including research, management and resilience building can enhance sustainable development efforts. Linking disaster risk management to broader sustainable development goals can be achieved through proactive and community-based resilience efforts (Cutter 2014) and is possible with the cogeneration of knowledge between science and wider society.

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Appendix 1: Basic terms in disaster science

The definitions below are reproduced exactly or with some modifications from the sources referred.

By *natural hazards*, we refer to potentially damaging physical events and phenomena, which may cause the loss of life, injury or human life disruption, property damage, social, economic and political disruption, or environmental degradation. Natural hazards can be single, multiple or concatenated in time and local, regional and global in space. Each natural hazard event is characterized by its location, intensity and probability (Ismail-Zadeh et al. 2015).

By *community*, we refer to the full range of scales of community organization, from the scale of a neighborhood to the entire nation and a group of nations (The National Academies 2012).

Vulnerability is the potential for harm to the community and relates to physical assets (building design and strength), social capital (community structure, trust and family networks) and political access (ability to get government help and affect policies and decisions). Vulnerability also refers to how sensitive a population may be to a natural hazard or to disruptions caused by the hazard. Vulnerability is projected by the presence and effectiveness of measures taken to avoid or reduce the impact of the hazard through structural (e.g., levees, floodwalls or disaster-resistant construction) and nonstructural (e.g., relocation, temporary evacuation, land-use zoning, building codes, insurance, forecasts and early warning systems) actions (The National Academies 2012).

Exposure refers to the community's assets (people, property and infrastructure) subject to the hazard's damaging impacts. Exposure is calculated from data about the value, location and physical dimensions of an asset; construction type, quality and age of specific structures; spatial distribution of those occupying the structures; and characteristics of the natural environment such as wetlands, ecosystems, flora and fauna that could either mitigate effects from or be impacted by the hazard (The National Academies 2012).

A *disaster* can be referred to a serious disruption of the functioning of a community or a society involving widespread human, material, economic or environmental losses and impacts, which exceed the ability of the affected community or society to cope using its own resources (UNISDR 2009).

Risk can be determined as the probability of harmful consequences or expected losses and damages due to a natural event resulting from interactions between hazards, vulnerability and exposure values (Beer and Ismail-Zadeh 2003).

The term of *disaster risk management* (or simply *risk management*) is used to refer to as the suite of social processes engaged in the design, implementation and evaluation of strategies to improve understanding, foster disaster risk reduction and promote improvements in preparedness, response and recovery efforts (IPCC 2012).

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