Received: 6 June 2021 | Revised: 18 October 2021 | Accepted: 11 November 2021
DOI: 10.1002/wcc.753

ADVANCED REVIEW

WIREs CLIMATE CHANGE WILEY

The need for stewardship of lands exposed by deglaciation from climate change

Anaïs Zimmer[1] | Timothy Beach[1] | Julia A. Klein[2] | Jorge Recharte Bullard[3]

[1]Department of Geography and the Environment, The University of Texas at Austin, Austin, Texas, USA

[2]Department of Ecosystem Science and Sustainability, Colorado State University, Fort Collins, Colorado, USA

[3]Instituto de Montaña, Lima, Peru

Correspondence
Anaïs Zimmer, Department of Geography and the Environment, The University of Texas at Austin, Austin, TX, USA.
Email: anais.zimmer@utexas.edu

Funding information
National Science Foundation - Division of Environmental Biology, Grant/Award Number: 2113526; National Science Foundation - Human-Environment and Geographical Sciences Program, Grant/Award Number: 2105826

Edited by: Brendon M.H. Larson, Domain Editor and Mike Hulme, Editor-in-Chief

Abstract

Alpine glaciers worldwide will lose most of their volume by the end of the 21st century, placing alpine ecosystems and human populations at risk. The new lands that emerge from retreating glaciers provide a host of challenges for ecological and human adaptation to climate change. In these novel proglacial landscapes, ecological succession and natural hazards interplay with local agriculture, hydroelectric production, mining activities, and tourism. Research has emphasized the importance of understanding adaptation around socio-environmental systems, but regional and global management efforts that support local initiatives and connect novel proglacial landscapes to ecological, social, and cultural conservation opportunities are rare and nascent. The characteristics of these emerging lands reflect the nexus of alpine ecosystems with socio-political histories. Often overlooked in glacial-influenced systems are the interdependencies, feedbacks, and tradeoffs between these biophysical systems and local populations. There is no coordinated strategy to manage and anticipate these shifting dynamics, while affirming local practices and contexts. There is an opportunity to initiate a new conversation and co-create a governance structure around these novel landscapes and develop a new framework suitable to the Anthropocene era. This article first synthesizes the rapid socio-environmental changes that are occurring in proglacial landscapes. Second, we consider the need for integrating "bottom-up" with "top-down" approaches for the sustainable management of proglacial landscapes. Finally, we propose establishing a transdisciplinary initiative with policy-related goals to further dialogues around the governance and sustainable management of proglacial landscapes. We call for increased cooperation between actors, sectors, and regions, favoring multiscale and integrated approaches.

This article is categorized under:
Climate, Ecology, and Conservation > Conservation Strategies

KEYWORDS
climate change adaptation, glacier retreat, proglacial landscape, stewardship, sustainable management

1 | INTRODUCTION

Mountain glaciers and ice caps cover approximately 485,000 km^2 of the Earth's surface, excluding the large ice sheets of Greenland and Antarctic (Hock, Rasul, et al., 2019). Mountain glaciers are present in 44 countries (RGI Consortium, 2017), almost 25% of the world's countries. In most mountain regions of the world, glaciers are retreating, and ice-free lands are expanding as a consequence of climate change (Beniston et al., 2018; Bolch et al., 2012; Davaze et al., 2020; Dussaillant et al., 2019; Hugonnet et al., 2021; Menounos et al., 2019; Rabatel et al., 2013; Shean et al., 2020; Zemp et al., 2019). Paralleling the Anthropocene, mountain glaciers started shrinking at the end of the Little Ice Age (LIA), ~1850, and the rate of melting increased after the 1950s (Matthews & Briffa, 2005). Especially over the last two decades, global glacier thinning and mass loss have drastically accelerated (267 ± 16 gigatonnes per year), contributing to sea level rise, altering regional hydrology, and accentuating natural hazards (Hugonnet et al., 2021; Wang et al., 2020; Zemp et al., 2019). Recent glacier mass projections simulate substantial global scale glacier mass losses, especially for the higher emission scenarios (Representative Concentration Pathway RCP8.5; [Hock, Bliss, et al., 2019; Huss et al., 2017; Zekollari et al., 2019]).

As a result of the shrinking ice, approximately 227,000 km^2 of new lands will emerge by 2100 under the high emissions RCP8.5 scenario (A. Rabatel, personal communication—Appendix S1). This is equivalent to the area of the United Kingdom. Even under the more conservative RCP2.6 scenario, ~142,000 km^2 of ice-free lands are likely to emerge. The RCP8.5 scenario forecasts the complete disappearance of numerous glaciers within the next decades, especially in the Tropics. Rabatel et al. (2013) highlight the high vulnerability of tropical glaciers in the Andes located below 5400 m.a.s.l., which will probably disappear in one or two decades. Likewise, if current conditions persist, the East African and Australasian glaciers will disappear within the same timeframe (Mt Kilimanjaro: Thompson et al., 2009; Zawierucha & Shain, 2019; Puncak Jaya: Veettil & Wang, 2018). Globally, the complete extinction of 8–21 of the iconic World Heritage Glaciers is expected by the end of the century (Bosson et al., 2019). Glaciers cover a relatively small area, but the processes of deglaciation and emerging ice-free lands (henceforth "proglacial lands"; Box 1) will have disproportionately large effects worldwide on biological, hydrological, and geomorphological processes.

Rapidly melting glaciers will have significant implications for society both near and downstream of the glaciers, thus affecting much larger areas and human populations beyond the deglaciating landscapes themselves (Brighenti et al., 2019; Haeberli et al., 2019; Immerzeel et al., 2020). The process of deglaciation and the emergence of new lands and lakes may pose significant challenges, such as increased natural hazards or changes in water resources (Deline et al., 2021; Linsbauer et al., 2016). But they also represent opportunities for the development of soils and vegetation (Carlson et al., 2014; Egli et al., 2006; Eichel, 2019; Ficetola, 2021; Hock, Rasul, et al., 2019). Organisms can colonize ice-free areas rapidly, and in less than a century, even forests and wetland ecosystems can develop in these former glacier and permafrost lands. These new geosystems and ecosystems might contribute to key environmental services such as water amount and quality, aquifer recharge, carbon sequestration, biomass production, and biodiversity (Gobbi et al., 2021). And there are many studies on the implications of glacier retreat for the corresponding landscapes, downstream ecosystems, and water supplies (e.g., The Special Reports on Global Warming [Cuesta et al., 2019; Hock, Bliss, et al., 2019; IPCC, 2018, 2019]). Lastly, important research fields are emerging (e.g., modeling of new landscapes and environments; Haeberli, 2017), and adaptation-oriented studies and multipurpose projects have been developed within these new proglacial lands. Glacier retreat also has important socio-cultural and psychological dimensions. Historic and current social, economic, and environmental changes have influenced local and regional interpretations of risk and hazards and shaped responses in complex ways. For example, loss of landscape identity leads to the loss of the sense of place, local customs, identity, and religion (Deline et al., 2014; Drenkhan et al., 2019; Huggel et al., 2015; Jurt, Brugger, et al., 2015).

Proglacial landscapes reveal entangled biophysical, sociocultural, and economic (hereafter, socio-environmental) dynamics that require attention in the face of unprecedented and accelerating human-induced environmental changes (Huss et al., 2017; Vuille et al., 2018). Almost a fourth of the world's countries need to manage the current and forthcoming socio-environmental challenges associated with glacier shrinkage. However, incoherent policies and institutions hinder socio-environmental systems and local initiatives that are now in place or evolving. Globally, the major challenges for governance include unawareness by those living outside the mountains, contradictory policies—made in many cases by outsiders who do not understand local situations, poverty, and asymmetrical competition for valuable natural resources (Kellner & Brunner, 2021; Klein et al., 2019; Tucker et al., 2021). The Rio Earth Summit (UNCED; Mountain Agenda, 1992) marked the key starting point of global concern for mountains, but mountain systems research has made minimal connection to both local and global policy. International mechanisms—such as the

Mountain Agenda[1] or the Warsaw International Mechanism for Loss and Damage[2] are crucial to support local solutions to climate change impacts because in the near future proglacial lands will be critical for regulating fresh water for billions of people. Mountains occur on all continents in diverse socio-political contexts, which exacerbates the challenge of global policies that can fit local contexts (Debarbieux & Price, 2012). A global strategy should be also highly decentralized in addition to being flexible. Local agency and knowledge, and horizontal dialogue between parties are the major assets to identify solutions and move toward sustainable management options.

This advanced review draws on research from biophysical and social sciences to explore proglacial landscapes. The article identifies key socio-environmental challenges and opportunities for deglaciating landscapes and investigates existing governance arrangements to develop flexible but coordinated governance mechanisms that originate from local needs and contexts. It explores the policy and planning efforts that already exist in the alpine proglacial landscape to highlight future opportunities to support socially just, less hazardous, and ecologically sustainable responses to climate change. We intend to expand the purview of conservation theory and practice beyond what is and what was, to what might become a just, sustainable, and meaningful future.

Four overarching research questions guide this essay:

- What are the actual and most pressing socio-environmental challenges arising from emerging proglacial systems?
- What key opportunities do proglacial systems present to local actors and to the broader society?
- How do we ensure continuous learning and observation processes to meet the actual and incoming challenges, and identify opportunities?
- Which policies and planning efforts already exist in the alpine proglacial landscapes, and what types of governance arrangements would support socially just and ecologically sustainable management of these emerging lands?

We conclude our review by suggesting directions for further research and propose an initial governance framework for mediating challenges and fostering opportunities from emerging landscapes. This represents a “bottom-up” and “top-down” approach, promoting both local-based strategies and a co-created, transboundary, non-binding initiative for the sustainable adaptation and management of emerging alpine landscapes. The proposed initiative will invite local, regional, and global governance entities to co-develop an overarching framework for research, action, and allocation of necessary resources. Our motivations are to catalyze conversations between actors and sectors, foster locally driven mechanisms for continuous learning and observation, support the often politically and economically marginalized groups who inhabit and use the proglacial lands, and incentivize inclusion of these proglacial lands and their guardians in national adaptation plans.

2 | CHALLENGES FROM DEGLACIATION AND EMERGING LANDSCAPES

In this section, we present the most pressing challenges of the emerging proglacial landscapes. We focus on the biophysical impacts of glacier recession with a strong emphasis on the social–environmental dimensions, including risks/hazards and cultural values associated with the receding cryosphere. A comprehensive review of physical changes is beyond the scope of this review and covered well elsewhere (Haeberli & Whiteman, 2021; Heckmann & Morche, 2019; Zheng et al., 2021).

2.1 | High elevation (alpine) ecosystems and biodiversity

Glaciers, permafrost, and recently deglaciated areas are ecosystems in their own right and provide permanent or temporary habitat for a variety of specialized taxa from bacteria to vertebrates (Ficetola, 2021; Gobbi et al., 2021). The loss of mountain cryosphere—glacier and permafrost—and changes of the physiognomy of the emerging proglacial landscape threaten local high alpine biodiversity and ecosystems, such as altered hydrological, thermal and bio-geochemical cycles, glacier-fed streams, and glacier forelands (Brighenti et al., 2019). In addition, the accelerated pace of warming (Pepin et al., 2015) occurring in high elevations exacerbates the impacts of cryosphere loss, and biodiversity, ecosystem, and hydrological regime changes are lagging behind current climate change (Alexander et al., 2018; Huggel et al., 2015; Milner et al., 2017). The last several years have seen crucial advances in our understanding of biotic colonization and pedogenesis after glacier retreat (Anthelme & Lavergne, 2018; Cauvy-Fraunié & Dangles, 2019; Cuesta et al., 2019;

BOX 1 Terminology

Geo-ecosystems

Troll (1971) originally suggested the term geoecology in the theory of landscape ecology to explain how the geosphere exerts a dual influence on human activities and the natural environment. Haeberli et al. (2017) define glacier foreland as new landscapes with geosystems and ecosystems of rocks, debris, sparse vegetation, new lakes, and slowly thawing permafrost. We use the term geo-ecosystem to ensure a full consideration of the geological factors (e.g., structure, landform, rock, and water), terrestrial and freshwater ecosystems, and social interactions.

Proglacial landscapes

The literature uses a multitude of technical and non-technical terms to name the land emerging after glacier retreat (e.g., "ice-free lands", "proglacial", "postglacial", "cold mountain", "cold region", "deglaciated", or "deglacierized"). Here before a consensus is reached, we use the term "proglacial" to refer to the area emerging after glacier retreat. According to the *Glossary of glacier mass balance and related terms* (Cogley et al., 2011), proglacial means "pertaining to an object in physical contact with, or close to, the glacier margin ". We recognize in some cases glaciers have already completely vanished and disappeared, and in others ice remains for years, but for simplicity we use the term "proglacial lands" for both scenarios. Likewise, our objectives are to discuss adaptation and management before the complete disappearance of the glaciers.

Ficetola, 2021; Hågvar et al., 2020; Khedim et al., 2021). Although hundreds or thousands of years can be required for the full establishment of alpine ecosystems (D'Amico et al., 2017; Eichel, 2019; Erschbamer & Caccianiga, 2016; Temme, 2019), some colonization processes can be surprisingly fast (Anthelme et al., 2021; Benavent-González et al., 2019). Species' success in a glacier retreat and elevation-dependent warming context depends on several complex and interconnected factors, including (a) the biotic and abiotic local conditions (biotic factors include species and their interactions and abiotic factors include climate and geomorphology), (b) speed and ease of species migration toward higher elevation (dispersal capacity), (c) adaptive phenotypic plasticity, and (d) time scales of biological processes. However, these opportunistic ecological processes might not be fast enough to respond to the rate of environmental changes. Post glacial chronosequence studies suggest a time lag between the velocity of warming, the pace of glacier retreat, the upslope migration of alpine communities to the new terrain, and soil formation processes (Alexander et al., 2018; Anthelme & Lavergne, 2018; Cauvy-Fraunié & Dangles, 2019; Cuesta et al., 2019; Gottfried et al., 2012; Schmidt et al., 2012; Zimmer et al., 2018). As a result, in proglacial systems there are "losers" and "winners" of global warming (Cauvy-Fraunié & Dangles, 2019; Hågvar et al., 2020). Most of the "losers" are specialist species or slow-growing and adapted to a narrow range of glacial conditions. The "winners" are more generalist and competitive species that benefit from the higher temperatures and colonize from lower elevations. Expected long-term effects include the loss of high alpine biodiversity, especially for the cold adapted taxa and high elevation endemic floras (Cuesta et al., 2020; Gobbi et al., 2021). These expected biological extinctions within proglacial systems will lead to ecological cascading effects on aquatic and terrestrial systems (Cauvy-Fraunié et al., 2016). Changes in local environmental conditions (e.g., channel stability, temperature, and chemistry) are followed by complex ecological shifts in the stream and terrestrial communities and food webs, with a predicted loss of biotic diversity (Brighenti et al., 2019). In the Andes, studies have shown that changes in meltwater discharge from glaciers upstream strongly affect the spatial and temporal extent of alpine wetlands. Over the long-term, wetlands will likely shrink in size and lead to soil desiccation and wetland degradation (Jacobsen & Dangles, 2017; Polk et al., 2017). In addition, the lagged response time of glaciers to global climate change might exacerbate the climatic debt already experienced by high-alpine communities (Roe et al., 2021; Zekollari et al., 2020). Within two to three decades short-term effects of glacier melt include the displacement and shrinkage of wetlands and the shift of altitudinal treelines, modified woody plant abundance, and increased emergence of proglacial lands and water bodies at the expense of high elevation biodiversity (Carlson et al., 2017; Dangles et al., 2017; Huggel et al., 2015; Lizaga et al., 2019; Navas Izquierdo et al., 2019; Polk, 2016; Young et al., 2017). Biogeographical challenges exacerbate the rates and state of ecological changes: proglacial terrain is often fragmented and isolated—the classic patch dynamics, which creates fundamental constraints on most species adapted to these narrow, dynamic environments that make uphill migration and colonization even more arduous (Malanson et al., 2019; Rubel et al., 2017).

There is a growing amount of literature on glacial and proglacial biodiversity and ecosystem development (Ficetola, 2021); yet we still lack a comprehensive and integrative framework to predict the systematic biodiversity responses to glacier retreat across different mountain regions of the world and the implications for management (Anthelme et al., 2021; Cauvy-Fraunié & Dangles, 2019; Fischer et al., 2019; Lambert et al., 2020). Many cite the urgent need to characterize these emerging (novel proglacial landscapes) and disappearing (glacier and permafrost) habitat types, in order to plan monitoring and management of their biodiversity (Gobbi et al., 2021). In "Fairness to future generations", Edith Brown Weiss (1989) points out the moral issue of biodiversity loss between generations: "It is our duty, as human society, to ensure intergenerational equity, in the sense that each generation is entitled to inherit a robust planet". At a longer timescale, novel 21st-century climates may continue to modify environmental conditions and lead to unknown novel alpine environments, species assemblages, and ecosystems (Hock, Bliss, et al., 2019). The strong imbalance resulting from these continued unidirectional changes might have deeper impacts soon. One of them is the deep warming and degradation of permafrost that will induce long-term destabilization of icy slopes that will cascade into surrounding landscapes (Deline et al., 2021).

These biophysical changes interact with other factors. Anthropogenic factors, such as the local economy and external markets (e.g., local livelihood or tourism), can mediate or accelerate the rate of ecological changes. For instance, people respond to global warming by moving frost-tolerant crops further upslope (or to colder microclimates; Hussain et al., 2018 in Nepal; Skarbø & Vandermolen, 2014 in Ecuador; Sayre et al., 2017 in Peru), potentially facilitating biological invasions to higher elevation. Similarly, grazing (Speed et al., 2012), human-caused fires, and frequent disturbance by tourists (Barros et al., 2020; Kavan & Anděrová, 2020) may modify the natural advance of alpine plants to higher elevation. But land use can also mediate negative effects of warming in alpine environments (e.g., Klein et al., 2007).

2.2 | Environmental services

Climate change and glacier retreat also affect the environmental services for downstream regions and human populations (Milner et al., 2017; Palomo, 2017). The provision of water is one of the major environmental services that climate change affects in high mountain areas, with severe consequences for downstream populations (Barnett et al., 2005; Debarbieux & Price, 2012). While runoff from shrinking glaciers will often increase short-term, a reduction in runoff occurs on long-term scales, which affects water provision at the glacierized basin scale (Compagno et al., 2021; Mark et al., 2015; Mukherji et al., 2019; Xu et al., 2009). The infiltrating glacier meltwater produces groundwater flow and soil water, which cascades through downstream ecosystems (Milner et al., 2017), leading to geosystems and ecosystems disequilibria (Haeberli et al., 2019). The connections between glacier shrinkage, river discharge, and downslope alpine ecosystems, however, are complex and non-linear (Bury et al., 2013; Huss & Hock, 2018). There might be a time lag between the altered hydrological regime and the land cover transformation downstream. Researchers are only beginning to understand the repercussions of changing cycles of groundwater recharge from glacial melt (Baraer et al., 2015). These domino effects alter the biodiversity as well as the capacity of ecosystems to provide essential services such as water purification, aquifer recharge, carbon sequestration, and biodiversity (Milner et al., 2017; Palomo, 2017; Xu et al., 2009).

As for the natural ecosystems, shifts in species distributions in the new proglacial landscapes threaten agricultural biodiversity, and in turn, food and water security for people. Rural mountain communities are highly dependent on, and sensitive to, glacier runoff and meltwater fluctuation and quality, and therefore highly vulnerable to cryosphere loss (Qin et al., 2020; Rasul & Molden, 2019). First, the alteration of streamflow leads to reduced water availability for crop irrigation, decreasing farm production in mountain regions like the Andes (Bury et al., 2011), High Mountain Asia (Nüsser & Schmidt, 2017), and the Rocky Mountains, US (McNeeley, 2017). Second, glacier recession poses water quality challenges. For example, acid rock drainage mobilizes metals downstream, contaminating ecosystems, agriculture, and drinking water (Fortner et al., 2011; Guittard et al., 2020; Magnússon et al., 2020). Moreover, increased erosion and sediment load related to "glacier retreat," and newly exposed debris and deposits (Ballantyne, 2003) alter water quality, which in turn affects local stream biota and downstream human use. Similarly, highland subsistence farming and pastoralism are experiencing the impacts of cryosphere change with the appearance of new pests and diseases, dry spells, and unseasonal frosts (Bury et al., 2011, 2013; Postigo et al., 2008; Rasul & Molden, 2019). These local impacts on agriculture challenge crop productivity, cropping patterns, and land use, and together affect the local economy of mountain populations (Rasul & Molden, 2019). This process enhances uncertainty for local producers, destabilizes traditional adaptation strategies, and hence threatens household food security.

Mountain areas contribute a relatively small share in food production exports, but they provide a significant amount of subsistence-oriented and local/regional agricultural production from crops and livestock, and also can contribute important runoff to lowland irrigated agriculture (Biemans et al., 2019; Viviroli et al., 2020). Large irrigation and export-oriented agriculture projects are developing in lowland regions (e.g., along the coast of Peru projects like Chinecas and Chavimochic; Bury et al., 2013; Moulton et al., 2021; Vuille et al., 2018), which have created the largest hydrologic demand for agriculture over the past two decades (Bury et al., 2013). Therefore, changes in water provision influence both large scale agricultural production and smallholder agriculture and livelihood, which political and economic factors further exacerbate.

Globally, mountain communities are experiencing resource degradation, food scarcity, lack of basic services, social inequalities, conflicts, and lack of economic opportunities, and climate change accentuates these problems and impedes adaptation (French et al., 2015; Gentle & Narayan, 2012; Mukherji et al., 2019). Consequently, biocultural diversity is endangered, and alpine social-ecological systems must adapt to the altered ice-free mountain landscapes (Allison, 2015; Jurt, Burga, et al., 2015; Sayre et al., 2017). Land use changes, environmental governance, tenure rights, and economic goals also affect the rate and degree of climate change impacts (Klein et al., 2011; Young et al., 2017).

2.3 | Natural hazards and risks

Interactions between the cryosphere, emerging proglacial terrain, and the atmosphere, transform the natural environment and the societies living there (Carey et al., 2021). Climate interacts strongly with the cryosphere and the proglacial environment along multiple spatial and temporal scales (Haeberli & Whiteman, 2021). Climate change alters mountain process systems through both regular patterns and extreme events, modifying their geomorphic magnitude and frequency. Mountain glacier related hazards occur with increasing glacier instability and human activity (Wang et al., 2020).

Disasters, from avalanches to rockfalls, show increasing trends (Deline et al., 2021; Dussaillant et al., 2019; Haeberli et al., 2017; McColl & Draebing, 2019), where exposure is the most important driver and vulnerability the great unknown (IPCC, 2019). For example, the Andes and the Himalayas are facing difficulties with water supplies, moraine erosion, and glacial lake formation that can result in glacial lake outburst floods (GLOF; Wells et al., in press; Clague & O'Connor, 2021; Huggel et al., 2015, 2020; Zheng et al., 2021). While in the Alps decision-makers and civil society are concerned with increasing frequency and magnitude of mass wasting hazards like rock-ice avalanches and rockfalls (Coe et al., 2018). Emerging alpine proglacial landscapes are directly and indirectly connecting to glacial and icy peak dynamics, which are altering hydrologic and geomorphic regimes, water availability, and the frequency and severity of natural hazards. These physical adjustments of the cryosphere and proglacial systems cascade downstream on local and regional populations. For instance, glacier retreat is likely to expose new areas of unconsolidated glacial sediments and proglacial lands are very active in sediment transfer from upland to lowland (Morche et al., 2019). These physical processes alter water quality for downstream systems and use, affecting local populations, expensive infrastructure, and agriculture (Carrivick et al., 2018). Contaminated glacial sediments could contribute to natural contamination of water further downstream in catchments (Guittard et al., 2020; Magnússon et al., 2020).

In connection with glacier retreat, in recent years new lakes have emerged and enlarged from glacier melt (Haeberli et al., 2016; Otto, 2019). Recent studies have started to model glacier bed topographies over large ice-covered areas to anticipate proglacial landscape evolution and potential future lake formation, and national and regional inventories exist (Swiss Alps: Linsbauer et al., 2012; Himalaya-Karakoram region: Linsbauer et al., 2016; Peruvian Cordilleras: Colonia et al., 2017). Often these new lakes amplify natural hazards downstream (Colonia et al., 2017). They are related to impact/flood waves or GLOFs triggered by rock/ice avalanches from the peaks surrounding them (Haeberli et al., 2016), or in the deadliest scenario, moraine dam failures (Clague & O'Connor, 2021). However, new lakes also offer tourism opportunities, water supply, and hydropower production.

Activated sediment cascades, slope instability, and the expansion of existing and formation of new lakes, as well as resultant GLOFs will continue to occur (Deline et al., 2021; Haeberli et al., 2016). These physical phenomena have distinctive impacts upon society depending on the time and spatial scale of the event, the human perception of danger, and other cultural and emotional factors (see following section) (Carey et al., 2021; Chaudhary et al., 2011; Huggel et al., 2020; Jurt, Brugger, et al., 2015; Sherry et al., 2018; Zheng et al., 2021). Scientists differentiate shorter time scale and longer time scale phenomena to study glacial and periglacial hazards. And there is a connection between the scale of the event and human vulnerability to danger (Huggel et al., 2018; Richardson & Reynolds, 2000).

The concept of Loss and Damage—a mechanism of international climate change law and policy to evaluate and reduce the negative consequences of climate change—has expanded over the last decade (e.g., Warsaw International Mechanism for Loss and Damage; Huggel et al., 2018; Motschmann et al., 2020). Huggel et al. (2018) identify six types of loss and damages depending on space and time: loss and damage to culture, livelihoods, revenue, natural resources, life, and security. They distinguish physical and societal impacts, primary and secondary impacts, and short-term and long-term impacts. Biophysical impacts such as avalanches can occur during a very short-time scale (minutes). Impacts at the medium time scale include loss of seasonal meltwater (months) or ecosystem change and loss (years). Finally, biophysical impacts can show much slower onset (decades) as landscape change and loss (Huggel et al., 2018). These environmental alterations have social and economic effects, from sudden-onset like loss of lives and physical damages, to medium time-scale loss of natural resources, and to the slow onset of loss of income, livelihoods, security, social relationships, and ultimately loss of identity (cf. following section). The specific socio-cryospheric contexts and the different spatial and temporal scales within which they occur make resilience and adaptation difficult (Carey et al., 2021). Furthermore, important questions of responsibility and justice emerge from negative effects and risks related to the loss of the mountain cryosphere. Recent studies such as the case of lake Palcacocha in Peru have investigated the role of responsibility and justice in risk and hazards management (Huggel et al., 2020).

2.4 | Identity and cultural values

The effects of decline and loss of glaciers also profoundly disturb the beliefs and identities of local populations (Figure 1). Cultural values underpin many social and political processes and how humans perceive the environment. They also display strong local and regional specificities, which require spatially sensitive and context-dependent understanding. Cultural identities of people are inextricably interconnected with their surroundings (Allison, 2015). Cultural history and lifestyle are embedded in harsh mountain environments and extreme climatic conditions, shaping complex human–environmental relationships and responses (Jurt, Brugger, et al., 2015; Sherry et al., 2018). For example, attachment to place for diverse reasons—for example, spiritual relationship with a peak, glacier, or lake—can alter the local perceptions of risk and motivate people to inhabit endangered land (e.g., high GLOF risk zone from the lake Palcacocha in Peru—[Huggel et al., 2020] and/or lead to inaction [Huggel et al., 2020; Sherry et al., 2018]).

Over the Holocene, Earth's climate oscillations have left their marks on human socio-environmental systems. During the Little Ice Age, glacial advances were bewildering and disruptive events for the societies of the time (Grove, 2012; Lamb, 1977; Le Roy, 1971; Matthews & Briffa, 2005—e.g., Chamonix Valley in the French Alps; Haeberli, 2008; Mann, 2002). In the Andean, Himalayan, and African mountains, glaciers are often understood to represent important deities or even the embodiment of a deity. In Tanzania, people consider Mt. Kilimanjaro as the "house of god" (Molg et al., 2008). On the Tibetan Plateau snow-mountains are seen as the lords of the territory and masters of the weather (Diemberger et al., 2015). Mt. Everest, known as the Goddess Mother of the World, is part of the Buddhist religion and underlies deep local beliefs. Likewise, on the Indo-Nepalese border, recreational mountain climbing on the Kanchenjunga Mountain is forbidden due to the need to respect its sacredness. In the Andes, sacred mountains are referred to as *Jirca* or *Apus*, meaning "sacred mountain deities" in Quechua. In Ecuador, the mountain Cotacachi is thought to express anger and disappointment over inappropriate behavior and social conflict (Allison, 2015). Often, local communities and indigenous people make offerings to the mountains, asking the fertility goddess or Mother Earth, known as *Pachamama*, for rain, crop production, or protection. For generations, recurrent visits to these places have supported local cultural identities. An ancestral Andean custom consists of extracting glacier ice blocks to make *Raspadillas* or *Shikashika* (Borsdorf & Stadel, 2015). These Andean "snow cones" are harvested by the *Hieleros* ("Ice-makers") and sold in local towns as sweet treats with medicinal attributes. Now, this Pre-Columbian practice is on the verge of extinction (Dunbar et al., 2012). Today local practices are forced to adjust to both the reality of the receding glaciers and external market pressures from global processes (Allison, 2015; Jurt, Burga, et al., 2015; Sherry et al., 2018).

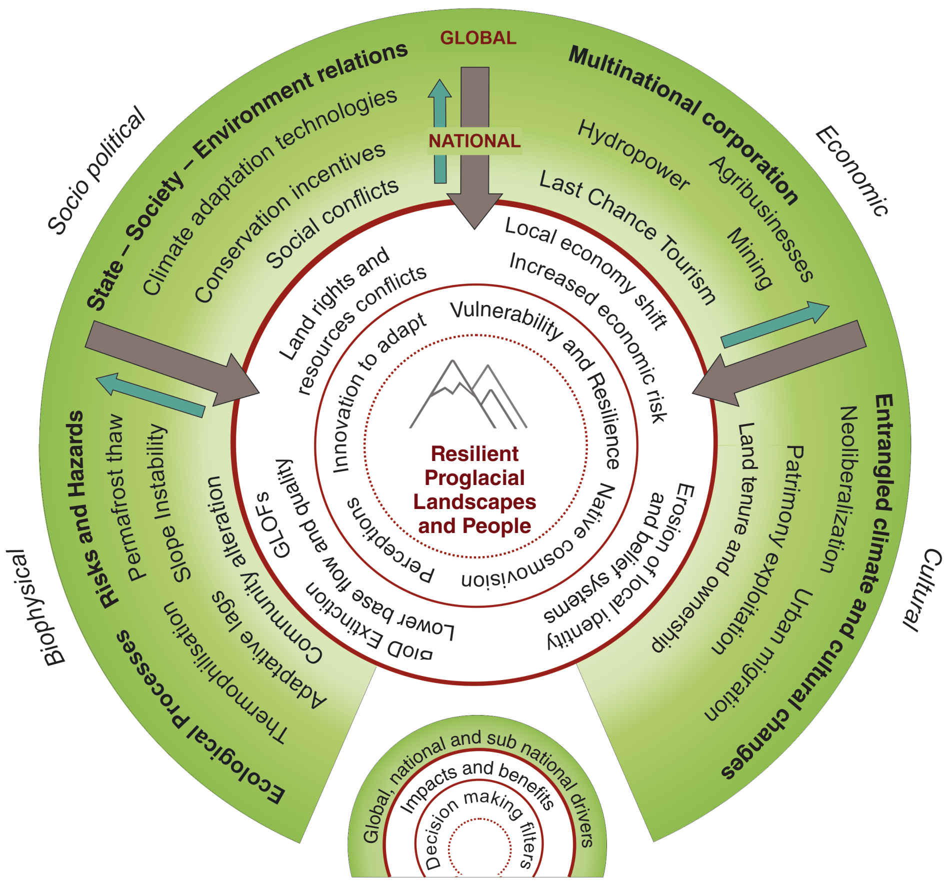

FIGURE 1 This illustrates the global and national drivers of change affecting proglacial landscapes: their cultural, biophysical, economic, and political dimensions, and variables affected at subnational levels. The outer circle variables represent external drivers affecting local proglacial landscapes and people. Inner circles represent potential place-based, context specific adaptation responses. From the inner to the outer circles, there are (i) local and indigenous values, (ii) local decision-making filters, and (iii) key impacts and benefits of glacier retreat that affect the future of proglacial landscapes, the people who will inhabit them, and their socio-environmental resilience

Studies report the effect of climate change-induced hazards and altered environmental services on out-migration, which is also affecting the local livelihood and traditions, and the local economy (Peruvian Andes: Alata et al., 2018; Nepal: Hussain et al., 2018; globally: Romeo et al., 2015; Tucker et al., 2021). These high-mountain communities respond to these changes adapting climate change to their social worlds (Rasmussen, 2016b). Understanding such local and regional socio-cultural and psychological dimensions of glacier changes is key to further local adaptive strategies, increase the resilience of people, and favor the sustainable adaptation of the emerging landscapes.

2.5 | Loci of multiscale, multiactor interactions, and inequity

At deglaciated landscapes there are growing concerns surrounding water allocation, ecological restoration and conservation, risk and disaster management, economic/livelihood activities, and cultural identity and values (previous sections and Figure 1). These burdens have led to an increasing number of conflicts between sectors and actors: industrial and local demands for water, governmental institutions and private corporations, economic land use, and conservation initiatives (Bury et al., 2013; Carey et al., 2021; Drenkhan et al., 2019; French et al., 2015; Haeberli et al., 2016; Vuille et al., 2018). These multiple entities have different priorities regarding use, control, regulation, and access to resources. Also, these divergent actors will have different perspectives, priorities, timescales of operation, degrees of visibility and power, and thus they will rarely find common ground to discuss shared objectives. For example, (i) mountain communities may need to deploy short-term responses as they live the local, material context of climate change, (ii) support organizations may respond with an evolving portfolio of conceptual projects reflecting global interests; and

(iii) governments will tend to focus on large scale impacts on resources like water or energy affecting the broader economy. Globally, external fluxes are embedded with local contexts and influence the local economy and social environment. The new lands that emerge following glacier retreat offer opportunities for several types of economic activities such as extractive and hydropower development (Bury, 2015; Farinotti et al., 2019; Huss et al., 2017; Vuille et al., 2018). Meanwhile local and ancestral livelihoods such as agropastoralism or tourism are facing many challenges from cryosphere loss, climatic extremes, external actors, and social tensions (Postigo et al., 2008; Sherry et al., 2018). Therefore, questions of equity, climate justice, power relations, and marginalization are also emerging and need great attention in view of future human adaptation to glacier retreat (Moulton et al., 2021; Skarbø & Vandermolen, 2014). Most resilience studies have until recently emphasized the ecological dimensions and scientific approaches to the biophysical systems, with a lack of attention to social contingency, including power relations, resource conflicts, and cultural factors (Carey et al., 2021). External forces—such as energy production, resource extraction (Bury, 2015), market and political pressures (Montaña et al., 2016; Sietz & Feola, 2016), and shifts in water governance (Rasmussen, 2016a)—prevent local adaptation actions and exacerbate the direct effect of glacier shrinkage. Power imbalances are also a limiting factor to local adaptation, favoring the unequal distribution of natural resources between actors and altering risk and vulnerability assessment (Moulton et al., 2021).

Land tenure arrangements of proglacial territories are often not explicit or legally recognized, which further complicates decision making and management. These local sociopolitical contexts and land tenure rights interact and often exacerbate conflicts between entities. In mountain regions it is usual to observe property borders described according to neighbors, cardinal points, mountain peaks, or rock or glacier limit. In the European Alps, the Swiss Civil Code classifies glaciers as objects that have no owner and are public common use property (Bütler, 2007). In the Andes, local activities such as livestock grazing are often in conflict with conservation incentives or tourism development initiatives. For example, national park creation comes after long-established grazing rights and access, and conflicts between local or indigenous communities and national entities make local adaptation challenging (e.g., National Park of Huascarán; Rasmussen, 2018). Thus, collective, equitable, and respectful land tenure allocation is crucial to limit conflict and ensure an equitable future. The fact that diverse actors are already utilizing these lands points to the need for future research on socio-cultural impacts of glacier retreat and a need to create an inclusive, informed dialogue regarding an adaptive framework for governance of proglacial landscapes. Some recent research has emphasized the importance of understanding adaptation around socio-cryospheric, socio-hydrologic (in Himalaya—Nüsser et al., 2019; in the Andes—Carey et al., 2014; Huggel et al., 2020) or socio-environmental systems (Lavorel et al., 2020). Such work shows the importance of integrating social science with biophysical science, developing inclusive and diverse collaborations and a transdisciplinary approach.

3 | OPPORTUNITIES FROM DEGLACIATION AND EMERGING LANDSCAPES

Our approach in this essay implies expanding the purview of conservation theory and practice beyond what is and what was to what might become a just, sustainable, and meaningful future. In this section we present the diverse opportunities and adaptation strategies that are emerging in the vicinity of the new proglacial landscapes. We introduce opportunities for novel alpine geo-ecosystems in terms of environmental services, socio-cultural aspects, and economic strategies for adaptation to climate change.

3.1 | Novel alpine geo-ecosystems and adaptation framework

The novel proglacial landscape emerging after the retreat and disappearance of glaciers display geo and ecosystems of rocks, debris, colonizing vegetation, soil formation, new lakes, and thawing permafrost (Haeberli et al., 2021). In a context of new biophysical and social dynamics, these novel alpine geo-ecosystems may have the capacity to (a) fulfill human objectives and provide valuable environmental services, and (b) be robust in terms of geo-ecosystem status and dynamics, and adapt to environmental changes (Lavorel et al., 2020). Resilient novel proglacial geo-ecosystems might supersede the function of glaciers, providing basin header services and acting as the new "water towers" (Immerzeel et al., 2020; Viviroli et al., 2020). They would support provisioning environmental services such as aquifer recharge or drinking water supply, and regulating services, most notably related to water quality, hazard generation/mitigation, and climate feedback via multiple cycles. For example, the formation of new proglacial lakes can locally interrupt and stabilize sediment cascades in deglaciating areas (Haeberli et al., 2021; Otto, 2019). The new lakes also offer opportunities for use in connection with tourism, water supply, and hydropower production (Haeberli et al., 2016; Kellner, 2021), which we discuss in the following sections.

Proglacial lands might offer an opportunity for crop adaptations. Globally, farmers are moving their frost-tolerant crops upslope to adapt to climate changes (e.g., potatoes and apples in Nepal—Huntington et al., 2017; Hussain et al., 2018, maize in Ecuador—Skarbø & Vandermolen, 2014, and potatoes in Peru—Sayre et al., 2017). Pastoralism can also adapt to the new environmental and social contexts (Diemberger et al., 2015; Postigo et al., 2008). Similarly, studies show that these emerging proglacial lands provide new habitat for endemic plant species (D'Amico et al., 2017; You et al., 2018). There is increasing agreement about the role of novel geo-ecosystems as potential refuge areas for high alpine biodiversity. Many studies of Quaternary Climate oscillations have demonstrated the role of microrefugia in maintaining mountain biodiversity during cold glacial or warm interglacial periods (Scherrer & Körner, 2011; Schönswetter et al., 2005; You et al., 2018). Similarly, in the Anthropocene, microclimatic changes will produce cold-air pooling and temperature inversions (Gentili et al., 2015) and possible colder microrefugia within the larger warming landscape. Therefore, some present-day environmental conditions might be maintained, at least in the near-term, as other habitats change (Brighenti et al., 2021), allowing for some cold adapted species threatened by summit traps ("nowhere to go" hypothesis; Loarie et al., 2009) to survive (Gobbi et al., 2021). The poor knowledge we have of this almost vanished cold habitat and climate dynamism, however, makes more research a necessity. There is an immense opportunity to develop monitoring programs for better adaptation planning in the new proglacial landscapes (Gobbi et al., 2021).

The concept of novel proglacial systems also brings the opportunity to progress toward a novel conservation and restoration framework more suitable to the Anthropocene era (Brighenti et al., 2019; Williams et al., 2021; Young & Duchicela, 2020). Historically, conservation initiatives aimed to reduce or prevent both abiotic and biotic changes to maintain certain historical or even mythical values (Corlett, 2016; McDonald et al., 2016). Restoration aims have usually been to mitigate biophysical changes to recreate ecological functions to provide resources guided by evidence for historical states (Hobbs et al., 2009). But changes in the Earth's climate are accelerating and these environmental transformations especially lead to situations that may be "non-analog" or unseen in the historical record. Environmental conditions will not only be different from the past but also from present-day conditions. These transformations are too fast, complex, and erratic to promote adaptation, resulting in a system in constant evolution. Ecological restoration and management goals need to adapt to the current climatic conditions and anticipate future conditions guided by the full range of past states provided by paleoecology (Tierney et al., 2020). Participatory scenario-based planning is necessary in combination with systematic and dynamic local monitoring and scientific learning (Thorn et al., 2021).

3.2 | Economic opportunities of glacier retreat

3.2.1 | Extractive industry and hydropower

Globally, the extraction and hydropower industries are expanding to the ice margin. Certain extraction technologies, such as chemical leaching of minerals, create frontiers for mining development (Bebbington & Bury, 2013). The "super cycle" of growth in energy and mineral exploration, production, and consumption is a significant pressure for proglacial terrains and the contemporary cryosphere. Many new deposits of oil, gas, and minerals have recently been discovered along the edges of glaciers (e.g., the Pascua Lama mine in Chile, La Rinconada in Peru, or Kumtor mine in Kyrgyzstan; Bury, 2015). Extractive industries are known to be a major source of contamination, with economic benefits realized by just a few, mostly multinational corporations (Patrick & Bharadwaj, 2016).

Similarly, high elevation hydropower production relies on water resources that are also influenced by deglaciation. In Switzerland, hydropower engineering is taking advantage of the shrinking ice and many reservoirs are already located in proglacial environments. The forthcoming biophysical and socio-economic changes might challenge the existing infrastructure but will also provide a new perspective for new hydropower plants (Ehrbar et al., 2018). Studies have been focused on the impact of glacier mass loss on existing hydropower production (in Switzerland—Schaefli et al., 2019; and Peru—Vergara et al., 2007). At a global scale, Farinotti et al. (2019) showed that future glacier-free basins will contain immense hydropower potential, but high economic and environmental costs exist. And this exacerbates the challenge of outsiders controlling mountain resources. Reservoirs in proglacial areas also have water storage potential and could mitigate future seasonal scarcity (Farinotti et al., 2016; Jaeger et al., 2017). But reservoirs have their own downstream problems (Baird et al., 2021), and many sites are unsuitable because of difficult logistics, small catchments, slope stability problems from glacially de-buttressed slopes, or rapid sedimentation from activated erosion rates. In addition, new lakes are places of hazards and risk and can be sources of conflicts (Haeberli et al., 2016; NELAK Project: NELAK, 2013). Multipurpose projects combining flood retention, hydropower production, freshwater supply, and tourism may represent an adaptation strategy (Kellner & Brunner, 2021), but could also present new challenges. In Switzerland, the first dam project as a multipurpose reservoir in a recently deglaciated area has been socially and politically accepted with realistic funding opportunities. The success of the acceptance process was mainly due to the political process of the Swiss Energy Strategy and experiences with previous dam projects in the region (Kellner, 2019). This case highlights the crucial role of participatory planning (Haeberli et al., 2016) and polycentric governance (Kellner, 2019). A similar case has emerged in Peru, as a participatory pilot initiative (CARE, 2018). Given the complexity of proglacial socio-environmental systems and rapid post-glacial changes, it is crucial to have baseline data as well as ensure the local ownership and social acceptance of the initiative through participatory processes.

3.2.2 | Tourism

Glacier recession leads to a sequence of economic and ecological effects related to glacier tourism (Salim et al., 2021; Wang & Zhou, 2019; Welling et al., 2015). Glacier recreation is important to the economy of local communities near glacier tourist sites, where tourism such as alpine mountaineering attracts visitors from around the world (Espiner & Becken, 2014; Vuille et al., 2018). But changing conditions have made access more complicated (*Mer de Glace* in the French Alps—Mourey & Ravanel, 2017; the *Tasman*, *Fox*, and *Franz Joseph* glaciers in New Zealand—Espiner & Becken, 2014). Globally, the popularity of the glaciers over the last 30 years has been dependent on the availability of easy foot access to the ice, the frequency and intensity of cryosphere hazards and risk, and the ability of commercially guided walking groups to walk on the glaciers (Salim et al., 2019). Glacier recession gives rise to a new kind of tourism and conservation landscape (Lemieux et al., 2018; Rasmussen, 2018; Wang et al., 2010). As controversial as it sounds, glacier retreat offers a niche for a particular kind of nature-based tourism: last chance tourism (LCT; Salim et al., 2021). Lemelin et al. (2010) describe LCT as a "niche tourism market where tourists explicitly seek vanishing landscapes ..., and/or disappearing natural and/or social heritage". For example, places such as the Glacier Pastoruri in Peru or Chacaltaya in Bolivia have evolved from being sites of major touristic destinations and ski competition to being abandoned ruins of glacier recession, and icons of climate change. In Peru, the national entity of the Huascarán National Park established the *Ruta del Cambio Climático*, an educational tool and conservation initiative to share science-based information and promote awareness about climate change (Kaenzig et al., 2016; Rasmussen, 2018). In the Yulong Snow Mountain in China, recent touristic infrastructures include the glacier museum and telescope (Wang et al., 2010). Similar trends are emerging in the European Alps. The most frequently visited French glacier is Montenvers-Mer-de-Glace, which is becoming a LCT destination (Salim & Ravanel, 2020). The extension of tourism activities into fragile environments can have natural and cultural impacts. Both glacial and post-glacial tourism can have detrimental effects on high alpine biodiversity and ancient cultural customs, as well as consequences for the perceptions and evaluations of glaciers among local stakeholders and communities (cultural value and resilience: Espiner & Becken, 2014; Jurt, Brugger, et al., 2015; tourism adaptation: Kaenzig et al., 2016; Vuille et al., 2018).

3.2.3 | Historical legacy

While glacier retreat threatens religious practices, beliefs, and local identities, the melting glacier's ice is providing us with some important clues to the long-term trajectory of the relationship between people and climate. In recent decades archeological and paleontological remains have melted out of glaciers and ice patches in several mountain regions including the Ötztal Alps ("Otzi" a 5300 Year Old Iceman; Bohleber et al., 2020), the Andes (Inca Mummies in Argentina; Ceruti, 2015; and Incan maiden found in Ampato glacier in Peru; Johan, 2016), the Tibetan Plateau (Middle Pleistocene Denisovan mandible; Chen et al., 2019), the Altai Mountains (Arrow shaft from 3000 BP), Ethiopia (Obsidian lithic artifact from the Middle Stone Age; Ossendorf et al., 2019), the Rocky Mountains (Bison remains from ∼2280 BP (Lee, 2012; Lee et al., 2006), and Canada (Human remains from 550 years BP; Beattie et al., 2000). These discoveries hold unique information for archaeology, faunal history, and glacial ecology (Rosvold, 2018). They may also give unique insights into human physiological and genetic adaptation to high latitude and past climate change, as well as prehistoric material culture (Dixon et al., 2014; Ossendorf et al., 2019). The emerging land from the retreat of the ice is witness to human cultural heritage and needs protection and regulation.

The adaptive capacity of human populations depends on their own perceptions of risks and opportunities and their capacity to act and adapt (Figure 1). In high mountain inhabited landscapes, local populations live with the cryosphere and its dynamics and rely on both their local adaptive capacity, management and innovations, in addition to regional and national policies (Turner et al., 2003). Commonly, local knowledge and local perceptions play a critical role in adaptation and risk management (Beach et al., 2019; Carey et al., 2012; Dahal & Hagelman III, 2011; Gagné et al., 2014; Orlove et al., 2019). In general, populations are more likely to prepare well for slow-onset changes that they recognize and which are predictable and manageable, rather than for sharp and unexpected shocks (Alley et al., 2003; Dillehay & Kolata, 2004; Penny & Beach, 2021). In a context of poverty, however, local people and jurisdictions may be motivated to intervene and monitor only to assess short-term changes and solutions. First, understanding site-specific processes of change of proglacial landscapes is crucial to engage in productive dialogue with mountain populations responding to climate change. Second, support organizations and agencies may have the financial capacity and motivations to monitor for long-term and more complex dimensions of change. Third, local and indigenous knowledge and value systems, representing centuries to millennia of observation, are critical sources for adaptation and sustainability (Whyte et al., 2018). Fourth, future-oriented participatory planning must be scenario-based, which involves modeling new landscapes and environments, and promoting transdisciplinary and horizontal research and exchange (Haeberli, 2017).

This illustrates the global and national drivers of change affecting proglacial landscapes: their cultural, biophysical, economic, and political dimensions, and variables affected at subnational levels. The outer circle variables represent external drivers affecting local proglacial landscapes and people. Inner circles represent potential place-based, context specific adaptation responses. From the inner to the outer circles, there are (i) local and indigenous values, (ii) local decision-making filters, and (iii) key impacts and benefits of glacier retreat that affect the future of proglacial landscapes, the people who will inhabit them, and their socio-environmental resilience.

4 | TOWARD STEWARDSHIP OF PROGLACIAL LANDSCAPES

4.1 | Existing governance arrangements, tools, and strategies

In 1992 The Earth Summit at Rio de Janeiro recognized the importance of mountains in sustainable development in Agenda 21 (UNCED, 1992), which continued in subsequent summits (UNCSD, 2012; WSSD, 2002). Thus, mountains became a mainstay of international protection, achieving such recognition as the International Year of Mountains, celebrated in 2002. Most initiatives with regard to the cryosphere and emerging ice-free land occur at the national scale; yet, only a few of the 44 countries with glaciers have started to regulate activities on glaciers and glacierized surroundings, and the scarce initiatives are generally weakly enforced. Over the last decade, nations have developed Glacier Protection Laws (GPLs) to specifically protect mountain glaciers within Argentina, Kyrgyzstan, and Chile. The Argentine National Glacier Act (2010) was the first legislation in the world to recognize glaciers as a public good, establish the National Glacier Inventory, and prohibit development, specifically harmful activities (e.g., extractive industries), from occurring in glacial or proglacial regions. In 2014, the Kyrgyz Parliament passed the Glacier Law, though their president vetoed it (Cox, 2016). In Chile, the third version of such a law has been under discussion in parliament since 2016 (Anacona et al., 2018). These cases demonstrate the desire, but difficulty, of passing national environmental policy after industries or intensive economic activities have been established.

Regional or international mountain proglacial legal instruments are rare. In the Himalayan region no proglacial protection initiatives have been registered, but transboundary cooperation does occur (e.g., ICIMOD; Molden et al., 2017). In the Alps and Andes, the Alpine Convention and the Andean Community are the two major international conventions, but they have economic and development purposes rather than the establishment of adaptation strategies, local community involvement or protection goals, or conservation incentives (Church, 2012). Various other regional groups are discussing the need for glacier protection laws, such as in Alberta, Canada (Cox, 2016) and the French Mont Blanc massif in the Alps. Recently the French government has established the Mont Blanc Natural Habitat Protected Area. Although the Prefectural Decree is part of a range of new biodiversity and environmental policies, it includes little mentions of the emergence of proglacial habitats and the changing cryosphere. The Mont Blanc Natural Habitat Protected Area disregards the surrounding proglacial habitats, is restricted to the French tourist area, and does not refer to transboundary governance opportunities (Prefectural Decree DDT-2020-1132). While a protection framework dedicated to the receding cryosphere that protects the rights of local communities and indigenous people is necessary, the existing initiatives are not suitable for this purpose. The key for developing climate change adaptation measures in current glacier-covered alpine landscapes is to develop a framework that considers the remaining cryosphere, the emerging proglacial terrains, and the surrounding activities integratively.

Climate change adaptation is a deeply nested process and requires a comprehensive approach. A useful starting point is improved communication between academic scholars, conservation professionals, decision makers, and local and indigenous communities. Glacial territories are transitioning from uninhabitable ecosystems to postglacial inhabitable, intervened, and managed ecosystems. What would glacial and postglacial governance look like? Below we make some suggestions for first steps, although we recognize this needs to be a highly collaborative, co-developed process.

As a starting point, local actors play a critical role in currently managing their systems and therefore must be at the front line of governance processes (Ostrom, 2010; Tucker et al., 2021). People in the highest elevations are the ones losing their lands since agroecological systems, economic activities, and conservation incentives are migrating upward. Therefore, equity issues need to be considered in governance arrangements. An equity-centered framework coupled with monitoring systems would allow for vulnerability assessments focusing on casualties and enhance resilience to the vanishing cryosphere.

Second, we must include local perspectives to initiate dialogue between differing knowledge systems about risks and hazards (Huggel et al., 2020), conservation, and economic development, inter alia, rather than a hierarchical knowledge exchange (IPCC, 2019; Thompson et al., 2021). We believe the key characteristic is to build dialogue mechanisms that integrate global and local bottom-up and top-down approaches that provide shared goals and ways to meet and assess these goals.

Third, the increasing rate of change within the new proglacial landscapes, as compared with the time involved with decision making and implementation, make adaptation a moving target and urgent task: a task that requires transdisciplinary and participative planning with respect to applying future-oriented systems knowledge, harmonizing possibly diverging targets, and looking for optimal in-time transformation in practice of corresponding findings (Haeberli, 2017; IPBES, 2019; Klein et al., 2019; Knapp et al., 2019; Wise et al., 2014).

Fourth, cross-level governance and cooperation, which includes a flexible supra-national strategy can enhance national commitments and contribute to the sustainability of local initiatives. It should integrate (a) local and medium scale co-operative efforts among local actors, local–regional-or-national governments, and/or private sector actions with (b) collaborative multilevel efforts—participative planning—involving multiple actors from local to global (state, private and civil society, and intergovernmental organizations), as a multinational effort (e.g., Antarctic Treaty, Alpine Convention, Montreal Protocol).

Finally, a key point is to essentially focus on the diminishing cryosphere and emerging lands, as novel socio-environmental systems. Focusing exclusively on proglacial landscapes, their specific issues, and their connections within the changing mountain environment, is the "sweet spot" to mobilize attention to sustainable and inclusive development in broader mountain regions; this must be, however, nested within broader mountain agendas and integrated with other initiatives across scales.

4.2 | An opportunity for HiCALL—High Mountain Call to Action for Landscapes and Livelihoods

In view of promoting adaptation to glacier retreat and transformations toward sustainable and just futures, we propose an integrated strategy based on voluntary partnership agreements between local communities and indigenous peoples, state organizations, international actors, and the private sector (Figure 2). The main actors of the strategy are Alliances of Indigenous Peoples and Local Communities, Business Groups and Civil Society, Government Agencies, and Mountain Conservation Organizations, to ensure the broadest possible ownership of the process (Figure 2).

The instrument, based on a cooperative governance model, could be facilitated by the intergovernmental organizations organized under a council representing all actors involved. The main objective would be to promote the adaptation and sustainable management of all types of proglacial alpine landscapes, and to strengthen long-term political and financial commitments to this end, although the specific goals and vision would be co-produced. The strategy will help coordinate local, regional, and global governance entities to provide an overarching framework for research, action, and allocation of necessary resources, as fit to local contexts (Klein et al., 2019; Ostrom, 2010; Tucker et al., 2021).

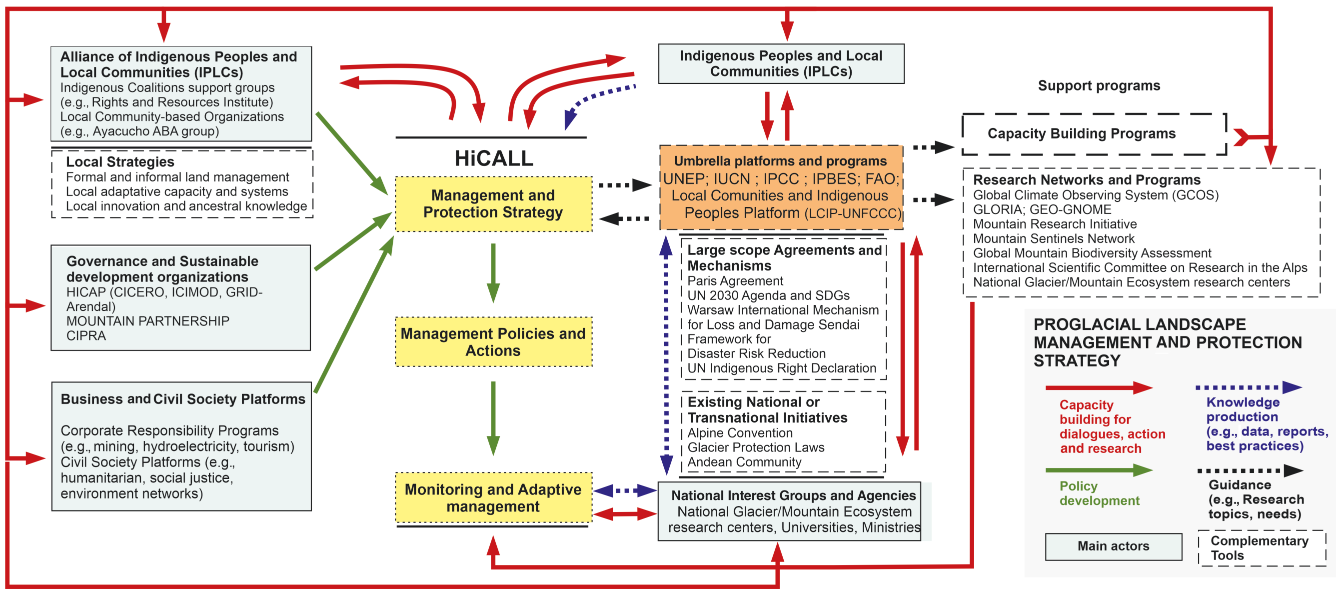

FIGURE 2 Some opportunities for the HiCALL include: Indigenous Peoples and Local Communities (IPLCs), Himalayan Climate Change Adaptation Programme (HICAP), Center for International Climate Research (CICERO), International Commission for the Protection of the Alps (CIPRA), Global Climate Observing System (GCOS), Global Observation Research Initiative in Alpine Environments (GLORIA), Group on Earth Observations Initiative—Global Network for Observations and Information in Mountain Environments (GEO-GNOME), United Nations environment Programme (UNEP), Local Communities and Indigenous Peoples Platform (LCIP-UNFCCC), International Union for Conservation of Nature (IUCN), Intergovernmental Panel on Climate Change (IPCC), and Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES)

We propose a non-binding structure to facilitate multi sector participation. Binding governance has been shown to foster weaker state engagement and less willingness for states to join because of national and international special interests (Maguire, 2013). Under the auspices of a Proglacial Landscapes Council, however, States and sovereign territories might negotiate binding agreements, creating their own collaborations. The Council would provide a way for the States to meet and address issues in detail as they arise. It could act as an innovation and monitoring hub for compliance, communication, collaboration, and financing.

The multistakeholder Council would have the task to develop a coordinated *Global Strategy*, as an international tool (e.g., Declaration or Protocol) to promote climate justice, equitable solutions, management and sustainable adaptation of the emerging proglacial landscapes. As a starting point, we call this the *HiCALL*. Potential international organizations that might work closely with the Council to secure access to specialized climate science, policy incidence, and representation of local communities and indigenous people groups and local actors include the United Nations, through the United Nations Environment Programme (UNEP) and the Local Communities and Indigenous Peoples Platform (LCIP-UNFCCC), the Intergovernmental Panel on Climate Change (IPCC), the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), the International Union for Conservation of Nature (IUCN), and the FAO Secretariat of the Mountain Alliance. The international organizations, called here umbrella platforms, might help HiCALL to align with larger scope agendas, agreements, and frameworks such as the Paris Agreement, UN 2030 agenda and SGGs, Warsaw International Mechanism for Loss and Damage (WIM), Sendai Framework for Disaster Risk Reduction (UNDRR), and the UN Declaration on the Rights of Indigenous Peoples (UNDRIP). The umbrella platforms and programs might contribute to six major areas of the strategy: guidelines formulation, international science assessment, indigenous and local knowledge and rights, decision making, financial support, and education and advocacy. HiCALL will reinforce existing legislative mechanisms already dealing regionally with mountain conservation, development, and regulation (e.g., Alpine Convention, Andean Community, GLPs, and National Decrees) and provide assurances that ethical and collaborative processes take place.

The strategy is based on horizontal and open dialogue mechanisms that integrate local and global approaches to provide shared goals and ways to meet and assess these goals. The HiCALL strategy, at the center of Figure 2, is applicable to global, regional, national, and subnational processes. The HiCALL is the connection between all actors and allows for the transmission of capacity building between actors, development of policies and actions, and monitoring

TABLE 1 Potential goals and objectives of HiCALL

Goal 1: *Global recognition of proglacial biophysical systems with their hazard potential, and acknowledging their potential to contribute to the future provision of mountain environmental services and climate change adaptation strategies*
a. National inventories including register of glaciers lost and impacts and classification of proglacial systems.
b. Basic science to inventory soil risks and formation (e.g., Carrivick & Tweed, 2021; Wojcik et al., 2021).
c. Social–environmental modeling studies of new landscapes and environments to develop scenario-based planning of management options (Aguiar et al., 2020; Colloff et al., 2021; Haeberli, 2017; Wise et al., 2014).
d. Pathways and participatory scenario development exploring desired futures and pathways to them (Aguiar et al., 2020).
e. Incorporation of proglacial landscapes in national resources management and conservation tools (e.g., land cover maps, national adaptation or mitigation plans, national energy strategies, national strategy for agricultural development).
f. Integration of proglacial landscapes in global assessment and environmental policy mechanisms.
Goal 2: *Conservation of biodiversity and affirmation of biocultural values, recognition of multiple ways of knowing, and recognition and systematization of local and Indigenous knowledge and rights*
a. Set target of high alpine adaptive biodiversity conservation to maintain viable populations of native and/or endemic species.
b. National identification and systematization of local innovations and ancestral knowledge in order to conserve and further the development of cultural heritage, local traditions, and Indigenous innovations.
c. Ensure that indigenous and local knowledge holders and their organizations are equal participants in the HiCALL process, such as in Goal 3.
d. Adopt as a guiding principle the UN Declaration of the Rights of Indigenous Peoples; identify and support local, site-specific local communities and indigenous people's rights and initiatives and ensure they have a voice and power in HiCALL.
Goal 3: *Establishment of a Transdisciplinary and Transboundary High Alpine Research and Action Agenda*
a. Development of a global transdisciplinary research and action network or working group within an existing network.
b. Identification of remaining knowledge gaps and ongoing and future challenges, including risk and hazards evaluation, socio economic potential through tourism development, hydroelectricity, resource extraction or agriculture development, and protection of high alpine ecosystems and biodiversity (Gobbi et al., 2021; Williams et al., 2021).
c. Deliver co-developed solutions and recommendations for policy makers that fit local contexts and future changes.
Goal 4: *Formulation of guidelines for states to assist the sustainable management of proglacial socio-environmental systems and encourage local adaptation initiatives. Examples are*:
a. Local adaptation and transformation initiative empowerment
b. Loss and damage evaluation.
c. Formation or expansion of protected areas, while respecting local and Indigenous land tenure and rights.
d. Sustainable development of Proglacial Landscapes. Ensure preservation and support for local livelihoods, especially for groups whose lands are lost to climate change and upward migration of downslope activities and ecosystems.

and adaptive management. HiCALL would receive and share science knowledge (local and international) with National Interest Groups and Agencies and participate in global decision-making processes at a global scale, interacting with the umbrella platforms and programs.

A highly decentralized action-learning mechanism will be most effective. Local institutions, organizations and actors will play a key role within the overall strategy and be represented at the Council level. The recurrent back and forth between global, national, regional, and local actors would transmit local scale needs and innovations to the higher state of governance, making sure local opportunities and challenges are taken into consideration and integrated into governance processes. Concurrently, the global process will insure the sustainability in time of these local and regional initiatives, as well as their propagation/replication regionally, as appropriate.

Research networks and programs, existing national or transnational initiatives, and large scope agreement will reinforce and support HiCALL. The HiCALL umbrella platforms and programs will have reciprocal capacity building and education with local communities and national interest groups. The HiCALL Umbrella will steer research networks to produce usable knowledge relevant to the strategy and will support actions to process science knowledge in forms that are accessible to decision makers at local, national, and regional levels (e.g., information provided by the Global Climate Observing System). The Research Network and Programs will have to answer socially informed questions to steer capacity building and policy development. The Umbrella platforms and National Interest Groups and Agencies will exchange knowledge to produce reports, share results, and participate in decision making. Similarly, HiCALL will support national and local efforts to capture monitoring and assessment of strategy goals at local and national levels, aggregating lessons learned. The Capacity Building Programs will share and present necessary knowledge to favor an informed decision making. The programs will originate a feedback flow of information directed to all actors to constantly promote and actualize capacity building.

Through its back-and-forth interactions with all actors, HiCALL will provide policy-relevant information related to questions about processes, change detection, model validation, and environmental impacts in a trans-disciplinary knowledge exchange to the scientific community as well as to policy makers, the media, and the public.

Figure 2 presents a potential structural framework for the Council, and the *HiCALL*, as a starting point for dialogue.

As a starting point for the dialogue, we identify four potential goals of the HiCALL: (a) the recognition of proglacial biophysical systems with their hazard potential, and, acknowledging their potential to contribute to the future provision of mountain environmental services and climate change adaptation strategies; (b) the conservation of biocultural diversity and values, recognition of multiple ways of knowing, and legitimizing local and indigenous rights; (c) the establishment of a Transdisciplinary and Transboundary High Alpine Research and Action Agenda for Proglacial Landscapes, including but not limited to: integrating ecosystem services science and local and indigenous knowledge; modeling and managing new landscapes, risk and hazard assessment, economic potential for hydroelectricity, resources extraction, tourism and agriculture, and ecosystem and biodiversity protection; participatory scenario development to understand desired futures and multiple pathways toward them; and (d) the formulation of global guidelines and strategies for States to adapt to local contexts to assist the sustainable management of proglacial socio-environmental systems and support local adaptation and transformation initiatives. Table 1 lists the potential goals and objectives of the strategy as a starting point for further dialogue.

5 | CONCLUSION

The beneficial roles of glaciers for social, ecological, and hydrological systems are diminishing worldwide. While new lands emerge from deglaciation, new socio-environmental interactions also arise and pose major challenges, but also opportunities for the new proglacial landscape societies. A transdisciplinary and participative approach is required to address these cross-scale, cross-level, and multiactor complexities that are unfolding.

Climate change inspires us to rethink what a sustainable and just future on Earth looks like and how to achieve it. This challenges humans to think through the effectiveness and sustainability of adaptive strategies in a context of constant adjustment of the environmental conditions. Today's adaptation strategies need to consider current challenges and anticipate future ones; multilevel transformation, integrative modeling and monitoring of new landscapes and environments are necessary. This reframing requires transformative, transdisciplinary action, wherein scientists, stakeholders, local and indigenous populations, and policy makers collaborate to address these challenges using comprehensive and integrative approaches that consider international science and local and indigenous knowledge, culture, policy, and practices.

We propose an initiative, called the HiCALL, based on horizontal and inclusive dialogue mechanisms that integrate local and global approaches for the establishment of a legal and practical framework for the sustainable adaptation and management of emerging proglacial landscapes. Our intent is a call to encourage and empower the international community to (a) recognize proglacial ecosystems as full-fledged systems with their hazard potential, and acknowledging their potential to contribute to the future provision of mountain environmental services and climate adaptation strategies; (b) further the conservation of biocultural diversity and values, recognition of multiple ways of knowing, and recognition of local and indigenous rights; (c) work on a Transdisciplinary and Transboundary High Alpine Research and Action Agenda for Proglacial Landscapes, and (d) formulate of global guidelines and strategies for states to assist the sustainable management of proglacial socio-environmental systems and support local adaptation and transformation initiatives. As next steps to move forward we propose, first, to set up a global survey to validate the challenges and opportunities of emerging proglacial landscapes, by region and by country, and identify the most relevant governmental and non-governmental organizations that could form national or regional committees of proglacial landscapes and be part of a global council. Second, we propose the organization of an international science-policy workshop, with diverse voices represented, to co-create a preliminary guideline for the establishment of an international platform (e.g., the proposed HiCALL) to discuss the future sustainable adaptation and management of recently deglaciated alpine landscapes.

ACKNOWLEDGMENTS

Thanks are due to the journal editors for inviting and accepting this “Invited Article” about a need for stewardship of lands exposed by deglaciation from climate change, an emerging topic with important future potential for the mountain science policy research field. We thank Wilfried Haeberli and an anonymous reviewer, whose comments have greatly improved the manuscript. We gratefully acknowledge Antoine Rabatel (Univ. Grenoble Alpes, IGE) who quantified the future deglacierized surface areas from Hock et al. (2019) data and whose comments helped to substantially improve this manuscript. Additional thanks are due to Fabien Anthelme, Alton Byers, Brad Carlson, Sheryl Luzzadder-Beach, Sophie Vallée, and Kenneth Young, for helpful discussions and editing of the manuscript. Additionally, we are particularly grateful to Edith Brown Weiss for her contributions on International Law. Finally, we are grateful to Christian Huggel for his comments and feedback during the revision process of the article. We thank the following organizations National Science Foundation, The University of Texas at Austin Soils, Water Quality, & Geoarchaeology Labs and the Centennial Professorship.

CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

AUTHOR CONTRIBUTIONS

Anaïs Zimmer: Conceptualization and Writing (lead). **Timothy Beach**: Conceptualization and Writing. **Julia Klein**: Conceptualization and Writing. **Jorge Recharte**: Conceptualization and Writing.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

ORCID

Anaïs Zimmer https://orcid.org/0000-0002-4902-4199
Timothy Beach https://orcid.org/0000-0003-0097-7973
Julia A. Klein https://orcid.org/0000-0003-1486-7994
Jorge Recharte Bullard https://orcid.org/0000-0001-9989-1170

ENDNOTES

[1] United Nations Conference on Environment and Development (UNCED)'s The Mountain Agenda emerged to draw the attention of governments, policy makers and the general public to the unsustainable exploitation, and to the neglect of the world's mountain heritage (Mountain Agenda, 1992).

[2] The Warsaw International Mechanism for Loss and Damage (WIM) was established in 2013 at COP 19 as part of the broader Cancun Adaptation Framework (CAF). WIM addresses loss and damage associated with impacts of climate change, including extreme events and slow onset events, in developing countries that are particularly vulnerable to the adverse effects of climate change.

RELATED WIREs ARTICLES

The changing water cycle: Climatic and socioeconomic drivers of water-related changes in the Andes of Peru
The controversial debate on the role of water reservoirs in reducing water scarcity
Glaciers and society: Attributions, perceptions, and valuations
Glaciers and climate change: Narratives of ruined futures
The spiritual significance of glaciers in an age of climate change

Further Reading

Boers, N. (2021). Observation-based early-warning signals for a collapse of the Atlantic meridional overturning circulation. *Nature Climate Change*, *11*(8), 680–688. https://doi.org/10.1038/s41558-021-01097-4

Nyima, Y., & Hopping, K. A. (2019). Tibetan Lake expansion from a pastoral perspective: Local observations and coping strategies for a changing environment. *Society and Natural Resources*, *32*(9), 965–982. https://doi.org/10.1080/08941920.2019.1590667

Rahmstorf, S., Box, J. E., Feulner, G., Mann, M. E., Robinson, A., Rutherford, S., & Schaffernicht, E. J. (2015). Exceptional twentieth-century slowdown in Atlantic Ocean overturning circulation. *Nature Climate Change*, *5*(5), 475–480.

REFERENCES

Aguiar, A. P. D., Collste, D., Harmáčková, Z. V., Pereira, L., Selomane, O., Galafassi, D., van Vuuren, D., & van der Leeuw, S. (2020). Co-designing global target-seeking scenarios: A cross-scale participatory process for capturing multiple perspectives on pathways to sustainability. *Global Environmental Change*, *65*, 102198. https://doi.org/10.1016/j.gloenvcha.2020.102198

Alata, E., Fuentealba, B., & Recharte, J. (2018). Depopulation in the Puna: Effects of climate change and other factors. *Revista Kawsaypacha: Sociedad y Medio Ambiente*, *2*, 49–68. https://doi.org/10.18800/kawsaypacha.201801.003

Alexander, J. M., Chalmandrier, L., Lenoir, J., Burgess, T. I., Essl, F., Haider, S., Kueffer, C., McDougall, K., Milbau, A., Nuñez, M. A., Pauchard, A., Rabitsch, W., Rew, L. J., Sanders, N. J., & Pellissier, L. (2018). Lags in the response of mountain plant communities to climate change. *Global Change Biology*, *24*(2), 563–579. https://doi.org/10.1111/gcb.13976

Alley, R. B., Marotzke, J., Nordhaus, W. D., Overpeck, J. T., Peteet, D. M., Pielke, R. A., Pierrehumbert, R. T., Rhines, P. B., Stocker, T. F., Talley, L. D., & Wallace, J. M. (2003). Abrupt climate change. *Science*, *299*, 2005. https://doi.org/10.1007/978-3-319-90975-2_4

Allison, E. A. (2015). The spiritual significance of glaciers in an age of climate change. *Wiley Interdisciplinary Reviews: Climate Change*, *6*(5), 493–508. https://doi.org/10.1002/wcc.354

Anacona, P. I., Kinney, J., Schaefer, M., Harrison, S., Wilson, R., Segovia, A., Mazzorana, B., Guerra, F., Farías, D., Reynolds, J. M., & Glasser, N. F. (2018). Glacier protection laws: Potential conflicts in managing glacial hazards and adapting to climate change. *Ambio*, *47*(8), 835–845. https://doi.org/10.1007/s13280-018-1043-x

Anthelme, F., Cauvy-fraunié, S., Francou, B., & Cáceres, B. (2021). Living at the edge: Increasing stress for plants 2–13 years after the retreat of a tropical glacier, *9*, 584872. https://doi.org/10.3389/fevo.2021.584872

Anthelme, F., & Lavergne, S. (2018). Alpine and arctic plant communities: A worldwide perspective. *Perspectives in Plant Ecology, Evolution and Systematics*, *30*, 1–5. https://doi.org/10.1016/j.ppees.2017.12.002

Baird, I. G., Silvano, R. A. M., Parlee, B., Poesch, M., Napoleon, A., Lepine, M., & Hallwass, G. (2021). The downstream impacts of hydropower dams and indigenous and local knowledge: Examples from the peace–Athabasca, Mekong, and Amazon. *Environmental Management*, *67*, 682–696. https://doi.org/10.1007/s00267-020-01418-x

Ballantyne, C. K. (2003). Paraglacial landform succession and sediment storage in deglaciated mountain valleys: Theory and approaches to calibration. *Zeitschrift Für Geomorphologie*, *132*, 1–18.

Baraer, M., Mckenzie, J., Mark, B. G., Gordon, R., Bury, J., Condom, T., Gomez, J., Knox, S., & Fortner, S. K. (2015). Contribution of groundwater to the outflow from ungauged glacierized catchments: A multi-site study in the tropical cordillera Blanca, Peru. *Hydrological Processes*, *29*(11), 2561–2581. https://doi.org/10.1002/hyp.10386

Barnett, T. P., Adam, J. C., & Lettenmaier, D. P. (2005). Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature*, *438*(7066), 303–309. https://doi.org/10.1038/nature04141

Barros, A., Aschero, V., Mazzolari, A., Cavieres, L. A., & Pickering, C. M. (2020). Going off trails: How dispersed visitor use affects alpine vegetation. *Journal of Environmental Management*, *267*, 110546. https://doi.org/10.1016/j.jenvman.2020.110546

Beach, T., Luzzadder-Beach, S., & Dunning, N. (2019). Out of the soil: Soil (dark matter biodiversity) and societal "collapses" from mesoamerica to the mesopotamia and beyond. In P. Dasgupta, P. Raven, & A. McIvor (Eds.), *Biological extinction: New perspectives* (pp. 138–174). Cambridge University Press. https://doi.org/10.1017/9781108668675.008

Beattie, O., Apland, B., Blake, E. W., Cosgrove, J. A., Gaunt, S., Greer, S., Mackie, A. P., Mackie, K. E., Straathof, D., Thorp, V., & Troffe, P. M. (2000). The Kwädāy Dän Ts'ínchi discovery from a glacier in British Columbia. *Canadian Journal of Archaeology*, *24*(1), 129–147.

Bebbington, A., & Bury, J. (2013). *Subterranean struggles: New dynamics of mining, oil, and gas in Latin America*. University of Texas Press.

Benavent-González, A., Raggio, J., Villagra, J., Blanquer, J. M., Pintado, A., Rozzi, R., Green, T. G. A., & Sancho, L. G. (2019). High nitrogen contribution by Gunnera magellanica and nitrogen transfer by mycorrhizas drive an extraordinarily fast primary succession in sub-Antarctic Chile. *New Phytologist*, *223*(2), 661–674. https://doi.org/10.1111/nph.15838

Beniston, M., Stoffel, M., Giacona, F., Farinotti, D., Andreassen, L. M., Magnusson, J., Marty, C., Morán-Tejéda, E., Morin, S., Naaim, M., Provenzale, A., Rabatel, A., Six, D., Stötter, J., Strasser, U., & Terzago, S. (2018). The European mountain cryosphere: A review of its current state, trends, and future challenges. *The Cryosphere*, *12*(2), 759–794. https://doi.org/10.5194/tc-12-759-2018

Biemans, H., Siderius, C., Lutz, A. F., Nepal, S., Ahmad, B., Hassan, T., Von Bloh, W., Wijngaard, R. R., Wester, P., Shrestha, A. B., & Immerzeel, W. W. (2019). Importance of snow and glacier meltwater for agriculture on the indo-Gangetic plain. *Nature Sustainability*, *2*(7), 594–601. https://doi.org/10.1038/s41893-019-0305-3

Bohleber, P., Schwikowski, M., Stocker-Waldhuber, M., Fang, L., & Fischer, A. (2020). New glacier evidence for ice-free summits during the life of the Tyrolean iceman. *Scientific Reports*, *10*(1), 1–11. https://doi.org/10.1038/s41598-020-77518-9

Bolch, T., Kulkarni, A., Kääb, A., Huggel, C., Paul, F., Cogley, J. G., Frey, H., Kargel, J. S., Fujita, K., Scheel, M., Bajracharya, S., & Stoffel, M. (2012). The state and fate of Himalayan glaciers. *Science*, *336*(6079), 310–314. https://doi.org/10.1126/science.1215828

Borsdorf, A., & Stadel, C. (2015). *The Andes: A geographical portrait*. Springer.

Bosson, J. B., Huss, M., & Osipova, E. (2019). Disappearing world heritage glaciers as a keystone of nature conservation in a changing climate. *Earth's Future*, *7*(4), 469–479. https://doi.org/10.1029/2018EF001139

Brighenti, S., Hotaling, S., Finn, D. S., Fountain, A. G., Hayashi, M., Herbst, D., Saros, J. E., Tronstad, L. M., & Millar, C. I. (2021). Rock glaciers and related cold rocky landforms: Overlooked climate refugia for mountain biodiversity. *Global Change Biology*, *27*(8), 1504–1517. https://doi.org/10.1111/gcb.15510

Brighenti, S., Tolotti, M., Bruno, M. C., Wharton, G., Pusch, M. T., & Bertoldi, W. (2019). Ecosystem shifts in alpine streams under glacier retreat and rock glacier thaw: A review. *Science of the Total Environment*, *675*, 542–559. https://doi.org/10.1016/j.scitotenv.2019.04.221

Bury, J. (2015). The frozen frontier. The extractives super cycle in a time of glacier recession. In C. Huggel, U. Zürich, & M. Carey (Eds.), *The high-mountain cryosphere*. Cambridge University Press.

Bury, J. T., Mark, B. G., McKenzie, J. M., French, A., Baraer, M., Huh, K. I., Zapata Luyo, M. A., & Gómez López, R. J. (2011). Glacier recession and human vulnerability in the Yanamarey watershed of the cordillera Blanca, Peru. *Climatic Change*, *105*(1), 179–206. https://doi.org/10.1007/s10584-010-9870-1

Bury, J., Mark, B. G., Carey, M., Young, K. R., McKenzie, J. M., Baraer, M., French, A., & Polk, M. H. (2013). New geographies of water and climate change in Peru: Coupled natural and social transformations in the Santa River watershed. *Annals of the Association of American Geographers*, *103*(2), 363–374. https://doi.org/10.1080/00045608.2013.754665

Bütler, M. (2007). Glaciers: Objects of law and international treaties. In R. Psenner & R. Lackner (Eds.), *Alpine space-man & environment* (Vol. 3, pp. 7–19). Innsbruck University Press.

CARE. (2018). *Proyectos multipropósitos en recursos hídricos en zonas de alta montaña [sistematización]*. CATE. https://www.proyectoglaciares.pe/materiales/2204/

Carey, M., Baraer, M., Mark, B. G., French, A., Bury, J., Young, K. R., & McKenzie, J. M. (2014). Toward hydro-social modeling: Merging human variables and the social sciences with climate-glacier runoff models (Santa River, Peru). *Journal of Hydrology*, *518*, 60–70. https://doi.org/10.1016/j.jhydrol.2013.11.006

Carey, M., Huggel, C., Bury, J., Portocarrero, C., & Haeberli, W. (2012). An integrated socio-environmental framework for glacier hazard management and climate change adaptation: Lessons from Lake 513, cordillera Blanca. *Peru. Climatic Change*, *112*, 733–767. https://doi.org/10.1007/s10584-011-0249-8

Carey, M., McDowell, G., Huggel, C., Marshall, B., Moulton, H., Portocarrero, C., Provant, Z., Reynolds, J., & Vicuña, L. (2021). A socio-cryospheric systems approach to glacier hazards, glacier runoff variability, and climate change. In W. Haeberli & C. Whiteman (Eds.), *Snow and ice-related hazards, risks, and disasters* (pp. 215–257). Elsevier.

Carlson, B. Z., Corona, M. C., Dentant, C., Bonet, R., Thuiller, W., & Choler, P. (2017). Observed long-term greening of alpine vegetation—a case study in the French Alps. *Environmental Research Letters*, *12*(11), 114006. https://doi.org/10.1088/1748-9326/aa84bd

Carlson, B. Z., Georges, D., Rabatel, A., Randin, C. F., Renaud, J., Delestrade, A., Zimmermann, N. E., Choler, P., & Thuiller, W. (2014). Accounting for tree line shift, glacier retreat and primary succession in mountain plant distribution models. *Diversity and Distributions*, *20*(12), 1379–1391. https://doi.org/10.1111/ddi.12238

Carrivick, J. L., Heckmann, T., Turner, A., & Fischer, M. (2018). An assessment of landform composition and functioning with the first proglacial systems dataset of the central European Alps. *Geomorphology*, *321*, 117–128. https://doi.org/10.1016/j.geomorph.2018.08.030

Carrivick, J. L., & Tweed, F. S. (2021). Deglaciation controls on sediment yield: Towards capturing spatio-temporal variability. *Earth-Science Reviews*, *221*, 103809. https://doi.org/10.1016/j.earscirev.2021.103809

Cauvy-Fraunié, S., Andino, P., Espinosa, R., Calvez, R., Jacobsen, D., & Dangles, O. (2016). Ecological responses to experimental glacier-runoff reduction in alpine rivers. *Nature Communications*, *7*, 1–7. https://doi.org/10.1038/ncomms12025

Cauvy-Fraunié, S., & Dangles, O. (2019). A global synthesis of biodiversity responses to glacier retreat. *Nature Ecology & Evolution*, *1*, 1675–1685. https://doi.org/10.1038/s41559-019-1042-8

Ceruti, M. C. (2015). Frozen mummies from andean mountaintop shrines: Bioarchaeology and ethnohistory of Inca human sacrifice. *BioMed Research International*, *2015*, 35–36. https://doi.org/10.1155/2015/439428

Chaudhary, P., Rai, S., Wangdi, S., Mao, A., Rehman, N., Chettri, S., & Bawa, K. S. (2011). Consistency of local perceptions of climate change in the Kangchenjunga Himalaya landscape. *Current Science*, *101*(4), 504–513.

Chen, F., Welker, F., Shen, C. C., Bailey, S. E., Bergmann, I., Davis, S., Xia, H., Wang, H., Fischer, R., Freidline, S. E., Yu, T. L., Skinner, M. M., Stelzer, S., Dong, G., Fu, Q., Dong, G., Wang, J., Zhang, D., & Hublin, J. J. (2019). A late middle pleistocene denisovan mandible from the Tibetan plateau. *Nature*, *569*(7756), 409–412. https://doi.org/10.1038/s41586-019-1139-x

Church, J. M. (2012). Environmental regionalism: The challenge of the alpine convention and the "strange case" of the Andean community. *Journal of Food System Research*, *19*(3), 225–355. https://doi.org/10.5874/jfsr.19.225

Clague, J. J., & O'Connor, J. E. (2021). Glacier-related outburst floods. In W. Haeberli & C. Whiteman (Eds.), *Snow and ice-related hazards, risks, and disasters* (pp. 467–499). Elsevier.

Coe, J. A., Bessette-Kirton, E. K., & Geertsema, M. (2018). Increasing rock-avalanche size and mobility in Glacier Bay National Park and Preserve, Alaska detected from 1984 to 2016 Landsat imagery. *Landslides*, *15*(3), 393–407. https://doi.org/10.1007/s10346-017-0879-7

Cogley, J. G., Hock, R., Rasmussen, L. A., Arendt, A. A., Bauder, A., Braithwaite, R. J., Jansson, P., Kaser, G., Möller, M. & Nicholson, L. (2011). Glossary of glacier mass balance and related terms. IHP-VII Technical Documents in Hydrology No. 86, IACS.

Colloff, M. J., Gorddard, R., Abel, N., Locatelli, B., Wyborn, C., Butler, J. R. A., Lavorel, S., Van Kerkhoff, L., Meharg, S., Múnera-Roldán, C., Bruley, E., Fedele, G., Wise, R. M., & Dunlop, M. (2021). Adapting transformation and transforming adaptation to climate change using a pathways approach. *Environmental Science and Policy*, *124*, 163–174. https://doi.org/10.1016/j.envsci.2021.06.014

Colonia, D., Torres, J., Haeberli, W., Schauwecker, S., Braendle, E., Giraldez, C., & Cochachin, A. (2017). Compiling an inventory of glacier-bed overdeepenings and potential new lakes in de-glaciating areas of the peruvian Andes: Approach, first results, and perspectives for adaptation to climate change. *Water*, *9*(5), 336. https://doi.org/10.3390/w9050336

Compagno, L., Eggs, S., Huss, M., Zekollari, H., & Farinotti, D. (2021). Brief communication: Do 1.0, 1.5, or 2.0° C matter for the future evolution of alpine glaciers? *The Cryosphere*, *15*(6), 2593–2599. https://doi.org/10.5194/tc-15-2593-2021

Corlett, R. T. (2016). Restoration, reintroduction, and Rewilding in a changing world. *Trends in Ecology and Evolution*, *31*(6), 453–462. https://doi.org/10.1016/j.tree.2016.02.017

Cox, J. (2016). Finding a place for glaciers within environmental law: An analysis of ambiguous legislation and impractical common law. *Appeal*, *21*, 21.

Cuesta, F., Llambí, L. D., Huggel, C., Drenkhan, F., Gosling, W. D., Muriel, P., Jaramillo, R., & Tovar, C. (2019). New land in the neotropics: A review of biotic community, ecosystem, and landscape transformations in the face of climate and glacier change. *Regional Environmental Change*, *3*, 1623–1642. https://doi.org/10.1007/s10113-019-01499-3

Cuesta, F., Tovar, C., Llambí, L. D., Gosling, W. D., Halloy, S., Carilla, J., Muriel, P., Meneses, R., Meneses, I., Beck, S., Ulloa-Ulloa, C., Yager, K., Aguirre, N., Viñas, P., Jacome, J., Suárez-Duque, D., Buytaert, W., & Pauli, H. (2020). Thermal niche traits of high alpine plant species and communities across the tropical Andes and their vulnerability to global warming. *Journal of Biogeography*, *1*, 1–13. https://doi.org/10.1111/jbi.13759

Dahal, K. R., & Hagelman, R., III. (2011). People's risk perception of glacial Lake outburst flooding: A case of Tsho Rolpa Lake, Nepal. *Environmental Hazards*, *10*, 154–170. https://doi.org/10.1080/17477891.2011.582310

D'Amico, M. E., Freppaz, M., Zanini, E., & Bonifacio, E. (2017). Primary vegetation succession and the serpentine syndrome: The proglacial area of the Verra Grande glacier, north-western italian alps. *Plant and Soil*, *415*, 283–298. https://doi.org/10.1007/s11104-016-3165-x

Dangles, O., Rabatel, A., Kraemer, M., Zeballos, G., Soruco, A., Jacobsen, D., & Anthelme, F. (2017). Ecosystem sentinels for climate change? Evidence of wetland cover changes over the last 30 years in the tropical Andes. *PLoS One*, *12*(5), 1–22. https://doi.org/10.1371/journal.pone.0175814

Davaze, L., Rabatel, A., Dufour, A., Hugonnet, R., & Arnaud, Y. (2020). Region-wide annual glacier surface mass balance for the European Alps from 2000 to 2016. *Frontiers in Earth Science*, *8*, 1–14. https://doi.org/10.3389/feart.2020.00149

Debarbieux, B., & Price, M. F. (2012). Mountain regions: A global common good? *Mountain Research and Development*, *32*, 7–11. https://doi.org/10.1659/MRD-JOURNAL-D-11-00034.S1

Deline, P., Gruber, S., Amann, F., Bodin, X., Delaloye, R., Failletaz, J., Fischer, L., Geertsema, M., Giardino, M., Hasler, A., Kirkbride, M., Krautblatter, M., Magnin, F., McColl, S., Ravanel, L., Schoeneich, P., & Weber, S. (2021). Ice loss from glaciers and permafrost and related slope instability in high-mountain regions. In W. Haeberli & C. Whiteman (Eds.), *Snow and ice-related hazards, risks, and disasters*. Elsevier. https://doi.org/10.1016/b978-0-12-817129-5.00015-9

Deline, P., Gruber, S., Delaloye, R., Fischer, L., Geertsema, M., Giardino, M., Hasler, A., Kirkbride, M., Krautblatter, M., & Schoeneich, P. (2014). Ice loss and slope stability in high-mountain regions. In W. Haeberli & C. Whiteman (Eds.), *Snow and ice-related hazards, risks, and disasters*. Elsevier. https://doi.org/10.1016/B978-0-12-394849-6.00015-9

Diemberger, H., Hovden, A., & Yeh, E. (2015). The honour of the snow mountains is the snow: Tibetan livelihoods in a changing climate. In M. Shahgedanova (Ed.), *The high mountain cryosphere: Environmental changes and human risks* (pp. 249–271). Cambridge University Press.

Dillehay, T. D., & Kolata, A. L. (2004). Long-term human response to uncertain environmental conditions in the Andes. *Proceedings of the National Academy of Sciences*, *101*(12), 4325–4330. https://doi.org/10.1073/pnas.0400538101

Dixon, E. J., Callanan, M. E., Hafner, A., & Hare, P. G. (2014). The emergence of glacial archaeology. *Journal of Glacial Archaeology*, *1*(0), 1–9. https://doi.org/10.1558/jga.v1i1.1

Drenkhan, F., Huggel, C., Guardamino, L., & Haeberli, W. (2019). Managing risks and future options from new lakes in the deglaciating Andes of Peru: The example of the Vilcanota-Urubamba basin. *Science of the Total Environment*, *665*, 465–483. https://doi.org/10.1016/j.scitotenv.2019.02.070

Dunbar, K. W., Damacia, K., & Marcos, M. (2012). Singing for shaved ice: Glacial loss and Raspadilla in the Peruvian Andes. In J. Sinclair & A. C. Pertierra (Eds.), *Consumer culture in Latin America* (pp. 195–205). Palgrave Macmillan.

Dussaillant, I., Berthier, E., Brun, F., Masiokas, M., Hugonnet, R., Favier, V., Rabatel, A., Pitte, P., & Ruiz, L. (2019). Two decades of glacier mass loss along the Andes. *Nature Geoscience*, *12*(10), 802–808. https://doi.org/10.1038/s41561-019-0432-5

Egli, M., Wernli, M., Kneisel, C., & Haeberli, W. (2006). Melting glaciers and soil development in the proglacial area Morteratsch (Swiss Alps): I. soil type chronosequence. *Arctic, Antarctic, and Alpine Research*, *38*(4), 499–509. https://doi.org/10.1657/1523-0430(2006)38[499:MGASDI]2.0.CO;2

Ehrbar, D., Schmocker, L., Vetsch, D. F., & Boes, R. M. (2018). Hydropower potential in the periglacial environment of Switzerland under climate change. *Sustainability*, *10*(8), 1–14. https://doi.org/10.3390/su10082794

Eichel, J. (2019). Vegetation succession and biogeomorphic interactions in glacier forelands. In D. Heckmann & M. Tobias (Eds.), *Geomorphology of proglacial systems* (pp. 327–349). Springer.

Erschbamer, B., & Caccianiga, M. S. (2016). *Glacier forelands: Lessons of plant population and community development. In Progress in botany* (Vol. 78, pp. 259–284). Springer.

Espiner, S., & Becken, S. (2014). Tourist towns on the edge: Conceptualising vulnerability and resilience in a protected area tourism system. *Journal of Sustainable Tourism*, *22*(4), 646–665. https://doi.org/10.1080/09669582.2013.855222

Farinotti, D., Pistocchi, A., & Huss, M. (2016). From dwindling ice to headwater lakes: Could dams replace glaciers in the European Alps? *Environmental Research Letters*, *11*(5), 054022. https://doi.org/10.1088/1748-9326/11/5/054022

Farinotti, D., Round, V., Huss, M., Compagno, L., & Zekollari, H. (2019). Large hydropower and water-storage potential in future glacier-free basins. *Nature*, *575*(7782), 341–344. https://doi.org/10.1038/s41586-019-1740-z

Ficetola, G. F. (2021). Dynamics of ecological communities following current retreat of glaciers. *Annual Review of Ecology, Evolution, and Systematics*, *52*, 405–426. https://doi.org/10.1146/annurev-ecolsys-010521-040017

Fischer, A., Fickert, T., Schwaizer, G., Patzelt, G., & Groß, G. (2019). Vegetation dynamics in alpine glacier forelands tackled from space. *Scientific Reports*, *9*(1), 1–13. https://doi.org/10.1038/s41598-019-50273-2

Fortner, S. K., Mark, B. G., McKenzie, J. M., Bury, J., Trierweiler, A., Baraer, M., Burns, P. J., & Munk, L. A. (2011). Elevated stream trace and minor element concentrations in the foreland of receding tropical glaciers. *Applied Geochemistry*, *26*(11), 1792–1801. https://doi.org/10.1016/j.apgeochem.2011.06.003

French, A., Barandiarán, J., & Rampini, C. (2015). Contextualizing conflict:Vital waters and competing values in glaciated environments. In C. Huggel, M. Carey, & J. J. Clague (Eds.), *The high-mountain cryosphere: Environmental changes and human risks (pp. 315–336)*. Cambridge University Press. https://doi.org/10.1017/CBO9781107588653.017

Gagné, K., Rasmussen, M. B., & Orlove, B. (2014). Glaciers and society: Attributions, perceptions, and valuations. *Wiley Interdisciplinary Reviews: Climate Change*, *5*(6), 793–808. https://doi.org/10.1002/wcc.315

Gentili, R., Baroni, C., Caccianiga, M., Armiraglio, S., Ghiani, A., & Citterio, S. (2015). Potential warm-stage microrefugia for alpine plants: Feedback between geomorphological and biological processes. *Ecological Complexity*, *21*, 87–99. https://doi.org/10.1016/j.ecocom.2014.11.006

Gentle, P., & Narayan, T. (2012). Climate change, poverty and livelihoods: Adaptation practices by rural mountain communities in Nepal. *Environmental Science and Policy*, *21*, 24–34. https://doi.org/10.1016/j.envsci.2012.03.007

Gobbi, M., Ambrosini, R., Casarotto, C., Diolaiuti, G., Ficetola, G. F., Lencioni, V., Seppi, R., Smiraglia, C., Tampucci, D., Valle, B., & Caccianiga, M. (2021). Vanishing permanent glaciers: Climate change is threatening a European Union habitat (code 8340) and its poorly known biodiversity. *Biodiversity and Conservation*, *30*(7), 2267–2276. https://doi.org/10.1007/s10531-021-02185-9

Gottfried, M., Pauli, H., Futschik, A., Akhalkatsi, M., Barančok, P., Benito Alonso, J. L., Coldea, G., Dick, J., Erschbamer, B., Fernández Calzado, M. R., Kazakis, G., Krajči, J., Larsson, P., Mallaun, M., Michelsen, O., Moiseev, D., Moiseev, P., Molau, U., Merzouki, A., … Grabherr, G. (2012). Continent-wide response of mountain vegetation to climate change. *Nature Climate Change*, *2*(2), 111–115. https://doi.org/10.1038/nclimate1329

Grove, J. M. (2012). *The little ice age*. Routledge.

Guittard, A., Baraer, M., McKenzie, J. M., Mark, B. G., Rapre, A. C., Bury, J., Carey, M., & Young, K. R. (2020). Trace metal stream contamination in a post peak water context: Lessons from the cordillera Blanca, Peru. *ACS Earth and Space Chemistry*, *4*(4), 506–514. https://doi.org/10.1021/acsearthspacechem.9b00269

Haeberli, W., Huggel, C., Paul, F., & Zemp, M. (2021). The response of glaciers to climate change: Observations and impacts. In *Reference module in earth systems and environmental sciences*. Elsevier. ISBN 9780124095489. https://doi.org/10.1016/b978-0-12-818234-5.00011-0

Haeberli, W. (2008). *Changing views of changing glaciers* (pp. 23–32). Glacier Retreat, Science and Society, University of California Press, Los Angeles.

Haeberli, W. (2017). Integrative modelling and managing new landscapes and environments in de-glaciating mountain ranges: An emerging trans-disciplinary research field. *Forestry Research and Engineering*, *1*(1), 36–38. https://doi.org/10.15406/freij.2017.01.00005

Haeberli, W., Buetler, M., Huggel, C., Friedli, T. L., Schaub, Y., & Schleiss, A. J. (2016). New lakes in deglaciating high-mountain regions: Opportunities and risks. *Climatic Change*, *139*(2), 201–214. https://doi.org/10.1007/s10584-016-1771-5

Haeberli, W., Oerlemans, J., & Zemp, M. (2019). The future of alpine glaciers and beyond. In *Oxford research encyclopedia of climate science*. Oxford University Press. https://doi.org/10.1093/acrefore/9780190228620.013.769

Haeberli, W., Schaub, Y., & Huggel, C. (2017). Increasing risks related to landslides from degrading permafrost into new lakes in de-glaciating mountain ranges. *Geomorphology*, *293*, 405–417. https://doi.org/10.1016/j.geomorph.2016.02.009

Haeberli, W., & Whiteman, C. (2021). Facing challenges of rapid change and long-term commitments. In W. Haeberli & C. Whiteman (Eds.), *Snow and ice-related hazards, risks, and disasters* (pp. 1–33). Elsevier.

Hågvar, S., Gobbi, M., Kaufmann, R., Ingimarsdóttir, M., Caccianiga, M., Valle, B., Pantini, P., Fanciulli, P. P., & Vater, A. (2020). Ecosystem birth near melting glaciers: A review on the pioneer role of ground-dwelling arthropods. *Insects*, *11*(9), 1–35. https://doi.org/10.3390/insects11090644

Heckmann, T., & Morche, D. (2019). Geomorphology of proglacial systems. In T. Heckmann & D. Morche (Eds.), *Landform and sediment dynamics in recently deglaciated alpine landscapes*. Springer.

Hobbs, R. J., Higgs, E., & Harris, J. A. (2009). Novel ecosystems: Implications for conservation and restoration. *Trends in Ecology and Evolution*, *24*(11), 599–605. https://doi.org/10.1016/j.tree.2009.05.012

Hock, R., Bliss, A., Marzeion, B. E. N., Giesen, R. H., Hirabayashi, Y., Huss, M., Radiac, V., & Slangen, A. B. A. (2019). GlacierMIP-A model intercomparison of global-scale glacier mass-balance models and projections. *Journal of Glaciology*, *65*(251), 453–467. https://doi.org/10.1017/jog.2019.22

Hock, R., Rasul, G., Adler, C., Cáceres, B., Gruber, S., Hirabayashi, Y., Jackson, M., Kääb, A., Kang, S., Kutuzov, S., Milner, A., Molau, U., Morin, S., Orlove, B., & Steltzer, H. I. (2019). Chapter 2: High Mountain areas. In H.-O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, & N. M. Weyer (Eds.), *IPCC special report on the ocean and cryosphere in a changing climate* (pp. 131–202). IPCC.

Huggel, C., Carey, M., & Clague, J. J. (2015). *The high-mountain cryosphere*. Cambridge University Press.

Huggel, C., Carey, M., Emmer, A., Frey, H., Walker-Crawford, N., & Wallimann-Helmer, I. (2020). Anthropogenic climate change and glacier lake outburst flood risk: Local and global drivers and responsibilities for the case of lake Palcacocha, Peru. *Natural Hazards and Earth System Sciences*, *20*(8), 2175–2193. https://doi.org/10.5194/nhess-20-2175-2020

Huggel, C., Muccione, V., Carey, M., James, R., Jurt, C., & Mechler, R. (2018). Loss and damage in the mountain cryosphere. *Regional Environmental Change*, *19*, 1387–1399. https://doi.org/10.1007/s10113-018-1385-8

Hugonnet, R., McNabb, R., Berthier, E., Menounos, B., Nuth, C., Girod, L., Farinotti, D., Huss, M., Dussaillant, I., Brun, F., & Kääb, A. (2021). Accelerated global glacier mass loss in the early twenty-first century. *Nature*, *592*, 2020–2731. https://doi.org/10.1038/s41586-021-03436-z

Huntington, H. P., Begossi, A., Gearheard, S. F., Kersey, B., Loring, P. A., Mustonen, T., Paudel, P. K., Silvano, R. A. M., & Vave, R. (2017). How small communities respond to environmental change: Patterns from tropical to polar ecosystems. *Ecology and Society*, *22*(3), 9.

Huss, M., Bookhagen, B., Huggel, C., Jacobsen, D., Bradley, R. S., Clague, J. J., Vuille, M., Buytaert, W., Cayan, D. R., Greenwood, G., Mark, B. G., Milner, A. M., Weingartner, R., & Winder, M. (2017). Toward mountains without permanent snow and ice. *Earth's Future*, *5*(5), 418–435. https://doi.org/10.1002/2016EF000514

Huss, M., & Hock, R. (2018). Global-scale hydrological response to future glacier mass loss. *Nature Climate Change*, *8*(2), 135–140. https://doi.org/10.1038/s41558-017-0049-x

Hussain, A., Rasul, G., Mahapatra, B., Wahid, S., & Tuladhar, S. (2018). Climate change-induced hazards and local adaptations in agriculture: A study from Koshi River basin, Nepal. *Natural Hazards*, *91*(3), 1365–1383. https://doi.org/10.1007/s11069-018-3187-1

Immerzeel, W. W., Lutz, A. F., Andrade, M., Bahl, A., Biemans, H., Bolch, T., … Baillie, J. E. M. (2020). Importance and vulnerability of the world's water towers. *Nature*, *577*(7790), 364–369. https://doi.org/10.1038/s41586-019-1822-y

IPBES (2019). In E. S. Brondizio, J. Settele, S. Díaz, & H. T. Ngo (Eds.), *Global assessment report on biodiversity and ecosystem services of the intergovernmental science-policy platform on biodiversity and ecosystem services* (p. 1148). IPBES secretariat. https://doi.org/10.5281/zenodo.3831673

IPCC (2018). Impacts of 1.5°C of global warming on natural and human systems. In O. Hoegh-Guldberg, D. Jacob, M. Bindi, S. Brown, I. Camilloni, A. Diedhiou, R. Djalante, K. L. Ebi, F. Engelbrecht, J. Guiot, Y. Hijioka, S. Mehrotra, A. Payne, S. I. Seneviratne, A. Thomas, R. Warren, & R. B. Zougmoré (Eds.), *2018: Impacts of 1.5°C global warming on natural and human systems. An IPCC special report*. IPCC.

IPCC. (2019). *IPCC special report on the ocean and cryosphere in a changing climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, & N. M. Weyer (eds.)]*. IPCC.

Jacobsen, D., & Dangles, O. (2017). *Ecology of high altitude waters*. Oxford University Press.

Jaeger, W. K., Amos, A., Bigelow, D. P., Chang, H., Conklin, D. R., Haggerty, R., Langpap, C., Moore, K., Mote, P. W., Nolin, A. W., Plantinga, A. J., Schwartz, C. L., Tullos, D., & Turner, D. P. (2017). Finding water scarcity amid abundance using human–natural system models. *Proceedings of the National Academy of Sciences of the United States of America*, *114*(45), 11884–11889. https://doi.org/10.1073/pnas.1706847114

Johan, R.. (2016). The plant remains of the "ice-maiden," the Inca mummy from Mt. Ampato, Peru (co-authored with Klaus Oeggl [PA]). In Paper presented at the 4th International Glacial Archaeology Symposium, Innsbruck, Austria, 12–16 October, 2016.

Jurt, C., Brugger, J., Dunbar, K. W., Milch, K., & Orlove, B. (2015). Cultural values of glaciers. In C. Huggel, M. Carey, & J. J. Clague (Eds.), *The high-mountain cryosphere: Environmental changes and human risks* (pp. 90–106). Cambridge University Press.

Jurt, C., Burga, M. D., Vicuña, L., Huggel, C., & Orlove, B. (2015). Local perceptions in climate change debates: Insights from case studies in the Alps and the Andes. *Climatic Change*, *133*(3), 511–523. https://doi.org/10.1007/s10584-015-1529-5

Kaenzig, R., Rebetez, M., & Serquet, G. (2016). Climate change adaptation of the tourism sector in the Bolivian Andes. *Tourism Geographies*, *18*(2), 111–128. https://doi.org/10.1080/14616688.2016.1144642

Kavan, J., & Anděrová, V. (2020). Impacts of increased tourism on polar environment-case studies from Svalbard and Iceland. *Czech Polar Reports*, *10*(1), 59–68. https://doi.org/10.5817/CPR2020-1-6

Kellner, E. (2019). Social acceptance of a multi-purpose reservoir in a recently deglaciated landscape in the Swiss Alps. *Sustainability*, *11*(14), 3319. https://doi.org/10.3390/su11143819

Kellner, E. (2021). The controversial debate on the role of water reservoirs in reducing water scarcity. *WIREs: Water*, *8*(3), 1–11. https://doi.org/10.1002/wat2.1514

Kellner, E., & Brunner, M. I. (2021). Reservoir governance in world's water towers needs to anticipate multi-purpose use. *Earth's Future*, *9*(1), 1–19. https://doi.org/10.1029/2020EF001643

Khedim, N., Cécillon, L., Poulenard, J., Barré, P., Baudin, F., Marta, S., Rabatel, A., Dentant, C., Cauvy-Fraunié, S., Anthelme, F., Gielly, L., Ambrosini, R., Franzetti, A., Azzoni, R. S., Caccianiga, M. S., Compostella, C., Clague, J., Tielidze, L., Messager, E., … Ficetola, G. F. (2021). Topsoil organic matter build-up in glacier forelands around the world. *Global Change Biology*, *27*(8), 1662–1677. https://doi.org/10.1111/gcb.15496

Klein, J. A., Tucker, C. M., Nolin, A. W., Hopping, K. A., Reid, R. S., Steger, C., Grêt-Regamey, A., Lavorel, S., Müller, B., Yeh, E., Boone, R., Bougeron, P., Bustic, V., Castellanos, E., Chen, X., Greenwood, G., Keiler, M., Marchant, R., & Yager, K. (2019). Catalyzing transformations to sustainability in the World's mountains. *Earth's Future*, *7*(5), 547–557. https://doi.org/10.1029/2018EF001024

Klein, J. A., Harte, J., & Zhao, X. Q. (2007). Experimental warming, not grazing, decreases rangeland quality on the Tibetan plateau. *Ecological Applications*, *17*(2), 541–557. https://doi.org/10.1890/05-0685

Klein, J. A., Yeh, E., Bump, J., Nyima, Y., & Hopping, K. (2011). Coordinating environmental protection and climate change adaptation policy in resource-dependent communities: A case study from the Tibetan plateau. In J. D. Ford & L. Berrang-Ford (Eds.), *Climate change adaptation in developed nations* (pp. 423–438). Springer. https://doi.org/10.1007/978-94-007-0567-8_31

Knapp, C. N., Reid, R. S., Fernández-Giménez, M. E., Klein, J. A., & Galvin, K. A. (2019). Placing transdisciplinarity in context: A review of approaches to connect scholars, society and action. *Sustainability*, *11*(18), 1–25. https://doi.org/10.3390/su11184899

Lamb, H. H. (1977). *Climatic history and the future: Present, past and future* (Vol. 2, p. 835). Methuen.

Lambert, C. B., Resler, L. M., Shao, Y., & Butler, D. R. (2020). Vegetation change as related to terrain factors at two glacier forefronts, Glacier National Park, Montana, USA. *Journal of Mountain Science*, *17*(1), 1–15. https://doi.org/10.1007/s11629-019-5603-8

Lavorel, S., Locatelli, B., Colloff, M. J., & Bruley, E. (2020). Co-producing ecosystem services for adapting to climate change. *Philosophical Transactions of the Royal Society of London Series B, Biological Sciences*, *375*(1794), 20190119. https://doi.org/10.1098/rstb.2019.0119

Le Roy, L. E. (1971). *Times of feast, times of famine: A history of climate since the year 1000*. Trans. B. Bray. Doubleday & Company.

Lee, C. M. (2012). Withering snow and ice in the mid-latitudes: A new archaeological and paleobiological record for the rocky mountain region. *Arctic*, *65*, 165–177.

Lee, C. M., Benedict, J. B., & Lee, J. B. (2006). Ice patches and remnant glaciers: Paleontological discoveries and archeological possibilities in the Colorado high country. *Southwestern Lore*, *72*(1), 26–43.

Lemelin, H., Dawson, J., Stewart, E. J., Maher, P., & Lueck, M. (2010). Last-chance tourism: The boom, doom, and gloom of visiting vanishing destinations. *Current Issues in Tourism*, *13*(5), 477–493. https://doi.org/10.1080/13683500903406367

Lemieux, C. J., Groulx, M., Halpenny, E., Stager, H., Dawson, J., Stewart, E. J., & Hvenegaard, G. T. (2018). "The end of the ice age?": Disappearing world heritage and the climate change communication imperative. *Environmental Communication*, *12*(5), 653–671. https://doi.org/10.1080/17524032.2017.1400454

Linsbauer, A., Frey, H., Haeberli, W., Machguth, H., Azam, M. F., & Allen, S. (2016). Modelling glacier-bed overdeepenings and possible future lakes for the glaciers in the Himalaya-Karakoram region. *Annals of Glaciology*, *57*(71), 119–130. https://doi.org/10.3189/2016AoG71A627

Linsbauer, A., Paul, F., & Haeberli, W. (2012). Modeling glacier thickness distribution and bed topography over entire mountain ranges with glabtop: Application of a fast and robust approach. *Journal of Geophysical Research: Earth Surface*, *117*(3), 1–17. https://doi.org/10.1029/2011JF002313

Lizaga, I., Gaspar, L., Quijano, L., Dercon, G., & Navas, A. (2019). NDVI,137Cs and nutrients for tracking soil and vegetation development on glacial landforms in the Lake Parón catchment (Cordillera Blanca, Perú). *Science of the Total Environment*, *651*, 250–260. https://doi.org/10.1016/j.scitotenv.2018.09.075

Loarie, S. R., Duffy, P. B., Hamilton, H., Asner, G. P., Field, C. B., & Ackerly, D. D. (2009). The velocity of climate change. *Nature*, *462*(7276), 1052–1055. https://doi.org/10.1038/nature08649

Magnússon, R., Cammeraat, E., Lücke, A., Jansen, B., Zimmer, A., & Recharte, J. (2020). Influence of glacial sediments on the chemical quality of surface water in the Ulta valley, cordillera Blanca, Peru. *Journal of Hydrology*, *587*, 125027. https://doi.org/10.1016/j.jhydrol.2020.125027

Maguire, R. (2013). *Global forest governance: Legal concepts and policy trends*. Edward Elgar Publishing.

Malanson, G. P., Resler, L. M., Butler, D. R., & Fagre, D. B. (2019). Mountain plant communities: Uncertain sentinels? *Progress in Physical Geography*, *43*, 521–543. https://doi.org/10.1177/0309133319843873

Mann, M. E. (2002). Little ice age. In T. Munn (Ed.), *Encyclopedia of global environmental change* (Vol. 1, pp. 504–509). Wiley.

Mark, B. G., Baraer, M., Fernandez, A., Immerzeel, W., Moore, R. D., & Weingartner, R. (2015). Glaciers as water resources. In M. Shahgedanova (Ed.), *The high-mountain cryosphere: Environmental changes and human risks* (pp. 184–203). Cambridge University Press.

Matthews, J. A., & Briffa, K. R. (2005). The "little ice age": Re-evaluation of an evolving concept. *Geografiska Annaler, Series A: Physical Geography*, *87*(1), 17–36. https://doi.org/10.1111/j.0435-3676.2005.00242.x

McColl, S. T., & Draebing, D. (2019). Rock slope instability in the proglacial zone: State of the art. In D. Heckmann & M. Tobias (Eds.), *Geomorphology of proglacial systems* (pp. 119–141). Springer.

McDonald, T., Gann, G. D., Jonson, J., & Dixon, K. W. (2016). *International standards for the practice of ecological restoration – including principles and key concepts*. Society for Ecological Restoration. https://cieem.net/wp-content/uploads/2019/07/SER_Standards_2016.pdf

McNeeley, S. M. (2017). Sustainable climate change adaptation in indian country. *Weather, Climate, and Society*, *9*(3), 393–404. https://doi.org/10.1175/WCAS-D-16-0121.1

Menounos, B., Hugonnet, R., Shean, D., Gardner, A., Howat, I., Berthier, E., … Dehecq, A. (2019). Heterogeneous changes in Western north American glaciers linked to decadal variability in zonal wind strength. *Geophysical Research Letters*, *46*(1), 200–209. https://doi.org/10.1029/2018GL080942

Milner, A. M., Khamis, K., Battin, T. J., Brittain, J. E., Barrand, N. E., Füreder, L., Cauvy-Fraunié, S., Gíslason, G. M., Jacobsen, D., Hannah, D. M., Hodson, A. J., Hood, E., Lencioni, V., Ólafsson, J. S., Robinson, C. T., Tranter, M., & Brown, L. E. (2017). Glacier shrinkage driving global changes in downstream systems. *Proceedings of the National Academy of Sciences of the United States of America*, *114*(37), 9770–9778. https://doi.org/10.1073/pnas.1619807114

Molden, D., Sharma, E., Shrestha, A. B., Chettri, N., Pradhan, N. S., & Kotru, R. (2017). Advancing regional and Transboundary cooperation in the conflict-prone Hindu Kush-Himalaya. *Mountain Research and Development*, *37*(4), 502–508. https://doi.org/10.1659/MRD-JOURNAL-D-17-00108.1

Molg, T., Hardy, D. R., Cullen, N. J., & Kaser, J. (2008). Tropical glaciers, climate change, and society. In B. H. L. B. Orlove & E. Wiegandt (Eds.), *Darkening peaks: Glacier retreat, science, and society* (pp. 168–182). University of California Press.

Montaña, E., Diaz, H. P., & Hurlbert, M. (2016). Development, local livelihoods, and vulnerabilities to global environmental change in the south American dry Andes. *Regional Environmental Change*, *16*(8), 2215–2228. https://doi.org/10.1007/s10113-015-0888-9

Morche, D., Baewert, H., Schuchardt, A., Faust, M., Weber, M., & Khan, T. (2019). Fluvial sediment transport in the Proglacial Fagge River, Kaunertal, Austria. In D. Heckmann & M. Tobias (Eds.), *Geomorphology of proglacial systems* (pp. 219–229). Springer.

Motschmann, A., Huggel, C., Carey, M., Moulton, H., Walker-Crawford, N., & Muñoz, R. (2020). Losses and damages connected to glacier retreat in the cordillera Blanca, Peru. *Climatic Change*, *162*(2), 837–858. https://doi.org/10.1007/s10584-020-02770-x

Moulton, H., Carey, M., Huggel, C., & Motschmann, A. (2021). Narratives of ice loss: New approaches to shrinking glaciers and climate change adaptation. *Geoforum*, *125*, 47–56. https://doi.org/10.1016/j.geoforum.2021.06.011

Mountain Agenda. (1992). *An appeal for the mountains. Prepared on the occasion of the UNCED conference 1992 in Rio de Janeiro*. Mountain Agenda, Centre for Development and Environment, Institute of Geography, University of Bern.

Mourey, J., & Ravanel, L. (2017). Evolution of access routes to high mountain refuges of the Mer de Glace Basin (Mont Blanc massif, France). *Revue de Géographie Alpine*, *105*, 4–16. https://doi.org/10.4000/rga.3790

Mukherji, A., Sinisalo, A., Nüsser, M., Garrard, R., & Eriksson, M. (2019). Contributions of the cryosphere to mountain communities in the Hindu Kush Himalaya: A review. *Regional Environmental Change*, *4*, 1311–1326. https://doi.org/10.1007/s10113-019-01484-w

Navas Izquierdo, A., Castillo, A., Schuller, P., Gaspar Ferrer, L., Lizaga Villuendas, I., Quijano Gaudes, L., & Slaets, J. (2019). Combining 137Cs and soil organic carbon for assessing patterns of soil formation in the rapidly changing proglacial environment of the Grey Glacier (Torres del Paine, Chilean Patagonia).

NELAK (2013). New lakes in deglaciating high-mountain areas: Climate-related development and challenges for sustainable use (NELAK). In W. Haeberli, M. Buetler, C. Huggel, H. Müller, & A. Schleiss (Eds.), *Scientific Report of the National Research Programme NRP61* (p. 300). vdf Hochschulverlag AG an der ETH Zürich.

Nüsser, M., Dame, J., Kraus, B., Baghel, R., & Schmidt, S. (2019). Socio-hydrology of "artificial glaciers" in Ladakh, India: Assessing adaptive strategies in a changing cryosphere. *Regional Environmental Change*, *19*(5), 1327–1337. https://doi.org/10.1007/s10113-018-1372-0

Nüsser, M., & Schmidt, S. (2017). Nanga Parbat revisited: Evolution and dynamics of Sociohydrological interactions in the northwestern Himalaya. *Annals of the American Association of Geographers*, *107*(2), 403–415. https://doi.org/10.1080/24694452.2016.1235495

Orlove, B., Milch, K., Zaval, L., Ungemach, C., Brugger, J., Dunbar, K., & Jurt, C. (2019). Framing climate change in frontline communities: Anthropological insights on how mountain dwellers in the USA, Peru, and Italy adapt to glacier retreat. *Regional Environmental Change*, *19*(5), 1295–1309. https://doi.org/10.1007/s10113-019-01482-y

Ossendorf, G., Groos, A. R., Bromm, T., Tekelemariam, M. G., Glaser, B., Lesur, J., Schmidt, J., Akçar, N., Bekele, T., Beldados, A., Demissew, S., Kahsay, T. H., Nash, B. P., Nauss, T., Negash, A., Nemomissa, S., Veit, H., Vogelsang, R., Woldu, Z., … Miehe, G. (2019). Middle stone age foragers resided in high elevations of the glaciated Bale Mountains, Ethiopia. *Science*, *365*(6453), 583–587. https://doi.org/10.1126/science.aaw8942

Ostrom, E. (2010). Polycentric systems for coping with collective action and global environmental change. *Global Environmental Change*, *20*(4), 550–557. https://doi.org/10.1016/j.gloenvcha.2010.07.004

Otto, J.-C. (2019). Proglacial lakes in high mountain environments. In D. Heckmann & M. Tobias (Eds.), *Geomorphology of proglacial systems* (pp. 231–247). Springer.

Palomo, I. (2017). Climate change impacts on ecosystem services in high mountain areas: A literature review. *Mountain Research and Development*, *37*(2), 179–187. https://doi.org/10.1659/MRD-JOURNAL-D-16-00110.1

Patrick, R., & Bharadwaj, L. (2016). Mining and campesino engagement: An opportunity for integrated water resources management in Ancash, Peru. *Water International*, *41*(3), 468–482. https://doi.org/10.1080/02508060.2016.1160311

Penny, D., & Beach, T. P. (2021). Historical socioecological transformations in the global tropics as an Anthropocene analogue. *Proceedings of the National Academy of Sciences*, *118*(40), e2022211118. https://doi.org/10.1073/pnas.2022211118

Pepin, N., Bradley, R. S., Diaz, H. F., Baraer, M., Caceres, E. B., Forsythe, N., Fowler, H., Greenwood, G., Hashmi, M., Liu, X., Miller, J., Ning, L., Ohmura, A., Palazzi, E., Rangwala, I., Schöner, W., Severskiy, I., Shahgedanova, M., Wang, M., & Yang, D. Q. (2015). Elevation-dependent warming in mountain regions of the world. *Nature Climate Change*, *5*(5), 424–430. https://doi.org/10.1038/nclimate2563

Polk, M. H. (2016). *"They are drying out": Social-ecological consequences of glacier recession on mountain Peatlands in*. Huascarán National Park.

Polk, M. H., Young, K. R., Baraer, M., Mark, B. G., McKenzie, J. M., Bury, J., & Carey, M. (2017). Exploring hydrologic connections between tropical mountain wetlands and glacier recession in Peru's cordillera Blanca. *Applied Geography*, *78*, 94–103. https://doi.org/10.1016/j.apgeog.2016.11.004

Postigo, J. C., Young, K. R., & Crews, K. A. (2008). Change and continuity in a pastoralist community in the high Peruvian Andes. *Human Ecology*, *36*(4), 535–551. https://doi.org/10.1007/s10745-008-9186-1

Qin, Y., Abatzoglou, J. T., Siebert, S., Huning, L. S., AghaKouchak, A., Mankin, J. S., Hong, C., Tong, D., Davis, S. J., & Mueller, N. D. (2020). Agricultural risks from changing snowmelt. *Nature Climate Change*, *10*(5), 459–465. https://doi.org/10.1038/s41558-020-0746-8

Rabatel, A., Francou, B., Soruco, A., Gomez, J., Cáceres, B., Ceballos, J. L., Basantes, R., Vuille, M., Sicart, J.-E., Huggel, C., Scheel, M., Lejeune, Y., Arnaud, Y., Collet, M., Condom, T., Consoli, G., Favier, V., Jomelli, V., Galárraga-Sánchez, R., & Wagnon, P. (2013). Current state of glaciers in the tropical Andes: A multi-century perspective on glacier evolution and climate change. *The Cryosphere*, *7*(1), 81–102. https://doi.org/10.5194/tc-7-81-2013

Rasmussen, M. B. (2016a). Reclaiming the lake: Citizenship and environment-as-common-property in highland Peru. *Focaal*, *2016*(74), 13–27. https://doi.org/10.3167/fcl.2016.740102

Rasmussen, M. B. (2016b). Unsettling times living with the changing horizons of the Peruvian Andes. *Latin American Perspectives*, *43*(4), 73–86. https://doi.org/10.1177/0094582X16637867

Rasmussen, M. B. (2018). Rewriting conservation landscapes: Protected areas and glacial retreat in the high Andes. *Regional Environmental Change*, *15*, 1371–1385. https://doi.org/10.1007/s10113-018-1376-9

Rasul, G., & Molden, D. (2019). The global social and economic consequences of mountain cryospheric change. *Frontiers in Environmental Science*, *7*, 91. https://doi.org/10.3389/fenvs.2019.00091

RGI Consortium. (2017). Randolph glacier inventory: A dataset of global glacier outlines, Version 6.0. GLIMS Technical report. Colorado, USA. Digital Media. http://www.glims.org/RGI/Randolph60.html

Richardson, S. D., & Reynolds, J. M. (2000). An overview of glacial hazards in the Himalayas. *Quaternary International*, *66*, 31–47. https://doi.org/10.1016/S1040-6182(99)00035-X

Roe, G. H., Christian, J. E., & Marzeion, B. (2021). On the attribution of industrial-era glacier mass loss to anthropogenic climate change. *The Cryosphere*, *15*(4), 1889–1905. https://doi.org/10.5194/tc-15-1889-2021

Romeo, R., Vita, A., Testolin, R., & Hofer, T. (2015). *Mapping the vulnerability of mountain peoples to food insecurity*. FAO.

Rosvold, J. (2018). Faunal finds from alpine ice: Natural or archaeological depositions? *Journal of Glacial Archaeology*, *3*, 79–108. https://doi.org/10.1558/jga.32414

Rubel, F., Brugger, K., Haslinger, K., & Auer, I. (2017). The climate of the European Alps: Shift of very high resolution Köppen-Geiger climate zones 1800-2100. *Meteorologische Zeitschrift*, *26*(2), 115–125. https://doi.org/10.1127/metz/2016/0816

Salim, E., Mourey, J., Ravanel, L., Picco, P., & Gauchon, C. (2019). Mountain guides facing the effects of climate change. What perceptions and adaptation strategies at the foot of Mont Blanc? *Journal of Alpine Research*, *107-4*, 1–14. https://doi.org/10.4000/rga.5865

Salim, E., & Ravanel, L. (2020). Last chance to see the ice: Visitor motivation at montenvers-mer-de-glace, French Alps. *Tourism Geographies*, *1*, 1–23. https://doi.org/10.1080/14616688.2020.1833971

Salim, E., Ravanel, L., Deline, P., & Gauchon, C. (2021). A review of melting ice adaptation strategies in the glacier tourism context. *Scandinavian Journal of Hospitality and Tourism*, *1*, 1–18. https://doi.org/10.1080/15022250.2021.1879670

Sayre, M., Stenner, T., & Argumedo, A. (2017). You can't grow potatoes in the sky: Building resilience in the face of climate change in the Potato Park of Cuzco, Peru. *Culture, Agriculture, Food and Environment*, *39*(2), 100–108. https://doi.org/10.1111/cuag.12100

Schaefli, B., Manso, P., Fischer, M., Huss, M., & Farinotti, D. (2019). The role of glacier retreat for Swiss hydropower production. *Renewable Energy*, *132*, 615–627. https://doi.org/10.1016/j.renene.2018.07.104

Scherrer, D., & Körner, C. (2011). Topographically controlled thermal-habitat differentiation buffers alpine plant diversity against climate warming. *Journal of Biogeography*, *38*(2), 406–416. https://doi.org/10.1111/j.1365-2699.2010.02407.x

Schmidt, S. K., Nemergut, D. R., Todd, B. T., Lynch, R. C., Darcy, J. L., Cleveland, C. C., & King, A. J. (2012). A simple method for determining limiting nutrients for photosynthetic crusts. *Plant Ecology and Diversity*, *5*(4), 513–519. https://doi.org/10.1080/17550874.2012.738714

Schönswetter, P., Stehlik, I., Holderegger, R., & Tribsch, A. (2005). Molecular evidence for glacial refugia of mountain plants in the European Alps. *Molecular Ecology*, *14*(11), 3547–3555. https://doi.org/10.1111/j.1365-294X.2005.02683.x

Shean, D. E., Bhushan, S., Montesano, P., Rounce, D. R., Arendt, A., & Osmanoglu, B. (2020). A systematic, regional assessment of High Mountain Asia glacier mass balance. *Frontiers in Earth Science*, *7*, 363. https://doi.org/10.3389/feart.2019.00363

Sherry, J., Curtis, A., Mendham, E., & Toman, E. (2018). Cultural landscapes at risk: Exploring the meaning of place in a sacred valley of Nepal. *Global Environmental Change*, *52*, 190–200. https://doi.org/10.1016/j.gloenvcha.2018.07.007

Sietz, D., & Feola, G. (2016). Resilience in the rural Andes: Critical dynamics, constraints and emerging opportunities. *Regional Environmental Change*, *16*(8), 2163–2169. https://doi.org/10.1007/s10113-016-1053-9

Skarbø, K., & Vandermolen, K. (2014). Irrigation access and vulnerability to climate-induced hydrological change in the Ecuadorian Andes. *Culture, Agriculture, Food and Environment*, *36*(1), 28–44. https://doi.org/10.1111/cuag.12027

Speed, J. D. M., Austrheim, G., Hester, A. J., & Mysterud, A. (2012). Elevational advance of alpine plant communities is buffered by herbivory. *Journal of Vegetation Science*, *23*(4), 617–625. https://doi.org/10.1111/j.1654-1103.2012.01391.x

Temme, A. J. A. M. (2019). The uncalm development of proglacial soils in the European Alps since 1850. In D. Heckmann & M. Tobias (Eds.), *Geomorphology of proglacial systems* (pp. 315–326). Springer.

Thompson, L. G., Brechera, H. H., Mosley-Thompson, E., Hardy, D. R., & Mark, B. G. (2009). Glacier loss on Kilimanjaro continues unabated. *Proceedings of the National Academy of Sciences of the United States of America*, *106*(47), 19770–19775. https://doi.org/10.1073/pnas.0906029106

Thompson, L. G., Davis, M. E., Mosley-Thompson, E., Porter, S. E., Corrales, G. V., Shuman, C. A., & Tucker, C. J. (2021). The impacts of warming on rapidly retreating high-altitude, low-latitude glaciers and ice core-derived climate records. *Global and Planetary Change*, *203*, 103538. https://doi.org/10.1016/j.gloplacha.2021.103538

Thorn, J. P. R., Klein, J. A., Steger, C., Hopping, K. A., Capitani, C., Tucker, C. M., Reid, R. S., & Marchant, R. A. (2021). Scenario archetypes reveal risks and opportunities for global mountain futures. *Global Environmental Change*, *69*, 102291. https://doi.org/10.1016/j.gloenvcha.2021.102291

Tierney, J. E., Poulsen, C. J., Montañez, I. P., Bhattacharya, T., Feng, R., Ford, H. L., … Zhang, Y. G. (2020). Past climates inform our future. *Science*, *370*(6517). https://doi.org/10.1126/science.aay3701

Troll, C. (1971). Landscape ecology (geoecology) and biogeocenology: A terminological study. *Geoforum*, *8*, 43–46. https://doi.org/10.1016/0016-7185(71)90029-7

Tucker, C. M., Alcántara-Ayala, I., Gunya, A., Jimenez, E., Klein, J. A., Xu, J., & Bigler, S. L. (2021). Challenges for governing mountains sustainably: Insights from a global survey. *Mountain Research and Development*, *41*(2), R10–R20. https://doi.org/10.1659/mrd-journal-d-20-00080.1

Turner, B. L., Kasperson, R. E., Matsone, P. A., McCarthy, J. J., Corell, R. W., Christensene, L., Eckley, N., Kasperson, J. X., Luers, A., Martello, M. L., Polsky, C., Pulsipher, A., & Schiller, A. (2003). A framework for vulnerability analysis in sustainability science. *Proceedings of the National Academy of Sciences of the United States of America*, *100*(14), 8074–8079. https://doi.org/10.1073/pnas.1231335100

United Nations Conference on Environment and Development (UNCED). (1992). *Agenda 21*. UN.

United Nations Conference on Sustainable Development (UNCSD). (2012). *The future we want*. UNCSD.

Veettil, B. K., & Wang, S. (2018). State and fate of the remaining tropical mountain glaciers in australasia using satellite imagery. *Journal of Mountain Science*, *15*(3), 495–503. https://doi.org/10.1007/s11629-017-4539-0

Vergara, W., Deeb, A. M., Valencia, A. M., Bradley, R. S., Francou, B., Zarzar, A., Grunwaldt, A., & Haeussling, S. M. (2007). Economic impacts of rapid glacier retreat in the Andes. *Eos*, *88*(25), 2–4. https://doi.org/10.1029/2007EO250001

Viviroli, D., Kummu, M., Meybeck, M., Kallio, M., & Wada, Y. (2020). Increasing dependence of lowland populations on mountain water resources. *Nature Sustainability*, *3*(11), 917–928. https://doi.org/10.1038/s41893-020-0559-9

Vuille, M., Carey, M., Huggel, C., Buytaert, W., Rabatel, A., Jacobsen, D., Soruco, A., Villacis, M., Yarleque, C., Timm, O., Condom, T., Salzmann, N., & Sicart, J. E. (2018). Rapid decline of snow and ice in the tropical Andes: Impacts, uncertainties and challenges ahead. *Earth-Science Reviews*, *176*, 195–213. https://doi.org/10.1016/j.earscirev.2017.09.019

Wang, S., He, Y., & Song, X. (2010). Impacts of climate warming on alpine glacier tourism and adaptive measures: A case study of Baishui glacier no. 1 in Yulong Snow Mountain, southwestern China. *Journal of Earth Science*, *21*(2), 166–178. https://doi.org/10.1007/s12583-010-0015-2

Wang, S. J., & Zhou, L. Y. (2019). Integrated impacts of climate change on glacier tourism. *Advances in Climate Change Research*, *10*(2), 71–79. https://doi.org/10.1016/j.accre.2019.06.006

Wang, X., Liu, Q., Liu, S., & He, G. (2020). Manifestations and mechanisms of mountain glacier-related hazards. *Sciences in Cold and Arid Regions*, *12*(6), 436–446. https://doi.org/10.3724/SP.J.1226.2020.00436

Weiss, E. B. (1989). *In fairness to future generations*. Brill Nijhoff.

Welling, J. T., Árnason, Þ., & Ólafsdottír, R. (2015). Glacier tourism: A scoping review. *Tourism Geographies*, *17*(5), 635–662. https://doi.org/10.1080/14616688.2015.1084529

Wells, G., Dugmore, A., Beach, T., Baynes, E., Sæmundsson, Þ., & Luzzadder-Beach, S. (in press). Reconstructing glacial outburst floods (jökulhlaups) from geomorphology: Challenges, solutions, and an enhanced interpretive framework. *Progress in Physical Geography*.

Whyte, K., Caldwell, C., & Schaefer, M. (2018). Indigenous lessons about sustainability are not just for "all humanity". In K. Whyte, C. Caldwell, & M. Schaefer (Eds.), *Sustainability* (pp. 149–179). New York University Press.

Williams, J. W., Ordonez, A., & Svenning, J. C. (2021). A unifying framework for studying and managing climate-driven rates of ecological change. *Nature Ecology and Evolution*, *5*(1), 17–26. https://doi.org/10.1038/s41559-020-01344-5

Wise, R. M., Fazey, I., Stafford Smith, M., Park, S. E., Eakin, H. C., Archer Van Garderen, E. R. M., & Campbell, B. (2014). Reconceptualising adaptation to climate change as part of pathways of change and response. *Global Environmental Change*, *28*, 325–336. https://doi.org/10.1016/j.gloenvcha.2013.12.002

Wojcik, R., Eichel, J., Bradley, J. A., & Benning, L. G. (2021). How allogenic factors affect succession in glacier forefields. *Earth-Science Reviews*, *218*, 103642. https://doi.org/10.1016/j.earscirev.2021.103642

World Summit on Sustainable Development (WSSD). (2002). *Plan of implementation of the world summit on sustainable development*. UN.

Xu, J., Grumbine, R. E., Shrestha, A., Eriksson, M., Yang, X., Wang, Y., & Wilkes, A. (2009). The melting Himalayas: Cascading effects of climate change on water, biodiversity, and livelihoods. *Conservation Biology*, *23*(3), 520–530. https://doi.org/10.1111/j.1523-1739.2009.01237.x

You, J., Qin, X., Ranjitkar, S., Lougheed, S. C., Wang, M., Zhou, W., Ouyang, D., Zhou, Y., Xu, J., Zhang, W., Wang, Y., Yang, J., & Song, Z. (2018). Response to climate change of montane herbaceous plants in the genus Rhodiola predicted by ecological niche modelling. *Scientific Reports*, *8*(1), 1–12. https://doi.org/10.1038/s41598-018-24360-9

Young, K. R., & Duchicela, S. (2020). Abandoning holocene dreams: Proactive biodiversity conservation in a changing world. *Annals of the American Association of Geographers*, *1*, 1–9. https://doi.org/10.1080/24694452.2020.1785833

Young, K. R., Ponette-González, A. G., Polk, M. H., & Lipton, J. K. (2017). Snowlines and treelines in the tropical Andes. *Annals of the American Association of Geographers*, *107*(2), 429–440. https://doi.org/10.1080/24694452.2016.1235479

Zawierucha, K., & Shain, D. H. (2019). Disappearing Kilimanjaro snow—Are we the last generation to explore equatorial glacier biodiversity? *Ecology and Evolution*, *9*(15), 8911–8918. https://doi.org/10.1002/ece3.5327

Zekollari, H., Huss, M., & Farinotti, D. (2019). Modelling the future evolution of glaciers in the European Alps under the EURO-CORDEX RCM ensemble. *The Cryosphere*, *13*(4), 1125–1146. https://doi.org/10.5194/tc-13-1125-2019

Zekollari, H., Huss, M., & Farinotti, D. (2020). On the imbalance and response time of glaciers in the European Alps. *Geophysical Research Letters*, *47*(2), 1–9. https://doi.org/10.1029/2019GL085578

Zemp, M., Huss, M., Thibert, E., Eckert, N., McNabb, R., Huber, J., Barandun, M., Machguth, H., Nussbaumer, S. U., Gärtner-Roer, I., Thomson, L., Paul, F., Maussion, F., Kutuzov, S., & Cogley, J. G. (2019). Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016. *Nature*, *568*(7752), 382–386. https://doi.org/10.1038/s41586-019-1071-0

Zheng, G., Allen, S. K., Bao, A., Ballesteros-Cánovas, J. A., Huss, M., Zhang, G., Li, J., Yuan, Y., Jiang, L., Yu, T., Chen, W., & Stoffel, M. (2021). Increasing risk of glacial lake outburst floods from future third pole deglaciation. *Nature Climate Change*, *11*(5), 411–417. https://doi.org/10.1038/s41558-021-01028-3

Zimmer, A., Meneses, R. I., Rabatel, A., Soruco, A., Dangles, O., & Anthelme, F. (2018). Time lag between glacial retreat and upward migration alters tropical alpine communities. *Perspectives in Plant Ecology, Evolution and Systematics*, *30*, 89–102. https://doi.org/10.1016/j.ppees.2017.05.003

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

How to cite this article: Zimmer, A., Beach, T., Klein, J. A., & Recharte Bullard, J. (2022). The need for stewardship of lands exposed by deglaciation from climate change. *Wiley Interdisciplinary Reviews: Climate Change*, *13*(2), e753. https://doi.org/10.1002/wcc.753