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ORIGINAL ARTICLE

The social–ecological dimension of vulnerability and risk to natural hazards

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Abstract

The impacts of natural hazards on local communities are increasing worldwide and are projected to rise further due to urban expansion and climate change. To address these threats, a large amount of literature has characterized and assessed the physical, social, economic and institutional dimensions of disaster risk. However, much less attention has been paid to the social–ecological dimension of vulnerability and risk. The lack of consideration of this dimension represents a major knowledge gap, especially when considering that environmental degradation is regarded as one of the primary drivers of risk to natural hazards worldwide. While the international community advocates for the restoration of ecosystems as an important strategy for disaster risk reduction, the relationship between environmental health, vulnerability and risk of populations is often overlooked in vulnerability and risk assessment, a precondition for the design and implementation of effective ecosystem-based adaptation strategies. Possible explanations for this gap are: (1) the contradictory results on the role of ecosystem health in determining risk of local communities; (2) the poor theoretical framing of the social–ecological dimension of vulnerability and risk to natural hazards; or (3) the lack of clarity regarding how to assess this dimension of risk. This paper addresses potential reasons (2) and (3). It first reviews the available literature related to social–ecological drivers of vulnerability and risk of local communities exposed to natural hazards. Second, it discusses and provides a definition of social–ecological vulnerability and risk. Third, it reviews assessment methods and, finally, it suggests an improved conceptual framework that illustrates the main interactions between natural hazards, the ecosystem and the social system.

Keywords Social–ecological vulnerability · Natural hazards · Environmental degradation · Disaster risk reduction · Ecosystem-based approach

Introduction

In 2018, 281 disasters occurred globally, affecting 61.7 million people and resulting in more than 10,700 deaths (UNISDR 2019). Although mortality associated with natural hazards has decreased in many countries, economic losses are on the rise globally (UNISDR 2015a). Further, mortality and economic losses associated with extensive natural hazards (i.e. minor but recurrent hazards) are also increasing, particularly in low- and middle-income countries (UNISDR 2015a). The increased risk to natural hazards is generally attributed to growing populations that settle in urban and hazard-prone areas, and to the increase in exposed assets (Alexander 2006; Bouwer 2011; UNDESA 2015).

However, environmental degradation, land use change and climate change, by affecting the functioning of biophysical systems, are also increasingly recognized as main drivers behind the surge in the frequency and intensity of hazards and in the vulnerability of local populations (Adger and Brooks 2003; Kaly et al. 2004). Several international reports and policy documents have raised awareness of the state of the environment as a principal component of risk to natural hazards. The Millennium Ecosystem Assessment (2005) states that environmental degradation increases vulnerability of human populations to natural hazards and that appropriate management of ecosystems constitutes an important

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tool to reduce it. The role of ecosystems for disaster risk reduction (DRR) is emphasized in the Sendai Framework for DRR 2015–2030, which urges national and local authorities to "strengthen the sustainable use and management of ecosystems and implement integrated environmental and natural resource management approaches that incorporate disaster risk reduction" (UNISDR 2015b). Multiple international agencies and initiatives, including the UN Sustainable Development Goals, the UNFCCC Paris Climate Agreement and the Convention for Biological Diversity (CBD), have identified ecosystem-based approaches as soft options and "low regret" measures for DRR and climate change adaptation (CCA). In July 2018, the CBD adopted a recommendation specifically on "Biodiversity and climate change: ecosystem-based approaches to climate change adaptation and disaster risk reduction" (CBD 2018).

Despite this recognition, the role of the environment in shaping risk to natural hazards has for long been the least-explored aspect of DRR (Estrella et al. 2010; Renaud et al. 2013). The elements of coupling between the social and the ecological system with respect to the hazard and vulnerability (see Table 1 and the Appendix for a list of definitions) still need to be fully understood, characterized and conceptualized (Beroya-Eitner 2016; Berrouet et al. 2018; Birkmann 2011; Bollettino et al. 2017; Hagenlocher et al. 2018; Lo 2016; Sebesvari et al. 2016; Thiault et al. 2018a).

An explanation for this knowledge gap might reside in the scant knowledge available on how ecosystems attenuate impacts of extreme events on the human system (Carpenter and Folke 2006; MA 2005). Evidence of the benefits provided by ecosystems in terms of exposure reduction are in some cases contentious (Balmford et al. 2008), have so far led to contradictory results or have, in some cases, been overemphasized (Renaud et al. 2013). Another important reason might be the lack of common conceptual frameworks adequately defining the social–ecological dimension of vulnerability and risk, rendering this aspect invisible to a domain in which conceptualization is a precondition for practical assessment and design of effective adaptation plans and policies (Estrella et al. 2010; Lo 2016).

In this paper, I provide an enhanced definition and conceptualization of social–ecological vulnerability and risk to natural hazards and I suggest approaches and indices to measure them, drawing mainly on the ecosystem services literature. In the following sections, I review the available literature which directly or indirectly addresses the interactions between ecosystem health and risk to natural hazards ("State of the art" section). "Defining the social-ecological dimension of vulnerability and risk to natural hazards" section characterizes and defines social–ecological risk according to its two components: hazard and vulnerability. In "Natural hazards and social-ecological processes of coupling" section, I also discuss the adaptation component of the framework. In "Assessing the social-ecological dimension of risk and vulnerability" section, I review methods, indices and approaches to assess social–ecological vulnerability. Finally, Discussion" and "Conclusions" section are given.

State of the art

Since the last decades of the 20th century, the field of DRR has shifted its focus from the descriptive features of hazards (i.e. magnitude, frequency and intensity), principally

Table 1 Main definitions related to the social–ecological dimension of risk and vulnerability to natural hazards

Term	Definition	Source
Coupling	Refers to the fact that a defined hazard is given form and meaning by interaction with social–ecological systems, and similarly, social systems are influenced by their actual and perceived environmental and hazard contexts	Adapted from Birkmann et al. (2013)
Social–ecological vulnerability	The extent to which environmental degradation and climate change cause negative changes in exposure, susceptibility and in the capacity of the social–ecological system to anticipate, cope and recover from the hazard	Author's definition
Social–ecological risk	The extent to which environmental degradation and climate change affect the frequency and magnitude of the hazard and cause negative changes in exposure, susceptibility and in the capacity of the social–ecological system to anticipate, cope and recover from the hazard	Author's definition
Ecosystem-based Disaster Risk Reduction (Eco-DRR)	The sustainable management, conservation and restoration of ecosystems to reduce disaster risk	Adapted from Estrella and Saalismaa (2013)
Ecosystem-based Adaptation (EbA)	The use of biodiversity and ecosystem functions and services, as part of an overall adaptation strategy, contributing to the well-being of societies, including indigenous peoples and local communities, and helping people adapt to the adverse effects of climate change	CBD (2018)

analysed in the domain of natural sciences, to that of the propensity of the system exposed to suffer harm from hazardous events (Blaikie et al. 2014; Cannon 2008; Cardona 2004). From this point of view, disasters are no longer seen as the result of unavoidable acts of nature, but rather as the combination of the hazards' features and those of the system exposed. In this sense, disasters are seen as partially or totally socially constructed. The term 'vulnerability' was introduced to describe precisely the predisposition of a community to suffer damage in the face of a destabilizing phenomenon (Cardona 2004). According to this perspective, the losses experienced by the system are mostly avoidable and contingent upon the ability of the system to adapt to potential hazards. In other words, hazards might become disasters primarily because of the vulnerability of the system itself (Oliver-Smith 1999).

Within this perspective, mounting research has explored the physical (Kappes et al. 2012; Papathoma-Köhle et al. 2011; Uzielli et al. 2008), social (Adger 1999; Cutter et al. 2003; Cutter and Finch 2008; Lee 2014; Rygel et al. 2006), economic (Felsenstein and Lichter 2014; Kienberger et al. 2009), political (Collins 2008; Oliver-Smith 2004; Pelling 1999), institutional (Birkmann et al. 2008; Kahn 2005) and cultural (Cannon 2008; Donovan et al. 2012) dimensions of vulnerability. Conversely, the social-ecological dimension, or the ways in which the state of the environment determine vulnerability and risk, is little defined and poorly integrated into conceptual frameworks, practical assessments, plans and decisions (Depietri et al. 2013b; Renaud et al. 2013, 2016). To date, different bodies of literature have only partially or fragmentarily covered the multiple ways in which the social and the ecological system interact to shape risk. These are reviewed in the following sections.

From a focus on the ecosystem to an integrated approach

The available literature on the interactions occurring between the state of the environment and the risk to natural hazards often looks at the vulnerability of ecosystems themselves to natural and anthropogenic hazards (Barnett et al. 2008; ECLAC 2003; Kaly et al. 2004; UNEP and SOPAC 2005; Villa and McLeod 2002). These studies focus on the inability of an ecosystem, in all its levels of organization (from species, to communities, to the entire ecosystem), to tolerate pressures over certain thresholds, in time and space (Villa and McLeod 2002). The social relevance of this claim is that, the more degraded an ecosystem is, the more susceptible it is to be affected by a hazard and the more vulnerable becomes the social system associated with it. Barnett et al. (2008) criticizes this approach for being reductionist, confining complex issues to a series of indicators, as well as for the largely indirect social relevance of the approach. In the methods and indices presented in this litterature (such as the environmental vulnerability index—EVI—developed by South Pacific Applied Geosciences Commission—SOPAC), there is a fundamental ambiguity regarding what is considered as vulnerable: the social system or the ecological system? (Luers 2005).

Other literature looks specifically at the vulnerability of ecosystems to climate change and at how it affects species physiology, distribution and phenology (Hughes 2000; Root et al. 2005). The links between coral bleaching, increased greenhouse gases and climate change have, for instance, been proven incontrovertible (Hoegh-Guldberg et al. 2007; Hughes et al. 2003). Shifts in the distribution of species caused by climate changes in different regions of the world, such as the European Nordic region and in the Mid-Atlantic region of the US, have also been widely documented (Lassiter et al. 2000; NCM 2009). In this literature, the social–ecological component enters predominantly as a source of disturbance and of stress for the social–ecological system (Lindoso 2017). The degradation of the environment on which humans rely and that is brought about by climate change, remains the focus of these studies (Berrouet et al. 2018; Collier et al. 2009; Lo 2016; Luers 2005; O'Brien et al. 2004).

A more in-depth attempt to link ecosystem health with human safety is made by the resilience thinking literature which was initiated, in the field of ecology, by Holling (1973). The term vulnerability is rarely used in this field (Luers et al. 2003). Resilience is used instead, which many have been described as the flip side of vulnerability (Berkes 2007). However, from the perspective of the DRR community, this relation is not seen as simply symmetrical (Gallopín 2006), and the lack of resilience is described as one of the three components of vulnerability, together with exposure and susceptibility (Birkmann et al. 2013).

Besides that, resilience studies also analyse the behaviour of social–ecological systems in response to hazards or disturbances. Here, the focus is on ecosystem integrity and on the capacity of the social–ecological system to learn, renew and re-organize as it absorbs shocks while retaining its structure (Folke et al. 2004; Folke, 2006; Gunderson 2000; Walker et al. 2004). Regime shifts may occur when ecological resilience is eroded, and the system is severely disturbed, for instance, due to an extreme event (Adger 2005; Gunderson 2010; Renaud et al. 2010). According to Folke et al. (2004), regime shifts are principally caused by unsustainable human interventions in the ecosystem. An example is rangeland overgrazing, which leads to the selective removal of drought-resistant species and, when a drought occurs, the system can more easily transition into a shrub-dominated ecosystem, reducing its capacity to provide ecosystem services (Gunderson 2010). Hazards on degraded ecosystems, such as small eutrophic ponds, fragmented ecosystems or ecosystems with a high presence of alien species, can in fact lead the ecosystems under stress to lose their functions and be temporarily or permanently unable to provide services (Blaikie et al. 2014; Moritz et al. 2014). The identification of an ecosystem threshold, or the tolerable level of disturbance, is often seen as a necessary step towards the characterization of vulnerability (or resilience in this case) (Adger 2006).

The social relevance of resilience in this literature is also often indirect. Social and ecological components are generally treated separately, joining them only in a second moment (Adger 2005; Beroya-Eitner 2016; Berrouet et al. 2018). The object exposed is often the ecological system and the social system is only secondarily affected due to the loss of ecosystem services produced by the disturbance (Day et al. 2007; Marshall et al. 2013). Resilience is also difficult to operationalize for implementing DRR due to the multiple, and often loose, definitions given to the concept (Alexander 2013; Handmer and Dovers 1996; Klein et al. 2003). In the DRR literature, resilience describes the capacity of the system to anticipate, cope and recover from the hazard. Exposure and susceptibility, instead, provide information about the system exposure to the hazard and its fragilities, components which are only marginally conveyed by the resilience literature. However, it is important to retain from the literature reviewed so far the lesson that ecosystems, especially when degraded, can be themselves be affected by a natural hazard and can cross irreversible thresholds, leading to the cessation of the supply of ecosystem services for human well-being, further increasing risk.

Social-ecological vulnerability frameworks

The traditional dichotomy between the ecological and the social, which leads us to see these systems as distinct from each other, affects the interpretation we give to social–ecological risk. The multiple interactions, the dependencies and the feedbacks that take place between the two systems in the context of hazard risk are in fact only partially accounted for or are obfuscated in the disaster risk literature (Berrouet et al. 2018; Demeritt 2002; Oliver-Smith 2004). However, in a contrasting view, the very concepts of risk and vulnerability appear to refer to a multidimensional problem which is conceptually located at the intersection between the ecological and the social system, expressed by the concept of 'mutuality' or 'coupling' (Flint and Luloff 2005; Oliver-Smith 2004). Humans shape the environment as much as they are shaped by it, and it is in periods of stress that this interplay between social and ecological systems is the most evident (Zimmer 2010).

The term 'coupling' was introduced only recently in the DRR literature to describe the interactions between the hazard features, the ecosystem and the social context (e.g., Birkmann et al. 2013). According to Damm (2010), integrated studies considering both social and ecological dimensions of vulnerability were initially place-based studies, which then developed to encompass multi-dimensional assessments, and finally became defined as coupled social–ecological approaches. At the same time, frameworks for the analysis of risk and vulnerability have also evolved. Social–ecological vulnerability frameworks are: the Holistic Framework to Disaster Risk Assessment (Cardona and Barbat 2000), the Turner framework on social–ecological coupling (Turner et al. 2003a), the BBC framework based on sustainable development principles (Birkmann 2006), the MOVE framework (Birkmann et al. 2013), the Delta-SES framework (Sebesvari et al. 2016) and the one recently suggested by Berrouet et al. (2018). All these frameworks explicitly acknowledge the processes of coupling happening between the social system, the ecological system and the hazard.

Turner et al. (2003a) describe coupling as determining both the entity of the hazard and the sensitivity (or susceptibility) of the system itself. The MOVE Generic Framework, described in Birkmann et al. (2013), acknowledges the multidimensional nature of vulnerability and the presence of processes of coupling between the hazard and the social–ecological system. Sebesvari et al. (2016) describe social–ecological vulnerability as a combination of social exposure, susceptibility, coping and adaptive capacity, on the one hand, and of ecosystem exposure, susceptibility and robustness, on the other. Similarly, the framework developed by Berrouet et al. (2018) expresses social–ecological vulnerability as the combination of the ecological vulnerability (or impacts of the hazard on the ecosystem) and the subsequent potential impacts incurred by the social system due to the loss of ecosystem services. According to these two last frameworks, the change in the level of provision of ecosystem services when a hazard strikes, is the threat that the social system faces in the context of social–ecological vulnerability. These descriptions do not significantly differ from the approach focusing on ecosystem health described in the previous section, which has only indirect social relevance.

Overall, besides clearly stating the existence of processes of coupling between the hazard and the social–ecological system, the mentioned frameworks do not unpack the full complexity and the multiple ways in which the ecological and the social system interact and affect each other, as well as the hazard, while shaping vulnerability and risk of the exposed system.

Defining the social–ecological dimension of vulnerability and risk to natural hazards

The social–ecological dimension of vulnerability of coupled systems can be expressed through the nature and the quality of the dependencies of communities and their economic activities on ecosystems (Adger 2000; Renaud et al. 2010; Thiault et al. 2018a). I thus make use of ecosystem services concept to analyse the multiple ways the ecological system, the social systems and the natural hazard interact while co-determining vulnerability and risk. I also adopt the MOVE framework developed by Birkmann et al. (2013) as a starting point, as this is a generic and holistic framework applicable both in the context of DRR and of CCA. In it, vulnerability is characterized according to three components: exposure (i.e. "the extent to which a unit of assessment falls within the geographical range of a hazard event"); susceptibility (i.e. "the predisposition of elements at risk to suffer harm"); and lack of resilience (i.e. the "limitation in access to and mobilisation of the resources of a community or a social–ecological system in responding to an identified hazard", compromising the capacity to anticipate, to cope and to recover of the system) (Birkmann et al. 2013, p. 200). Adaptive capacity, instead, refers to longer term changes needed in the system to reduce vulnerability and risk. This is different from the term resilience which refers to the strategies readily available to a community to anticipate, cope and recover from the hazard (Birkmann et al. 2013).

Based on these premises, I define social–ecological risk as the extent to which environmental degradation and climate change affect the frequency and magnitude of the hazard and cause negative changes in exposure, susceptibility and in the capacity of the social–ecological system to anticipate, cope and recover from the hazard (see Table 1). In this definition, I consider the human population as the subject ultimately exposed and not the ecological system, as it was the case in most of the previous literature (Sebesvari et al. 2016; Thiault et al. 2018b; Turner et al. 2003a). This definition is in line with the characterization of the other dimensions of vulnerability to natural hazards which consider human beings as the ultimate subject affected. Nonetheless, I also acknowledge that the damages that might occur to the ecosystem following a hazard can cause a temporary or permanent decline in ecosystem services, which indirectly leads to additional losses or stress that human beings in the system might experience.

In the next sections, I describe the interactions (or coupling) that take place between the hazards and the social–ecological system and that might affect the hazard intensity and/or frequency ("Natural hazards and social-ecological processes of coupling" section), as well as the interactions which might lead to an increase in social-ecological vulnerability ("The social-ecological dimension of vulnerability" section). Adaptation strategies designed to tackle drivers of this risk through green infrastructures, nature-based solutions and other ecosystem-based approaches are described in "Ecosystem-based disaster risk reduction and adaptation" section. In "Hazards' impacts on ecosystems, ecosystem restoration and biodiversity conservation" section, I elaborate on the additional sources of social-ecological risk that could be produced by the loss of ecosystem services resulting from the impacts of the hazard on the ecosystem itself.

Natural hazards and social–ecological processes of coupling

In describing the processes of coupling that take place between the hazard and the social–ecological system, it is worth making a distinction between a well-adapted, healthy system, and a maladapted, degraded system. Natural hazards are part of the functioning of ecosystem, bringing regeneration and renewal and should not be merely suppressed. It follows that the system needs to be well adapted, living with extreme events and not only against them. Instead, a degraded and maladapted ecosystem can exacerbate hazard intensity and frequency, especially in the long term (e.g. in the case of Hurricane Katrina in New Orleans) (Day et al. 2007).

Well-adapted social–ecological systems

A system that does not simply shift environmental pressures elsewhere (e.g., that does not rely only on engineering work to cope with floods, encouraging urban sprawl and making the population at risk from rarer, but more catastrophic events) is considered as a well-adapted social–ecological system. It is consistent and works with existing environmental processes. It is in tune with them and continuously adapts to account for evolving environmental conditions (Magnan 2014). As mentioned, natural hazards do not only bring destruction to social–ecological systems. It is well-established in the literature that natural hazards are an integral part of ecosystems' long-term functioning (Colding et al. 2003; Drever et al. 2006; Nyström et al. 2000). They provide many benefits, including: system renewal, maintenance of biological diversity, and sustaining a dynamic complexity of biomes and ecotones (Banks et al. 2013; Bazzaz 1983). Natural disturbances lead to patchiness in ecosystems which fosters habitat and species diversity (Pulliam and Johnson, 2002; White and Jentsch 2001). Ecosystems in hazard-prone areas are generally composed of species highly adapted to recurrent disturbances which help maintain essential functions in ecosystems, such as productivity and resilience during and after an event (Pausas et al. 2008; White and Jentsch 2001). A riverine landscape depends, to a large extent, on periodic flooding (also known as "flood pulse"), which is crucial for maintaining ecological integrity and diversity as it creates unique habitats that are essential to the survival and reproduction of many species (Jungwirth et al. 2002).

Floods provide critical habitats for fishes, waterfowls and other wildlife, helping to sustain high plant diversity (Bayley 1991; Sparks 1995). Some species are even dependent on natural disturbances to flourish. It has been documented that fish yields generally increase following a flood (Bayley 1991). Some terrestrial species are also highly dependent on the occurrence of fires for their reproduction. These only germinate when stimulated by the heat of fire, smoke or charred wood (Pausas et al. 2008). Some anthropogenic disturbances, such as sustainable ecosystem modifications by humans, can also be beneficial. An example is induced and contained forest fires in agroecosystems (Bar Massada et al. 2009). Water biota can be extremely resilient to periods of drought by accessing dispersed, low-water refugia (Bayley 1991). Coral reefs are also particularly well-adapted to coastal storms (Nyström et al. 2000).

Humans also directly profit from natural disturbances. Such is the case of typhoons in Hong Kong which, despite the physical and social losses that these might produce, also alleviate droughts and water scarcity in the region, while bringing cool air and reducing electricity demand (Lam et al. 2012). Inland flooding fertilizes soil and improves natural varieties of food grains, replenishes water supply in lakes, ponds and groundwater and purges the rural, and sometimes urban, environment, with major positive impacts on public health (Cuny 1991). Sand bars formed by floods produce flood barriers which can be used as construction materials (Cuny 1991).

It is thus necessary to fully integrate controlled disturbances into the management of ecosystems and natural resources (Bergeron et al. 1999), such as sustainable grazing, slash and burn clearing, or allowing for flood pulses (White and Jentsch 2001). Well-adapted human societies do not affect hazards' frequency and magnitude, and do not modify or suppress natural hazards regimes; they plan with and not against them. They allow natural hazards to occur in the system and make use of green infrastructures or hybrid approaches (see Appendix for definitions) to adapt to them. Heathy and well-distributed ecosystems provide multiple co-benefits besides buffering from the impacts of natural hazards, such as food and water supply, as well as opportunities for cultural and recreational activities. Well-adapted systems generally suffer reduced impacts and are better able to recover from hazards.

These positive interactions (or coupling between the hazard and the social–ecological system) are summarised in Fig. 1a. Note that, in Figs. 1a, b, 2, the environment encompasses both ecosystem biotic and abiotic (soil, water, atmosphere) components, including humans.

Natural hazards, environmental degradation and maladapted social–ecological systems

In a degraded environment many are the negative interactions that occur between the hazard and the social–ecological system. A maladapted, degraded system is one that generates or supports conditions that introduce or exacerbate existing risks (Schipper 2009). These conditions can interact with the hazard by modifying its intensity and/or frequency, especially in the long run. Modified hazards are also called socio-natural hazards, as they are associated both with natural and anthropogenic causes (UNISDR 2009). For instance, the removal or the accumulation of organic matter in soils can exacerbate disturbance regimes such as fires and soil erosion (Mack and D'Antonio 1998). Some other human-induced environmental changes that increase the magnitude

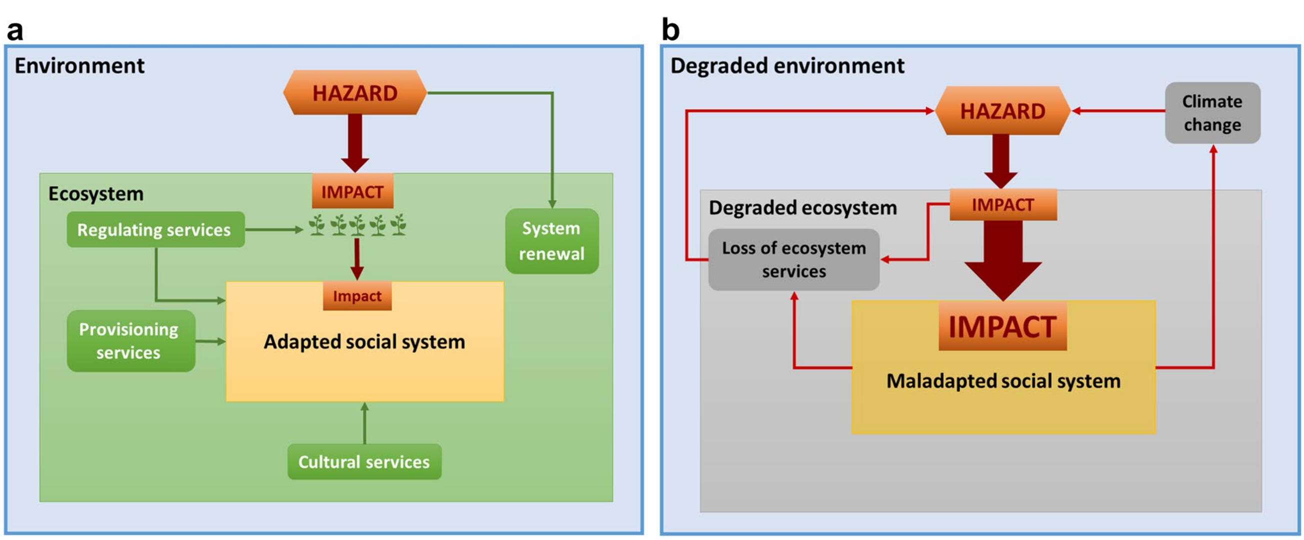

Fig. 1 **a**, **b** Representation of the interactions between a well-adapted socio-economic system and the hazard taking place in a healthy environment (**a**), and of the interactions tacking place between a maladapted and degraded social–ecological system and the hazard component (**b**)

Table 2 Features of degraded ecosystems that might lead to catastrophic impacts of hazards in the cases of extreme fire and inland flooding

	Sources
Fires	
Accumulation of organic matter in soil	Bond and Keane (2017), Pausas et al. (2008)
Land abandonment (including the reduction of pastoral activities)	
Homogenization of the landscape	
Introduction of highly inflammable invasive species (e.g. tall non-native grass invasion into woody ecosystems)	
Inland flooding	
Reduced connectivity between river beds, river channels and floodplains; regulation and fragmentation of rivers through dikes, hydroelectric power plants and other hydraulic measures	EEA (2016), Jungwirth et al. (2002)
Land drainage and wetlands' reclamation	
River bed dredging	
Soil sealing	

and intensity of forest fires and floods are summarized in Table 2.

Humans have directly and continuously worked to modify disturbance regimes to protect urban expansion and economic exploitation. However, the modification or even the removal of natural disturbances generally leads to unpredictable and disastrous effects in the long term (Nyström et al. 2000; White and Jentsch 2001). Such is the case of forest fires (Pausas et al. 2008). Some large wildfires in the US and in Mediterranean-type ecosystems have been blamed on ongoing fire suppression, amongst other causes (Bond and Keane 2017; Pereira et al. 2017). Environmental degradation can also introduce entirely new disturbances (Mack and D'Antonio 1998). Climate change directly increases hydro-meteorological hazard intensity, duration and frequency, posing additional risks to human populations, potentially leading to catastrophic impacts. In addition to that, in degraded environments, the ecosystem does not buffer local communities from the impacts of natural hazards (increasing their exposure, as describe below), is itself affected by the hazard and can cease to provide most or all other ecosystem services supporting human well-being. These negative interactions or coupling between the hazard and the social–ecological system are summarized in Fig. 1b.

The social–ecological dimension of vulnerability

After reviewing the coupling that takes place between the hazard and the social–ecological system, I look at the coupling occurring between the social and ecological system and the ways in which this shapes and affects the vulnerability of local human populations to natural hazards. Generally, the social and the ecological dimensions of vulnerability are defined separately and joined at a later stage of the assessment (e.g., Sebesvari et al. 2016; Thiault et al. 2018b). I provide instead an integrated definition. As suggested by Sowman and Raemaekers (2018), the sources of social–ecological vulnerability are to be identified in environmental stressors, which are also themselves embedded in the political economy of resource use (Adger 2005). The social–ecological vulnerability can thus be defined as the extent to which environmental degradation and climate change cause negative changes in the exposure, susceptibility and in the capacity of the social–ecological system to anticipate, cope and recover from the hazard. The state of the ecosystem and its capacity to provide services at different scales largely determine the social–ecological vulnerability of the system.

First, degraded ecosystems lose their capacity to buffer local communities from the impacts of hazards, increasing system's exposure. For instance, the reduction of coastal wetlands increases the exposure of local communities to coastal storms (Gedan et al. 2011), while the loss of inland wetlands increases exposure and flood risk in urban watersheds (see Depietri et al. 2012 for a review). As an example, the Marikina City (in the Philippines) has become more exposed to potentially destructive floods as a result of uncontrolled forest encroachment and unregulated disposal of waste (Yu and Sayor, 2008). Settling in degraded environments, such as deforested and eroding slopes and other hazard-prone areas, also increases exposure to natural hazards.

Second, ecosystems contribute with livelihoods for the world population by providing clean water, food and fibres, either locally or at broader scales. Conversely, degraded environments fail to suppy these resources, increasing the susceptibility of the populations exposed to natural hazards. When provisioning services are lost, due to extensive deforestation, desertification and salinization, poverty also increases. In these conditions, malnutrition and related illnesses undermine the health of human beings, increasing their likelihood to suffer from the impacts of natural hazards. For instance, the overexploitation of marine resources, and subsequent decline in fish species and in individual catches, can increase the susceptibility of a malnourished population if under stress

(Sowman and Raemaekers 2018). Polluted and insalubrious environments also increase susceptibility. Air pollution, for instance, has been associated with an increased risk for city dwellers to suffer harm from the impacts of heat waves, such as by experiencing more heat strokes (Fischer et al. 2004; Piver et al. 1999; Rainham 2003). Populations exposed to epidemics, linked to poor sanitation or poor water quality, also see their susceptibility to hazards increased. Climate change further amplifies the variability of weather conditions and patterns, potentially undermining sources of food or water for population exposed to extreme events (Allison et al. 2009; Cinner et al. 2013).

Finally, the loss of ecosystems and their services due to environmental degradation increases the lack of resilience of local communities by reducing their capacity to anticipate, cope and recover from a hazard. This occurs when the alternative sources of regulating and provisioning services, that generally improve the capacity of the system to absorb the shock and recover from it, have been lost or are compromised. Degraded and reclaimed wetlands stop retaining water and slowly release it in periods of droughts, potentially increasing water scarcity. Similarly, access to parks provides relief to heat stress, while poor distribution of green areas in cities are missed opportunities to provide access to cooler areas. Ecosystems also offer alternative sources of livelihoods for local communities when a hazard strikes (Sudmeier-Rieux et al. 2006). When ecosystems are degraded these alternative strategies are compromised and resilience is reduced. In the case of the 2004 tsunami, environmental degradation, including land clearing, coastal erosion, overfishing, and coral mining, has reduced the potential for recovery because of many sources of livelihoods were lost (Adger 2005). Generally, traditional agro-ecological systems are better adapted to cope with impacts of natural hazards. Instead, the loss of knowledge regarding alternative strategies to cope with and recover in the aftermath of a disaster increases vulnerability (Adger 2005; Singh and Haas 2013).

These interactions are summarized in the central part of Fig. 2. As mentioned, the framework is based on the MOVE generic framework described in Birkmann et al. (2013) and points to the ways the ecosystem interacts with the social system to shape risk in the present and how it can be improved through ecosystem-based adaptation (or medium- or long-term ecosystem-based interventions and changes in the system). These long-term changes in the systems are represented in the right part of the framework and are described in the next section.

Ecosystem-based disaster risk reduction and adaptation

Risk governance encompasses all the different institutional efforts to design and implement adaptation strategies to curb vulnerability and risk at different spatial and temporal scales (see Fig. 2). Adaptation can be defined as “the longer-term and constantly unfolding process of learning, experimentation and change that feeds into vulnerability” (Birkmann et al. 2013, p. 196). It entails learning and developing new knowledge and approaches to reduce vulnerability and risk in the medium- to long-term perspective (Folke et al. 2005; Marshall et al. 2013; Olsson et al. 2004).

Based on the assessment of social–ecological vulnerability described below in “Assessing the social-ecological dimension of risk and vulnerability” section, ecosystem-based DRR (Eco-DRR) and ecosystem-based adaptation (EbA) can be planned (see Table 1 and Appendix for definitions). Eco-DRR and EbA are management approaches that aim precisely at tackling social-ecological vulnerability and risk by significantly modifying the structure and functioning of the exposed system making use of green infrastructures and other nature-based solutions (or ecosystem elements) (Murti and Mathez-Stiefel 2018). The long-term time horizon and the need to make changes in the structure of the system, differentiates adaptation from short-term processes of anticipating, coping and recovering (or resilience).

An expanding field of research, working especially at the international level (such is the work of the partnership for environment and disaster risk reduction—PEDRR—http://pedrr.org/), aims at studying and demonstrating how ecosystem-based approaches, nature-based solutions, green infrastructures or hybrid solutions can provide viable alternatives to hard infrastructures or engineered approaches for reducing risk from natural hazards (see Appendix for definitions).

Initial studies have suggested that well-managed ecosystems and their regulating services can contribute, to some extent, to the reduction of risk and are very often cost-effective, multifunctional, and win–win solutions, especially in the long run (EEA 2014; Renaud et al. 2013; Sudmeier-Rieux et al. 2013). Examples of ecosystem-based approaches to reduce exposure include: the restoration of forests and grasslands to protect communities and settlements from soil erosion and sandstorms (Lo 2016); integrating native vegetation into urban spaces to provide relief from extreme heat, improve air quality and increasing water infiltration reducing flood risk (Depietri et al. 2012); or restoring coastal and inland wetlands to reduce flooding and storm surges (Bullock and Acreman 2003). The Sanjay Gandhi National Park Mumbai (India), for instance, protected the city from experiencing increased impacts from floods (Trzyna 2014).

Livelihood enhancement, based on ecosystem approaches, also seeks both to reduce susceptibility and reinforce existing household coping strategies. According to Twigg (2015), some available interventions entail: food or cash transfers seeds, the promotion of off-farm activities and overall livelihood diversification. Other measures are grain

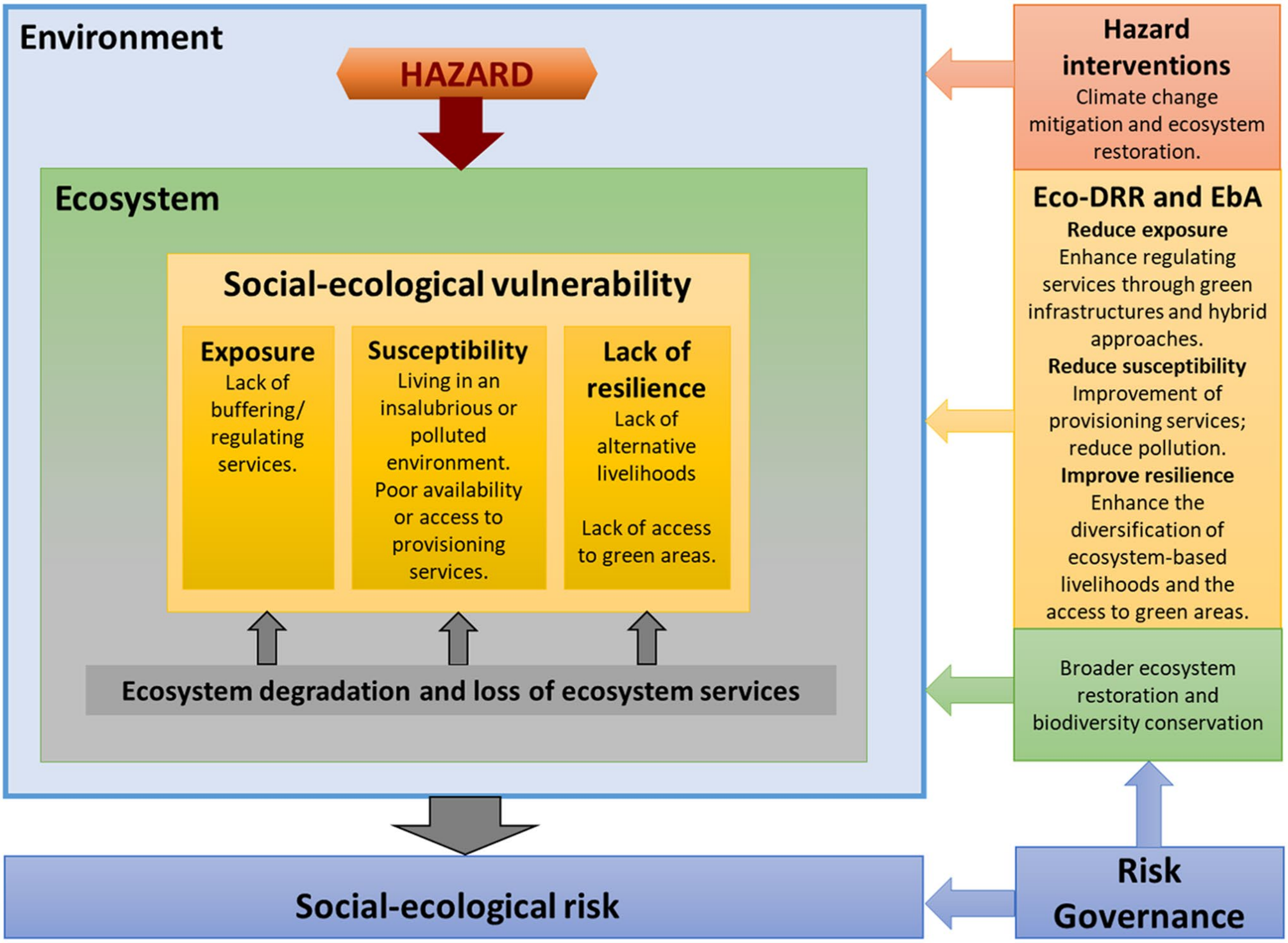

Fig. 2 Framework representing the elements and interactions that shape social–ecological vulnerability and risk of exposed systems to natural hazards in the context of risk governance Adapted from the MOVE framework presented in Birkmann et al. (2013)

stores and improved land use to avoid concentrating livelihoods on a single geographical area. Pollution reduction at the source might also be needed to reduce social-ecological susceptibility.

Ecosystem-based approaches for DRR and CCA provide a range of co-benefits, such as enhanced carbon sequestration, enhanced community engagement, recreation and broader livelihood opportunities (Sudmeier-Rieux et al. 2006). Another advantage of ecosystem-based approaches is their reduced economic cost, especially when assessed in the long-term perspective (Brouwer and van Ek 2004; Hoang Tri et al. 1998). Maintenance costs in this case are in fact very low, especially when compared to grey infrastructures (Renaud et al. 2013). Despite this, more research is needed on providing concrete cases highlighting the contributions of ecosystem-based approaches to DRR (Renaud et al. 2016, 2013).

Hazards' impacts on ecosystems, ecosystem restoration and biodiversity conservation

It is important to acknowledge that ecosystems can themselves be affected by hazards and cease to supply services to local populations further increasing the risk faced by the population. Such was the case during the 2004 tsunami wave, which had severe consequence on local communities highly dependent on coastal resources, such as fishing (Birkmann 2011). This situation can happen temporarily, after an extreme event strikes (Marshall et al. 2013), but can also be protracted in time if the ecosystem is particularly degraded and damaged. In these conditions, hazards might cause ecosystems to cross thresholds and produce undesirable situations which can be irreversible (Renaud et al. 2010).

The capacity of ecosystems to overcome impacts of a hazard and keep adapting resides in some features of the system itself. Biodiversity stabilizes ecosystems subject to extreme climate events, creating system robustness and resilience (Admiraal et al. 2013; Baumgärtner 2008; Folke et al. 2004;

Isbell et al. 2015). Naeem and Li (1997) look at functional diversity and Walker et al. (2004) at functional redundancy as additional measures providing information on the capacity of the ecosystem to cope with perturbations or environmental variability. For some authors, functional redundancy could be even more important than species richness for expressing the resilience of the system (Díaz and Cabido 2001; Elmqvist et al. 2003; White and Jentsch 2001). The health of keystone species is also a factor considered as influencing the capacity of exposed ecosystems to cope with a disturbance, together with the number of introduced and endangered species per unit of surface (De Lange et al. 2010). The European Environment Agency (EEA) integrates indicators of habitat health in its methodology for assessing ecosystem services, this to account for the actual capacity of the ecosystem to adequately provide and continue providing services if disturbed. One of these indicators is the minimum size suitable to host mammals, as these animals require large and well-connected natural areas for their survival and movement (EEA 2014). Overall these features determine the insurance value of ecosystems (see Appendix for a definition).

It is worth noting once more that this indirect source of vulnerability of the social–ecological system is generally what is described as the primary source of the social–ecological vulnerability to hazards in the literature (e.g. Beroya-Eitner 2016; Berrouet et al. 2018; Sebesvari et al. 2016; Thiault et al. 2018b). Here, instead, I consider it as only secondarily and indirectly contributing to the social–ecological vulnerability and risk of people. Broader biodiversity conservation and ecosystem restoration are necessary to tackle this source of risk.

Assessing the social–ecological dimension of risk and vulnerability

The assessment of social–ecological risk is also vaguely addressed in the literature (Thiault et al. 2018a). Focusing on the hazard, to assess changes in hazard frequency and intensity due to environmental degradation, one needs to rely on biophysical, hydrologic, atmospheric or geological modelling (e.g. Ciabatta et al. 2016; Van Beek and Van Asch 2004). These are not reviewed here. Instead, I explore how we can assess social–ecological vulnerability to natural hazards. This can be done both in a qualitative, participatory way, or in a quantitative way, using proxies and (composite) indicators. Sowman and Raemaekers (2018), for instance, adopted a community-based rapid vulnerability assessment methodology to understand the extent to which suceptibility might be affected by various socio-ecological and environmental changes in fishing villages in Angola, Namibia and South Africa. Using workshops, the authors assessed stressors linked to losses in livelihoods affecting the ability of local communities to respond to disturbances. Other authors used surveys to assess the level of resource dependency and adaptive capacity of the population potentially affected by a natural hazard (Marshall et al. 2013). The Turner framework (2003a) was applied to three case studies which illustrate how unsustainable land management practices can increase overall risk to natural hazards and limit access to biophysical resources, thus increasing household sensitivity to hazards (Turner et al. 2003b). The authors analysed social–ecological vulnerability through qualitative methods mainly based on workshops, interviews and focus groups.

Other available research measures social–ecological vulnerability as a composite indicator, resulting separately from a number of biophysical indicators of ecosystem health (assessed via field measurements) and a number of social indicators captured through survey methods (e.g. Cinner et al. 2013; Damm 2010; Hagenlocher et al. 2018; Thiault et al. 2018a). Sebesvari et al. (2016), for instance, list several indicators that can be used for assessing separately social and ecological susceptibility and robustness in deltaic environments.

As mentioned, the concept of ecosystem services offers a distinctive and suitable conceptual framing to characterize, explore and assess the dependencies of the social systems on ecosystems in the context of risk, overcoming the separation which derives from assessing the social and ecological components independently. Depietri et al. (2013b), for instance, assessed the links between social vulnerability and the ecosystem in shaping risk of the city of Cologne (Germany) to heat waves. In this study, both quantitative (spatial assessment) and qualitative data (experts' interviews) were used to evaluate the reliance of the social system on the ecosystem by estimating the availability and quality of relevant ecosystem services in case of a hazardous event.

In Table 3, I suggest potential indicators that link the state of the environment with the well-being of human populations in the context of hazard risk. These are intended for quantitative assessments but can also provide suggestions for identifying dependencies to be explored through qualitative methods. A fundamental step of this type of assessments is the clear characterization of the groups relying or benefiting from the services (Berrouet et al. 2018). Table 3 builds on previous review studies authored or co-authored by the author (see Depietri 2015; Depietri et al. 2013a, b, 2012; Guadagno et al. 2013). The categories in the left column of the Table reflect the central part of the framework presented in Fig. 2.

Table 3 List of potential indicators and proxies of ecosystems services to assess social–ecological vulnerability and risk

Component of risk and vulnerability	Ecosystem service	Proxy for quantitative assessment	Description	References
Hazard	Climate regulation	Tons of carbon in above and below ground vegetation or habitat type Amount of tree cover	Carbone storage	Chan et al. (2006), Egoh et al. (2008), Haase et al. (2012), Reyers et al. (2009)
Exposure	Cooling capacity	Land surface thermal emissions or surface emissivity	Total amount of energy emitted by a surface (Landsat 7 ETM + thermal band 6.1)	Haase et al. (2012), Schwartz et al. (2011)
		Surface air temperature	Derived by a thermal scan of land surface temperatures	Haase et al. (2012)
		Evapotranspiration	*f* value for evapotranspiration potential of a land use class	Larondelle and Haase (2013), Schwartz et al. (2011)
	Riverine, local flood regulation	Water infiltration capacity of soils	Includes percent vegetation cover, per cent agricultural cover, flow distance from 100-year floodplain, per cent vegetation cover within riparian zone (whose width depends on stream order) (unit-less score)	Chan et al. (2006)
		Riparian areas	Regional ecosystems vegetation and land use datasets for riparian areas: “green zones” which lie between stream channels and uplands	Pert et al. (2010)
		Ground water recharge	Percentage (%) contribution of groundwater to base-flows	Egoh et al. (2008)
			Millions of cubic metres of groundwater recharge per 1-km^2 grid cell	Reyers et al. (2009)
		Percentage of sealed soil	Soil infiltration capacity	Haase and Nuissl (2007)
	Coastal, storm surge regulation	Mangrove area	Buffer storm surge impacts lowering intensity	Das and Vincent (2009), Hoang Tri et al. (1998), Zhang et al. (2012)
		Extension of the coastal dunes	No dunes/discontinuous dunes; bulldozed dunes; sparse vegetation	Bush et al. (1999)
	Erosion regulation	Loss of soil particles by wind or water; vegetation cover	Vegetative cover plays an important role in soil retention and the prevention of landslides	Burkhard et al. (2012)

Table 3 (continued)

Component of risk and vulnerability	Ecosystem service	Proxy for quantitative assessment	Description	References
Susceptibility	Food supply	Plants/ha; kJ/ha	Crops: cultivation and import of edible plants	Burkhard et al. (2012), O'Brien et al. (2004)
		Animals/ha; kJ/ha	Livestock: keeping and importing of edible animals	
		Fishes available for catch/ha; kJ/ha	Fisheries: catch of commercially interesting fish species, which are accessible to fishermen	
		Soil quality and depth	Areas with more productive soil available for agriculture are better able to supply food	
	Water supply	Litres or m^3/ha	Presence of freshwater	
	Energy supply	Biomass	Presence of trees or plants with potential use as energy source (wood or plant biomass/ha; kJ/ha)	
	Water purification	Epidemics and pollution	High risk of epidemics and low ecosystems' capacity to purify water which can also be a source of impurities	
	Air purification	Leaf area index	Low total amount of pollutants removed via dry deposition on leaves (ton ha^{-1} $year^{-1}$) for land cover classes	
		Dry deposition velocity per pollutant concentration	Deposition velocity is the inverse sum of three resistances. The main ecosystem-based parameters affecting deposition velocity are the height of the vegetation (related to the roughness length of the land) and the leaf area index	Maes et al. (2011)
Lack of resilience	Lack of alternative sources of food	Plants/ha; kJ/ha; Animals/ha; kJ/ha; Other fishes available for catch/ha; kJ/ha	Alternative sources of food like imports of food, water and energy are important to assess in case the traditional supply fails when a hazard strikes	Adapted from Burkhard et al. (2012)
	Lack of alternative sources of water	Litres or m^3/ha		
	Lack of alternative sources of energy	Wood or plant biomass/ha; kJ/ha		
	Lack of access to cooler places	Temperature; albedo; evapotranspiration; % green area	Access to green areas offer relief from extreme heat	

Discussion

While the social–ecological dimension of risk to natural hazards is understudied in the DRR literature, most of the recent studies addressing social–ecological vulnerability only partially address the multiple ways in which the hazard, the social and the ecological system interact affecting risk. Most of these studies define social–ecological vulnerability as a combination of ecological vulnerability (or the potential that the ecosystem be affected by the hazard) and social vulnerability, indirectly affected by the loss of ecosystem services caused by the hazard (Barnett et al. 2008; Beroya-Eitner 2016; Berrouet et al. 2018). I instead focused on the ways a degraded environment can affect hazard patterns as well as the vulnerability of a local population, by increasing its exposure, susceptibility and lack of resilience. In doing so, I considered the impacts on the ecosystem and the subsequent loss in services as only secondarily determining social–ecological vulnerability and risk. I also looked at how ecosystem-based approaches (i.e. Eco-DRR and EbA) can curb, in the medium or long term, vulnerability.

Focusing on the elements of coupling between the social–ecological system and the hazard, I distinguished two situations: (1) of a well-adapted system, which accounts for the notion that natural hazards are an integral part of the functioning of ecosystems and can bring numerous benefits, including regeneration and renewal; and (2) of a maladapted system, or one in which the hazard intensity and frequency are increased by environmental degradation and inadequate ecosystem management. The first case reinforces the notion of planning with the hazard, and not merely against it. This perspective also acknowledges that the way we traditionally deal with hazards, through suppression and hard infrastructures, has often led to increased risk in the long run. Ecosystem-based approaches are more suitable to accommodate frequent but less intense hazards, while minimizing the risk of rarer but potentially catastrophic events (Depietri and McPhearson 2017).

The conceptualization of the social–ecological dimension of vulnerability is a fundamental step towards its assessment and consideration in the DRR context. The lack of it has caused this dimension to often be ignored in holistic vulnerability assessments. I thus extensively described the multiple ways in which environmental degradation affects people increasing their vulnerability to natural hazards. I suggested a definition of social–ecological vulnerability which is integrated and does not result from the separate consideration of social vulnerability and of ecological vulnerability. In "Assessing the social-ecological dimension of risk and vulnerability" section I also provided ways in which to empirically assess the quality of different components of social–ecological vulnerability. This is as a fundamental step to design improved Eco-DRR and EbA approaches to reduce risk in the long term (Marshall et al. 2013). Extended biodiversity conservation and ecosystem restoration might be required to reduce indirect causes of social-ecological risk. Overall, the framework presented in Fig. 2 is precisely intended to guide this work.

It is also important to note that sources of environmental degradation originate at multiple spatial scales, from local to regional to international. Therefore, factors and causes of social–ecological risk and ecosystem-based approaches to tackle it need to be investigated at multiple spatial units.

Finally, environmental degradation, increasing social–ecological vulnerability, cannot be studied in isolation from the wider political economy of resource use (Adger 2006). Social–ecological vulnerability may result from failure of exchange, access, transfer, endowments or production to and of ecosystem services (Adger 2006). Potential socioeconomic causes and drivers of social–ecological risk (e.g. trade liberalization) need to be investigated and incorporated if one wants to tackle root causes of social–ecological risk.

Conclusions

It is internationally acknowledged that disasters can be prevented also from an environmental perspective, meaning that their impacts can be significantly lowered if environmental degradation is adequately reversed. However, while a vast amount of literature is dedicated to the conceptualization and assessment of the social, economic, physical and institutional dimensions of vulnerability and risk to natural hazards, their social–ecological dimension goes generally overlooked.

I attempted to unpack the complexity around the conceptualization of the social–ecological dimension of risk and vulnerability of local populations from natural hazards with the objective to improve its consideration in DRR and CCA studies. In doing so, I looked at the nature and at the quality of the dependencies of the social system on the ecosystem and how these co-determine vulnerability and risk. Differently from previous studies which look separately at the social and the ecological dimensions of vulnerability, I considered human beings as the subject ultimately exposed and I focused on the ways in which environmental degradation increase exposure, susceptibility and lack of resilience of local communities. I defined social–ecological risk as the extent to which environmental degradation and climate change affect the frequency and magnitude of the hazard and cause negative changes in exposure, susceptibility and in the capacity of the social–ecological system to anticipate, cope and recover. I then looked at the role of Eco-DRR and EbA as long term strategies to reduce this type of vulnerability and risk. I also looked at additional sources of risk that might originate from impacts of the hazard on the ecosystem itself and at how these can be tackled. Finally, I suggested ways to assess social–ecological vulnerability, which are intended to support the design of improved Eco-DRR and EbA strategies.

Overall, the framework presented in this paper marks a departure from previous ways of conceptualizing social–ecological vulnerability and risk to natural hazards, which mostly focus on the potential impacts of the hazard on the ecosystem and consequent losses the social system would incur. While the social relevance of most of the previous studies addressing social–ecological risk is indirect, I put human beings at the centre of social-ecological vulnerability and risk by identifying and describing the multiple ways in which degraded environments can increase these conditions of the system.

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