# Regional Environmental Change

## Loss and damage in the mountain cryosphere

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**Abstract:**

The mountain cryosphere, which includes glaciers, permafrost and snow, is one of the Earth's systems most strongly affected by climate change. In recent decades, changes in the cryosphere have been well documented in many high-mountain regions. Whilst there are some benefits from snow and ice loss, the negative impacts, including from glacier lake outburst floods, and variations in glacier runoff, are generally considered to far outweigh the positive impacts, particularly if cultural impacts are considered. In international climate policy, there has been growing momentum to address the negative impacts of climate change, or 'loss and damage' (L&D) from climate change. It is not clear exactly what can and should be done to tackle L&D, but researchers and practitioners are beginning to engage with policy discussions and develop potential frameworks and supporting information. Despite the strong impact of climate change on the mountain cryosphere, there has been limited interaction between cryosphere researchers and L&D. Therefore, little work has been done to consider how L&D in the mountain cryosphere might be conceptualized, categorized and assessed. Here we make a first attempt to analyze L&D in the mountain cryosphere by conducting a systematic literature review to extract L&D impacts and examples from existing literature. We find that L&D is a global phenomenon in the mountain cryosphere and has been more frequently documented in the developing world, both in relation with slow and sudden onset processes. We develop a categorization of L&D, making distinctions between physical and societal impacts, primary and secondary impacts,

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**Title: Loss and damage in the mountain cryosphere**

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**Abstract**

The mountain cryosphere, which includes glaciers, permafrost and snow, is one of the Earth's systems most strongly affected by climate change. In recent decades, changes in the cryosphere have been well documented in many high-mountain regions. Whilst there are some benefits from snow and ice loss, the negative impacts, including from glacier lake outburst floods, and variations in glacier runoff, are generally considered to far outweigh the positive impacts, particularly if cultural impacts are considered. In international climate policy, there has been growing momentum to address the negative impacts of climate change, or 'loss and damage' (L&D) from climate change. It is not clear exactly what can and should be done to tackle L&D, but researchers and practitioners are beginning to engage with policy discussions and develop potential frameworks and supporting information. Despite the strong impact of climate change on the mountain cryosphere, there has been limited interaction between cryosphere researchers and L&D. Therefore, little work has been done to consider how L&D in the mountain cryosphere might be conceptualized, categorized and assessed. Here we make a first attempt to analyze L&D in the mountain cryosphere by conducting a systematic literature review to extract L&D impacts and examples from existing literature. We find that L&D is a global phenomenon in the mountain cryosphere and has been more frequently documented in the developing world, both in relation with slow and sudden onset processes. We develop a categorization of L&D, making distinctions between physical and societal impacts, primary and secondary impacts, and identifying seven types of L&D (including L&D to culture, livelihoods, revenue, natural resources, life, and security). We hope this conceptual approach will support future work to understand and address L&D in the mountain cryosphere.

Keywords: mountain cryosphere, climate change impacts, loss and damage, risks

Length of manuscript: 7781 words, plus 3 figures.

## 1 Introduction

The mountain cryosphere is one of the Earth's systems most strongly affected by climate change. Glaciers have been receding and shrinking worldwide over recent decades, permafrost is thawing and snow lines are rising (IPCC 2014). Much of this change is irreversible under current climate change scenarios of ongoing warming over the next century. Cryosphere change implies a suite of impacts on natural resources such as water, on ecosystems, and eventually on a range of economic sectors such as agriculture, hydropower or tourism (Huss et al. 2017; Vuille et al. 2017). Shrinking glaciers and thawing permafrost can furthermore involve mass flow hazards, including landslides, ice and rock avalanches, or glacier lake outburst floods with devastating consequences for downstream communities (Carrivick and Tweed 2016; Haeberli et al. 2017). Many of these changes have negative impacts, even death in some cases, and involve damage to and loss of natural systems and resources, economic productivity, cultures and traditions, livelihoods and assets valued by people. This loss and damage is of increasing concern but has not been addressed explicitly or substantively in mountain cryosphere research, policies, or planning.

Meanwhile, in international climate policy there has been increasing focus on 'Loss and Damage' (L&D) from climate change. Since the creation of the UN Climate Framework Convention on Climate Change (UNFCCC) in the early 1990s, the Alliance of Small Island States has been highlighting the need to address L&D from climate change, particularly the impacts of sea level rise. At the time, they made a proposal for an international insurance pool to compensate for L&D (Mace and Verheyen 2016). This proposal, and subsequent calls for compensation, have been highly controversial in UNFCCC discussions. Nevertheless, after several decades, countries agreed that there should be some discussion and consideration for how to address L&D or the adverse impacts of climate change in developing countries particularly vulnerable to climate change. This was signaled by the establishment of a work programme on L&D at the Conference of Parties (COP) 16 in Cancun in 2010, as part of the broader Cancun Adaptation Framework (CAF). L&D was considered to include impacts from extreme events and slow onset processes, and examples given included impacts from cryosphere change such as glacier retreat. In 2013, the Warsaw International Mechanism for Loss and Damage associated with Climate Change Impacts (WIM) was established at COP 19 under the CAF, again referring to impacts from slow onset and extreme events. Following COP 20 in 2014, the Executive Committee (ExCom) and the first workplan of the WIM were established. At COP 21 in 2015 in Paris, the issue of L&D continued to be much debated and contested. It therefore came as a surprise to many observers that a separate article on L&D was established in the Paris Agreement (Article 8). The article specifies a number of areas of cooperation and facilitation to enhance understanding of and action to address L&D, for instance in relation to irreversible L&D, slow onset processes, early warning systems and risk management.

The WIM makes explicit reference to physical processes in the mountain cryosphere, identifying glacier retreat and related impacts as a component of slow onset processes, and specifically mentioning impacts such as erosion, mudslides, flooding and glacier lake outburst floods (GLOFs), reduction of runoff and water shortages affecting ecosystems, hydropower, drinking water and human livelihoods (UNFCCC 2012). The WIM's ExCom has a mandate to promote understanding and implementation of actions to address L&D, and has released several calls for inputs from researchers and practitioners, including on slow onset processes. Therefore, there is a demand from policy-makers for information about L&D, including with reference to the mountain cryosphere.

Researchers focusing on the cryosphere, and the socio-cryospheric system, encompassing societies surrounding the mountain cryosphere (Carey et al. 2014), potentially have significant relevant evidence to contribute to this emerging policy process. The understanding of cryospheric change has significantly improved in recent years, thanks to modelling, monitoring and measuring efforts of physical processes through both on-site fieldwork and remote sensing. Glaciers in particular are now extensively monitored over large areas using satellite data as reflected by an impressively growing body of literature from all parts of the world (Paul et al. 2013). Moreover, climate change impact research and social vulnerability studies have produced a range of important evidence related to questions of L&D of the mountain cryosphere. Examples include reported loss of lives due to glacier lake outburst floods (GLOF), ice and rock avalanches (Carey 2005; Evans et al. 2009; Carrivick and Tweed 2016), or anthropological studies that have examined how local (indigenous) people perceive and cope with the loss of glaciers and snow in the Andes and the Himalayas (Byg and Salick 2009; Diemberger et al. 2015; Jurt et al. 2015a). However, L&D has hardly been explicitly addressed in this wealth of research.
And in fact, both in research and policy, many aspects of L&D still remain largely unclear. Emerging academic analyses of L&D have highlighted the importance of ambiguity for the establishment of L&D policy (Vanhala and Hestbaek 2016). Discussions of L&D are often associated with calls for compensation, which countries have very different views about, making the subject very controversial. As a result, the text of the WIM and Article 8 of the Paris Agreement are rather vague. There is no definition of L&D, and it is not clear, particularly from a scientific perspective, exactly what counts as 'loss and damage from climate change' (James et al. 2014). For example, it is unclear whether UNFCCC L&D mechanisms only apply to L&D that can be attributed to anthropogenic climate change. Boyd et al. (2017) highlight that, whilst this flexibility in terminology is important politically, it is challenging for researchers and practitioners wishing to support climate policy on L&D.

In this paper, we address this barrier between science and policy, by analyzing existing literature to identify examples of L&D in the mountain cryosphere, and developing a framework for categorizing L&D which could be used in future research. While there remain unclear aspects of L&D, and different perspectives on how L&D should be addressed (Boyd et al. 2017), there is nevertheless a growing body of literature which conceptualizes L&D (e.g. Warner and van der Geest 2013; Okereke et al. 2014), including permanent or irreversible loss, or non-economic loss (Serdeczny et al. 2018). We draw on this literature to identify and categorize L&D in the mountain cryosphere. Our study is intended to provide evidence for policymakers about L&D in the cryosphere, and develop a framework for future researchers to contribute further evidence. It could also generate an example for researchers of other systems which experience L&D from climate change, for example in coastal regions, of a framework to collate information for L&D policy.

To achieve these goals, we conducted a systematic literature review and analysis. While we do not envisage this review to be complete or fully comprehensive, we expect new insights and understanding of negative impacts in the mountain cryosphere under a L&D perspective. To prepare the ground for identifying the types of L&D in the mountain cryosphere and to situate them in the broader L&D debate, we start by revisiting the discussions on L&D policy and approaches to define and categorize L&D. We then present the methods and results of the literature review, and propose a conceptual approach to support a more systematic understanding of processes and causal factors driving L&D in the mountain cryosphere, in order to facilitate progress in L&D policy and research. We envisage the audience of this paper to be both cryosphere and L&D researchers across the natural and social sciences, as well as interested policymakers, planners, or diplomats (e.g. negotiators under the UNFCCC), and have designed the paper to bridge these different fields.

## 2 Loss and damage debate and approaches

Given the limited attention to L&D in the mountain cryosphere, it is necessary to provide a summary of the L&D discourse and approaches to prepare the field for a better understanding and placement of the mountain cryosphere within the larger L&D debate. The issue of L&D can be confusing for researchers and practitioners (Boyd et al. 2017), in part because of the ambiguous nature of L&D policy texts (Vanhala and Hestbaek 2016). The controversy surrounding the topic also makes it difficult to have open conversations in the policy space, and discussing science can be challenging.

The contentious nature of the topic is perhaps unsurprising. The question of how to deal with L&D from human-induced climate change raises uncomfortable questions about historical responsibility (Calliari 2016), and the potential for liability. The issue has often been characterized as a point of intense disagreement between developed and developing countries. Vanhala and Hestbaek (2016) describe how the L&D debate evolved, with two important frames: one on compensation and liability for L&D, and one on promoting risk management and insurance to address L&D. Under the WIM and Paris Agreement, these have been integrated into one master frame, but only through ambiguity (Vanhala and Hestbaek 2016). It is also worth noting that the decision text accompanying the Paris Agreement explicitly states that Article 8 does not provide a basis for any liability or compensation, yet some legal analysts suggest that this still leaves ‘all options open’ (Mace and Verheyen 2016).

Despite progress in L&D policy, the creation of Article 8 does not indicate that there is clarity for defining and understanding L&D. Important elements of disagreement between developing and developed nations remain, including the positioning of L&D with respect to adaptation, associated ethical, legal and scientific arguments, and the embedding of L&D in the contested discourse about historical and differentiated responsibilities (Calliari 2016). Concerning adaptation, the debate centers on the question whether L&D mechanisms are part of or distinct from adaptation. Some authors suggest that L&D refers to impacts that have not been avoided through mitigation and adaptation (Warner and van der Geest 2013; Okereke et al. 2014), and therefore L&D mechanisms should address impacts 'beyond adaptation' or 'residual risks'. Others, including developed country negotiators, have suggested that all L&D can be dealt with through mitigation and adaptation, and there is thus no grounds for additional actions to deal with loss (Boyd et al. 2017). In the Paris Agreement, L&D is now anchored in an article separate from adaptation but this has not necessarily solved the discord, with distinction in emphasis between those who focus on preventing L&D through climate risk management, and those who emphasize actions to deal with L&D which cannot be avoided (Boyd et al. 2017). Ethical aspects of the debate are concerned with different types of responsibilities and fairness but also how to deal with non-economic L&D (NELD). Legal issues refer to government responsibility and liability for L&D, often related to claims of compensation (Huggel et al. 2016b; Lees 2017). The science of attribution of climate change and extremes, and more recently of their impacts, to anthropogenic emissions has a role in this debate, and has been promoted or even instrumentalized for this purpose by different representatives of the debate, leading to a certain politicization of science (James et al. 2014, 2018).

In spite of these unresolved issues, an increasing number of UNFCCC texts and research papers have generated progress in understanding several aspects of L&D. The UNFCCC, based on the CAF, refers to the impacts associated with the adverse effects of climate change including both impacts from extreme events and slow onset processes (UNFCCC 2013). Impacts, mitigation, adaptation and L&D are thereby inherently linked and dependent in the sense that stronger mitigation and adaptation reduce the cost or magnitude of L&D, although not in a linear way. One commonly-cited framework for understanding L&D builds on the mitigation-adaptation nexus suggesting a distinction between avoided, unavoided and unavoidable L&D (Verheyen and Roderick 2008; Verheyen 2012). Avoided L&D refers to climate change impacts which do not lead to negative outcomes due to commensurate adaptation and risk reduction measures put in place. Unavoided L&D refers to impacts that could have been avoided had additional, better or more effective adaptation measures been implemented. Consequently, unavoidable L&D are impacts that could not been avoided by adaptation (or mitigation). Examples include effects related to sea level rise or glacier melt that cannot be adequately addressed by adaptation. This means that the actual unavoidable L&D relates to i) level of efforts of mitigation, and ii) the extent to which adaptation is implemented and effective. Unavoided and unavoidable L&D may also be termed residual L&D (Verheyen 2012).
Boyd et al. (2017) identified a typology of four perspectives on L&D based on interviews with stakeholders to the L&D discussions, from  research, policy and practice. The typology represents a continuum from (i)

the perspective that L&D can be dealt with through adaptation and mitigation, to (ii) an emphasis on integrated management of all climate-related risk, to (iii) a focus on understanding L&D beyond the limits of adaptation, and (iv) an emphasis on addressing the inevitable harm which climate change will impose on vulnerable countries and people, including irreversible and non-economic losses.

At the level of the UNFCCC, the Executive Committee of the WIM defined nine action areas in its initial two-year workplan established at COP20 in 2014 in Lima. Action areas 3 and 4 address dimensions of L&D where more evidence and understanding is required, i.e. slow-onset processes and non-economic losses, respectively. Note that the UNFCCC refers to slow-onset events but we adopt here the term slow-onset processes, which we consider a more appropriate description of slowly evolving or cumulative processes. In its Action Area 3, the WIM defined eight slow-onset processes and related risks, namely rising temperatures, desertification, loss of biodiversity, land and forest degradation, glacier retreat and related impacts, ocean acidification, sea level rise and salinization.

NELD (WIM Action Area 4) has been proposed to refer to impacts which are not accounted for in the formal process of L&D accounting, drawing on anthropological work which demonstrates that often formal measurement does not capture the aspects of life that people value the most (Morrissey and Oliver-Smith 2013). NELD thus comes into play where the value of loss is unknown or difficult to measure. Limited understanding of the value of loss refers to the fact that value is socially and culturally constructed and thus varying according to context. For instance, the value given to (the loss of) glaciers, water resources, ecosystems or human lives may significantly vary between and within cultural, social, economic and political contexts of the Andes, Central Asia, or Europe. Tschakert et al. (2017) emphasize the importance of adopting a value based perspective on L&D, where what people value is central, as well as what they decide to preserve and what to let go, or in other words, what they perceive as an acceptable and inacceptable loss.

For economists a common characteristic of NELD is that it is not traded on the market. Fankhauser et al. (2014) suggest that NELD occurs in three distinct areas: private individuals, society and the environment. The UNFCCC distinguishes loss of life, health, human mobility, territory, cultural heritage, indigenous knowledge, biodiversity and ecosystem services (UNFCCC 2013), while Serdeczny et al. (2016) additionally consider human life and identity, among other forms of NELD. Tschakert et al. (2017), however, are critical of static lists of (non-) economic L&D and propose a more dynamic framework as a function of what people value in their daily lives and the magnitude of climate change impacts.

An additional category relevant to the mountain cryosphere is irreversible L&D (as also mentioned in the Paris Agreement), including for instance the loss of glaciers as a landscape element, cultural identity, or freshwater reserves (Huggel et al. 2016a). Furthermore, GLOFs and different types of avalanches can all cause irreversible loss of human lives.

## 3 A systematic literature review of loss and damage in the mountain cryosphere

### Methodological approach

The previous section revealed a considerable variety of conceptual approaches to L&D, including a number of proposed categories referring to both natural and human systems. Comparably little evidence and research exists, however, that track L&D in reality based on specific natural or social processes.

In this study a core interest is precisely to better understand where L&D related to the mountain cryosphere is occurring and where and how it is documented. We are also interested in piecing together the status of knowledge on the societal impacts of climate change resulting from cryosphere changes and to understand to what extent they can fit within the various perspectives and typologies of the L&D discourses introduced in the previous section. We therefore conducted a systematic review of the scientific literature on current knowledge on cryosphere related impacts to human systems. Laurans et al. (2013, p. 209) define systematic review as "*a process through which one methodically chooses a sample of works, extracts the targeted information and reports the results with transparency on the methods that were used at each step*". Systematic reviews illustrate the state of knowledge on a given topic and highlight gaps as well as future directions in research (Ford and Pearce 2010). Following a similar procedure described by McDowell et al. (2014) on adaptation in glaciated mountain regions, we examine the peer-reviewed English literature published between January 2013 and 2017. We chose 2013 for the cut-off date of our papers as the year the WIM on L&D of the UNFCCC was officially launched. A test search including time periods before 2013 showed that the majority of papers mentioning L&D were in fact published after 2013. We decided to focus only on peer-reviewed publications because they provide well-informed, robust knowledge and have a rather uniform structure. Keyword searches were performed in the literature databases Scopus and ISI Web of Knowledge. We searched for articles by applying iteratively different combinations of keywords, namely: 1) Glacier Change and Climate Change; 2) Glacier Change and Impacts; 3) Damage and Glacier and Climate Change. This search returned a total of 178 papers between 2013 and 2017. To this initial result, we applied a number of selection criteria. Inclusion and exclusion criteria were defined as follows: 1) we included articles that explored the whole chain from primary physical events in the mountain cryosphere, to secondary (bio-physical) impacts, and associated societal L&D; 2) we excluded papers focusing only on monitoring, observations and/or modelling of glacier processes and changes; 3) papers were also excluded if they focused primarily on impacts of glacier changes on natural ecosystems without discussing any human/societal impacts; 4) we excluded papers exploring the cryosphere changes with other processes and in other environments such as Arctic sea-ice, Greenland and Antarctica ice sheets and consequent sea level rise; 5) we also excluded book chapters. Furthermore, to maintain a sharper focus, we concentrated on impacts related to glacier shrinkage and permafrost degradation and did not consider snow-related negative effects. Snow has a strong seasonal character and its importance extends far beyond high-mountain regions, which are the focus of our study.

We performed cross checks between the three searches, with a first selection based on the above defined inclusion/exclusion criteria resulting in only 33 papers, which fully responded to our search criteria. Furthermore, we performed a final search with the keywords: Permafrost and Mountains and Climate Change. This search returned a total of 79. However, we noticed that the bulk of the papers focused on describing processes and physical impacts. We also noticed that several papers had already previously been selected. Hence, we added only 8 additional papers and a total of 41 papers which were retained for the final analysis.

A detailed overview of our search protocol with the inclusion/exclusion criteria is provided in Table S1 of the supplementary material. With the selected material we performed a full text read and classified information based on a questionnaire and a coding strategy to allow for standardization and replication of the results (McDowell et al. 2014). Since we are interested in understanding where and how L&D is happening and how it relates to the concepts introduced in Section 2, we used the following questions to guide us in the document analysis:

1. What is the geographical scope of the study?
2. Which processes are explored in the paper, in particular slow-onset and sudden-onset processes or both?
3. What are the human impacts and related L&D resulting from the (bio-) physical impacts related to cryosphere change?
4. Which categories of L&D can be identified in the paper, and how do they refer to the concept of avoided, unavoided, or unavoidable L&D?
5. How does the paper discuss actions to address those impacts and L&D?

L&D as such is not reported in the literature we analyzed, and therefore we refer here also to the term impacts and investigate how these impacts can be framed in terms of L&D. To address question 2, we looked in the papers at both biophysical impacts in terms of slow-onset processes, such as changes in water runoff and seasonal water availability, as well as sudden-onset processes related to slope instability and outburst floods from glacier lakes. To address question 3, we selected from each paper the corresponding text describing the human impacts as close as possible to the notion of L&D and reported the result in a qualitative fashion. We performed an open coding of the selected text to try to identify categories and relations within the data. This approach is routinely used in document analysis in order to detect patterns and organize the data into categories (Saldaña 2015). Based on the logic of content analysis, we defined the themes or categories in the process of going through the selected texts. Such categories are defined based on the research questions with the objective to extract the elements of interest out of the multitude of data available (Mayring 2014). This process facilitates the allocation of texts from the passage in the documents to the corresponding categories. Hence, categories are established and refined before (deductive) and during the coding process (inductive). In a final step, we grouped categories to have a more structured and reduced number of categories for the purpose of outlining the main results. We claim that the process of coding cannot be fully objective, but it is guided by the research questions, the assumptions as well as the possible interpretations of the data. Question 4 was addressed respectively by applying the typology of impacts introduced in section 2, i.e. avoided, unavoided and unavoidable (Verheyen and Roderick 2008; Verheyen 2012). To answer these questions, we worked first deductively and extracted from the text passages that could be attributed to one or more of the three typologies of L&D. In the analysis of the raw material we also noted that a number of passages in the text required the identification of an additional category, and in this case we worked inductively to define the category of avoidable L&D from the raw material. This category is used to categorize impacts that could be avoided in the future. Finally, to address question 5, we analyzed the literature for types of actions and response to the described impacts or L&D.

## Results

We first examined the geographic distribution of the publications per mountain range (Fig. 1). Interestingly, the highest number of documented L&D does not come from Europe and North America, which are typically the best documented regions in terms of climate change impacts (Huggel et al. 2016b). Instead, the highest concentration is found in the Andes (18) and Greater Himalaya ranges (17), followed by the Central Asia/Chinese mountains and the European Alps. Only a handful of papers focus on other mountain ranges, such as the North American Rockies and Scandinavian mountains. In general, we notice that none of the papers referred to the L&D mechanism explicitly or hinted in any way at the discussion surrounding L&D.

Almost half of the papers analyzed mention slow-onset processes (18), including mainly hydrology related processes such as changes in river runoff, surface and underground water availability. A small number of papers refer to the physical alterations of the landscape due to glacier retreat as well as changes in ecosystem processes, habitats and biodiversity. The other bulk of the papers (17) focus on sudden and slow-onset processes together, and only five papers focus on sudden-onset events only. The sudden-onset events most addressed in the publications are GLOFs, with about one-fourth of all papers specifically concerned with GLOFs. Although GLOFs as such are a sudden-onset process, in many cases they can be classified under both slow and sudden-onset because a GLOF is typically the results of glacier retreat and lake formation, which is a slow-onset process. Other sudden-onset events include different landslide and mass flow processes, such as rock falls, debris flows and ice avalanches, related to glacier and permafrost processes and changes (Haeberli et al. 2017).

Following the coding and categorization described in the previous section, we grouped the socio-economic impacts under the following categories, which emerged inductively and deductively: 1) cultural L&D; 2) L&D to livelihoods; 3) L&D to productivity and revenue; 4) L&D to natural resources; 5) loss of lives; 6) loss of security and social order; 7) damage to people and assets. A more detailed discussion on the categories is provided further below in the analysis of the results and in Table 1. Per each category, we report on the impacts as discussed in the different papers. Our categories include both economic and non-economic L&D, but it is notable that more categories of NELD than economic L&D emerged (five versus two). Most of our NELD categories capitalize on conceptual approaches by Fankhauser et al. (2014), except the loss of and damage to livelihoods, and the loss of security and social order. L&D to livelihoods was introduced as a distinct category from L&D to productivity and revenue, as we noticed that in several papers impacts were discussed more in relation to the resource basis upon which small and rural communities depend, and less in terms of economic impacts to sectors and large societies. Examples of L&D to livelihoods are given, amongst others, in Beniston et al. (2014), Allison (2015), Jurt et al. (2015b). The category of 'loss of security and social order' emerged as a distinct category possibly because of a tendency in the recent literature to link the intensification of biophysical impacts resulting from climate change to the emergence of conflicts and reduced social order. For example, Rangecroft et al. (2016) discuss the impact of permafrost thawing on water supplies for the large urban centres of El Alto and La Paz in Bolivia. Pre-existing water stresses in these cities could be amplified as a result of climate change and growing populations, eventually leading to long-term disruptions in social systems. A similar argument is touched upon by Thorsteinsson et al. (2013) in an analysis of the consequences of runoff changes in the mountainous regions of Central Asia. They conclude that dispute over water availability between India and Pakistan could lead in the future to potential threat to security and peace in the region.

Figure 2 shows the relation between the different categories of L&D and the type of event (e.g. sudden and slow-onset processes and combinations thereof). The category with the highest number of papers is damage to and loss of natural resources, followed by L&D to productivity and revenue. It is interesting to note that these two categories are referred to by a similar number of papers with slow-onset processes and combined sudden and slow-onset processes, but by none with sudden-onset events only. The only reported categories of impacts associated with sudden-onset events are loss of lives and damage to people, infrastructure and assets.

At a further stage, we looked into the type of L&D. More than half of the papers discuss potential future impacts that are yet to be realized, often hinting at a number of strategies to address such impacts. The majority of papers (28) fall into our new category of avoidable L&D, while a similar number of papers can be associated with unavoided (13) and unavoidable (12) L&D, and only a minimal number with avoided L&D (2); 12 papers were not associated with a particular category. Verheyen (2012) suggests that glacier melting as a physical slow-onset change belongs to the category of unavoidable. Due to the delayed response of glaciers to climatic changes, glaciers will in fact continue to shrink for some defined future time period, even if further warming could be prevented (Johannesson et al. 1989). However, several studies have found that low-emission versus high-emission scenarios make very significant differences for mountain glaciers, as demonstrated with regional-scale studies for the Andes and Asia (Schauwecker et al. 2017; Kraaijenbrink et al. 2017) and with global-scale analyses (Marzeion et al. 2018). However, while further glacier shrinkage and melt is unavoidable, the impacts of such melting on humans and the consequent L&D could still be averted through appropriate measures such as risk management and adaptation. Our category of avoidable L&D refers to this logic and encompasses the corresponding evidence found in the analyzed papers.

Finally we investigated how the papers discussed actions to address impacts and L&D. About half of the papers highlighted adaptation actions which might be needed to prepare for cryospheric change. A fourth of the papers also stated the importance of risk management and insurance as a response, e.g. to deal with risk of flooding. A minority (10%) of the papers referred to more fundamental responses such as migration and resettlement. One among four papers did not discuss responses.

## 4 Discussion

This study represents a first attempt to explicitly analyze the societal impacts of climate change in the mountain cryosphere under a L&D framework. We performed our analysis starting from an overview on the political context and the discourse surrounding L&D and its relation to the cryosphere, and then looked more closely at the current literature by means of a systematic literature review.

Our main findings are: 1) mountain cryosphere research remains disconnected from the L&D discussion; 2) L&D in the mountain cryosphere is a global phenomenon, and the literature suggests that the developing world is particularly affected; 3) seven distinct categories of L&D stand out as particularly relevant to the mountain cryosphere; 4) a proposal for a more process- and system-based approach to L&D in the mountain cryosphere is demonstrated, which offers a path for discussing possible implications and opportunities for L&D policy and research.

Although the L&D discussion has gained significant pace in some research fields in recent years, and in particular in global climate policy, our review indicates a clear disconnect between the cryosphere mountain research community and the L&D approach. This is not necessarily surprising, given the recent nature of L&D policy developments, but is potentially a missed opportunity, considering that the mountain cryosphere is among the most sensitive Earth systems to climate change, where impacts of climate change can be observed more clearly and over longer historical time periods than in many other systems. The limited involvement of the mountain cryosphere research community in L&D discussions furthermore implies that concepts of L&D have not been systematically analyzed and applied for these environmental and associated human systems. The reference of official policy documents to specific geophysical changes, including in the mountain cryosphere, remains vague, broadly referring to glacier retreat and related impacts as seen above (UNFCCC 2012). This highlights the relevance of further conceptualization by scientists, and our study should therefore be understood as a first attempt to frame the mountain cryosphere impacts within the L&D discourse.

Our study suggests that L&D in the mountain cryosphere is a global phenomenon and can be identified in all major mountain ranges of the Earth. Contrary to earlier assessments of observed impacts of climate change (across all systems) in the IPCC 5$^{th}$ Assessment Report (Cramer et al. 2014; Huggel et al. 2016b) our literature sample reflects a higher number of L&D events reported in Non-Annex I (developing) countries compared to Annex I (developed) countries. Whether this finding demonstrates that L&D is actually occurring more frequently in the mountains of the developing world, or whether the existing literature has simply studied and documented L&D in the developing world more often than in Annex I nations, needs to be investigated in more depth. Indicators for the occurrence of L&D could be the size (area) of, or the number of people living in the respective mountain region. The Himalayas are home to 286 million, the Andes to 73 million people while the European Alps only host about 22 million people (numbers from 2012) (Stäubli et al. 2017).

Our literature review converged into the identification of seven different categories of L&D in the mountain cryosphere. The categories include physical and non-physical, economic and non-economic L&D. Especially the debate on NELD is attracting considerable interest in research and policy (Serdeczny et al. 2018). Up to five of our seven L&D categories identified can be termed NELD. Values play a key role in NELD and are reflected in our category 'cultural L&D'. To understand the relation of values to L&D in the mountain cryosphere, it is helpful to consider that values provide meaning for the people in their world, and shared meanings contribute to the understanding of people themselves in terms of who they are and how they behave. Jurt et al. (2015a), for instance, found that people at three different sites (in Peru, Italy and the US) are concerned about glacier retreat in terms of community, identity and self-reliance, yet in different ways. Values allow groups to organize themselves at a collective level and are crucial for collective answers to changes in the environment. If such meanings are inextricably given to physical objects, such as glaciers, the loss of these objects also leads to a loss of meaning, and as such cultural integration, traditions and identities might be impinged upon (Morrissey and Oliver-Smith 2013). Because of the obvious and tangible loss in the case of glaciers, the mountain cryosphere offers a striking example of NELD, which could have far-reaching implications for other systems and sites.

We specifically looked at how sudden-onset and slow-onset processes produce L&D, and found that sudden-onset processes tend to result in physical damage to and/or loss of lives and assets while slow-onset processes rather have impacts on a number of economic sectors or on social and cultural aspects of human life. L&D related to sudden-onset processes can often be attributed to cryospheric (or related) processes in a more direct causal relationship than can L&D related to slow onset processes. For instance, loss (or reduction) of cultural and place-based identity may not only be driven by receding and disappearing glaciers and snow but also by in- and out-migrating people, urbanization processes, or generational changes in traditions (Jurt et al. 2015b).

The reflection on the type of processes resulting in L&D formed a basis to develop a more analytical and process-based approach to understand L&D in the mountain cryosphere, where processes include both

physical and social aspects and dynamics. We therefore propose here the following conceptual approach: in a nutshell and broadly in line with (Huss et al. 2017), we consider (1) primary physical processes in the mountain cryosphere, (2) secondary (bio-) physical impacts (sudden and slow-onset), and finally (3) associated societal effects where L&D typically materializes (Figure 3). The distinction of these three levels of processes and impacts is useful to foster a comprehensive understanding of how observed L&D is connected, driven and caused by climate and cryosphere change, but also how it is related to other factors and developments (e.g. social, political, economic). We distinguish between the three mountain cryosphere elements, i.e. glaciers, snow and permafrost. Changes in these cryosphere elements are primarily of slow-onset type, representing cumulative and irreversible processes over the time horizon of a warming climate, with glaciers continuously shrinking, thinning and retreating. Snow has a higher year-to-year variability than glaciers and permafrost but over climatically relevant periods of about 30 years the decreasing trends in snow cover extent and duration are clear (Vaughan et al. 2013).
The next level of bio-physical impacts distinguishes between sudden and slow-onset processes. A GLOF, for example, is a sudden-onset process while change and loss of landscapes represent a slow process. However, it is important to recognize that both slow and sudden processes overlay. A GLOF is a sudden event occurring within minutes but is ultimately the result of much slower and cumulative processes of glacier retreat and lake formation. The categories of slow and sudden-onset that are very widespread in technical documents and language of global climate policy may thus not be appropriate for the mountain cryosphere, and also not for processes in other systems such as coastal erosion in the Arctic (Huggel et al. 2015b). The third level of societal impacts of our concept contains L&D to people or to objects that people value, economically, or non-economically. We included a few examples of L&D in Figure 3 which can be grouped into the seven L&D categories defined based on the literature review above. The term 'loss' may refer to full or partial loss, a distinction that is often not explicitly made in the L&D literature.

From the concept in Figure 3 we learn that L&D in the mountain cryosphere is typically produced as a cascade of impacts, vertically through the different levels (from top to bottom). Cascading impacts and loss can furthermore also be produced horizontally through different types of L&D in the bottom layer of Figure 3, as has also been mentioned in the literature (Tschakert et al. 2017). For example, glacier and snow changes involving seasonal shifts or reduction of water availability may result in loss of crop area and yield of small-scale farmers at high elevations, a reduction of income eventually leading to migration and loss of identity and place. A consequence of cascading and multiple levels of L&D and multi-dimensional driving factors is the challenge to track L&D back to the source and analyze the causal relationships.
GLOFs represent another pertinent example of cascading impacts. Associated L&D is often strongly driven by non-climatic factors, such as social, economic or political processes; for instance, increasing exposure of people and assets in flood-prone areas greatly enhances potential L&D. This example shows the close connection of L&D and risk research, where risk is a function of (climatic) hazard, and exposure and vulnerability of assets or people (IPCC 2014), and can be interpreted as the probability of L&D. This risk framework calls for a comprehensive view on L&D and related risks which goes beyond the analysis of

impacts of climate and cryosphere change and looks into the drivers and people's coping mechanisms of risks and L&D. Disaster research has begun to more systematically analyze the root causes of risks and disasters, an emerging field sometimes termed disaster forensics (Keating et al. 2016). This approach essentially involves a dynamic rather than a static view on risks. The role of anthropogenic climate change as a growing driver of risk over time makes a dynamic perspective indispensable for the L&D debate. However, more research on dynamic changes and drivers of risks is needed, which in general is more straightforward for exposure (Rimal et al. 2018) than for vulnerability whose changes over time remain poorly understood (Mechler and Bouwer 2015; Huggel et al. 2015a).

The role of anthropogenic climate change in driving climatic hazards such as heat waves, floods or storms is a key focus of attribution research (Bindoff et al. 2013), which has also started to adopt the aforementioned comprehensive risk perspective (Huggel et al. 2013). Only a limited amount of attribution studies have focused on the mountain cryosphere so far, including attribution of global glacier shrinkage and GLOF occurrence to climate change (Marzeion et al. 2014; Harrison et al. 2018). Nevertheless, in global assessment studies the cryosphere has been identified among those systems with the highest confidence in attribution (Cramer et al. 2014; Hansen and Stone 2016). A stronger connection between disaster and attribution research may generate important progress and also tangible input to L&D policy. To illustrate this link we take again the case of GLOF risk or L&D. We would need to analyze how GLOF hazard can be attributed to anthropogenic emissions through an impact chain from climate change to glacier shrinkage, lake growth, and flood hazard. Evaluating the contribution of exposure and vulnerability to GLOF risk could involve aspects such as the historical development and dynamics of residential areas and land-use change in the exposed areas, and how risk governance, preparedness or early warning were successful or not. We do not ignore that such an approach is highly challenging and furthermore limited by availability of data, but even on a semi-quantitative or qualitative basis it may produce important insights.

## 5 Conclusions and implications for research and policy

The mountain cryosphere is one of the most affected systems by climate change, and cryosphere change is thus one of the most visible indicators of anthropogenic climate change. Many scholars have studied the impacts of cryosphere change on downstream ecosystems and societies but hardly made explicit reference to the concept of L&D. Although repeatedly invoked in policy documents, L&D in the mountain cryosphere has not been analyzed under a L&D lens in a more systematic way so far.

Our systematic literature review resulted in the identification of seven distinct categories of L&D for the mountain cryosphere and surrounding societies. The categories range from physical damage and loss (of lives or natural resources) to economic loss of productivity and revenue, and to less tangible aspects of cultural loss. Our findings could be helpful for those working on socio-cryospheric systems and possibly also inform L&D policy, as sketched in the following.

To start, we suggest that both L&D science and policy could benefit from a more process- and system-based approach. As we have shown, L&D needs to be tracked along a cascade of impacts (Fig. 3). L&D is a product of physical and social processes and their interactions, in this case in a dynamic socio-cryospheric system. A more precise use of L&D terminology would account for the processes that produce L&D, considering that L&D primarily materializes on the level of social and economic impacts (cf. Fig. 3). A process-based perspective also includes an analysis of the role of mitigation and adaptation and thus can eventually facilitate improved action to reduce or avoid L&D. It is important to identify and further investigate the limits of mitigation and adaptation, in particular the non-physical / technical limits. For the cryosphere, L&D policy and science should take into account the already committed (or unavoidable) change due to the delayed response of glaciers to climate change (Marzeion et al. 2018), which underlines the importance of effective adaptation and the support developing countries need for this purpose.

Furthermore, our L&D analysis in the mountain cryosphere may contribute to the science and policy discussion of responsibilities and climate justice which underlies and notoriously undermines the L&D policy as discussed previously. As seen in Figure 3 mitigation efforts propagate from climate and cryosphere change to bio-physical impacts and social and economic impacts, with the importance of adaptation proportionally increasing towards social and economic impacts and L&D. To revisit again the GLOF example, even though further glacier shrinkage and lake formation may be unavoidable, loss of lives due to a GLOF will in most cases be avoidable, depending on measures that either protect the exposed human populations or move them out of the hazard zone, or reduce the hazard by draining the lake before a flood even occurs. Our additional category of avoidable L&D accounts for these connections. Due to missing capacities and resources developing countries may need assistance in ensuring that the unavoidable impacts on the cryosphere are effectively managed to avoid societal L&D. Because L&D in the mountain cryosphere affects developing countries more than the developed world, according to the sources analyzed in this study, our analysis underlines the responsibility of developed countries to assist developing countries in reducing or avoiding L&D, through both adaptation and mitigation efforts, which is in line with climate justice discussions (Miller 2008; Wallimann-Helmer 2015). A process-based view deciphering the different levels of L&D (Fig. 3) may help to identify targeted and evidence-based policy approaches.

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**Figure captions and Table**

Figure 1 Geographic distribution of the publications per major mountain range. The Greater Himalaya region includes the Himalaya, Pamir, Karakoram, Hindukusk, Hengduam and Kunlun mountains. Tien Shan+ includes several other Chinese mountain ranges.

Figure 2: Relation between the type of events and the categories of loss and damange as defined in Table 1.

Figure 3: Conceptual approach of cascading impacts in the mountain cryosphere resulting in loss and damage (L&D). The first level represents the physical effects of climatic change on the mountain cryosphere while the second level shows the associated bio-physical impacts with a timescale indicating sudden-onset to slow-onset processes (from left to right). The third level outlines a number of resulting L&D where grey shading refers to non-economic L&D and white to economic L&D. Processes and L&D represent examples and not a complete list. The wedges on the right indicate that the varying importance of climate mitigation and adaptation for the respective level in view of reducing or avoiding L&D.

Table 1: The table provides a rationale for the broader categories of loss and damage (L&D) originating from cryosphere impacts. The first column lists the impacts as established before and during the coding process based on the whole body of selected literature. The second column shows the final identified L&D categories. It is possible that the same impact may fall under more than one category.

| **Categories established before and during the coding** | **Final (grouped) category of loss and damage** |
|---|---|
| Cultural and lifestyle changes; loss of identity; loss of self-determination and influence; emotional and psychological losses; loss in cultural, spiritual and recreational landscape. | Cultural loss and damage |
| General loss of and damage to livelihoods reflecting mainly the resource basis of rural communities, such as shift away from traditional livelihoods (horticulture and pastoralism); damage to subsistence farming; loss of cultivable land; loss of yields. | Loss of and damage to livelihoods |
| Loss (including temporary) of and damage to any type of income, productivity, and investment potential which results in reduced economic prosperity and development. These include loss of revenue from tourism; reduced energy generation (e.g. hydropower and mining); reduced agricultural productivity; loss of yield; loss of revenue from cultivable land; general losses of any type of revenue and productivity from economic sectors depending on water. | Loss and damage to productivity and revenue |
| Reduced water access, availability and supply (both upstream and downstream); reduced water quality; shortages of drinking water; loss of and damage to ecosystem services; loss of habitat and biodiversity; damage to forest resources and loss of forest fertility. | Damage to and loss of natural resources |
| Loss of human lives | Loss of lives |
| Adoption of a long-term perspective rather than the chaos originating after a sudden event. It includes loss of order in the world; conflict over water access; decreased security from hazard impacts; social instability and conflicts loss of water security; conflicts over water supply; conflicts over water allocations | Loss of security and social order |
| Primarily physical damage from cryosphere related hazards to people, infrastructures and society, such | Damage to people and assets |

| | |
|---|---|
| as destruction and disruption of properties and infrastructures; damage to farmland; damage to agricultural land; widespread damage to downstream communities; damage to roads and bridges, farmlands and various buildings. | |

**Reponse to editor and review comments (second revision)**

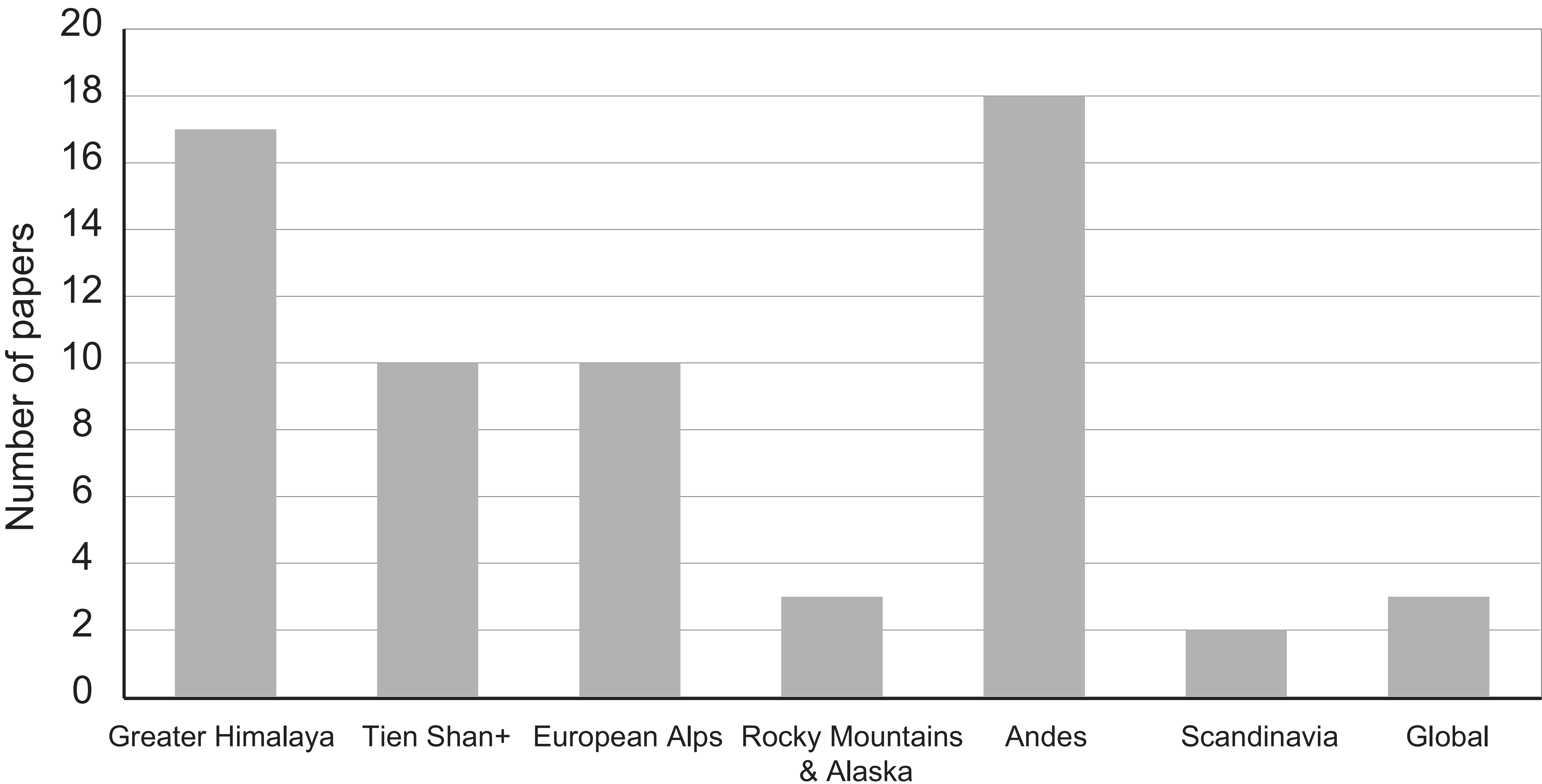
Dear Editors, dear Ben and Christopher,

Thank you for the exchange we had on the language issues. Based on that we have now thoroughly gone again through the manuscript and revised the text where considered appropriate and necessary. We have also corrected the abbreviations in the figures, figure captions and table (caption). With this I believe we have completed all necessary and requested revisions.

Best wishes,

Christian

Figure 1



Number of papers
20
18
16
14
12
10
8
6
4
2
0
Greater Himalaya
Tien Shan+
European Alps
Rocky Mountains & Alaska
Andes
Scandinavia
Global

Figure 2

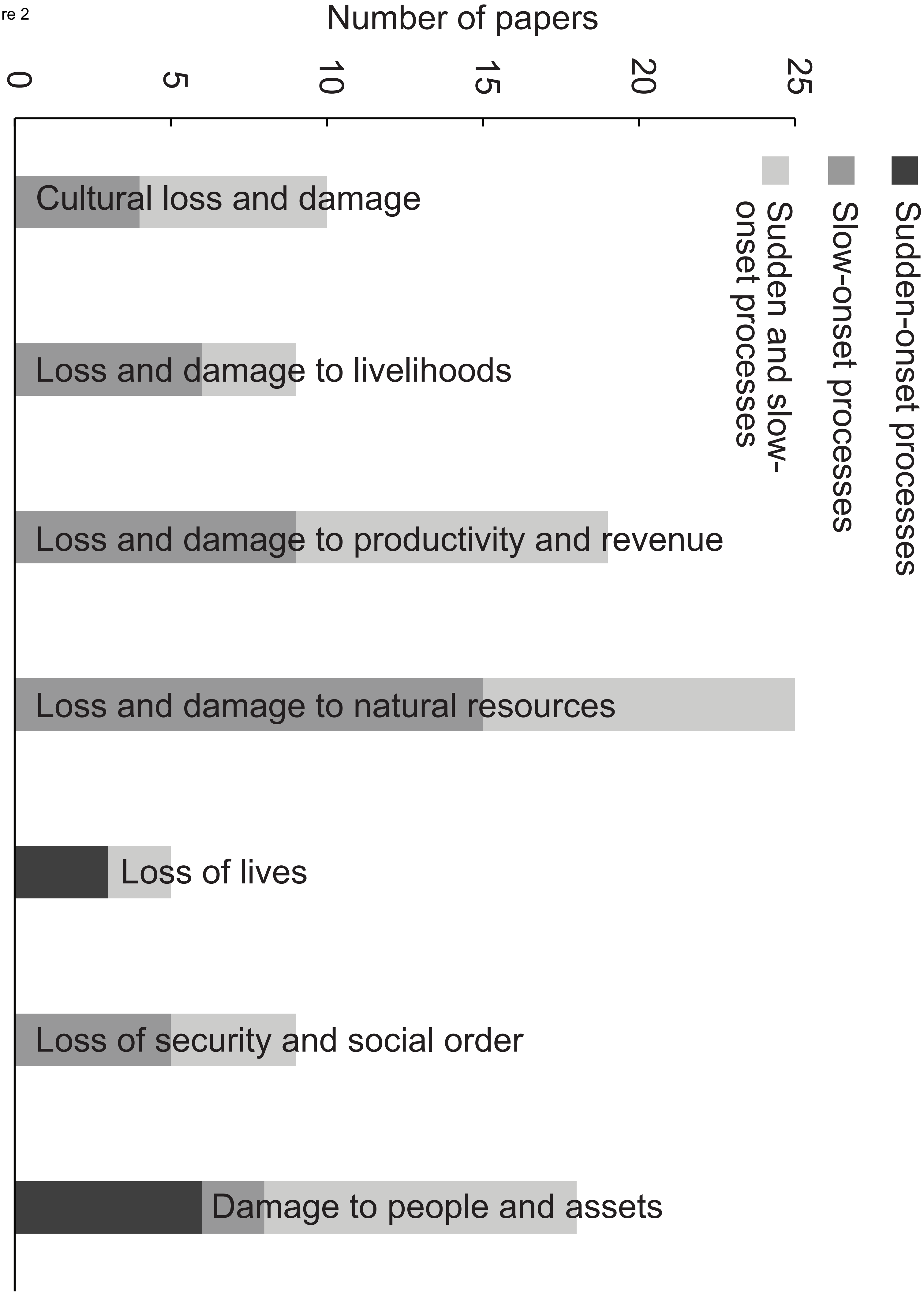
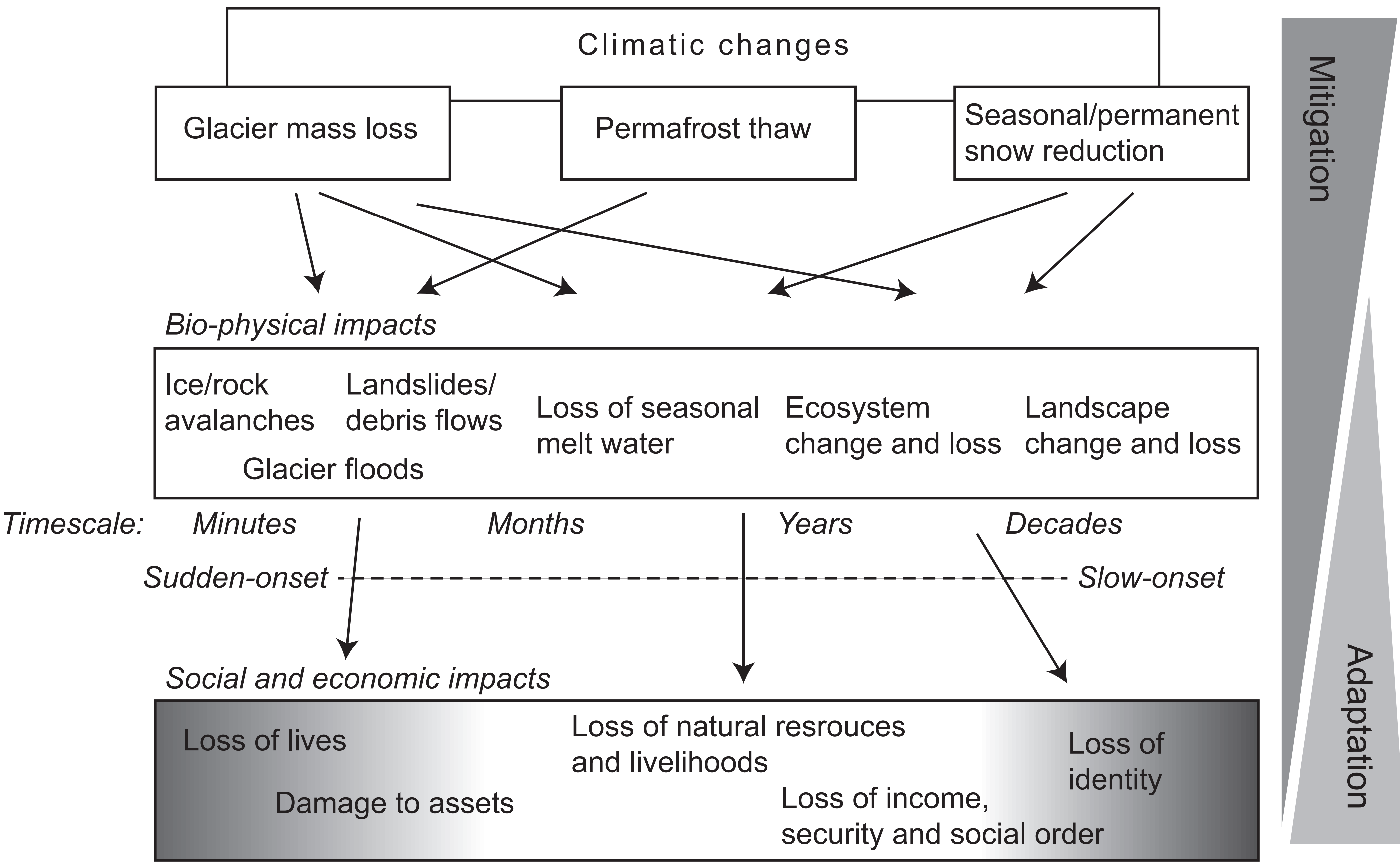

Number of papers
0
5
10
15
20
25
Sudden-onset processes
Slow-onset processes
Sudden and slow-onset processes
Cultural loss and damage
Loss and damage to livelihoods
Loss and damage to productivity and revenue
Loss and damage to natural resources
Loss of lives
Loss of security and social order
Damage to people and assets

Figure 3


Climatic changes
Glacier mass loss
Permafrost thaw
Seasonal/permanent snow reduction
Bio-physical impacts
Ice/rock avalanches
Landslides/ debris flows
Glacier floods
Loss of seasonal melt water
Ecosystem change and loss
Landscape change and loss
Timescale:
Minutes
Months
Years
Decades
Sudden-onset
Slow-onset
Social and economic impacts
Loss of lives
Damage to assets
Loss of natural resrouces and livelihoods
Loss of income, security and social order
Loss of identity
Mitigation
Adaptation