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ORIGINAL ARTICLE

Trends in climate adaptation solutions for mountain regions

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Abstract

This study addresses the critical need for documented adaptation progress in mountain regions by reviewing recently implemented or ongoing adaptation solutions collected from the Adaptation at Altitude Solutions Portal (A@A Solution Portal). Using a data driven approach, the research explores the characteristics, feasibility, and transformative potential of these solutions. Findings reveal a predominant focus on addressing droughts and floods, aligning with the IPCC's emphasis on water-related impacts in mountains. Notably, watershed management practices emerge as popular solutions, showcasing their capacity to address multiple concerns beyond climate impacts. Education and awareness, along with land use practices, dominate the types of solutions, reflecting their positive impact on project acceptability and low associated risk of maladaptation. Agricultural land and forests are the main ecosystems where solutions are reported, with an evident association with education and awareness and land use change solutions. Most SDGs and Sendai targets are found to be addressed by the solutions emphasising the importance of documenting project experiences as way to bridge previously reported gaps between policy frameworks and on-the-ground implementation. Despite community involvement being high in many of the solutions, challenges such as gender inequality persists. While solutions often demonstrate local relevance and depth of change, upscaling remains challenging, with limited evidence of mainstreaming and replication. Sustainability criteria are moderately met, incorporating inclusive decision-making but with uncertainty regarding long-term plans. Furthermore, findings underscore the significance of co-developing and maintaining adaptation solution portals, illustrating how this approach enriches our understanding of adaptation progress in mountains. Moreover, this research contributes to broadening the scope of systematic adaptation assessments by providing a nuanced perspective that integrates local needs and diverse knowledge systems. In essence, this study makes a valuable contribution to the evolving landscape of adaptation research, emphasizing the importance of practical insights and collaborative efforts to address the complex challenges posed by climate-related impacts and corresponding adaptation efforts.

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1 Introduction

Climate change is having a significant impact on mountain ecosystems, which are home to a quarter of the world's population and a source of freshwater for billions of people (Adler et al. 2022). Mountain communities are highly dependent on natural resources for their livelihoods, and changes in the mountain environment can have significant social, economic, and cultural impacts (Huss et al. 2017; Mengistu et al. 2020; Schmeller et al. 2022; Reader et al. 2023a). Alongside climate and environmental change, demographic change, land use change and urbanisation also create numerous disruptions, in particular when settlements and infrastructures appear in hazard-prone areas (Viviroli et al. 2020; Thornton et al. 2022). Therefore, adapting to climate change in mountains is essential to ensure the well-being of mountain and lowland communities, as well as the long-term sustainability of mountain ecosystems (McDowell et al. 2019b; Adler et al. 2022).

Evidence from mountain specific research confirms that climate adaptation is taking place in many mountain countries, often as a reaction to realised impacts, and sporadically as part of coordinated strategies and plans (McDowell et al. 2019b; Adler et al. 2022). The status quo of mountain adaptation is that of small adjustments to existing risk management strategies with limited scope and extent. Yet, as risks become ever more complex and pervasive, the need to move from small adjustments to substantial innovation and systemic changes, is becoming more pressing (Colloff et al. 2017; Klein et al. 2019; Palomo et al. 2021; McDowell et al. 2021). Indeed, in terms of the hallmark approaches taken to adaptation, those of incremental and transformational adaptation, are perhaps the two most prominent (Kates et al. 2012). Although, as many authors have noted, there is no fixed definition for transformative adaptation and its interpretation differs among different users and contexts (Fedele et al. 2019), its relevance and necessity are nevertheless widely recognized (Klein et al. 2019; Bentz et al. 2022). Such importance appears to lie in the need to move from business-as-usual or traditional incremental strategies to systemic commitments that better address the complex challenges linked to climate change risks through a shift in paradigms and values (Lonsdale et al. 2015). Lately, the success of adaptation, whether transformative or incremental, has become strongly interrelated to its effectiveness in reducing climate risks (Owen 2020; Chausson et al. 2020), with the feasibility of adaptation as an indication of potential barriers, limits or maladaptation (Singh et al. 2020; Thomas et al. 2021).

In the pursuit of achieving a synthetic picture of the overall landscape of adaptation, its characteristics, effectiveness and transformative potential, numerous systematic reviews and meta-analyses have emerged in the past decade (McDowell et al. 2014, 2019b; Berrang-Ford et al. 2015, 2019; Berrang-Ford, Sietsma, et al., 2021). Berrang-Ford et al. 2021a combined traditional review methods with machine learning to take stock of empirical adaptation globally. Meanwhile, other reviews have focused on specific sub-topics within the adaptation literature, such as health (Berrang-Ford et al. 2021b), equity (Araos et al. 2021), adaptation limits (Thomas et al. 2021), and government adaptation (Berrang-Ford et al. 2019). Systematic reviews of adaptation also exist for specific topological regions, including the Arctic (Canosa et al. 2020) and mountain areas (McDowell et al. 2014, 2019b; Terzi et al. 2019; Vij et al. 2021).

These reviews have proved extremely valuable to tracking adaptation progress, and some have played a key role in global assessments such as the IPCC (Berrang-Ford et al. 2021a; Adler et al. 2022; O'Neill et al. 2022). Notwithstanding, they predominantly assess adaptation if evidence is reported in the academic literature. Technical and logistical challenges have been identified when attempting at systematically assessing adaptation practice from the grey literature in ways that are comparable and on pair with the academic evidence (Berrang-Ford et al. 2021a). This is often because adaptation projects carried out in the public, NGO and private sectors are seldomly reported in peer-reviewed literature (McDowell et al. 2019b; Berrang-Ford et al. 2021a; Vij et al. 2021). In response, a number of portals have been developed over the years to track adaptation on the ground, such as Climate-Adapt of the European Environment Agency (Mattern and Jol 2018; Dubo et al. 2022), the Climate Change Knowledge Portal of the World Bank, and the Dutch adaptation web portal (Laudien et al. 2019). Facts and figures from these portals are starting to gain recognition by the scientific literature, and their usefulness is increasingly acknowledged (Laudien et al. 2019; Dubo et al. 2022; Jevne et al. 2023).

This study responds to the urgent need of shedding light on adaptation practice in mountains by compiling wide ranging facts and figures from a dedicated portal on adaptation solutions in mountain regions. It seeks to produce a comprehensive inventory of adaptation efforts taking place in mountains as part of realised and ongoing projects. The focus is placed on implemented adaptation solutions, where solutions are referred to as actual measures, approaches, or processes designed to adjust natural or human systems to current or anticipated climate-related impacts in ways that reduce climate risks and increase resilience (Haasnoot et al. 2020). Solutions were collected from the Adaptation at Altitude Solutions Portal (hereafter A@A Solution portal) (Adaptation at Altitude 2021), which was co-designed by scientists and practitioners in response to the increased needs of a more practice-oriented science of adaptation that takes into account local necessities and different knowledge systems (Muccione et al. 2019). We assessed 88 adaptation solutions initially featured in the A@A Solution portal, implemented across various mountain regions and countries by different organizations and project developers. We explored their characteristics, feasibility and transformative potential. By highlighting the importance of co-developing and maintaining an adaptation solution portal, we demonstrate how such an approach enriches our understanding of adaptation progress in mountains and contribute to broaden the landscape of systematic assessments ofadaptation.

2 Methods and data

The methodological approach used in this study was designed in the context of Adaptation at Altitude (hereafter A@A), launched in 2020. A@A aims to enhance the resilience and adaptive capacities of mountain communities (Adaptation at Altitude 2021). The programme addresses four main challenges of adaptation in mountains, namely: (1) data information and monitoring; (2) regional science-policy exchange and collaborative action; (3) knowledge generation and sharing; and (4) policy mainstreaming. To address challenge three, “knowledge generation and sharing”, an online survey was designed to systematically collect relevant information from mountain adaptation projects with the ultimate goal of building a live portal of adaptation solutions in mountains. To this end, the A@A Solution Portal collects, in one place, relevant information concerning numerous adaptation projects and their implementers around the world. The portal allows the sharing and exploring of past or ongoing tried-and-tested adaptation solutions in mountain regions. A schematic view on the methodological approach used in this study is given in Fig. 1 and explained in the next sub-sections.

Fig. 1 Schematic overview of the methodological approach used in the paper from survey design to assessment of the solutions

2.1 Survey design

The survey employed to populate the A@A solution portal was co-designed by the partner institutions of the programme and informed by a preparatory phase that included a user needs assessment, as well as a review of existing on-line climate adaptation platforms. The user needs assessment involved eleven semi-structured interviews and one on-line workshop with international actors engaged in the funding, evaluation, planning, management and/or implementation of climate adaptation activities in mountain regions. These stakeholders included representatives from A@A partners, the World Bank, Business for Nature, and lead authors of the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6). More detailed information on the project and its partners can be found on the A@A website (Adaptation at Altitude 2021). The user needs consultation was done bottom-up and allowed participants to define the type of information most valuable to practitioners and developers of adaptation projects, as well technical gaps or shortcomings of existing platforms. In parallel, the review of on-line platforms providing climate adaptation solutions was also conducted. This review consisted of three main phases: screening, in-depth analysis of selected platforms, and gaps identification. From the 55 platforms screened, 20 were selected for in-depth analysis. This analysis revealed that more than half of the platforms (54%) showcase climate change adaptation (CCA) solutions primarily at the local scale, followed by mixed (23%, this category includes local, regional, national, international and global), national (15%) and regional (8%) level solutions. None of the analysed platforms specifically focussed on mountain regions, nor considered a comprehensive range of factors that enable or limit transformative potential. The results of the preparatory phase are described in (Scolobig A. et al. 2020). The final product of the preparatory phase was a survey with multiple choices and open-ended questions that served to populate the solution portal. The survey was co-developed in an iterative process involving A@A partners in eight review rounds. Along with the descriptive information, the survey collected significant supporting documentation, and the contact details of some of the principal actors involved in the planning and/or implementation processes.

An overview of the main information collected through the survey is given in Table 1, while a copy of the survey can be found in the supplementary material. Project implementers fill in the survey through an electronic template. This process benefitted from the extensive media efforts of the A@A team that promoted the survey and ultimately the solution portal on websites of the partner institutions, Facebook, X (former Twitter) and LinkedIn, as well as in workshops, seminars, and conferences, mainly under the umbrella of the A@A programme. In addition to project implementers directly responding to the survey, the A@A team also actively collected information from project resources available online, in all cases iterating with project implementers to ensure accuracy of the information entered into the portal. Training resources for filling in the survey, such as a step-by-step guide, an

Table 1 Elements of the A@A survey. The table summarises the elements of the A@A survey that were extracted and analysed for this study. The first column indicates the name of the section in the survey and the second column indicates the corresponding information collected

Survey section name	Information collected
General	Title and description of the solution
Location	Country where the solution is implemented
Scale	Spatial scale of implementation
Sector(s)	Sector(s) where the solution is implemented
Climate impacts	Main climate impacts addressed by the solution
Mountain ecosystems	Main mountain ecosystems where the solution is implemented
Solution types	Categories of solutions
Benefits and co-benefits	Main benefits and co-benefits associated with the implementation of the solution
Capacities	*Open- and close-ended questions about the* capacities required for the design and implementation of the solution, e.g.: 1. Knowledge capacity: include the presence of scientific information, local, indigenous and other forms of knowledge that can assist in designing and implementation of the solutions. 2. Technological capacities: include the availability of technological resources and know-how needed for the design and implementation of the solution. 3. Political/legal: available policies, strategies, laws as well as a clear mandate to implement the solution. Willingness of local authorities to contribute to the implementation. 4. Institutional capacities: presence of cooperation amongst developers of the solution and local institutions and whether institutions to implement and maintain the solutions exist, including human resources and capacities to support implementation and definition of responsibility for managing the solution. 5. Socio-cultural capacities: social context within which the solution is embedded, acceptability of the solution vs. opponents to the solutions; inclusiveness of local stakeholders.
Transformation	*Open and close-ended questions about*: ● Relevance: Location, sectors, climate impacts. ● Depth of change: innovation evident from free text, Sustainable Development Goals (SDG), and Sendai targets addressed. ● Scalability of change: evidence of barriers being overcome, mainstreaming evident, replication evident. ● Sustainability: inclusive decision-making process evident, maintenance plan evident, future proofing-evident, solution viable under future climate conditions. In addition, free text on capacities and description of the solution was also used for the analysis of transformation.

example of a filled-in survey, and the inclusion of sample responses into the questionnaire were made available through the A@A website. To secure consistency and high quality of information, all completed surveys undergo a quality control evaluation, performed by the project team before the corresponding adaptation solution is published on the portal. At the time of writing this article, the A@A Solution Portal consisted of 88 solutions.

2.2 Analytical framework of the survey

For the purpose of this study, we assessed the (1) general characteristics of the solutions, namely location, climate impact addressed, type of mountain ecosystem, sectors where the solution was implemented and type of solution, (2) their feasibility and effectiveness, and (3) their transformation potential. To measure feasibility, we followed a concept developed by Singh et al. 2020 where feasibility is understood as the potential for an adaptation solution to be implemented. We measured the contribution made to the implementation of the solutions in terms of knowledge, technology, political/legal, institutional and socio-cultural factors, to which we refer as "capacities". Such list of factors was agreed upon using existing literature (Singh et al. 2020) and supplemented by the user needs consultations. The analogy of feasibility with capacity is related to the concept of adaptive capacity in adaptation science, which is the ability of a systems to prepare for, or respond to potential damages, and to take advantage of new opportunities by making the appropriate adjustments. The definition of each category is provided in Table 1. We measured each category using a qualitative scoring from 0 (not present) and 1 (very low), to 5 (very high). To capture effectiveness, we focused on the outcomes of adaptation (Singh et al. 2020), both as risk reduction benefits and as more extensive benefits derived from adaptation as improvement in environmental, economic or socio-political conditions (Remling and Persson 2015; Sharifi 2021).

Regarding the transformation potential of adaptation solutions, this was measured using the four key dimensions for transformations developed by the World Bank (World Bank Group 2016). This choice is justified by the need to focus on an approach coming from an applied or practical perspective. In a nutshell, we measured four dimensions:

1. **Relevance** – does the solution address a major constraint or problem of critical importance to sustainable development in mountain regions?
2. **Depth of change** – does the solution cause or support fundamental change in a governance system or behaviour?
3. **Scalability of change** – could the solution be feasibly scaled-up and duplicated in other mountain regions?
4. **Sustainability** – does the solution demonstrate financial, economic, and environmental sustainability?

One key difference from more academic approaches such as those that measure transformations as speed (how fast adaptation is being implemented), scope (breadth of the measures in terms of both sectorial and spatial extent), and depth (represents the novelty of adaptation actions) (Termeer et al. 2017; Berrang-Ford et al. 2021a), is that we allocated a greater emphasis on the potential for scaling up, rather than on the initial scale of the solution. This enabled the inclusion of small-scale solutions (e.g., community-based approaches) that may be only in the pilot phase but offer large potential for future replication and mainstreaming. An overview on the characteristics assessed, as well as proxies to measure feasibility, effectiveness and transformation (or transformative potential) is given in Table 1.

For the data analysis, the information included in the solution portal was downloaded from the A@A Portal website and saved in an excel sheet. The dataset was subjected to a series of pre-processing steps to ensure its suitability for subsequent analysis. The dataset was structured into a Pandas dataframe object. The dataframe serves as a two-dimensional, size-mutable, and heterogeneous tabular data structure, providing a convenient and intuitive way to perform data manipulation and analysis (Pandas 2024). To facilitate analysis of categorical variables, we applied one-hot encoding, converting categorical attributes into a binary representation. Such transformation is essential for preparing categorical data for certain types of analysis that require numerical input. To analyse the solution description text, we first utilize the spaCy (https://spacy.io/), which is an open-source natural language processing library specifically crafted for extracting information from text corpora. Subsequently, the term-frequency times inverse document frequency (TF-IDF) technique is employed to reducing the influence of frequently occurring words that lack informative value within the corpus (Leskovec 2014). TF-IDF serve diverse purposes, including facilitating the visualization of words via word clouds.

The capacities were scored on a five-point scale going from very low to very high. The score for each solution and its capacities was assessed by a minimum of 2 project members to check for consistencies and discussions were held until agreement was reached on the final score. The score was also triangulated with the qualitative description of the text on the corresponding capacity, which is also stored in the solution database.

At the time of analysis, the solution portal contained 88 discrete adaptation solutions. New solutions are being uploaded to the A@A Portal on an ongoing basis. The final dataset with the 88 solutions can be found in the supplementary material and the notebooks needed to reproduce all analysis and figures are available through the https://github.com/vmuccion/Adaptation-Altitude.

3 Results

3.1 General characteristics of solutions

The first entry in the database alongside the unique title, is a description of the solution. Figure 2 displays a word cloud illustrating the prevalence of the words extracted from the description text. Notably, “water” is highlighted as the most prevalent word, followed by other key words such as “community”, “land”, “local”, and “capacity”. This pattern indicated a prevalence of community and local based measures, with water being the dominant aspect, not only in terms of sector, but also concerning the typology of solutions.

The geographical distribution of solutions in Fig. 3 (top panel) shows that there is a considerable tendency in the portal towards specific regions such as North and Southwestern South America, East Africa, and the Hindukush Himalaya (HKH) region. Moreover, there is a handful of solutions in Europe and the Caucasus, but so far, none from North America or Oceania. This is because the solution portal was mainly an effort to collect solutions from the Global South, expressed through the stakeholder needs consultation. However, efforts are underway to have a more balanced geographical coverage that includes additional regions. When it comes to the impacts addressed (Fig. 3 bottom panel), a diversity can be observed in the majority of continents, except in Europe.

Fig. 2 World cloud of most frequent single words obtained from the summary description of the solutions

The general characteristics of the solutions are shown in Fig. 4. Across all solutions, drought emerges as the most common climate impact addressed (63), followed by flood (39), and almost in equal proportion, landslides, altered growing seasons, and heat stress. Wildfire is addressed by only 5 solutions. In addition to these main impacts, the portal retains information on secondary impacts as well. The open nature of this question resulted in greater diversity in terms of reported impacts. In this case, water stress is the most common secondary impact, followed by land degradation, and glacier lake outburst flood. Other secondary impacts include erosion, snow scarcity, and unseasonal frost. The distribution of solution types shows that education and awareness, as well as land use practice, are the most common solution types, followed by monitoring and engineering strategies. Finance solutions are the least common. The sectorial distribution is dominated by agriculture and water, reflecting the emphasis on addressing drought and flood. A similar distribution is seen amongst other sectors, namely human health and well-being, natural hazards, plans and policy, ecosystem, and biodiversity. Tourism and transport are the least covered sectors. Finally, there is a more proportional distribution in the ecosystem types, with a prevalence of agricultural land, forest and high alpine. Urban solutions represent the lowest percentage.

To gain deeper insights into adaptation efforts—particularly the nature, location, and methodologies of implemented solutions—we analyzed the co-occurrence of selected pairs of characteristics. As depicted in Fig. 5, this analysis focuses on the relationships between solution types and climate impacts (left panel), as well as between solution types

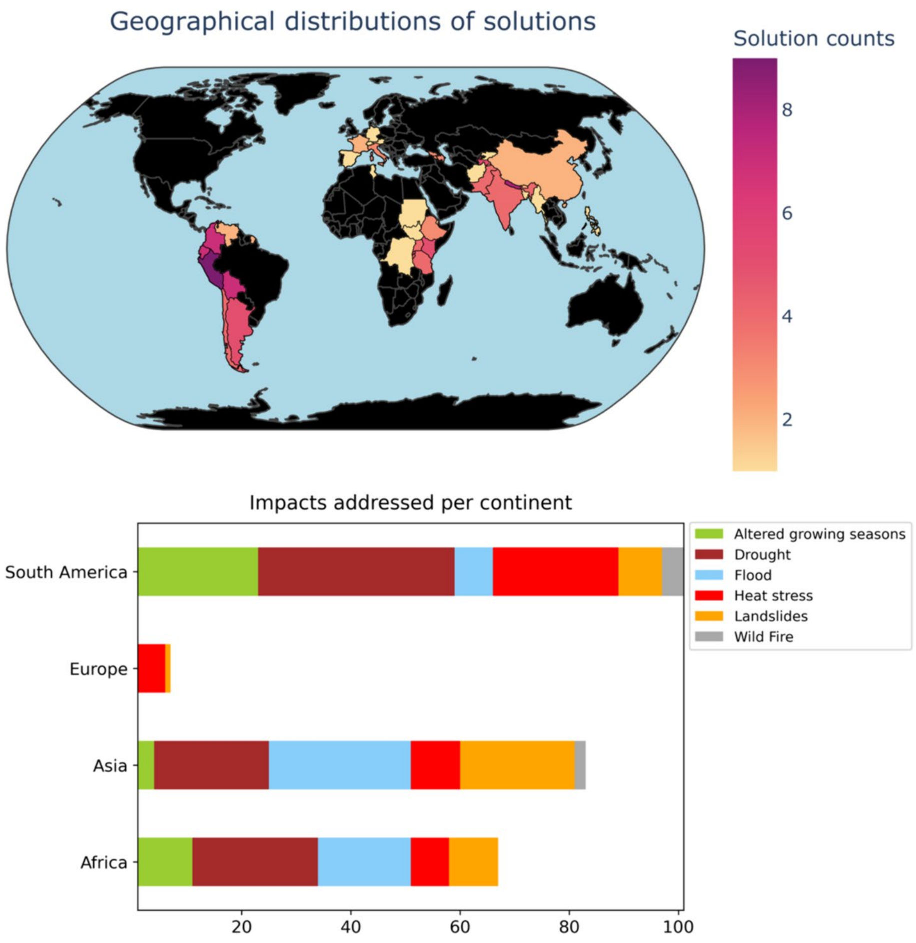

Fig. 3 Top figure shows a choropleth map of the solutions per country. The bottom figure shows the proportion of climate impacts addressed per continent. Only continents having at least one solution or more are shown

and ecosystems (right panel). Notably, education and awareness initiatives, along with land use practices, emerge as the predominant strategies employed to address a wide array of impacts. This includes adapting to the effects of droughts and floods, which constitute the primary climate impacts documented within our portal. Our observations reveal that solutions emphasizing education and awareness are frequently implemented in response to these challenges, complemented by the adoption of land use practices and engineering solutions. However, wildfire mitigation efforts are relatively limited, represented by only five documented solutions, thus revealing a lack of discernible co-occurrence patterns. Moreover, when examining the ecosystems wherein these solutions are enacted, it becomes evident that education and awareness types, alongside land use practices, are prevalent across diverse ecosystem types, spanning from agricultural lands to lakes and rivers. Conversely, fewer solutions are observed in ecosystems such as meadows, peatlands, and urban mountain areas, resulting in a lack of notable co-occurrence patterns within these contexts.

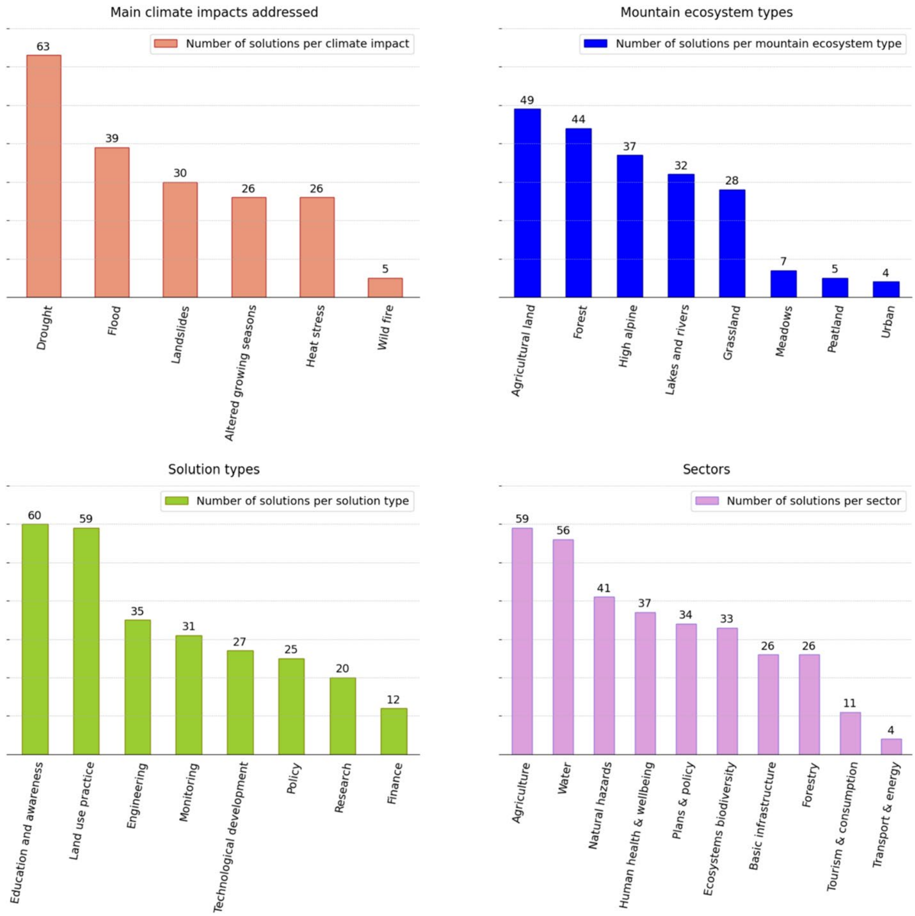

Fig. 4 Summary of the main characteristics across all solutions, from top to bottom clockwise, in orange the number of solutions per climate impact addressed, in blue the number of solutions per mountain ecosystem type, in green the number of solutions per solution type and finally in pink the number of solutions per sector

3.2 Feasibility and effectiveness

Presented here are the feasibility results assessed through the lenses of five capacity categories, scored on a qualitative scale ranging from very low to very high, as shown in Fig. 6. As can be observed, many of the solutions exhibit very high capacity in all the categories. Knowledge capacities ensure that adaptation is informed from the outset by diverse knowledge types, including scientific, evidence based, and indigenous knowledge. Overall, political/legal and technology capacities were evaluated by solution providers as less crucial than knowledge, institutional, and socio-cultural capacities in enabling the implementation of the solutions. In contrast, providers gave high evaluations to the role played by socio-cultural and institutional capacities. However, it should be noted that approximately one quarter of solutions do not report results on one or more

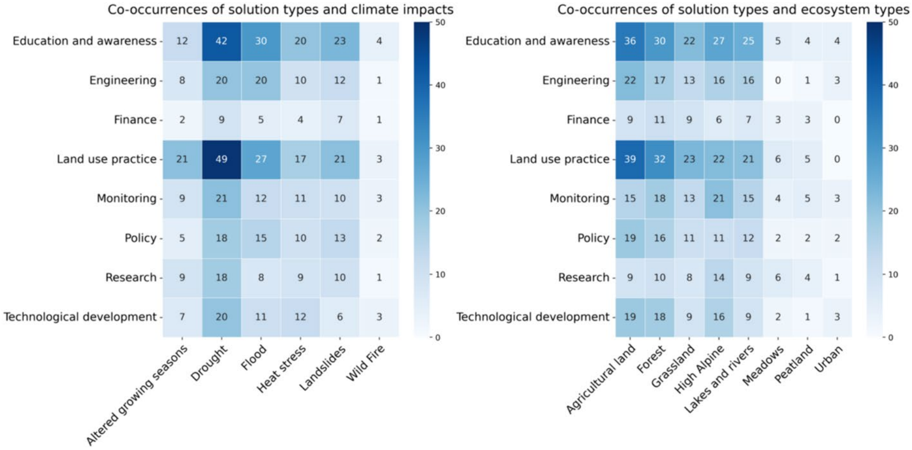

Fig. 5 The heatmap on the left side represents co-occurrence between solution types and climate impact addressed; the heatmap on the right side represents co-occurrence between solution types and ecosystem types. The numbers within each cell represent the observation counts in ascending order from light blue to dark blue

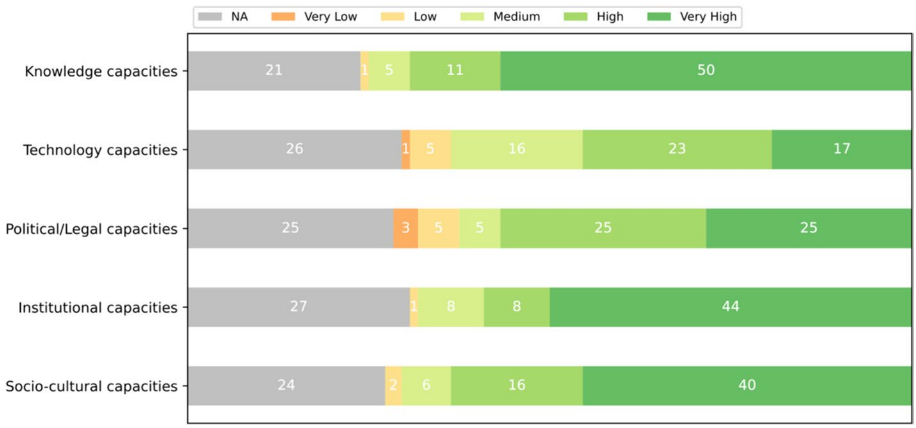

Fig. 6 The figure shows the number of self-assessed solutions with respect to the five dimensions of capacity on a qualitative scale going from very low to very high. NA means that the dimension was either not assessed or was not relevant

capacities. This gap in reporting complicates the determination of whether a specific capacity is relevant for that solution or not.

In order to understand the effectiveness of solutions in delivering positive changes ex-post, we explored various categories of benefits. All solutions have benefits associated to them. Our observations indicate that the majority of solutions have resulted in environmental benefits (33), followed by climate risk reduction (32). Other key benefits include social (13), economic (6), and technological (1) benefits. No solution indicates political benefits (Fig. 7).

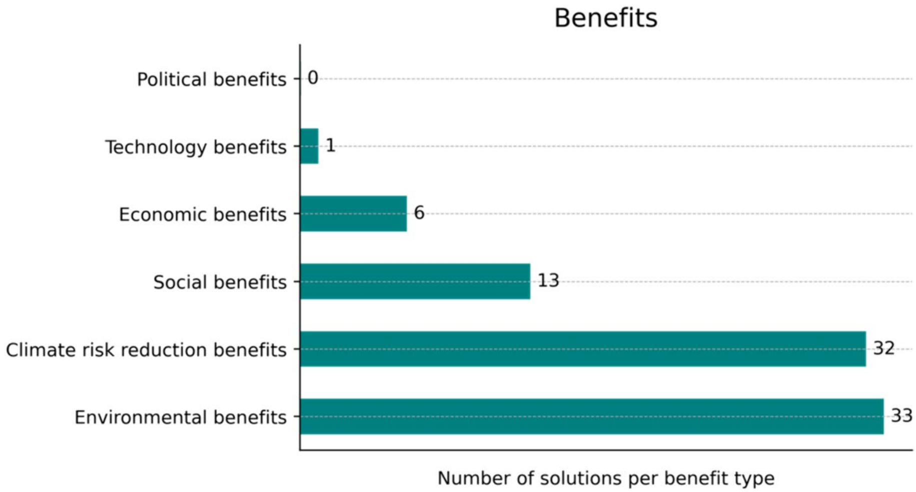

Fig. 7 Number of solutions reporting some type of benefits after implementation

3.3 Transformative potential

The last segment of the analysis focuses on the assessment of the transformative potential of solutions whereby transformation is assessed according to the indicators described in SM Fig. 1. The file used to assess the transformative potential is uploaded as supplementary dataset. Figure 8 summarises the results, depicting the number of solutions addressing specific criteria measured by corresponding sets of indicators. As it can be observed, relevance is prevalent across almost all the solutions, except for

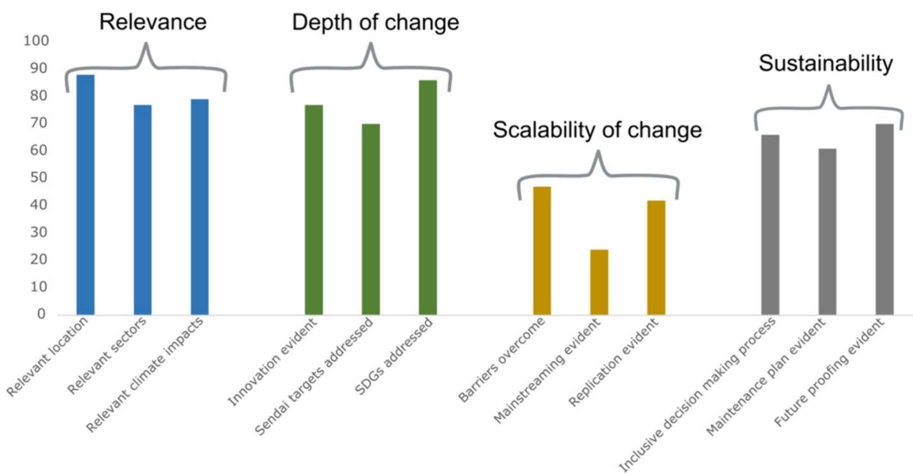

Fig. 8 Number of solutions for each indicator of transformative potential. A score of 1 is given for each of the indicators being present and 0 when there is no evidence of such. Indicators corresponding to the same dimension of transformations are grouped by colour to facilitate observations. The dimension is shown on top of each group of indicators

a handful which either address only one sector or report no specific climate impacts. The depth of change also shows a similar behaviour, with most solutions showing evidence of innovation within their own context and addressing multiple SDGs and Sendai Targets. Further details on specific SDGs and Sendai Target, as well as on their relationship, is provided later in this section. Sustainability is reported in more than two thirds of the solutions, while only a few solutions provide evidence on the scalability of change. While we acknowledge the importance of tailoring adaptation solutions to local environmental, cultural, social and institutional contexts, under transformative adaptation there is an expectation to see learnings and a pathway forward as to how the basic fundamentals of the solution could be transferred to another community, village, district, country or region. Evidence of mainstreaming into wider policies and plans is reported in less than one third of the solutions, and approximately half of them offer evidence of overcoming barriers and successful replication.

In line with the survey design and scope of the study, this analysis includes a review of the principal contributions that the solutions provided to the SDGs (United Nations, 2022). Likewise, the survey also sought to investigate evidence of supporting at least one of the 7 global targets set under the Sendai Framework for Disaster Risk Reduction. Observations indicate that most solutions address at least one SDG, while 18 solutions do not address any of the Sendai targets. Overall, all SDGs, except "life under water" (Fig. 9), and all of the Sendai targets (Fig. 10) are addressed by the solutions. Some solutions address more than one SDG or Sendai target. As it could be expected given its relevance on the matter of climate adaptation, the most common SDG addressed is Goal 13 (Climate Action), followed by Goal 15 (Life on Land), and Goal 1 (No Poverty). Goals 4 (Quality Education), 7 (Affordable and Clean Energy), and 16 (Peace, Justice and Strong Institutions) are the least frequent. In the case of Sendai Targets, target B, "Substantially reduce the number of affected people globally by 2030", is addressed by almost 2/3 of the solutions. Target A, "Substantially reduce global disaster mortality by 2030", is the least addressed target.

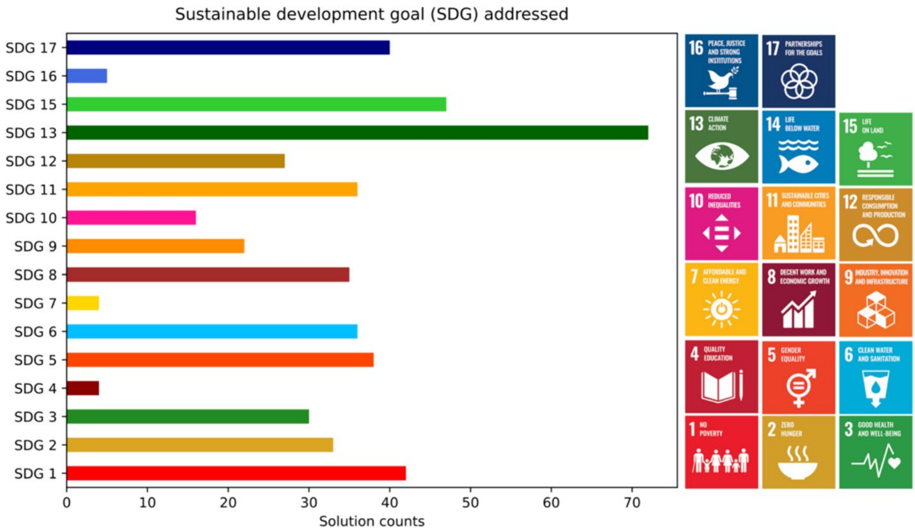

Fig. 9 The figure shows the number of solutions addressing each of the 17 Sustainable Development Goals (SDGs). Details on the SDGs are provided on the right side of the figure

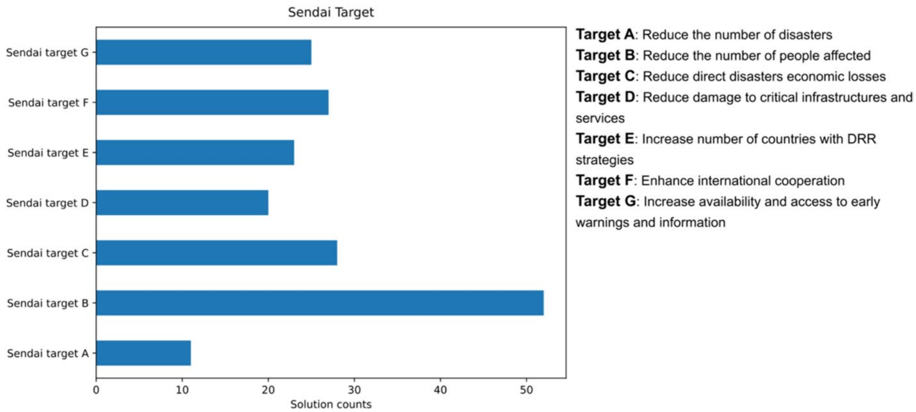

Fig. 10 The figure shows the number of solutions addressing each of the 7 Sendai Targets. Details on the targets are provided on the right side of the figure

4 Discussions and conclusions

Documented adaptation efforts which are measurable and comparable are critical to track progress on the status of implementation (Magnan and Chalastani 2019, Nalau 2021). Therefore, it is essential to assess adaptation experiences by systematically collecting and analysing information on implementation that is happening on the ground (McDowell 2019). To respond to this need and as testimony of increasing adaptation efforts, several adaptation portals have appeared in the past few years. These portals facilitate organized tracking of adaptation progress and are well suited for further analysis and assessments (Cebrián-Piqueras 2023). In this study, we analysed and assessed the recently implemented or ongoing adaptation solutions in mountain regions, that were collected from the Adaptation at Altitude Solution's Portal.

The initial survey employed to populate the portal, was co-designed with a bottom-up process by experts and practitioners, this with the aim to capture the elements of adaptation which matter to both groups.

Our research results illustrate that drought (63) is largely the most targeted climate impact, followed by flood (39). This finding is corroborated by systematic reviews, and research articles consistently highlights drought as the primary climate impact targeted for adaptation, followed by flood, in mountain regions (Dubo et al. 2022; Wyss et al. 2022). Furthermore, the latest IPCC report also indicates that drought and flood pose key risks with the potential for severe consequences for mountain people and livelihoods and highlighted the significance and urgency of addressing water-related hazards in mountains (Adler et al. 2022). The prevalence and importance of water for mountains and adaptation are visible in the key words analysis of solutions summary description in Fig. 2. Interestingly, it is observed that many of the solutions addressing water-related impacts prioritize the integration of watershed management practices. These practices have demonstrated their capacity to effectively tackle multiple concerns beyond climate impacts, including the improvement of water quality (Shin et al. 2023), the promotion of aquifer recharge (Bigdeli Nalbandan et al. 2023), and the enhancement of the natural linkages between upstream and downstream areas through transdisciplinary planning process (Cheng et al. 2017).

When examining the type of solutions, there is a prevalence of education and awareness focused solutions, followed by land use practices. These solutions although implemented to address the majority of climate impacts, appear to be commonly implemented to respond to impacts from floods and droughts (see Fig. 5). Evidence indicates that the implementation of this type of solutions is often accompanied by improvements in project acceptability and reduced risk of maladaptation (Nalau and Cobb 2022). This positive outcome is attributed to the fact that awareness is, in most cases, the result of community involvement (Oliver et al. 2023). The solutions showcased on the A@A Solutions Portal reveal a high involvement of local community groups and populations in project activities, well beyond the classical initial consultations. Remarkably, about 75% of solutions show inclusive decision making (see Fig. 8). However, despite the pivotal role of community participation, the exercise often faces a number of challenges and requires careful handling to prevent the reinforcement of social issues, such as gender inequality and class-based hierarchies (Nalau and Cobb 2022; Singh 2020).

Agriculture land and forests emerge as the main mountain ecosystems wherein solutions are reported, with agriculture and water being the main sectors within which solutions are mostly implemented. This further reflects the importance of tackling water-related impacts and risks for the management of critical sectors, given that mountains boast some of the highest proportions of water availability globally, as well as water withdrawal (Reader et al. 2023b). The type of solutions implemented in these mountain ecosystems point at a prevalence of education and awareness and land use practices since, as already mentioned, these are by far the most used solutions. It is not surprising that land use practices are highly present in forest and agricultural land areas. However, while the dataset highlights a significant contribution of education and awareness as adaptation solutions in almost every typology of ecosystem, it paradoxically reveals a low impact on Sustainable Development Goal 4 (SDG 4) regarding quality education (Fig. 7). This discrepancy may stem from the underreporting of capacity-building and awareness-raising activities under the broad category of education. Additionally, it prompts consideration of whether the targets outlined in SDG 4 are perceived as exclusively related to conventional curriculum-based education, potentially overlooking non-traditional forms of educational initiatives such as those related to awareness raising or building capacity. McKenzie et al. (2024) have argued that indeed it is currently difficult to track progress on SDG4 in relation to climate change due to a lack of quality and appropriate indicators. Despite this discrepancy, the overall picture remains positive, with many Sustainable Development Goals (SDGs) and Sendai targets being addressed laterally within the solution portal, with only a few exceptions (Fig. 7). This observation aligns with the significant synergies underscored in the IPCC WG2 Cross-Chapter paper on Mountains (Adler et al. 2022). Based on the findings of our research, we have identified that several Sustainable Development Goals (SDGs) and Sendai targets are indeed addressed within the solution portal. This evidence counters previously highlighted gaps that acknowledged the limited evidence of implementation of international agendas in addressing disaster risk reduction and adaptation in mountainous regions (Adler et al. 2022; Alcántara-Ayala et al. 2022). By tracking evidence collected from empirical adaptation, we underscore here the imperative for sustained efforts to bridge the disparity between policy frameworks and their practical implementation on the ground.

Nuanced concepts such as feasibility, effectiveness, and transformative potential, were assessed by means of proxy indicators. In the case of feasibility, we examined the score of five main categories of capacity that were present in the project survey and that are analogous to the characterisation of feasibility according to existing literature (Singh et al. 2020). Although the results in Fig. 6 would point at high to very high capacity for many categories, we recognise that there is a high proportion of solutions which do not provide such information and cannot be assessed. There are nonetheless some noticeable patterns as for example, the fact that knowledge capacities score very high for more than half of solutions, whereas technological capacities show a more heterogeneous picture as enablers of solution implementation. This could be due to technology in mountain areas, being used in diverse ways, such as the development of high-resolution models that incorporate climate and socio-economic impacts on natural ecosystems, and on significant resources such as hydrological components (Immerzeel et al. 2020). At the same time, adaptation initiatives may rely on the formulation of structural and physical components (e.g., hard adaptation), addressing agriculture and food security, water management, and infrastructure, for example, through the creation of reservoirs and modern irrigation systems, water conservation techniques, and hazard management technologies such as early warning systems (Adler et al. 2022). However, in contrast, solutions which focus on education and awareness raising do not rely upon strong technical capacities from the onset, but rather aim to build these capacities through the lifetime of the project. A more pessimistic explanation for the medium to low scores could be the lack of appropriate technological know-how and technology transfer where it is most needed (Wang et al. 2020). This though would be at odds with the high score in the knowledge capacities, which can be reasonably associated with technological knowhow, among other dimensions of knowledge. The effectiveness also scores low in technical and political benefits, which might again indicate a persistence in the low technologic and political scores even after solutions are implemented. This last assertion would confirm the findings in McDowell et al. 2021; which cite limited technological know-how and political willingness as hindrances to the full realization of adaptation solutions in mountainous areas. In general, we can infer that solutions are being effective in reducing risks and improving environmental conditions and are benefitting from high knowledge capacities to enable implementation. Nevertheless, solutions do not seem to spur technological or political improvements, or such improvements are not relevant to the project scope, which suggests possible missed opportunities for important co-benefits. Analogous studies which performed systematic assessments of the adaptation literature in mountain regions have reported also environmental co-benefits but limited political or institutional positive spill over (Aggarwal et al. 2022).

To get a sense of the transformative potential of solutions, we explored transformations through the lenses of four criteria, namely relevance, depth of change, scalability of change, and sustainability. We see from the results in Fig. 8 that solutions are being implemented where they are most relevant, and that almost all of them cause or support fundamental change (depth of change). As most solutions are local or sub-national (see Fig. 3), it is plausible to infer that such depth of change happens more at the community level. However, the fact that upscaling is difficult to achieve poses questions concerning the identification of the enabling factors that eventually lead to upscaling. This is also supported by the finding that only a handful of solutions provide evidence of mainstreaming and replication. Berrang-Ford et al. (2021a) confirmed this trend of limited scope of solutions in their global stocktake of human adaptation. Indeed, they reported that globally, adaptation solutions generally have a limited geographical extent and low levels of mainstreaming (Berrang-Ford et al. 2021a). In part, this comes down to the typical short duration of adaptation projects (4–5 years) where mainstreaming becomes something of an afterthought towards the end of the project cycle rather than a goal in itself. Nonetheless, the reported success of the mountain solutions in terms of depth of change at local or sub-national level bodes well for future mainstreaming and upscaling, even if this is not occurring as rapidly as would be desired.

In essence, we can say that while the criteria of relevance and, to a geographically limited extent, depth of change, have largely been met, solutions had difficulties in demonstrating that their contribution to deliver large-scale impact by introducing new measures into the local policy frameworks or by replicating their actions in other locations. Research on social innovation identifies different types of upscaling that may be instrumental also for climate adaptation (Moore et al. 2015), namely, scale up (impacting laws and policies), scale out (increasing number of people or communities impacted by the solution), and scale deep (impacting cultural values and beliefs). Given the longer time frames needed, designing project with a second phase dedicated to mainstreaming and upscaling efforts would significantly increase the transformative potential of adaptation solutions in mountain regions.

The sustainability criteria are moderately met for our analysed solutions, and it is encouraging to see that inclusive decision-making processes and future proofing are being embedded in many of them. It is less clear though, whether long term plans are being integrated, and again, this is something that confirms the limited scalability and mainstreaming potential of solutions. Limited scalability, mainstreaming, and long-term planning could be all explained by an observed tendency in climate project decision making to leave planning and discussion around scaling up or replication until very late stages or following the closure of interventions (Jain and Bardhan 2023). Furthermore, the gap in the implementation of adaptation mainstreaming seems closely related to the lack of political commitment and mandate at the higher governmental levels (Runhaar et al. 2018).

Far from being all encompassing, the A@A Solution Portal misses yet the showcasing of other important mountain regions, possibly because of a bias in the initial scope of the survey and solicitation efforts, which were mainly geared towards international development and cooperation. Fortunately, efforts are underway to have a more geographically balanced display of solutions that will enhance learning between mountain regions in the global south and north. It is worth pointing out that the portal collected information not only from the project developers and implementers but also triangulated this information with project evaluation reports, which are usually developed by independent evaluation bodies and consultants. Typical mid-term or final project reports are normally based on a mix of interviews conducted with those involved in project implementation and projected beneficiaries. To minimise bias in reporting, the information was thoroughly screened for quality control by the independent team members from the A@A project. For example, project reports only seldomly involve any longer-term monitoring and evaluation of the solutions. Hence, effort was made during the quality control to ensure that statements around the foreseen long-term success and sustainability of the solutions was well-supported with concrete evidence that financial and technical plans were in place. Obvious difficulties exist for reaching out to an independent and representative sample of stakeholders, particularly ensuring representation of the most vulnerable or marginalised members of the communities. Therefore, the implementation of adaptation project design should from the beginning include more regular external evaluations and broader stakeholder engagement, whose views would equally constitute the body of independent evidence for ex-post project assessment (Wamsler et al. 2020; Oliver et al. 2023). In absence of such independent information, it is often difficult to get a sense of the progress for those who are the direct beneficiaries of these solutions and therefore such views cannot fully by captured in the remit of this solution portal. The second phase of the A@A project will attempt to fill this gap for selected solutions, by undertaking focus group meetings and interviews with benefactors and other stakeholders to gain ground level insights on the long-term effectiveness of the implemented solutions.

Another challenge of adaptation is the persistent lack of integration of concepts and terminology across different strains of literature, whether adaptation, vulnerability, or impact driven (Berrang-Ford et al. 2021a). This has been identified as a persistent barrier to adaptation assessment. To this end we invoke here for a common adaptation taxonomy. Currently absent, such a taxonomy would require consensus within the broadest community, offering scholars and practitioners a detailed and common description of benefits, ecosystems, sectors, solutions, capacities, as well as other critical concepts. The survey conducted within this study presents intriguing entry points for such a taxonomy specific to mountain regions. For instance, it identifies solutions and their characteristics in mountains, including sectors, ecosystems, and solution types. Yet, further work is necessary to achieve a robust consensus.

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Authors' contributions VM developed the concept for the paper and wrote every section of the manuscript. She did extensive data pre-processing and most of the data analysis. SKA had the initial ideas for such a paper and contributed in developing the methodology to assess the transformative potential together with JA. AS and JA were actively involved in the development of the methodology for the data collection and quality control. RW and JB hosted the portal database and provided VM with the raw dataset from the Adaptation at Altitude website. RW maintained the Adaptation at Altitude Portal together with JZ, OS, and SKA. Everyone contributed to edit and revise the paper. Correspondence and requests for materials should be addressed to veruska.muccione@wsl.ch.

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Data availability Data and Jupyter notebooks for the analysis are all accessible through the following GitHub repository https://github.com/vmuccion/Adaptation-Altitude.

Code Availability The notebooks are accessible through GitHub: https://github.com/vmuccion/Adaptation-Altitude.

Declarations

Competing interests The authors declare no competing interests.

Ethical statement We confirm that the present manuscript is in compliance with the Ethical standards of the journal

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