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Closing the Adaptation Gap in Mountains

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Over 1 billion people are living at the frontlines of climate change in mountain areas, where warming rates outpace the global average and are driving significant changes in environments and ecosystem services. These changes are exacerbating socioeconomic difficulties faced by many mountain communities, and are already intensifying vulnerabilities across mountain areas globally. The situation is indicative of pervasive and consequential deficits in adaptation, and calls attention to the need for a better understanding of existing adaptation efforts, as well as the prospects for increasing the quantity and quality of adaptation action in mountain regions. In response, this MountainAgenda article introduces a conceptual framework for adaptation gaps. It then uses data from 2 major global-scale adaptation reviews to shed light on the nature and true magnitude of the adaptation gap in mountains. It reveals shortcomings in available adaptation options, deficits in the uptake of existing adaptation support, and a general lack of coherence between existing adaptations and keystone global agreements relevant to climate change adaptation. These shortcomings are largely related to soft limits to adaptation that constrain responses across mountain areas. In this article, we provide recommendations for closing the adaptation gap in mountains and suggest that this will require deeply collaborative efforts that are rooted in local needs, aspirations, and ways of knowing, but that are also supported by external capacity building and implementation resources. In many instances, this will resemble a transformative approach to adaptation. The conceptual framework presented here is broadly applicable and can also be utilized to identify and close adaptation gaps in social-ecological contexts beyond mountains.

Keywords: *mountains; climate change; adaptation; gaps; limits.*

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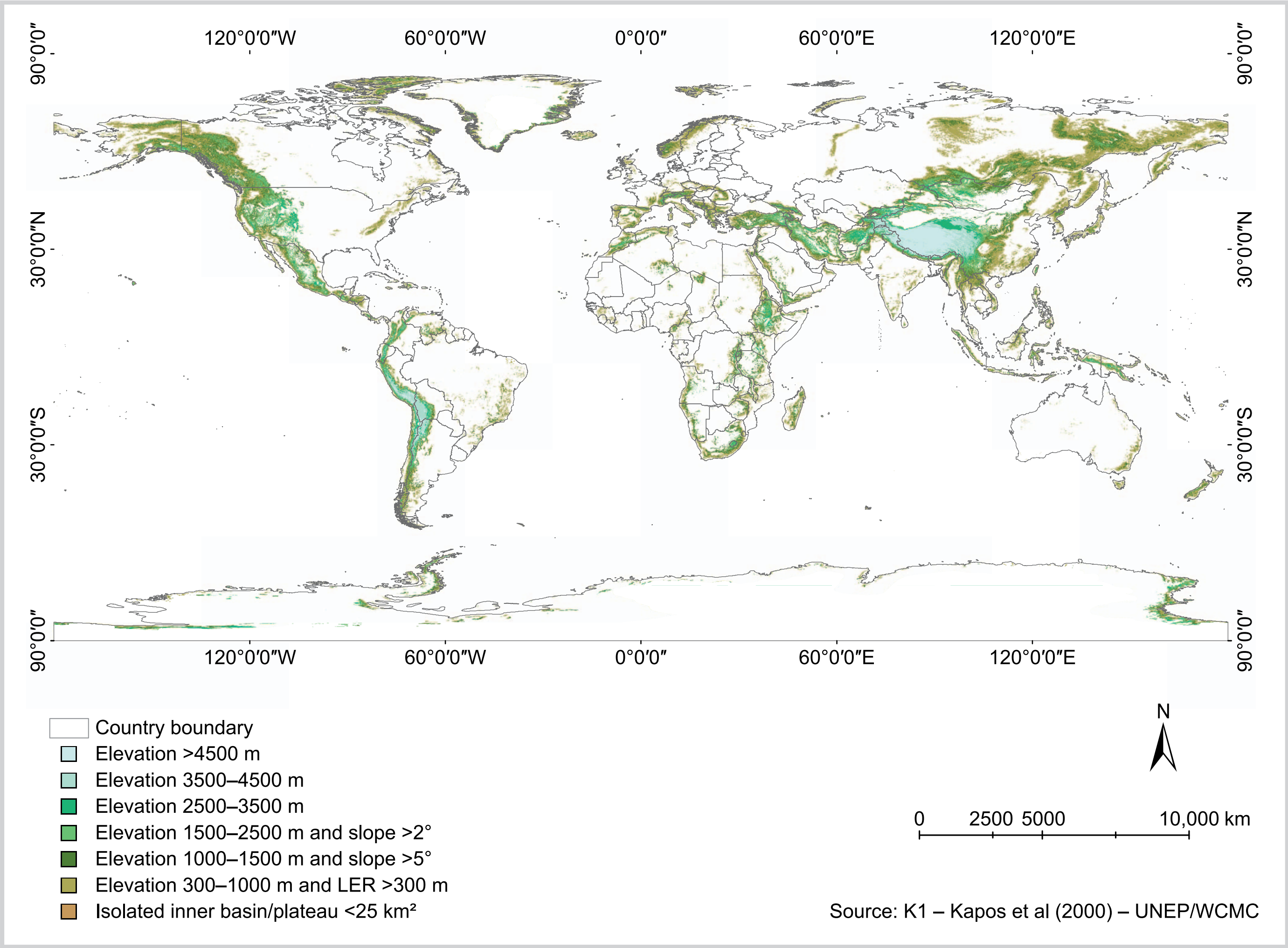
Introduction

Adaptation in mountain areas is an urgent priority. Warming rates in many mountain areas are higher than the global average (Pepin et al 2015; Palazzi et al 2019), leading to the rapid recession of mountain glaciers, changes in the availability and quality of freshwater, increases in geophysical hazards, and alterations of mountain ecosystems (Hock et al 2019). Such changes are projected to intensify in coming years, but they are already impacting mountain biodiversity, eroding ecosystem services, and increasing risks associated with living in mountains, compounding the socioeconomic difficulties already gripping many mountain populations (Hock et al 2019; Romeo et al 2020). Indeed, harmful effects of climate change are now widely observed across mountain geographies (Hock et al 2019). These include changing glacio-hydrological dynamics in the tropical Andes, jeopardizing community and industrial water resources, hydropower generation, and ecosystem services (Vuille et al 2018); declining snow cover in the Alps, adversely affecting tourism and recreation activities (Spandre et al 2019); and glacial lake outburst floods in the Himalayas, leading to the loss of life and property (Harrison et al 2018). The situation is indicative of pervasive and consequential deficits in adaptation action in mountain areas globally. It calls attention to the pressing need to know more about the characteristics of existing adaptation efforts, as well as prospects for increasing the quantity and quality of adaptation action in mountain communities at the frontlines of climate change (McDowell et al 2019, 2020). The lives of more than 1 billion people living in mountain areas are at stake (Romeo et al 2020).

In this MountainAgenda article, we show how a focus on adaptation gaps can enrich understanding of the relationship between adaptation and mitigation, the characteristics of existing adaptation efforts, and strategic

FIGURE 1 Distribution of mountain areas globally according to the Kapos et al (2000) definition of mountains. Greenland and Antarctic ice sheets excluded.



opportunities for ensuring more just and sustainable futures for those living in mountain areas. This is accomplished by introducing a conceptual framework for adaptation gaps and then bringing this framework to life with data from 2 global-scale adaptation review efforts. These include our mountain-focused re-analysis of data from the Global Adaptation Mapping Initiative (GAMI) (Berrang-Ford et al in press) as well as our first-of-its-kind assessment of major adaptation support programs relevant to advancing adaptation efforts in mountain areas (for full methodological details and datasets, see Appendices S1, S2, and S3, *Supplemental material*, https://doi.org/10.1659/MRD-JOURNAL-D-21-00033.1.S1, https://doi.org/10.1659/MRD-JOURNAL-D-21-00033.1.S2, https://doi.org/10.1659/MRD-JOURNAL-D-21-00033.1.S3). Our work is guided by the definition of adaptation proposed by Moser and Ekstrom (2010):

> *Adaptation involves changes in social-ecological systems in response to actual and expected impacts of climate change in the context of interacting non-climatic changes. Adaptation strategies and actions can range from short-term coping to longer-term, deeper transformations, aim to meet more than climate change goals alone, and may or may not succeed in moderating harm or exploiting beneficial opportunities.* (p 22026)

Data collection and analysis were carried out in relation to the Kapos et al (2000) definition of mountains, which indicates that mountains cover 24% of Earth's land surface (Figure 1). However, we emphasize that mountains provide goods, services, and meaning far beyond their borders (Körner and Ohsawa 2005; Schirpke et al 2019; Viviroli et al 2020), making human adaptation among the stewards of high places an issue of global concern.

Conceptualizing the adaptation gap in mountains

Our focus on adaptation gaps is informed by emerging work on adaptation assessment (eg Leiter 2015; Berrang-Ford et al 2019; Dilling et al 2019), antecedent work examining limits to adaptation (Adger et al 2009; Dow et al 2013; Eisenack et al 2014; Barnett et al 2015) and adaptation deficits (Bassett and Fogelman 2013; Dilling et al 2015; Ojha et al 2016), and, most explicitly, ideas introduced in the United Nations Environment Programme (UNEP) Adaptation Gap Report (UNEP 2014).

In our framework, the "exposure gap" refers to the difference between the magnitude of climatic stimuli and the sum of all adaptation options. We define adaptation options as including available support for formal adaptation initiatives (planned adaptations) as well as

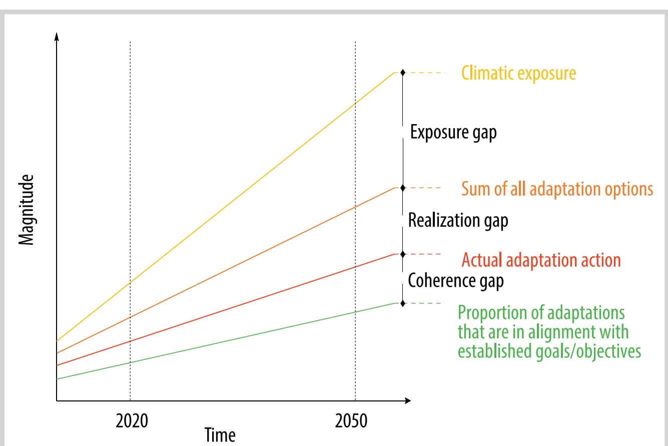
TABLE 1 Components of the adaptation gap.

Component	Description
Exposure gap	Gap between magnitude of climatic exposure and the sum of all adaptation options
Realization gap	Gap between all adaptation options and actual adaptation action
Coherence gap	Gap between actual adaptation action and proportion of adaptations that are in alignment with established goals/objectives

responses carried out without a formal adaptation plan (autonomous adaptations) that have an explicit but not necessarily exclusive focus on addressing climate change. The upper threshold of adaptation options is reached when hard limits, such as the loss of Indigenous languages and associated knowledges or the demise of glacier-fed rivers, render further adaptation action infeasible, ineffective, or unacceptable (eg further adaptation will entail unacceptable losses and damages). Notwithstanding hard limits, the ability of social actors to realize currently available options is also constrained by soft limits, such as poor access to higher education, information, or financial capital. This can impede efforts to mobilize existing adaptation support or to enact locally appropriate autonomous adaptations. We term the difference between potential and actual levels of adaptation the "realization gap." Adaptations can also fall short in terms of their alignment with priorities and goals established in global agreements relevant to adaptation, such as the Paris Agreement's Global Goal on Adaptation. Such responses can prove maladaptive in the long term, entrenching existing inequities or resulting in adverse ecological outcomes. We term this the "coherence gap." Here, deficiencies can also be related to soft limits to adaptation that hinder the capacity of actors to respond in accordance with key tenets of global agreements. The "total adaptation gap" is the sum of the exposure, realization, and coherence gaps (Table 1; Figure 2).

Adaptation gaps are context and scale specific and will differ across mountain social-ecological systems. For example, the realization gap might be particularly large in areas where social conditions inhibit adaptation action, while the gap might be much smaller in areas where high levels of social capital foster high adaptive capacity. Gaps are also dynamic and nonlinear over time and will evolve as climatic and social conditions change. For example, *ceteris paribus*, moving along an RCP 2.6 emissions pathway will reduce the exposure gap, increasing the utilization of available adaptation resources will decrease the realization gap, and enhancing efforts to align adaptation actions with established priorities and goals for adaptation will reduce the coherence gap. Importantly, however, progress on these constituent dimensions must be made in concert; it is not sufficient, for example, to close the realization gap if a coherence gap persists. Furthermore, despite being malleable in principle, both soft and hard limits to adaptation can impede progress toward closing gaps, with hard limits suggesting the possibility of inevitable losses and damages in mountain areas (Huggel et al 2019).

FIGURE 2 Conceptual framework for adaptation gaps. Straight lines in the figure are for illustrative purposes only. Actual gaps will be nonlinear over time and can expand or contract as social and climatic conditions evolve.



Taken together, our conceptual framework helps us to understand the nature and true magnitude of the adaptation gap in mountains. This includes the fact that the extent of robust adaptation action might be quite limited, despite apparently high levels of available adaptation support and actual adaptation action. It also provides insights into where positive interventions are possible, and where social and biophysical limits are likely to mean that incremental adaptation efforts are insufficient and transformative changes are necessary or inevitable.

Existing adaptation gaps in mountains

Adaptation baseline

A definition of adaptation gaps in mountains requires establishment of a baseline for the level and characteristics of current adaptations (see red line at year 2020 in Figure 2). To determine this baseline, we identified studies from the GAMI dataset that reported information about adaptations in mountain areas ($n = 423$ articles). Our re-analysis results are broadly consistent with those reported in other global-scale systematic reviews of adaptation in high mountain areas (ie those with permanent ice cover) (McDowell et al 2014, 2019; Rasul et al 2019). However, our work extended findings from prior systematic reviews by including information about adaptation from both high mountain areas—the focus of earlier analyses—as well as the large areas of lower elevation mountains outside of the cryosphere (ie all mountain areas globally according to the definition of Kapos et al 2000).

Our analysis revealed several notable characteristics of adaptations presently observed in mountain areas globally. For example, most adaptations are documented in the mountain areas of Asia (39%), followed by Africa (37%), and Central and South America (11%), and they are primarily led by individuals or households engaged in smallholder agriculture and/or pastoralism. Initiatives led by local governments (31%) and subnational or local civil society actors (29%) are less common. Around two thirds of adaptation actions are autonomous rather than planned (note that local autonomous responses can be based on formal community-level planning processes and implemented in ways that are considered to be formal in their respective sociocultural contexts). These findings may be somewhat biased by the nature of adaptation literature, which tends to focus on case studies in the global South, leading to underreporting of formal adaptation programs in Europe, for example. The climatic stimuli most commonly motivating adaptations are drought (69%), precipitation variability (57%), and extreme heat (37%). Other common climatic stimuli include changes in water supply, quality, and quantity, often associated with changes in glaciers and snowpacks, increased prevalence of pests and diseases, and enhanced seasonal unpredictability. However, adaptation efforts frequently address multiple stressors simultaneously, including socioeconomic pressures, pollution, and deforestation, which compound climate-related challenges. Most adaptations are behavioral/cultural in nature (84%), followed by ecosystem-based (64%), and technological or infrastructural (61%). These include changes to pastoralist migration patterns in the Himalayas (Joshi et al 2013; Li et al 2017), collaborative watershed management in the Andes (Hellin et al 2018; Lindsay 2018), household-scale natural hazard risk reduction in the Alps (Reichel and Frömming 2014; Thaler and Seebauer 2019), and the adoption of soil conservation practices in the East African highlands (Salat and Swallow 2018; Chesterman et al 2019). Around 69% of reported adaptations provide evidence of reducing risk or vulnerabilities, most commonly by improving financial security through livelihood diversification, enhancing water and food security, increasing agricultural productivity, and reducing exposure to hazards. However, evidence of transformative adaptations is limited—62% of adaptations are characterized by a limited depth of change, and 70% of adaptations are characterized by a limited scale of change. These results emphasize that most adaptations extend or modify existing practices in response to immediate shocks and stresses, rather than fostering systemic or structural changes capable of ameliorating entrenched socioeconomic difficulties that underpin the vulnerability of many mountain people. This is consistent with prior mountain-focused adaptation review work, where incremental responses to change are most commonly reported.

Existing exposure gap

Elevation-dependent warming in mountain regions is complex and insufficiently understood, but it is already leading to rates of warming in many mountain areas that exceed global averages (Pepin et al 2015; Hock et al 2019; Palazzi et al 2019). This is leading to profound changes in glacial environments, alpine hydrology, and mountains ecosystems, changes that are already being reflected in agriculture, water resources, energy production, tourism, increased natural hazards, and effects on intangible relationships with mountain places (Carey et al 2017; Huss et al 2017; Huggel et al 2019). Climatic exposures in mountain regions are already among the most significant observed globally, and they are only projected to intensify over the course of the next century (Hock et al 2019). At the high end of emission scenarios (RCP 8.5), this could lead to increases of up to 10°C in summer season temperatures compared to preindustrial levels in several mountain regions by the end of the century (Hock et al 2019). Even with aggressive mitigation action, it is unlikely that warming can be kept below 1.5°C by 2100 for most mountain areas; in fact, many mountain regions have already passed this level of warming (Masson-Delmotte et al 2018; Hock et al 2019).

To characterize the available adaptation options aspect of the exposure gap in relation to planned adaptations, we conducted a global-scale review that aimed to identify and characterize all major adaptation support programs relevant to advancing adaptation efforts in mountain areas. Major adaptation support programs were selected to establish this reference point because they are relatively straightforward to identify, tend to have websites where program details can be easily found, and, together, represent the majority of available support for adaptation globally. Specifically, our review targeted programs organized by the United Nations Framework Convention on Climate Change (UNFCCC), national governments, multi- and bilateral aid arrangements, the private sector, and nongovernmental organizations (NGOs). We identified 309 major adaptation support programs relevant to mountains. Of these programs, multilateral initiatives were most numerous (35%), followed by bilateral (24%) and NGO initiatives (17%). Importantly, however, the number of programs is not necessarily correlated with the amount of support available. For example, while there are only a few major support programs organized under the banner of the UNFCCC (eg Adaptation Fund) (4%), these programs are especially significant in terms of the amount of support provided. Private sector adaptation programs remain limited, although such programs appear to be growing in importance (DiBella 2020; UNFCCC 2021). Capacity building is the most common type of support available (44%) from existing adaptation programs, followed very closely by a mixed support model, where capacity building and implementation support are both provided (42%). Fewer programs focus exclusively on implementation (14%). There is a wide variety of support types within the broad categories of "capacity building" and "implementation," including knowledge exchange, training, evaluation support, funding, technical assistance, and material support (Table 2; for full review results and list of adaptation programs, see Appendices S1 and S3, *Supplemental material*, https://doi.org/10.1659/MRD-JOURNAL-D-21-00033.1.S1, https://doi.org/10.1659/MRD-JOURNAL-D-21-00033.1.S3).

It is also important to consider the potential scope of autonomous activities when characterizing adaptation options. Many communities have deep, place-based resilience that can be drawn upon to implement locally appropriate adaptations (Ford et al 2020), for example, mobilizing Indigenous knowledge to adapt agricultural and pastoral activities in ways that are consistent with context-specific social-ecological realities, drawing on knowledge of local hydrological systems to identify and access more reliable water sources, or using locally available materials to construct flood protection infrastructure (Ingty 2017; Iwama et al 2021). Notwithstanding the apparently high potential for both planned and autonomous adaptation in mountain

TABLE 2 Illustrative major adaptation support programs relevant to mountains by type.

Program type	Program name
UNFCCC	Adaptation Fund (AF)
Multilateral (non-UNFCCC)	The European Union Strategy for the Alpine Region (EUSALP)
Bilateral	Asia-Pacific Climate Change Adaptation Platform
Government	Building Regional Adaptation Capacity and Expertise (BRACE) Program
Private sector	Adaptation for Smallholders to Climate Change (AdapCC)
NGO/civil society	Oxfam Climate Change Adaptation Initiative

Note: UNFCCC, United Nations Framework Convention on Climate Change; NGO, nongovernmental organization.

areas, the high sensitivity of many mountain people to climatic stimuli combined with the severity of observed climatic changes suggest an exposure gap is already emerging in mountain areas. For example, tourism operators in Chukung, Nepal, have constructed gabions to protect lodge sites in the Lhotse glacier floodplain from englacial conduit floods. These measures, while perceived as effective in the immediate term, may not withstand the increasing frequency and magnitude of extreme weather events. Such changes may render incremental adaptation and mitigation efforts to address today's exposures insufficient to meet tomorrow's challenges (Rounce et al 2017).

Existing realization gap

The current level of actual adaptation falls short of the level of adaptation that could be achieved in principle. To characterize the realization gap in relation to planned adaptations, we examined how many of the 309 major adaptation support programs we identified had actually been utilized to advance adaptation efforts in mountain areas. We found that only around one quarter of such programs had a focus on implementing or building capacity for adaptation actions in mountainous contexts to date. This finding is indicative of soft limits to adaptation that constrain the ability of actors to identify, access, and mobilize existing resources for planned adaptations (Klein et al 2014; McDowell et al 2020). This is consistent with the predominance of autonomous adaptations identified in the GAMI data and prior reviews of adaptation in mountains. It is also highly consequential, because reviewed programs tend to have a significant focus on capacity building and implementation activities, with a high level of coordination capacity and material support, all of which can help to reduce the adaptation burden for frontline communities.

In addition, we posit that the potential level of autonomous adaptation in mountain areas is greater than observed levels documented in our re-analysis of the GAMI data. This insight is informed by research that has demonstrated the significance of socioeconomic constraints in impeding the full realization of autonomous adaptations (Adger et al 2009; Ford et al 2020). Specifically, soft limits to adaptation, such as those related to poverty and socioeconomic marginalization, can undermine the ability of communities to implement locally appropriate autonomous responses to climate change, widening the realization gap. This is not conjecture: 83% of studies reviewed as part of the GAMI re-analysis reported constraints or limits to adaptation. These included financial factors such as lack of access to credit (Basu et al 2015), barriers to accessing information, such as limited availability of climate forecasts (Son et al 2019), and impediments related to social inequities, particularly gendered division of labor and power (Ravera et al 2016). Based on these observations, we believe that there is a significant gap between the extent of possible adaptation and actual levels of adaptation in mountain areas. This finding casts light on the consequential effects of limits to adaptation for the implementation of both planned and autonomous responses to climate change.

Existing coherence gap

Notwithstanding the realization gap, the current level of adaptation action across mountain areas is significant and growing. However, existing adaptation efforts are not necessarily consistent with what is required to advance progress on the Paris Agreement's Global Goal on Adaptation, the Sustainable Development Goals, and the Sendai Framework for Disaster Risk Reduction, which are key global agreements relevant to adaptation that have been signed by a majority of United Nations (UN) member states (United Nations Climate Change Secretariat 2017). To evaluate the coherence gap we identified common tenets for adaptation that are referenced in the adaptation-relevant sections of these agreements. Namely, adaptations should (1) be guided by the best available evidence, (2) foster equitable and inclusive processes and outcomes, and (3) protect or improve environmental sustainability. Such tenets are echoed in other high-level documents, including the 2019 Safe Climate Report of the UN Special Rapporteur on Human Rights and the Environment (Boyd 2019), as well as the broader adaptation assessment literature. We evaluated adaptations from our GAMI re-analysis to characterize the current coherence gap in mountain areas, finding that many still lack coherence with these minimum but demanding criteria (Table 3).

On the whole, our assessment of existing climatic conditions and current adaptation action in mountain areas reveals evidence of all of the constituent adaptation gaps described in our conceptual framework. This finding, along with expected trajectories of climate change, the specter of hard biophysical limits to adaptation, and the persistence of socioeconomic inequities that constrain adaptive capacity, calls attention to the immediate need for action on closing adaptation gaps in mountain areas.

TABLE 3 Coherence gap in mountains.

Crosscutting tenets for adaptation	Detailed components from global agreements	Evidence of coherence gap
1. Adaptation should be evidence-based	Adaptation should be evidence-based, guided by the best available science (PA 7.5) and (as appropriate) Indigenous and local knowledge bases (PA 7.5; SF 19g, 24i). Adaptations should emphasize transparency (PA 7.5; SDG 13a) and accessibility of information (SF 19g, 24e, 24f) and be responsive to new information to foster resilience over short and long timescales (PA 7.5; SF 15; SDG 11b).	The majority of adaptations are autonomous and reactive and are likely not informed by scientific evidence about current and future climatic changes. Most adaptations do not reference contributions from local knowledge (65%) or Indigenous knowledge (66%). The implementation stage of adaptations is frequently unclear, and only 56% of adaptation assessments in the GAMI dataset provide indicators of effectiveness, suggesting challenges in terms of both monitoring and evaluation, with implications for learning and long-term resilience.
2. Adaptation should be equitable and inclusive	Adaptation should be equitable and inclusive (SF 19d; SDG 10.2, 16.b, 16.7), recognizing and addressing the vulnerabilities of marginalized groups, including women (PA 7.5; SF 7, 7d; SDG 5.1), Indigenous Peoples (SF 7), and people experiencing poverty (PA 7.5; SDG 1.5; SF 7) in order to ensure full promotion and protection of all human rights (SF 19c). Adaptations should be implemented through collaborative processes (SF 24o) that are participatory (PA 7.5; SF 7; SDG 16.7), nondiscriminatory (SF 19d; SDG 16.b), inclusive (SF 19d; SDG 10.2, 16.7), multisectoral, and built on an "all-of-society engagement and partnership (SF 19d)" model.	Equity concerns were only considered in 52% of adaptation planning processes, and they were only targeted in 53% of adaptation initiatives. Particularly vulnerable groups received little explicit focus in adaptation efforts, including: • low-income groups (30%); • women (13%); • Indigenous Peoples (11%); • ethnic minorities (5%); • elderly people (3%); • youth (3%); • migrants (2%); and • persons with disabilities (0%). Indigenous and local knowledge was only included in 34% and 35% of adaptations, respectively.
3. Adaptation should be environmentally sustainable	Adaptation should be environmentally sustainable (PA 7.5; SF 6, 19h; SDG 14.2, 15.1, 15.4, 15.5), exhibiting coherence across environmental goals (SF 19h) to support the sustainable management of natural resources (PA 7.9e) and the resilience of vulnerable ecosystems (PA 7.5).	Most adaptions are related to food, fiber, and other ecosystem products (76%), yet only 19% of adaptations address the vulnerability of terrestrial and freshwater ecosystem services. Many adaptations (64%) are ecosystem-based efforts, but only 38% of adaptations reviewed considered the risks of maladaptation. Despite little explicit focus on maladaptation, adverse ecological impacts associated with adaptation are commonly reported (eg changes to land or water management practices that are poorly suited to local ecological and social conditions).

Note: PA, Paris Agreement Global Goal on Adaptation; SDG, Sustainable Development Goals; SF, Sendai Framework for Disaster Risk Reduction.

Closing the adaptation gap in mountains

Closing the exposure gap

The most obvious way to begin closing the exposure gap in mountains is to increase mitigation efforts. However, even with aggressive mitigation efforts, the lag between emission reductions and effects on the climate system, the magnifying effects of elevation-dependent warming in mountain areas, and the high sensitivity of many mountain communities to climatic exposures suggest that mitigation alone will not be sufficient. Accordingly, closing the exposure gap will also require increasing the availability of adaptation options in mountain areas. Encouragingly, our review of major adaptation support programs found that existing programs relevant to mountains are already fairly numerous—in principle, the level of planned adaptation in mountain areas could be quite high. Notwithstanding this finding, closing the exposure gap now and in the future will require increasing adaptation support at a rate that outpaces the intensification of climatic exposures.

Closing the realization gap

The availability of major adaptation support and the potential for high levels of autonomous adaptation are necessary but not sufficient conditions for closing the exposure adaptation gap; actual progress in this regard requires addressing the realization gap. Here, identifying, understanding, and ameliorating soft limits to adaptation are key steps.

There is growing recognition that the often bureaucratic and broadly neoliberal model that shapes many large adaptation support programs can present practical impediments to translating available support into actual adaptation action (Khan and Roberts 2013; Nightingale 2017; McDowell et al 2020). This has led to procedural bias that favors state-level access, and it reinforces an approach to adaptation that prioritizes governmental actors who are meant to act on behalf of vulnerable populations. We appreciate that adaptation assistance to states is critical for enabling adaptation programs with high capital costs, logistical complexity, and large spatial/temporal scope (eg to support the development of National Adaptation Plans), but this state-led paradigm is increasingly questioned in terms of equity, efficiency, and effectiveness (Ojha et al 2016; Eriksen et al 2021). Direct-access modalities available for some UNFCCC-related support programs, for example, are helping to establish a more democratic model for accessing adaptation support (Manuamorn and Biesbroek 2020). However, barriers such as technocratic language and complex application procedures can impede community-level efforts to identify, apply to, and benefit from available adaptation support (Fenton et al 2014; McDowell et al 2020). While key global agreements emphasize the integration of support across scales and sectors (eg coordination between state-led initiatives and local civil society efforts), evidence on the effectiveness of existing partnerships across state-nonstate actor lines is limited. Furthermore, the western scientific and developmental framing of many adaptation support programs can run counter to the worldviews and aspirations of mountain communities, rendering the conditions for formal support incongruent with local adaptation goals (Nagoda 2015). Therefore, there is also a need to broaden the scope of acceptable uses for adaptation assistance, consistent with the right to self-determination outlined in the Universal Declaration of Human Rights and the United Nations Declaration on the Rights of Indigenous Peoples. This can only happen through meaningful engagement with affected populations. Initiatives such as the Local Peoples and Indigenous People Platform of the UNFCCC are indicative of the kinds of institutional mechanisms that are needed to enhance the fit between available adaptation support and adaptation needs in frontline communities. Progress in these areas will lead to a situation that better reflects the role of nonstate actors in climate action (as recognized in the Paris Agreement) and will help to address soft limits that currently impede the full realization of planned adaptation action in mountain areas.

There is also growing appreciation for the fact that autonomous responses can be appropriate, even preferable, when local resilience is high and knowledge of context-specific social-ecological dynamics is well developed (Thornton and Manasfi 2010; Mishra et al 2019; Ford et al 2020). However, many mountain communities continue to face socioeconomic difficulties that constrain their ability to enact their own locally appropriate responses to climate change. This leads to persistent vulnerabilities and greater reliance on external actors and outside intervention—wellbeing, dignity, and autonomy can suffer. Here, poverty, the erosion of local knowledge and skills, political marginalization, and insufficient information and technology, among others, are well-documented determinants of low adaptive capacity (Engle 2011; Ford et al 2013). Addressing such issues requires a deeper approach to adaptation, one that explicitly targets preexisting social inequalities (Ribot 2011), one that is rooted in normative commitments to social and environmental justice (Boyd 2019), and one that is, where necessary, transformative rather than incremental (Feola 2015). These observations call attention to the broader political economy of adaptation, and they show that adaptation is both enabled and constrained by existing socioeconomic, cultural, and political conditions. Ultimately, creation of more enabling conditions for both autonomous and planned adaptations will be required to close the realization gap in mountain areas. Progress on the Sustainable Development Goals (SDGs) is a salient metric for whether social-ecological conditions that would enable the realization of available adaptation options are emerging.

Closing the coherence gap

While closing the realization gap is essential, without adaptations that are evidence-based, equitable, and sustainable, responses to climate change may fail to achieve their goals, have unintended consequences, or be maladaptive (Muccione et al 2016; McDowell and Koppes 2017; Eriksen et al 2021). Closing the coherence gap requires addressing observed deficiencies in adaptation action.

The predominance of autonomous and reactive adaptations suggests that most adaptations are not informed by scientific information about climate change, with the effect that they might not be properly aligned with current and future climatic stressors. Likewise, only about one third of the adaptations documented in the GAMI re-analysis were explicitly informed by local or Indigenous knowledge, suggesting that potentially relevant information has not been incorporated into existing responses to climate change. In addition, few adaptations have been formally evaluated, limiting opportunities to revise adaptation efforts as new information about successes and failures emerges. However, given the dynamic nature of climate and social conditions, particularly over longer timescales, adaptations must be capable of flexibility in response to new information. These issues can be addressed through adaptation planning processes that engage with available scientific information—key references include the "High Mountain Areas" chapter in the *Intergovernmental Panel on Climate Change (IPCC) Special Report on the Oceans and Cryosphere in a Changing Climate* (Hock et al 2019) and the forthcoming "Cross-Chapter Paper on Mountains" in the *IPCC Sixth Assessment Report*—as well as community members whose familiarity with specific mountain regions can complement scientific assessments of locally relevant climatic changes (Quincey et al 2018; McDowell et al 2021). Because adaptation needs change over time, planning processes should attend to local priorities and knowledge bases on an ongoing basis, with flexibility comprising a core tenet of capacity-building approaches. Such iterative adaptation planning and action can be facilitated through the establishment of contextually appropriate adaptation monitoring and evaluation mechanisms. Although the objectives are somewhat different, Canada's Indigenous Guardians programs provide a compelling example of how local community members might be brought into monitoring and evaluation activities (Indigenous Leadership Initiative 2020).

Limited engagement with local and Indigenous Peoples in adaptation planning processes is consistent with the fact that less than half of existing adaptations in mountain areas have an explicit focus on equity. Consequently, efforts to address differentiated and often intersectional vulnerabilities, such as those borne by poor racialized women, are few. The failure to recognize and address differentiated experiences of climate change can lead to responses that further entrench power asymmetries, increasing inequality by enabling some to adapt while others remain vulnerable (Eriksen et al 2021). Such unintended consequences can be reduced through inclusive and participatory processes that enable vulnerable people to contribute to the development, implementation, and evaluation of adaptation projects. Here, avoiding the "illusion of inclusion" is critical (Few et al 2007).

Finally, the effects of human adaptations on mountain ecosystems were not considered in most existing adaptations, suggesting that adaptations with the objective of reducing human vulnerabilities might inadvertently damage mountain ecosystems. For example, new land management practices to combat precipitation change can unintentionally impact water quality and supply, with cascading effects for aquatic and riparian ecosystems as well as people who depend on river environments for their livelihoods and wellbeing (Postigo 2014; Kassian et al 2017). Such maladaptation is indicative of the kinds of pervasive harm that can be caused when adaptations neglect context-specific social-ecological relationships and interdependencies. Closing the coherence gap will therefore require deeper engagement with these entangled dynamics, and it will have to include insights from scientific studies as well as local biocultural knowledge. Enhanced understanding of social-ecological characteristics and dynamics will also help to identify and leverage synergies among human wellbeing, ecosystem services, and biodiversity conservation (Díaz et al 2019), enhancing the overall sustainability of adaptations. The major adaptation support programs identified above provide one pathway for advancing adaptations that address concurrent social and environmental objectives, as many programs explicitly seek to advance the Paris Agreement, SDGs, or Sendai Framework.

Outlook for adaptation in mountains

The size of the total adaptation gap indicates the magnitude of the adaptation challenge in mountain areas at a given point in time. However, by breaking this challenge down into constituent adaptation gaps, we begin to see pathways for achieving more equitable, sustainable, and climate-resilient futures.

Much progress can be made in closing adaptation gaps in mountains through aggressive mitigation action and by increasing the quantity and quality of adaptations. Ultimately, however, efforts to close adaptation gaps will require addressing pervasive limits to adaptation through deliberate transformative actions, particularly to remediate social issues that have long constrained the adaptive capacity of mountain people (Kates et al 2012). Transformative adaptations targeting such soft limits could, in principle, lead to the closure of the realization and coherence gaps. Observed adaptations that address the coupled vulnerabilities of social-ecological systems, for example, through implementation of nature-based solutions, offer innovative examples of such transformation (Fedele et al 2019; Palomo et al 2021). However, there is growing recognition that trajectories of climate change will present hard biophysical limits that will make closing the exposure gap difficult or impossible, leading to detrimental consequences on natural and human systems and to undesirable social-ecological transformations.

Navigating these challenges and opportunities in practice will require moving beyond treating adaptations as either "planned" or "autonomous" and toward a deeply collaborative approach to adaptation planning and action that is rooted in local needs, aspirations, and ways of knowing but that is also supported by external capacity building and implementation resources (Muccione et al 2019). Such an approach is coherent with key tenets of the Paris Agreement, the SDGs, and the Sendai Framework, but it is rarely observed in practice. Here, the transformative knowledge sharing, coproduction, and mobilization activities being advanced by the Canadian Mountain Network are instructive (see Kassi et al 2020). Ultimately, while there are significant opportunities for closing adaptation gaps in mountains, it is unfortunately also necessary to prepare for unavoidable losses and damages. Such preparation must be based on ethical and deliberative planning processes that give voice, support, and, where appropriate, compensation to mountain residents who bear the burden of climate change.

Using an adaptation gaps framework and data from 2 global-scale adaptation reviews, this MountainAgenda article revealed shortcomings in available adaptation options, deficits in the uptake of available adaptation support, and a general lack of coherence between existing adaptations in mountains and keystone global agreements relevant to climate change adaptation. Importantly, the composition of our gaps framework and the metrics used to assess the state of adaptation are illustrative rather than definitive; others might choose to use additional metrics or to redefine the gaps we have proposed. Furthermore, we presented the framework in relation to global-scale data, but, in practice, this framework will be most useful when situated in specific social-ecological contexts. Regardless of its exact composition or focal scale, we believe an adaptation gaps framework provides a useful heuristic for examining and navigating the adaptation puzzle in (and beyond) mountain areas.

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OPEN PEER REVIEW

This article was reviewed by Ignacio Palomo and Alton Byers. The peer-review process for all MountainAgenda articles is open. In shaping target knowledge, values are explicitly at stake. The open review process offers authors and reviewers the opportunity to engage in a discussion about these values.

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Supplemental material

APPENDIX S1 Methods and results.
APPENDIX S2 GAMI re-analysis data.
APPENDIX S3 Major adaptation programs data.

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