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An integrated community and ecosystem-based approach to disaster risk reduction in mountain systems

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ABSTRACT

The devastating 2015 earthquakes in Nepal highlighted the need for effective disaster risk reduction (DRR) in mountains, which are inherently subject to hazards and increasingly vulnerable to extreme events. As multiple UN policy frameworks stress, DRR is crucial to mitigate the mounting environmental and socioeconomic costs of disasters globally. However, specialized DRR guidelines are needed for biodiverse, multi-hazard regions like mountains. Ecosystem-based disaster risk reduction (Eco-DRR) emphasizes ecosystem conservation, restoration, and sustainable management as key elements for DRR. We propose that integrating the emerging field of Eco-DRR with community-based DRR (CB-DRR) will help address the increasing vulnerabilities of mountain people and ecosystems. Drawing on a global mountain synthesis, we present paradoxes that create challenges for DRR in mountains and examine these paradoxes through examples from the 2015 Nepal earthquakes. We propose four principles for integrated CB- and Eco-DRR that address these challenges: (1) governance and institutional arrangements that fit local needs; (2) empowerment and capacity-building to strengthen community resilience; (3) discovery and sharing of constructive practices that combine local and scientific knowledge; and (4) approaches focused on well-being and equity. We illustrate the reinforcing relationship between integrated CB- and Eco-DRR principles with examples from other mountain systems worldwide. Coordinated community and ecosystem-

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based actions offer a potential path to achieve DRR, climate adaptation, sustainable development, and biodiversity conservation for vulnerable ecosystems and communities worldwide.

1. Introduction

The devastating 2015 earthquakes and aftershocks in Nepal caused tragic loss of life, property, and biocultural heritage, killing ˜9000 and injuring more than 22,000 people, and focused global attention on the vulnerability of mountain people. Mountains are home to 10% of the world's population and cover 22% of the global land surface, occurring on all continents and within all biome types. Characterized by complex topography, many mountain communities are distant from centers of power and home to indigenous peoples who are often socially, economically and politically marginalized. Ninety percent of the global mountain population lives in transitional or developing countries (FAO, 2015). Mountain characteristics, including geographical and cultural complexity, result in high concentrations of valuable resources and services, such as water, hydropower, timber, and recreation opportunities. They also yield less tangible but equally important cultural services that include spiritual value. These ecosystem services are essential to the 13% of humanity who live in mountains and to billions of people downstream (Körner and Oshawa, 2005).

Globally, disasters caused $1.4 trillion in damage from 2005–2014, killing 700,000 people and affecting over 20% of the world's population (UNISDR, 2015). Over 500,000 of those deaths occurred in the 40 most mountainous countries (Fig. 1, Table 1 in Supplementary materials). The majority of deaths were due to earthquakes (336,112), which occur more often in mountains than lowlands and often trigger subsequent hazards such as landslides (Wymann von Dach et al., 2017). Others were caused by storms (e.g. hurricanes, blizzards; n = 146,529), floods (n = 15,998), epidemics (n = 8341), landslides (n = 4506), extreme temperatures (n = 4173), drought (n = 134), volcanic activity (n = 73) and wildfire (n = 61). Mountain regions are characterized by high kinetic energy with steep vertical gradients and are more likely to experience multi-hazard conditions than non-mountain regions (Zimmermann and Keiler, 2015). The increasing frequency of these extreme events under a warming climate threatens to intensify risks (Beniston, 2003; Keiler et al., 2010), especially in mountains (IPCC SR, 2018).

In March 2015, 187 countries adopted the Sendai Framework for DRR during the third UN World Conference, which encouraged signatories to "strengthen the sustainable use and management of ecosystems and implement integrated environmental and natural resource management approaches that incorporate disaster risk reduction" (SFDRR, 2015). Subsequently, at the UN COP21 climate talks in Paris, leaders from the Convention on Biological Diversity, the Convention to Combat Desertification, and the Global Environmental Facility urged governments to "consider using ecosystem-based approaches to climate change adaptation and disaster risk reduction to provide communities with safety nets in times of climate shocks and natural disasters" (SCBD, 2015). As leaders of the G7 convened in Japan in June 2016, science academies issued a statement urging the leaders to take stronger action on disaster risk reduction through "promotion of ecosystem-based approaches and green infrastructure" (Trinity College, 2016). These statements highlight the "Eco-DRR" approach, where ecosystem conservation, restoration, and sustainable management constitute key components of DRR (Doswald et al., 2014). Restoring and maintaining ecosystem functions are often less costly than hard infrastructure investments, and complementary portfolios of natural and built infrastructure solutions are gaining traction in DRR around the world (Renaud et al., 2013). Eco-DRR offers a valuable complement to community-based disaster risk reduction (CB-DRR), which engages at-risk communities in the DRR process (Cutter et al., 2008).

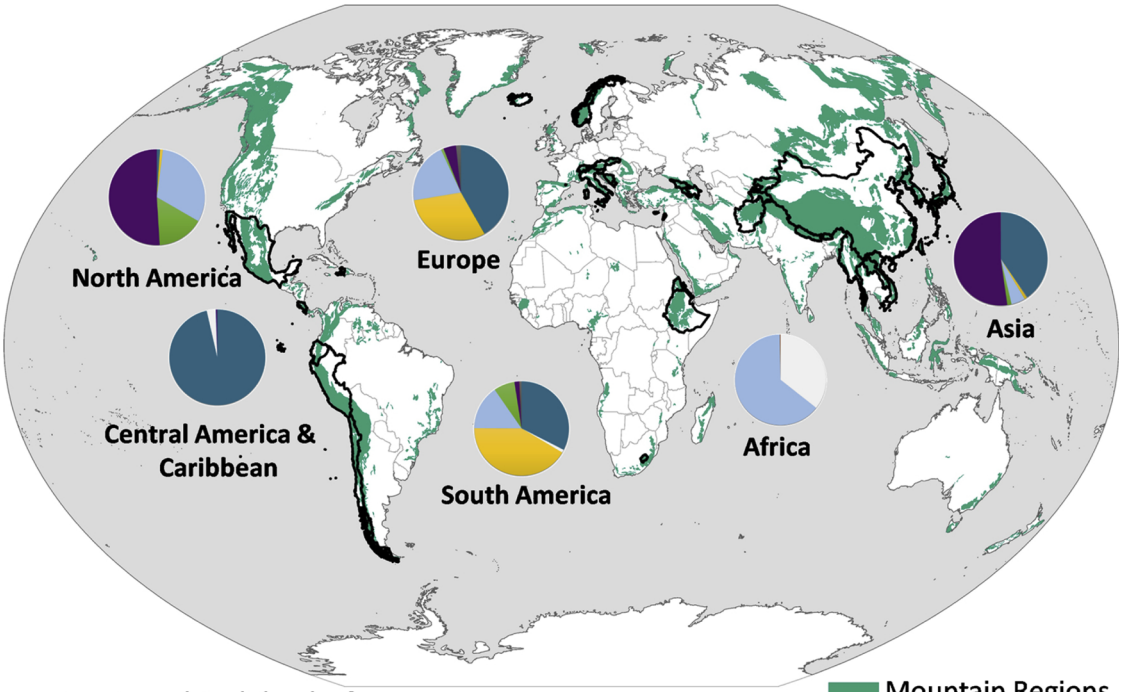
CB-DRR has become increasingly popular over the last 20 years (Allen, 2006) as a way to reduce vulnerabilities and build local-level capacity for disaster response and recovery. There is a growing awareness in CB-DRR of the value of local knowledge for securing livelihoods and building community resilience to address extreme events (Mercer et al., 2010). In CB-DRR, solutions come from the community in a bottom-up process, which is thought to empower communities to develop and manage locally appropriate strategies that are tailored to the particular locations and people in that area (Newnham et al., 2015).

While policymakers recognize the significant economic, human, and environmental costs of disasters, practical guidelines for implementing DRR are limited for vulnerable populations like those in mountains (but see Wymann von Dach et al., 2017). The recent IPCC Special Report 15 on 1.5 °C warming identified mountains as one of the systems that would be "more highly affected" by climate change and extreme events (IPCC SR15, 2018). The report also cited ecosystem-based approaches and local knowledge as two adaptation options to reduce climate-related risks (IPCC SR15, 2018), but did not directly speak to their integration. Here, we use a global synthesis to describe a set of paradoxes that present particular challenges to DRR in mountains. We discuss these challenges in light of the 2015 earthquakes in Nepal and present four principles for integrated CB- and Eco-DRR that can help address these challenges in mountains. We developed these principles from the literature, synthetic case study analyses, and on-the-ground experience of some co-authors who were present during and after the earthquakes (M.S.P., D.M., R.G., D.C. are based in Nepal at the International Centre for Integrated Mountain Development and The Mountain Institute). Our co-authors and their organizations' first-hand accounts are vital for understanding the attitudes and challenges of people and institutions involved in response, recovery, and reconstruction efforts, even as published literature on the earthquakes begins to emerge.

We illustrate the four principles – and the reinforcing relationships between CB-DRR and Eco-DRR – with examples from DRR projects in mountains worldwide. The geographic contexts and scales of action in these additional examples (Tables 1 and 2) are highly variable in order to illustrate the broad application of the four principles. While the deeper analysis, connections and examples we present are from the Nepal earthquakes and on-going recovery, the inclusion of cases from other mountain regions demonstrates that these principles are not unique to the situation in Nepal, but are more broadly relevant across mountain systems. The examples in Table 1 are from a coordinated, global program on "Ecosystem-Based Adaptation in Mountain Ecosystems", funded (2011–2016) by the International Climate Initiative and implemented jointly by UNDP, UNEP and IUCN in partnership with the governments of Nepal, Peru and Uganda. Co-authors from The Mountain Institute have also been engaged in Eco-DRR projects in Nepal, Peru and Uganda. The examples in Table 2 are from a diverse set of DRR projects of variable size and scope that we found illustrated well our four principles. These principles offer a path toward integrated CB- and Eco-DRR with implications for disaster risk reduction, climate adaptation, sustainable development, and biodiversity conservation worldwide.

2. Mountain paradoxes and the challenge for DRR

Vulnerability to disasters is exacerbated by mountain *paradoxes (P1-6)*, problems that link seemingly contradictory aspects of mountains, as identified in our synthetic case study analysis (Klein et al., in review). These paradoxes were evident as Nepal struggled to respond to the earthquakes.



40 Most Mountainous Countries

North America		**Europe**		**Asia**	
Mexico	52%	Andorra	100%	Bhutan	100%
Central America & Caribbean		Liechtenstein	100%	Armenia	88%
Haiti	59%	Monaco	100%	Nepal	86%
Costa Rica	58%	Montenegro	100%	Lao	83%
South America		San Marino	91%	Kyrgyzstan	82%
Chile	83%	Bosnia & Herzegovina	80%	Lebanon	82%
Peru	52%	Georgia	80%	Tajikistan	79%
Ecuador 47%		Switzerland	80%	North Korea	75%
Africa		Norway	76%	Taiwan	72%
Lesotho	97%	Slovakia	68%	Afghanistan	61%
Eritrea	50%	Slovenia	66%	South Korea	61%
Ethiopia 49%		Austria	63%	Viet Nam	60%
		Cyprus	62%	Japan	52%
		Italy	58%	Myanmar	52%
		Iceland	44%	China	49%
				Azerbaijan	45%

Fig. 1. Map of the 40 most mountainous countries worldwide. Mountain land area is from Körner et al. (2017); country boundaries are from Global Administrative Areas (2018). Percentages indicate % of the country covered by mountains, calculations made with the equal-area Mollweide projection. Pie charts represent proportions of the causes of disaster-related deaths from 2005 to 2014 in the 40 mountainous countries (averaged by region) based on EM-DAT (2018). Map is displayed using the Winkel Tripel projection.

2.1. Paradox 1: mountains are resource rich, but income poor

While mountains are resource rich, mountain peoples are among the world's poorest. In 2012, 45% of the ~605 million people living in rural mountain areas in developing countries were vulnerable to food insecurity (FAO, 2015). The lack of economic and educational opportunities for mountain people, combined with insecure land tenure, can lead to informal settlements in hazard-prone regions (Sudmeier-Rieux et al., 2014). Since 1950, the majority of all urban population growth has occurred in mountainous areas between 500 m and 1500 m in elevation (Kohler et al., 2014), often with inadequate planning (e.g., Esparza and Carruthers, 2000) that may exacerbate exposure to hazards.

Nepal's mountains have abundant water resources, high biological and cultural diversity, and are a major tourist destination, yet Nepal is among the world's poorest nations. The poverty and associated lack of basic infrastructure in Nepal exacerbated the earthquakes' devastation and impeded rapid response. While Nepal's overall poverty rate is 25%, most of its high-elevation districts have rates approaching 45% (Asian Development Bank 2013). The Nepal earthquake has been called a 'classquake' (Nelson, 2015) because homes of the poor – constructed from mud, mortar, and timber – crumbled, while newer concrete

Table 1
Examples of how three Eco-DRR projects in mountain countries of Nepal, Peru and Uganda integrated CB-DRR goals and addressed our four recommended principles (studies documented in UNDP, 2015).

	UGANDA	NEPAL	PERU
ACTIONS	Hydrological gravity flow schemes & reforestation; conservation agriculture; improved water retention; riverbank restoration.	Wetlands, pond, spring, forest restoration; women leased abandoned land to plant broom grass ; gabian walls; roadside stabilization.	Traditional water canal restored; land taken out of domestic grazing for vicuna grazing; wetland management; animal fiber production.
BENEFITS	Water & soil conservation; forest loss reduction.	Water conservation; improve degraded, land.	Grass & wetland restoration; vicuna (wildlife) conservation.
Environment			
DRR	Reduction of floods, erosion, landslides, drought impacts.	Reduction of floods, fires, landslides, drought impacts.	Decrease landslides, floods, fire risk, drought impacts.
PRINCIPLES			
Governance	Community water user groups formed; Mt Elgon Conservation Forum brought together up/ downstream actors for joint planning & decision-making; worked with government extension.	Strengthened institutional capacity for community management; used Panchase Protected Forest structure; worked with forest user groups and women's groups. Informed Forest Mgmt Plan.	Strengthened water, pasture committees; formed new committees & plans; worked in No Yauyos Chochas Landscape protected area; contributed to regional government's climate change strategy.
Capacity	Increased income from crops; enhanced social capital; communities less reliant on food aid.	Trainings promoted EbA[a]; reduced water conflicts & diseases ; enhanced incomes & employment.	Capacity building for livestock & vicuna management; income from vicuna and tourism; value chain development increased.
Knowledge[b]	Farmer to farmer exchanges, peer-to-peer learning.	Restored traditional water storage ponds.	Restored a forgotten traditional water management model.
Equity	Less time spent finding water and collecting firewood, especially for women.	Activities fit with women's schedules & workloads; women in different castes.	Communication training focused on women, youth and elders, as under-represented groups.

[a] EbA stands for ecosystem-based adaptation.
[b] All three projects combined participatory assessments that drew on local knowledge with vulnerability & impact assessments that were science-based to establish priority projects and scales.

buildings in better-off communities more often survived (Bennike, 2017). The epicenters struck in rural areas inhabited mainly by ethnic Tamang people living in traditional-style mud mortar homes, and who have a history of poverty, structural inequalities, and discrimination (Ghale, 2015). Information and communication technologies were used by many to raise awareness of damages and injuries via Facebook and other media, but application of these technologies was limited in rural areas due to lack of access (Crane et al., 2017). Many schools in poorer rural areas collapsed; schools that remained standing were located in wealthier urban areas or near District headquarters where seismic retrofitting had occurred. The earthquake thus disproportionally affected Nepal's poorest (Rasul et al., 2015).

2.2. Paradox 2: policies affecting mountain systems are made by outsiders

Profits from mountain resources and ecosystem services tend to flow to powerful non-mountain people and corporations. Mountain resources are often exploited for distant markets with problematic impacts on local inhabitants, such as cases of mining and water appropriation in the Andes (Brain, 2017). Decision-makers are typically lowlanders or city dwellers who apply policies and practices in mountain regions but overlook local ecological knowledge, conditions, innovations, and needs. Policies that are geared towards state or federal institutional interests may unintentionally compromise DRR in mountains when decision-makers neglect to engage with local knowledge.

For Nepal, India and China shape regional processes through their economic and political influence and relationships with international financial institutions. Simultaneously - after years of civil war, a complex and lengthy process of transitioning to democracy, and a lack of elected government officials – ineffective policy implementation and weak governance persist in Nepal, reinforcing the country's dependence on external inputs (Murton et al., 2016) and impeding efficient earthquake response (Lee, 2016). Actors outside of Nepal, including international NGO and donor agencies working on development activities, exacerbate this paradox by unintentionally absolving the government from responsibility to its citizens, weakening government response, and attracting skilled professionals away from government service (Karkee and Comfort, 2016).

While plans and strategies for decentralized disaster mitigation existed in Nepal at the time of the 2015 earthquakes (NSDRM, 2009), the implementation of many of these policies was weak or slow. Daly et al. (2017) assert there was failure at a critical moment because plans did not include capacity-building of local governments. The disconnect between disaster management policy and local response was observed across multiple sectors (Hall et al., 2017). In conjunction with weak governance in Nepal, the limited capacity of civil society - weakened by civil war – intensified vulnerabilities to hazards. Local elections were completed in January 2018 for the first time since 1997. Thus, Nepalese people had no local government representation during the earthquakes (DRCN, 2018), which limited the ability of citizens and local-level decision-makers to organize during and after the disaster. In the years since, the post-earthquake National Reconstruction Authority has struggled in its mission to support community-based reconstruction efforts and reinforce local government offices (Daly et al., 2017). The Nepalese army did play an important role in providing relief. External influences distant from mountain people and their interests - combined with weak local and national governance - have impeded effective implementation of policies for disaster preparedness and response in Nepal.

2.3. Paradox 3: mountains are remote, but vulnerable to global change

The isolation of mountains, coupled with topographic complexity, has resulted in diverse mountain ecosystems and societies with long-standing coping strategies to survive extreme environments and change. However, external factors are causing unprecedented global environmental changes that can overwhelm traditional coping strategies when disaster strikes. Certain processes – such as climate warming – are especially pronounced at higher elevations (Pepin et al., 2015), and climate change and disasters can have reinforcing effects. For example, melting glaciers and permafrost may alter the frequency and location of avalanches, landslides, and debris flows (Zimmermann and Keiler, 2015). Moreover, disasters can exacerbate undesirable climate change effects, such as decreases in water quality and availability. Policies aimed at reducing disaster vulnerability can undermine traditional coping strategies and compel dependency on outside assistance (Yeh et al., 2014). Increased reliance on outside funding, employment, and infrastructure (see paradox 2) has diminished local adaptive capacity, which is particularly crucial in remote areas.

In Nepal, there were several cascading, negative effects of climate change and the 2015 earthquakes that were compounded by affected communities' remoteness. The earthquakes increased the threat of

Table 2
Examples of four recommended principles, in rows, from six disaster-focused projects around the world, in columns (Shaw et al., 2003; UN Women, 2011; Das, 2013; World Bank, 2013; Huairou Commission, 2015; USAID, 2015).

	UN Women Vietnam	Patanka Navjivan Yojana India	Himalayan Climate Adaptation Partnership	High Mountain Partnership Nepal & Peru	Huairou Commission 21 Countries	Rural Resistence Initiative Ethiopia
Governance	Lobbying led to a government decree for the Women's Union to have a seat on the local decision-making board for flood control.	Partnerships among voluntary agencies, govts, donors, multi-lateral agencies, businesses, local community for DRR. Local institutions & leaders played a pivotal role.	Examines local adaptation strategies and their linkages with planned adaptation in the current policy environment.	In Peru established formal relationships with municipal govts & Ministry; coordinated with local Civil Defense group to promote DRR.	Position grassroots women as expert practitioners to claim recognition and resources in policy venues and UN events.	Partnership among NGOs, academia, micro-bank, insurance & reinsurance companies; govt; farmer cooperatives. Farmer design, monitoring and evaluation teams.
Capacity	Developed disaster preparedness using games, role playing, and simulation exercises during monthly women's clubs meetings.	Training for and implementation of earthquake resistant construction & retrofitting; new local company created, bolstered livelihoods & entrepreneurship.	One project implemented a community-based early warning system using sensors, solar transmitters, mobile phones to warn downstream villages.	Developed 'Local Adaptation Plans of Action', including mechanisms for local communities to integrate flood risks, and DRR methods for dangerous glacial lakes.	Channel funds directly to community based organizations and women's groups to initiate and scale up DRR strategies to locally identified risks and vulnerabilities.	Weather- based insurance to poor smallholder farmers paid through labor on community-based DRR activities. Also facilitates farmers' access to credit.
Knowledge	A radio soap opera with stories about disaster preparedness and response and the role of women was developed and broadcast before and during the disaster season.	Demonstration 'shake table tests' showcased DRR construction. Strong local participation brought local knowledge and practices to reconstruction.	Civil society-private sector partnership with climate adaptation strategies shared across actors and sectors through community social networks.	Field-based 'mobile workshop' in Nepal where Peru participants shared experience controlling glacial lakes with Nepalese communities & scientists.	Links grassroots women's groups within and across countries to create platforms for learning and advocacy.	Farmers learn about insurance, gain financial literacy through games, theater, stories; weather index-based insurance combines Western and local knowledge.
Equity	Project created gender-sensitive disaster preparedness and response plans addressing specific needs of diverse groups within the community.	Project goal was to create a more level playing field for vulnerable communities in face of future disasters and to empower local communities for DRR.	Identified impacts and adaptive capacities for women and men; defined strategies for equitable access to resources for minority, indigenous people, and women.	Included marginalized groups: e.g., Peru - single women with kids and female Quechua speakers. Nepal - poor, lower castes and women.	Empowers grassroots women's networks to gain support of local & national govts & donors to bring their priorities & practices to the forefront of policy and programming.	Drought insurance to poorest, chronically food-insecure; even those who cannot afford disaster insurance can have it. Before, only for companies and wealthy.

glacial lake outburst floods in several areas (Byers et al., 2015), and there were concerns that the earlier onset of the monsoon rains in 2015 (which have been linked to climate change, Turner and Annamalai, 2012) could exacerbate disease outbreaks in temporary shelters for people who had lost their homes in the earthquake (Buckley, 2015). Local empowerment and preparedness could have significantly reduced suffering and mortality in the time it took for national and international relief efforts to mobilize (Adhikari et al., 2016). Some communities experienced reconstruction delays due to their reliance on high-profile external actors who never fulfilled funding commitments. Meanwhile, settlements supported by local NGOs saw the greatest progress towards rebuilding (Daly et al., 2017). Some remote communities built makeshift shelters from local materials (e.g. bamboo); others simply waited for aid (Mishra et al., 2017). It became clear that rural communities may have to stand on their own for many days or weeks following disasters (Wendelbo et al., 2016). Local agency has suffered under weak governance in Nepal, and the remoteness of many communities hindered their access to aid following the disaster (Lord and Murton, 2017). These challenges are exacerbated by high exposure to global change.

2.4. Paradox 4: mountains experience de-stabilizing demographic shifts

Certain mountain regions experience in-migration due to perceived appeal, while others experience labor out-migration due to lack of economic opportunity. The combination of these demographic shifts can erode local support networks and destabilize community organization, which can reduce the ability to cope during disasters. Furthermore, the long-term implications of psychological stress from disasters are often overlooked, and inadequate support networks can intensify the depression, post-traumatic stress disorders, and anxiety experienced by survivors (Adhikari et al., 2017). Timely, culturally-appropriate mental health services are a challenge for international humanitarian practitioners (Greene et al., 2017), revealing a need for improved local response for community health and cohesion.

Emigration is the dominant demographic trend across much of Nepal. In 2011, 7.3% of the adult population was "absent" – a euphemism for migration, largely to India and the Gulf States (MLE, 2014). While many earthquake victims received support from urban relatives who returned to their villages to assist in relief distribution and recovery, those whose family members lived outside Nepal had more trouble securing immediate shelter and food, although many eventually received remittances (Maharajan et al., 2017). Out-migration also overburdened the elderly and women (Wendelbo et al., 2016), many of whom lacked resources to construct shelter before the monsoons, and trekked for days to hand-haul relief materials dropped off at road heads. Youth played an important role in providing earthquake relief. Urban and international emigration has also weakened social support systems, disproportionately affecting marginalized groups - women, minorities and caste-based communities – presenting particular challenges for earthquake recovery in Nepal (Wendelbo et al., 2016).

2.5. Paradox 5: mountains are difficult to access, but a range of people are drawn to them

Despite the difficulty in accessing remote mountain regions, diverse people are attracted to them – creating challenges for equitable decision-making and resource management. Many mountain regions have appeal as vacation destinations, thus wealth disparities are increasing in mountains. Significant challenges exist to manage the complex relationships among mountain communities and the national or global systems that benefit from them, and to integrate these diverse interests into a comprehensive DRR plan (Alcántara-Ayala and Moreno, 2016). Distribution of aid can accentuate inequities when high-tourism areas receive disproportionately more support than areas with less scenic and recreational value. Therefore, earthquake recovery efforts can inadvertently reinforce existing patterns of poverty and inequality.

In Nepal, individual donations and resources have favored certain communities within the Khumbu region, which has global connections through tourism on Mount Everest, with ˜37,000 international visitors annually. Communities off the tourist trail received less attention (L. Sherpa, 2015). Following the earthquakes, resource flows into Khumbu, accompanied by well-meaning and generous “adopt a family” philanthropy, divided communities into the lucky and the left-out. The government tried to centralize distribution to halt concentration of relief efforts; however, this delayed aid for the neediest due to limited government capacity. Simultaneously, there was concern that despite substantial damage, the entire Solukhumbu district (both tourist and non-tourist areas) was not included in the government’s list of critically affected districts – and therefore not eligible for large-scale relief and reconstruction aid – because the tourism sector did not want to deter tourists from visiting the region (Sherpa, 2015; Sherpa, 2017).

2.6. Paradox 6: mountains require fine-scale data, but data are lacking

The topographic and climatic heterogeneity in mountains require high-resolution data, yet these data are often scarce in mountains due to inaccessibility, marginalization of mountain communities, and neglect of data collection infrastructure. Land-use decisions with limited knowledge can lead to aggravated environmental degradation and exposure to hazards (Sudmeier-Rieux et al., 2014). Accurate analyses of mountain systems demand higher-resolution data than do topographically homogenous lowlands.

Following the earthquakes in Nepal, government and civil society responses were hamstrung by data and knowledge gaps, including insufficient information about at-risk infrastructure, technical options, and community vulnerabilities (Baharmand et al., 2017). Relief agencies often did not know where to land helicopters to deliver supplies in remote mountain regions (IRIN, 2015). A surprise response was how quickly people from inside and outside of Nepal reacted to fill in missing data gaps, often volunteering and spending long hours working on the situation (e.g. see Kargel et al., 2016). Yet, agencies only began mapping these locations and other crucial information after the disaster, finding additional uncertainties and data gaps in the process (Gallen et al., 2017). The advent of online mapping by volunteers using remote sensing data shows promise, but requires additional research to ensure the process meets needs on the ground (Hu et al., 2017). In some regions, social media platforms were effective tools for conveying damage, expressing needs, and coordinating relief efforts (P. Sherpa, 2017). Protected areas and eco-tourist destinations tend to be better mapped, with potential for more rapid and effective DRR. Acquisition of detailed geospatial products that show infrastructure and risk zones in advance (e.g., areas prone to wind shear for air relief) could reduce delays in delivering aid.

3. Four principles for integrated community and ecosystem-based DRR

Based on the literature, case studies, and on-the-ground experience of some co-authors, we present four principles that help address these paradoxes, each of which includes multiple goals (Fig. 2). These principles can facilitate DRR in mountains, and they require partnerships for simultaneous and coordinated action. Integrated community- and ecosystem-based approaches provide a means to incorporate these principles into DRR. We describe illustrative case studies below and in Tables 1 and 2.

3.1. Governance and institutional arrangements that fit local needs

To counteract the external dependencies that result from paradox two and the mal-adaptations that can result from paradox three, formal and informal governance arrangements need to be renewed bottom-up,

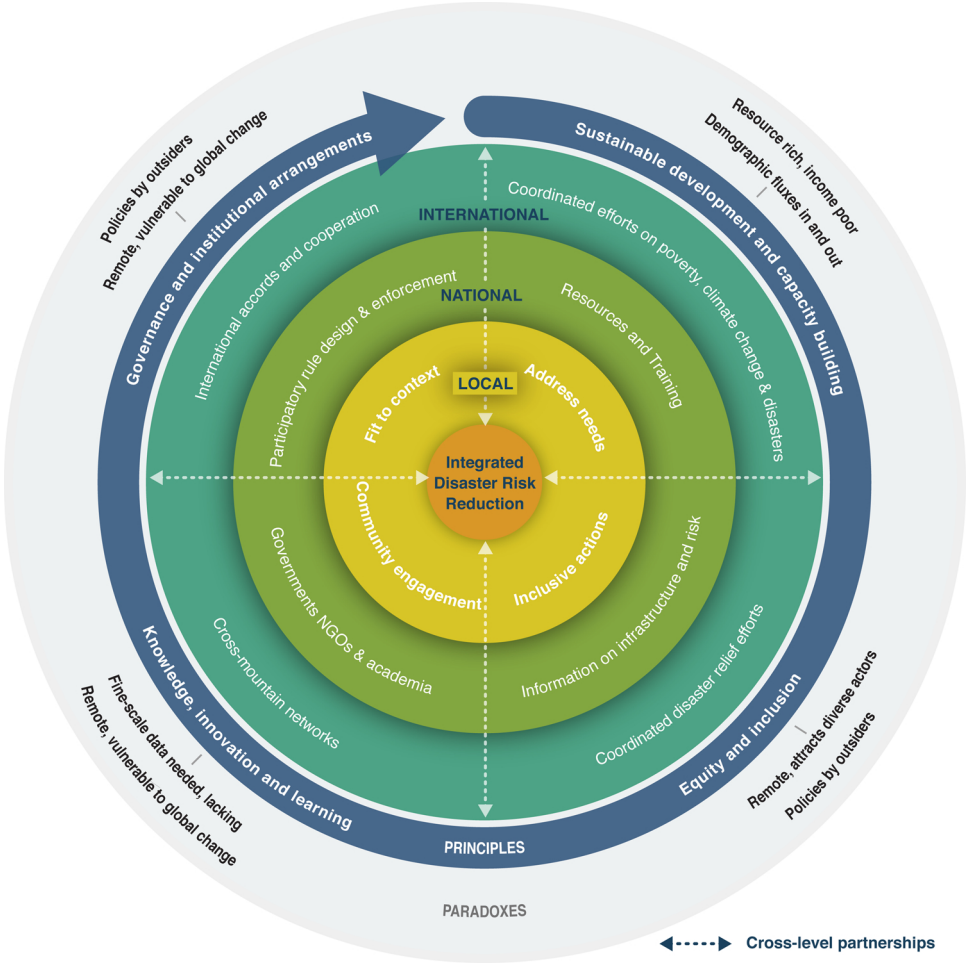


Fig. 2. Cross-level partnerships can facilitate the coordinated implementation of four principles that integrate community and ecosystem objectives in disaster resilience (colored rings) and help address paradoxes that pose challenges for DRR in mountains (grey ring).

prioritizing local participation in decision-making to fit local conditions. Effective local governance is critical for DRR - nested, overlapping institutional approaches coherent with local contexts are more successful than one-size-fits-all approaches (Ostrom, 2009). In keeping with the Sendai framework (SFDRR, 2015), policy should be developed through coordinated partnerships among local to global organizations, with attention to regional variability. This is because many of the actions needed during disaster response and recovery are rooted in everyday governance and cultural structures (Daly et al., 2017), and practical guidance from local stakeholders can result in standards and plans for DRR that fit local needs. Strategic networks can be built within and across communities, across levels of government, and with NGOs and other actors who influence governance outcomes related to disasters. This "redundancy" provides the ability to adopt alternative strategies for delivering critical services when certain aspects of the relief response are rendered inefficient by the disaster (Carpenter and Grünewald, 2016). These cross-scale and cross-governance approaches are particularly needed in mountains, where the possibility of secondary and cascading hazards is high (Liang and Zhou, 2016) and requires simultaneous mobilization of relief efforts for multiple on-going hazards (Zimmermann and Keiler, 2015).

Integrated CB- and Eco-DRR have been found to be effective approaches for empowering local actors, strengthening existing groups, and leading to new community groups and management plans (Table 1). Community-level engagement in governance builds legitimacy, while transparency improves chances that resources reach intended recipients.

Successful Eco-DRR projects engage communities to co-produce tangible approaches for income generation and capacity-building (UNDP, 2015). Eco-DRR involves conserving, managing, and restoring biodiversity and natural resources to reduce disaster risk (Estrella and Saalismaa, 2013). Often, these are resources of value to local people, utilizing knowledge and skills they have developed through their lived experiences. There can be, therefore, a natural bridge between Eco- and CB-DRR, with co-benefits that include DRR, biodiversity conservation, local empowerment, and more. In South Africa, an integrated CB- and Eco-DRR project included active engagement of local farmers and private sector investors, yielding new jobs that improved DRR (clearing non-native plants to decrease fire risk); ecosystem restoration (increasing water yield and decreasing pumping costs); institutional changes (including integrated CB- and Eco-DRR in national disaster legislation); and novel partnerships (forming the Disaster Resilience Learning Network for Eco-DRR) (Reyers et al., 2015). This project worked across governance scales to promote integrated community and ecosystem health.

3.2. *Fostering resilient communities through sustainable development and capacity-building*

Resilience in DRR involves the ability of a community to resist and absorb the impacts of a hazard so they can recover in a timely manner (UNISDR, 2009). Alternatively, resilience is also defined as a community's capacity to adapt and transform in the face of extreme conditions (Alexander, 2013). We assert that building more resilient, united

communities can bolster DRR by counteracting the impacts of poverty, out-migration, and the breakdown of traditional supportive community structures highlighted in paradoxes one and four (Oliver-Smith et al., 2017). Communities can reduce vulnerability to disasters through enhanced health, education, and income generation that provide increased options and flexibility. Factors that contributed to early recovery from the earthquakes in Nepal included a strong local economy, entrepreneurship, and access to natural resources (Mishra et al., 2017). Environmental resilience is often overlooked in DRR, or emphasized at national and regional rather than local levels – such as in the Sendai framework (SFDRR, 2015). The disproportionate prevalence of poverty (paradox one), use of marginal lands, and increasing threats from climate change in mountain systems (paradox four) demands increased attention to both the social and ecological aspects of resilience.

Carefully targeted integrated CB- and Eco-DRR initiatives can promote sustainable development and adaptive capacity, particularly when they include strategies for livelihood diversification, focus on green infrastructure, expand local capacity to address needs, and provide access to critical services. Locally appropriate and welcomed integrated CB- and Eco-DRR projects generating new products or enhanced ecosystem goods – such as the cultivation of broom grass in Nepal (UNDP, 2015) – can increase and diversify income. Further economic benefits from integrated CB- and Eco-DRR result from avoided disaster costs due to buffering by ecosystems (Doswald et al., 2014). In Uganda, an Eco-DRR project on conservation agriculture that also embraced CB-DRR formed new water user groups, successfully connecting upstream and downstream communities and fostering peer-to-peer learning networks. This enhanced local capacity by improving resilience to droughts and floods, increasing household savings, and reducing reliance on food aid (UNDP, 2015). Other examples from Nepal include village-level, renewable energy-based, smart micro-grids to facilitate earthquake recovery and decrease risk of forest overexploitation, and planting drought-tolerant millet to replace the water-intensive rice paddies that prevailed before the earthquakes (Rasul et al., 2015). The diversity of valuable ecosystem services in mountains offers great potential for improved social and ecological resilience when managed sustainably. Finally, we acknowledge that the terms “community” and “local capacity” often overlook the need for a disaggregated view within communities into local level disparities and inequities so that these actors are also strategically engaged in integrated CB- and ECO-DRR planning and management, and their specific voices and needs are also taken into consideration (see principle 4 below).

3.3. Cross-scalar integrated knowledge, innovation, and learning

Integrating local knowledge and community-level experimentation can address the information gaps apparent in paradox six. The Sendai framework calls for the use of indigenous knowledge to better understand disaster risks and prepare contextually appropriate policies and plans. Regulatory and financial incentives for local governments are proposed to facilitate collaboration with indigenous groups (SFDRR, 2015). However, these incentives alone will not produce effective collaboration with indigenous groups. Effective collaboration requires transparent and trusting relationships that address power asymmetries and foster mutual respect and understanding (Tengö et al., 2017). When communities, scientists, and practitioners share and learn together - drawing on local strategies, knowledge of hazards and disaster recovery, and ways to implement CB- and Eco-DRR - they can craft innovative solutions (Alcántara-Ayala and Moreno, 2016). Open-access disaster toolboxes, risk assessment and information platforms, and Massive Open Online Courses, such as the 2015 Eco-DRR MOOC (ADPC, 2017), can contribute to knowledge-building. Cross-scalar integrated learning within and across diverse mountain peoples and landscapes – facilitated by boundary-spanning groups (Byers et al., 2014) and individuals such as village leaders (Hopping et al., 2016) – can help to overcome spatio-temporal knowledge gaps to support adaptive strategies, especially in mountainous landscapes, which are inherently heterogenous, multi-hazard and complex (Klein et al., 2014).

Similar to transnational municipal climate networks (Brink et al., 2016), transdisciplinary CB- and Eco-DRR networks can facilitate cross-mountain learning by serving as knowledge platforms, consultants, commitment brokers, and advocates for the integrated DRR approach (Cutter et al., 2015). CB-DRR solutions can support communities to undertake their own research and develop solutions that enhance traditional coping strategies, thus reducing some of the external dependence seen in paradoxes two and three. Nepal’s Langtang Memory Project allows community members to tell their own post-disaster stories, describing their vulnerabilities and vocalizing desired pathways to recovery (Lord and Murton, 2017). In Peru, Eco-DRR projects that restored ancestral hydrological structures have increased resilience to floods and droughts, improving water provisioning for local mountain communities as well as downstream users (UNDP, 2015). Teams of local people worked with external researchers, engaging in field trips and workshops that helped identify vulnerabilities and needs as well as ideas for addressing them. The restoration of traditional water management systems demonstrated the value of local ecological knowledge for implementing solutions with benefits across scales in the watershed.

3.4. Relief focused on equity, inclusion and well-being

Regardless of local efforts and government commitment to DRR, some disasters will still exceed local and national capacities. The international community can provide valuable resources for relief, particularly when coordinated to avoid the reinforcement of inequality seen in paradox five. The Sendai framework calls for women and persons with disabilities be empowered to take on public leadership roles to improve equity in DRR planning, response, and reconstruction (SFDRR, 2015). Emergency relief should deliver aid to affected areas equitably, which requires trust between local communities and emergency response teams. Brink et al. (2016) found no mention of equity or gender in 85% of the 110 articles they reviewed on urban Eco-DRR approaches and called for greater attention to normative, ethical, and power dimensions in such projects. CB-DRR projects can fill this gap by providing more nuanced, place-based solutions to problems of economic and gender inequality. Similarly, Eco-DRR projects can enhance the impact of CB-DRR projects through the production of tangible and intangible goods and services that contribute to human well-being. Integrated CB- and Eco-DRR approaches should focus on empowerment and equity, taking a disaggregated look at local communities to strategically engage sub-groups with particular vulnerabilities and potential for leadership.

In Nepal, research demonstrated the increased vulnerability of women and children following the 2015 earthquakes, including menstruating women and girls with decreased access to sanitary products and attendance at school (Budhathoki et al., 2016); pregnant/lactating women and their children with inadequate housing and exposure to cooking fire smoke (Brunson, 2017); women and children subject to increased human trafficking (Gyawali et al., 2017); and increased physical and sexual abuse starting as early as 24 h after the disaster (Chaudhary et al., 2017; Fothergill and Squier, 2018). These vulnerabilities demonstrate a need for targeted interventions that assure funds are directed to the most marginalized groups. The power of integrating CB- and Eco-DRR to promote equity and well-being is immediately apparent in areas like Nepal that rely heavily on the land for subsistence. In Nepal, an integrated CB- and Eco-DRR project to limit landslides collaborated with the local women’s network. Women from different castes leased abandoned land, planted broom grass, and earned significant income through activities designed to fit their schedules and workloads (UNDP, 2015). When members of marginalized groups are integrated into DRR planning and response, they can achieve improved outcomes for both landscapes and livelihoods.

4. Moving forward with integrated DRR in mountains

Implementing these recommendations is a nontrivial challenge that involves overcoming obstacles and addressing specific issues unique to a given region. Coordinated community and ecosystem-based actions offer a path for sustaining ecosystems and livelihoods in biologically diverse, multi-hazardous mountain environments, where extreme events threaten to become the norm. Coordinated actions of CB- and Eco-DRR can help vulnerable regions prepare for and respond to disasters, address challenges (e.g. paradoxes), and improve socio-economic prospects for an equitable and just future for mountain people worldwide.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.envsci.2018.12.034.

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