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Climate change adaptation in global mountain regions requires a multi-sectoral approach

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Climate change is projected to cause significant and irreversible losses in mountain regions, severely impacting both people and ecosystems. Assessing adaptation in mountain regions is crucial to address diverse sectoral challenges and to mitigate the risks of maladaptation. Despite increasing awareness of the need to integrate adaptation across all sectors affected by climate change, the understanding of multi-sectoral solutions remains limited. Here we analyzed 118 research articles on human adaptation published between 2012 and 2022 and found disparities and commonalities across different regions, adaptation types and sectors. Behavioural/cultural responses, primarily reactive and linked to agriculture and pastoralism sectors, are most prevalent in Africa and Asia, particularly within rural settings. In contrast, technological/infrastructural and institutional responses, often anticipatory and associated with disaster-risk management, tourism, transportation and water sectors are highly prominent in Europe, especially in urban areas. Our findings underscore the need for collaborative efforts across multiple sectors and regions to effectively address these challenges.

The Paris Agreement established a global goal for adaptation encouraging parties to assess the effectiveness of their actions to reduce climate risk and build resilience[1–3]. However, assessing the success of adaptation remains challenging, with power dynamics playing a significant role, especially in north-south relations[4,5]. Institutional and technological capacities, as well as socioeconomic characteristics, may vary significantly between and within urban and rural areas, and between the global south and the global north[4,6–8]. Addressing these challenges requires a focus on the capacity of households and governments to explore diverse adaptation options, providing a strong foundation for effective climate risk management[5], particularly in the mountain regions.

Climate change is anticipated to bring about irreversible losses in mountain regions, affecting livelihoods and cultural identity[9,10]. Approximately 15% of the global population resides in these regions[11], with around 90% concentrated in the Global South[12]. Effective risk management strategies in these areas must integrate the adaptation needs of all affected sectors and draw upon diverse knowledge systems, including Indigenous knowledge and local knowledge (IK and LK), to reduce the severity of risks[1,13,14].

The effectiveness of adaptation strategies in mountain regions is increasingly challenged by the rising frequency of climate- and weather-related disasters, which have seen a significant rise over the past three decades[15]. Despite this growing threat, the majority of adaptation responses (hereafter also referred to as 'responses') to natural hazards in these areas are reactive[16,17] and focused solely on individual hazards without considering the diverse range of risks present[18–21]. In contrast, adaptation initiatives that engage in co-producing knowledge and identifying locally relevant climatic stressors have greater potential for acceptability and effectiveness[22–25].

Climate change has already induced widespread adverse impacts and losses across various systems, regions, and sectors, affecting both nature and people[15]. Economic damages are particularly noticeable in climate-sensitive sectors such as agriculture, forestry, fishery, energy, and tourism[26]. However, adaptation responses have predominantly been fragmented, incremental, and sector-specific, resulting in an unequal distribution across regions[15]. These responses, often aimed at short-term gains, frequently lead to maladaptation over time, entrenching vulnerabilities, exposures, and risks that have become increasingly difficult to reverse[26]. Adaptation is an intricate

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process that demands a holistic approach, yet current efforts are mostly sectoral in mountain regions[16]. To address this, the recent Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) emphasizes the importance of identifying "integrated, cross-cutting multi-sectoral solutions to enhance the effectiveness and feasibility of adaptation"[27].

In mountain regions, climate change has had widespread impacts across multiple sectors including water, agriculture, tourism, energy, infrastructure, health, disaster risk reduction, and IK and LK[10]. Natural hazards such as floods, landslides, and avalanches pose significant risks to the communities, hindering sustainable development[28]. Although global agreements offer opportunities for integrating disaster risk management and climate change adaptation, implementation in mountain areas is limited[4,29]. Furthermore, energy provision in mountain settlements is crucial, with renewable energy from hydropower playing a significant role but also creating trade-offs for local communities and ecosystems[14,30–32]. Changes in the cryosphere affect cultural values and human well-being[33]. Moreover, these changes also influence pastoralism, altering water availability and increasing disaster exposure, thus affecting human mobility and migration[34,35]. Additionally, tourism and recreation activities, including skiing and glacier tourism, have declined due to reduced snow cover and glaciers, diminishing mountaineering opportunities and route safety[14,36]. Over the past three decades, various institutional arrangements have been developed to address climate-related risks and create development opportunities through adaptation[14].

Although adaptations are increasing across all sectors worldwide, the effectiveness of these efforts is inadequate, and instances of maladaptation are on the rise[4,13,37]. To our knowledge, no systematic review of peer-reviewed research has identified and examined the multi-sectoral solutions to climate change adaptation across global mountain regions. In response, this study builds upon prior systematic review work focused on adaptation in mountains, including McDowell et al.[38] which evaluated adaptation responses in glaciated mountain regions globally, Muccione et al.[39] which analysed the scientific knowledge underpinning climate adaptation policies in eight different mountain regions, and more recent work by McDowell et al.[17,23] which focused on adaptation challenges and gaps in all mountain regions globally. Although these reviews have provided foundational contributions to our understanding of adaptation in mountain regions, there remains important gaps in knowledge related to adaptation research funding, multi-sectoral adaptation response, and variability in these factors across geographical contexts, including urban and rural settlements.

This study, therefore, contributes to the small but growing body of literature that employs systematic review methods to identify and examine the status of climate change adaptation in mountain regions. We systematically extracted information and evidence from existing articles, addressing key questions: What types of adaptation responses are documented? Which types of funding agencies interact with or collaborate on adaptation research? Which adaptation responses are multi-sectoral in nature? Which climatic and non-climatic stimuli are triggering these multi-sectoral responses? Which stimuli are affecting specific regions and sectors? And in what way, if at all, is there an association between region, timing, settlement, sector and type of adaptation responses? To answer these questions, we systematically examined the peer-reviewed research articles on human adaptation between 2012 and 2022, analyzing a total of 118 articles out of 1497 identified from Scopus, ScienceDirect, and Google Scholar. This review offers a comprehensive and systematic study of literature documenting human adaptation responses in global mountain regions in response to climate change.

Results

Geographical distribution of included studies

A total of 296 discrete adaptation responses were documented across ten sectors. The majority of responses are reactive (45%) in nature, while 26% are anticipatory (Fig. 1b). Most of the responses were reported in rural settlements (63%), while only 5% in urban settlements (Fig. 1b). The most commonly reported responses include multiple livelihood options (30 studies), change of sowing/harvest date (27 studies), crop diversification (26 studies), human migration (16 studies) and drought-tolerant varieties (15 studies). The reported adaptations span across 40 countries, with the highest number of papers reporting responses from India (19 studies), Nepal and Ethiopia (15 studies each) and China (10 studies), across 25 mountain ranges (additional information in Supplementary Fig. 1). Researchers have extensively documented adaptation responses in mountain ranges, focusing notably on the Himalayas (30 studies), Andes (23 studies), and European Alps (19 studies) (Fig. 1a).

Adaptation responses across major mountainous regions

Our analysis reveals distinct patterns of adaptation responses across different mountainous regions. Livelihood diversification is a prominent adaptation strategy, ranking first in the Himalayas and Karakoram, and third in the Andes, while also being implicitly reflected in other regions through practices such as tourism diversification in the European Alps. Human migration is another common response, particularly in the Himalayas, Andes, and Karakoram, highlighting its role as a coping mechanism in these regions, alongside species migration in the Pacific Coast Ranges. Adjustments in agricultural practices, such as changes in sowing or harvest dates, are common across the Himalayas, Ethiopian Highlands, and Karakoram, reflecting adaptive responses to shifting climatic conditions. Crop diversification is widely adopted, ranking third in the Himalayas and fourth in the Ethiopian Highlands, with drought-tolerant varieties also being prioritized in the Ethiopian Highlands and Pacific Coast Ranges. Water management practices are a recurring response across these regions. The expansion of irrigation infrastructure ranks fifth in the Himalayas and fourth in the Ethiopian Highlands, while irrigation management and water storage infrastructure are key strategies in the Andes.

Despite these similarities, these regions also display distinct adaptation priorities. In the Himalayas, the focus is on agricultural adaptations such as crop diversification, agroforestry, and irrigation infrastructure expansion, reflecting the region's reliance on farming for livelihoods. Additionally, migration, along with livelihood diversification, emerges as key strategies, highlighting the role of mobility and alternate income sources in coping with environmental and economic pressures. The Ethiopian Highlands primarily focus on soil and water conservation, alongside the use of improved seed cultivars, drought-tolerant crop varieties and changes in sowing or harvest dates, underscoring the region's vulnerability to water scarcity and climate variability. In contrast, the Andes prioritizes forest conservation, irrigation management, and water storage infrastructure, indicating a strong focus on ecosystem-based adaptations. The European Alps stand out for their emphasis on tourism-related adaptations, such as snowmaking and tourism diversification, as well as insurance and early warning system mechanisms to mitigate risks. The Pacific Coast Ranges focus on forest fire management, ecosystem restoration, and infrastructure adjustments, reflecting the region's vulnerability to wildfires and extreme weather events. Finally, the Karakoram region relies heavily on livelihood diversification and migration, with additional efforts in cash crop cultivation and irrigation channel development.

Funding agencies in adaptation research

Government is found to be the most frequently reported funding agency, representing 47% of coded studies (Fig. 2). The most prevalent combination involves Government and Academia (10 studies), followed by Academia and non-governmental organisation (NGO) partnerships (6 studies). There is limited evidence of cases involving governments in combinations with diverse funding agency types. Evidence of combinations between Academia, Government, and NGOs is sparse, with only one reported case. Similarly, instances involving collaborations among Academia, Government, intergovernmental organizations, and NGOs are scarce, documented in only two studies. Furthermore, the distribution of funding agency types varies between the global north and the global south. Among academia, government, intergovernmental organization and NGO, government funding is

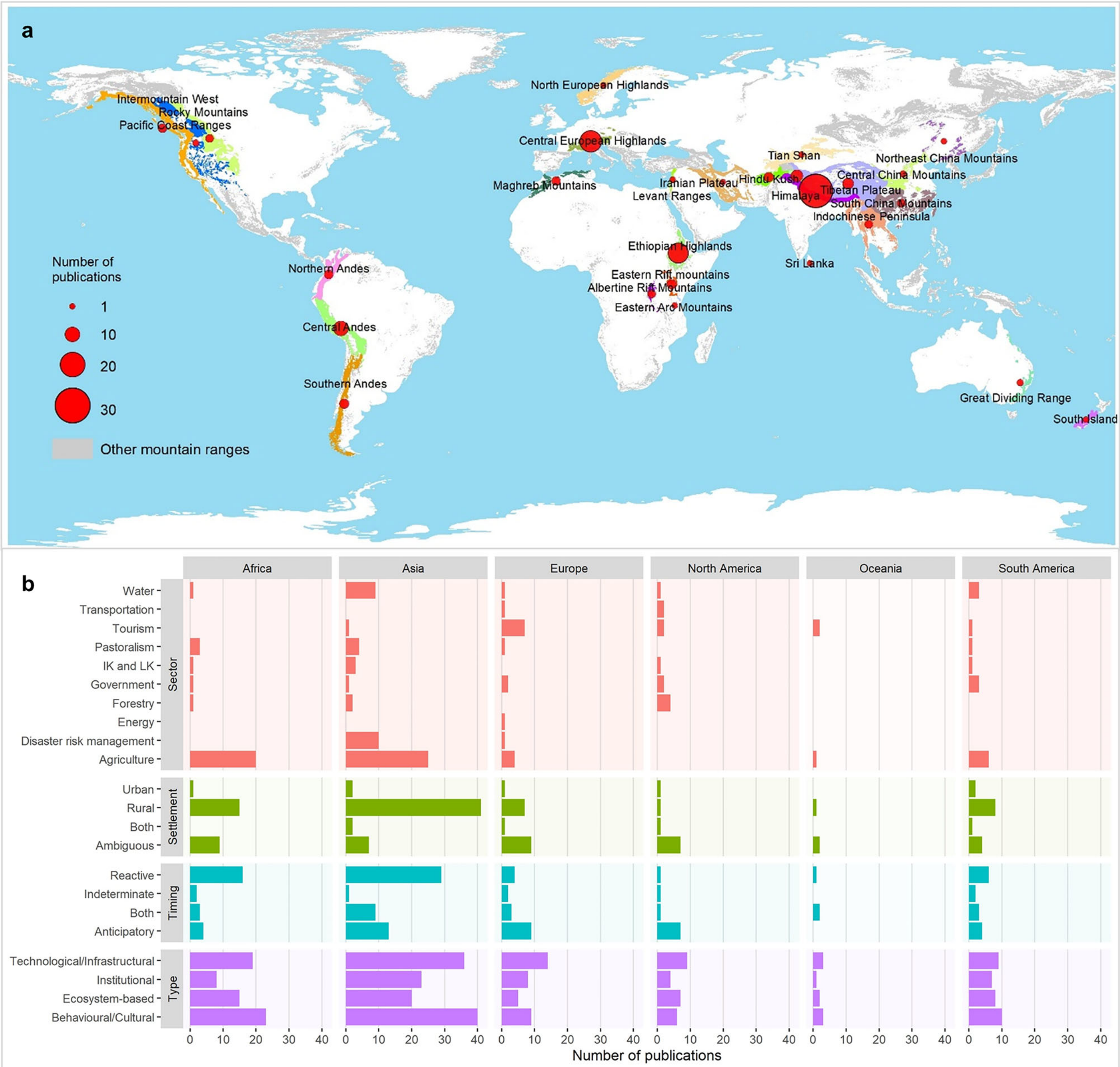

Fig. 1 | Geographical distribution and descriptive overview of included articles in the analysis. **a** Geographical distribution of included articles. **b** Total number of publications by global mountain region for categories of sector, settlement, timing and response type (additional information in Supplementary Method 3).

more associated with the global north than the global south. In contrast, funding by NGOs is slightly more associated with the global south than the global north (see Supplementary Table 5). Research consortium does not yield a statistically significant pattern for inclusion of funding agency.

Multi-sectoral adaptation responses

Among the 93 discrete multi-sectoral adaptation responses documented in 111 articles, the top three responses involving the highest number of sectors are multiple livelihood options, early warning systems, and community partnership and collaborative engagement (Fig. 3). Multiple livelihood options was documented across six sectors – agriculture, disaster risk management, IK and LK, pastoralism, tourism and water; and driven by 23 stimuli, mainly extreme events – drought, precipitation change and temperature change. Early warning systems was also documented across six sectors – agriculture, disaster risk management, government, IK and LK, transportation and water; and driven by 12 stimuli, mainly temperature change and extreme events such as drought, flood and landslide. Community partnership and collaborative engagement was documented across five sectors – agriculture, disaster risk management, forestry, pastoralism and water; and driven by 22 stimuli, mainly precipitation change, temperature change and water scarcity.

Sectoral distribution of multi-sectoral adaptation responses

Among 10 sectors reported, nine sectors reported multi-sectoral responses. The sectors with the highest reported multi-sectoral responses include agriculture, water and disaster risk management (Fig. 3). Agriculture leads with 69 discrete responses, mainly change of sowing/harvest date, crop diversification and multiple livelihood options. The water sector contributes 45 discrete responses, mainly drip irrigation, improved drainage system and institutional policy and reforms. Disaster risk management features 28 distinct responses, mainly early action and preparedness, insurance and early warning systems.

Fig. 2 | Combination of funding agencies in climate change adaptation research. Frequency of reported funding agency types (green horizontal lollipops), as well as their occurrences as sole funding agency type in a study (single black dots and pink lollipops) or in combination with others (connected black dots and pink lollipops). Solid line (—) denotes frequency of reported funding agency types in the global north and dashed line (‒‒‒) indicates frequency in global south.

Stimuli triggering multi-sectoral adaptation responses

Among 71 reported stimuli, 64 triggered responses which were multi-sectoral in nature, encompassing both climatic and non-climatic drivers (Fig. 3). Among the climatic stimuli, precipitation change stands out with 75 discrete multi-sectoral responses, followed by temperature change (63 responses) and extreme events – drought (59 responses). Among the non-climatic stimuli, economic stress emerges as a predominant stimulus, driving 14 discrete responses, followed by soil erosion (9 responses) and salinity (8 responses).

Type of adaptation responses

Among the types of responses, behavioural/cultural emerged as the most prevalent, comprising 41% of the total responses, followed by technological/infrastructural (31%). Ecosystem-based and institutional adaptations accounted for 16% and 12% of responses, respectively.

In terms of regions, behavioural/cultural responses are prominent in Africa and Asia while least-associated with Europe, North America, and South America (Fig. 4; see also Supplementary Table 12). Ecosystem-based responses are mainly associated with North America while least associated with Europe. Institutional responses are mainly associated with Europe while least associated with Africa. Nevertheless, technological/infrastructural responses are mainly associated with Europe while least associated with Asia.

Regarding timing, reactive responses are more associated with behavioural/cultural responses while least associated with institutional and technological/infrastructural responses. Anticipatory responses are more associated with institutional and technological/infrastructural while least associated with behavioural/cultural responses (Fig. 4; see also Supplementary Table 8).

In rural settlements, behavioural/cultural and ecosystem-based responses are more prominent, and least associated with institutional and technological/infrastructural responses. Urban settlements are mostly associated with institutional and technological/infrastructural responses, while least associated with behavioural/cultural responses (Fig. 4; see also Supplementary Table 7).

In terms of sectors, behavioural/cultural responses are more associated with agriculture and pastoralism, while least associated with forestry, government, transportation and water. Ecosystem-based responses are more associated with forestry, while least associated with tourism. Institutional responses are largely associated with disaster risk management, transportation and water, while least associated with agriculture and tourism. Technological/infrastructural responses are more associated with tourism, transportation and water, while least associated with IK and LK and pastoralism (Fig. 4; see also Supplementary Table 6).

Sector of adaptation responses

Sectoral focus across regions demonstrate distinct patterns. Responses in agriculture sector are mainly associated with Africa, while least associated with Europe and North America. Disaster risk management is more associated with Asia, while least associated with Africa, North America and South America. Government sector is least associated with Asia while IK and LK is least associated with Europe. Forestry sector is mainly associated with North America and pastoralism is more associated with Africa. Tourism is more associated with North America and least associated with Africa and Asia. Transportation is also least associated with Africa and Asia. Water is more associated with Asia and South America and least associated with Africa (Fig. 4; see also Supplementary Table 14).

In terms of timing, reactive responses are largely associated with agriculture and IK and LK, while least associated with forestry, government, tourism, transportation and water. In contrast, anticipatory responses are mainly associated with forestry, government, tourism, transportation and water, while least associated with agriculture, IK and LK and pastoralism (Fig. 4; see also Supplementary Table 10).

Responses in rural settlements are mainly associated with disaster-risk management, IK and LK, pastoralism and water, while least associated with government, tourism and transportation sectors. In contrast, responses in urban settlements are mainly associated with transportation and water, while least associated with agriculture sector (Fig. 4; see also Supplementary Table 9).

Settlement by region and timing

Geographically, responses in rural settlements are mainly associated with Asia, while least associated with North America. Further, responses in rural settlements are mainly reactive.

Stimuli affecting sector and region

In our review, we identified 70 stimuli of adaptation, with 36 climatic stimuli and 34 non-climatic stimuli. Prominent climatic stimuli include precipitation change (78 studies, 66%), temperature change (71 studies, 60%) and drought (36 studies, 30%). Key non-climatic stimuli include economic stress (7 studies, 6%), soil erosion (6 studies, 11%) and reduced soil fertility (4 studies, 3%). These stimuli also exhibit significant variation across regions and sectors.

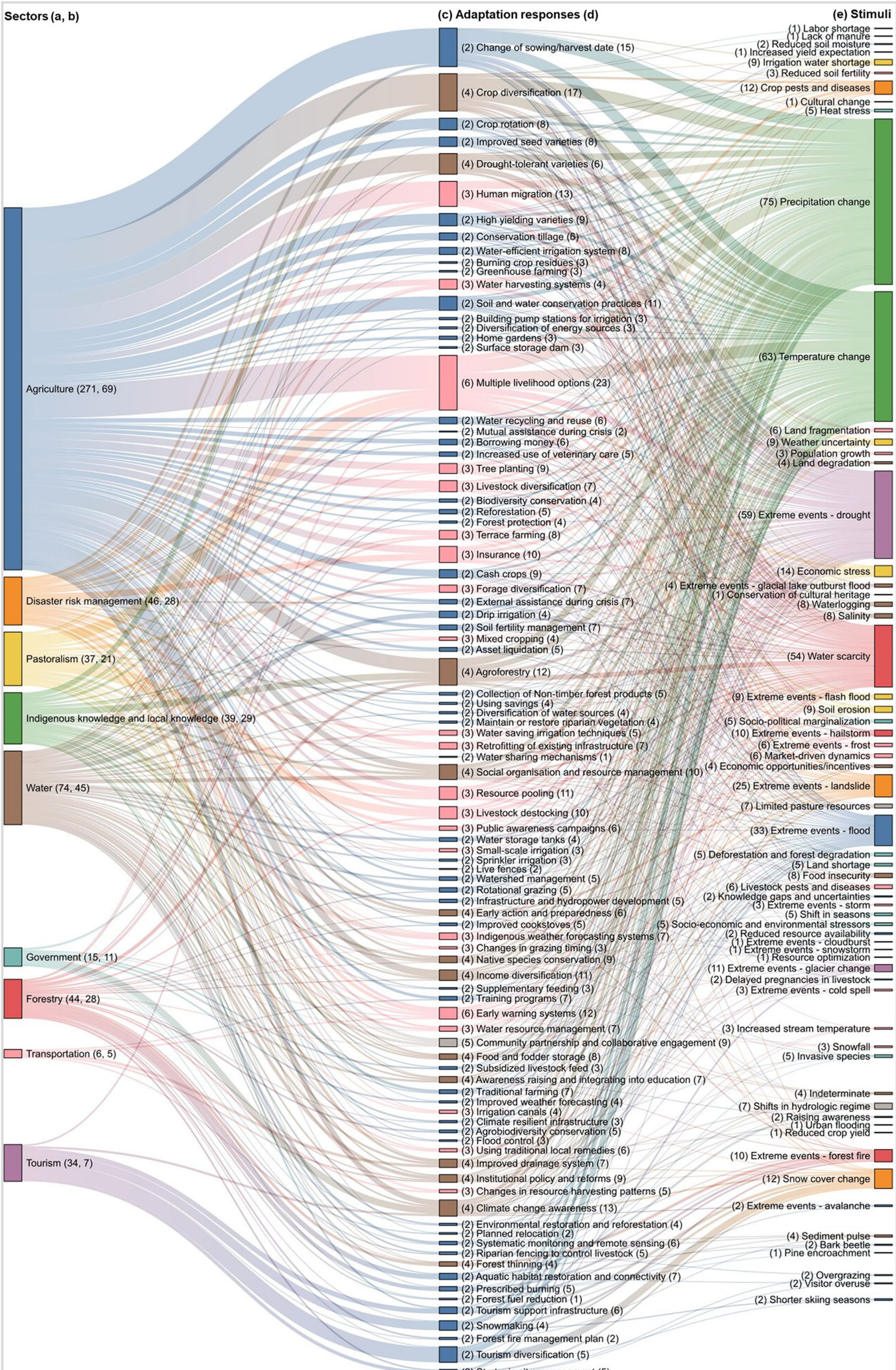

Fig. 3 | Sankey diagram of multi-sectoral adaptation responses and their stimuli. **a** Total number of multi-sectoral adaptation responses, (**b**) Number of discrete multi-sectoral adaptation responses, (**c**) Number of sectors related to the adaptation response, (**d**) Number of stimuli triggering the multi-sectoral response, (**e**) Number of multi-sectoral responses triggered by the stimuli.

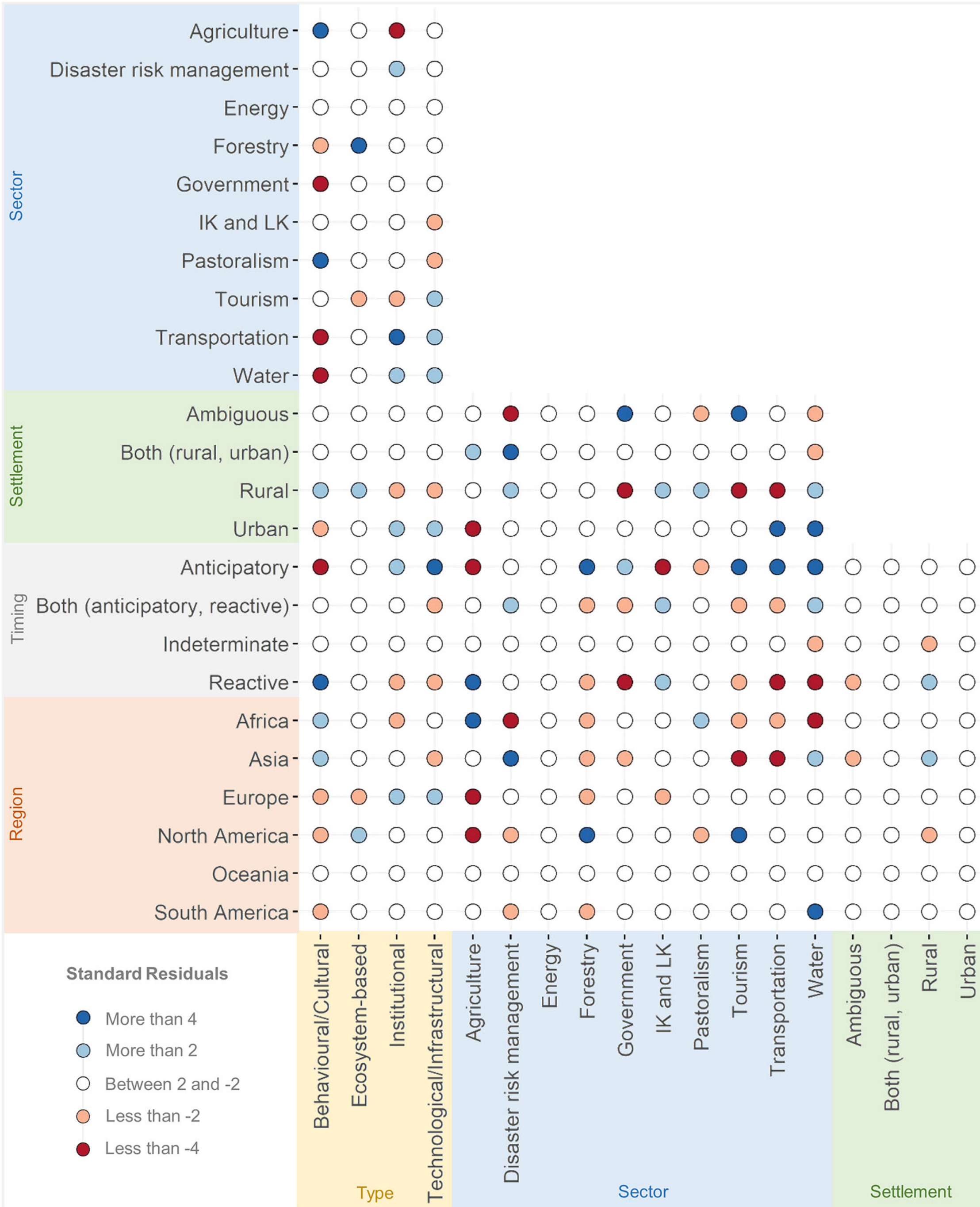

Fig. 4 | Combination of variables and their significance in climate change adaptation. Chi-square test illustrates residuals as the difference between observed and expected frequencies for each combination. Standard residuals below −2 and above 2 are considered significant ($P < 0.05$). Positive residuals (blue) indicate a higher-than-expected frequency, while negative residuals (red) indicate a lower-than-expected frequency. Observations with expected frequency below 5 are considered insignificant (see Supplementary Tables 6–14).

In Africa, most important drivers of responses include crop pests and diseases, extreme events – drought, precipitation change and temperature change (Fig. 5; see also Supplementary Table 15). In contrast, responses in Asia are triggered by extreme events – flash flood, hailstorm and landslide, irrigation water shortages, limited pasture resources and water scarcity. Responses in Europe and North America are triggered by extreme events—flood and snow cover change.

Across sectors, responses in agriculture is triggered by crop pests and diseases, extreme events – drought and storm, irrigation water shortages, precipitation change, temperature change, waterlogging and salinity (Fig. 5; see also Supplementary Table 16). Responses in disaster risk management is associated extreme events – flood. Responses in pastoralism is mostly associated with extreme events – drought. Responses in tourism is mostly associated with temperature change and in water sector it is associated with water scarcity.

Discussion

The analysis of the patterns of climate change adaptation responses reveal distinct regional, sectoral, and settlement-specific trends. These patterns highlight the varied needs across different contexts and underscore areas where support is needed to enhance adaptation. Geographically, the majority of documented responses in mountain areas emerge from Asia

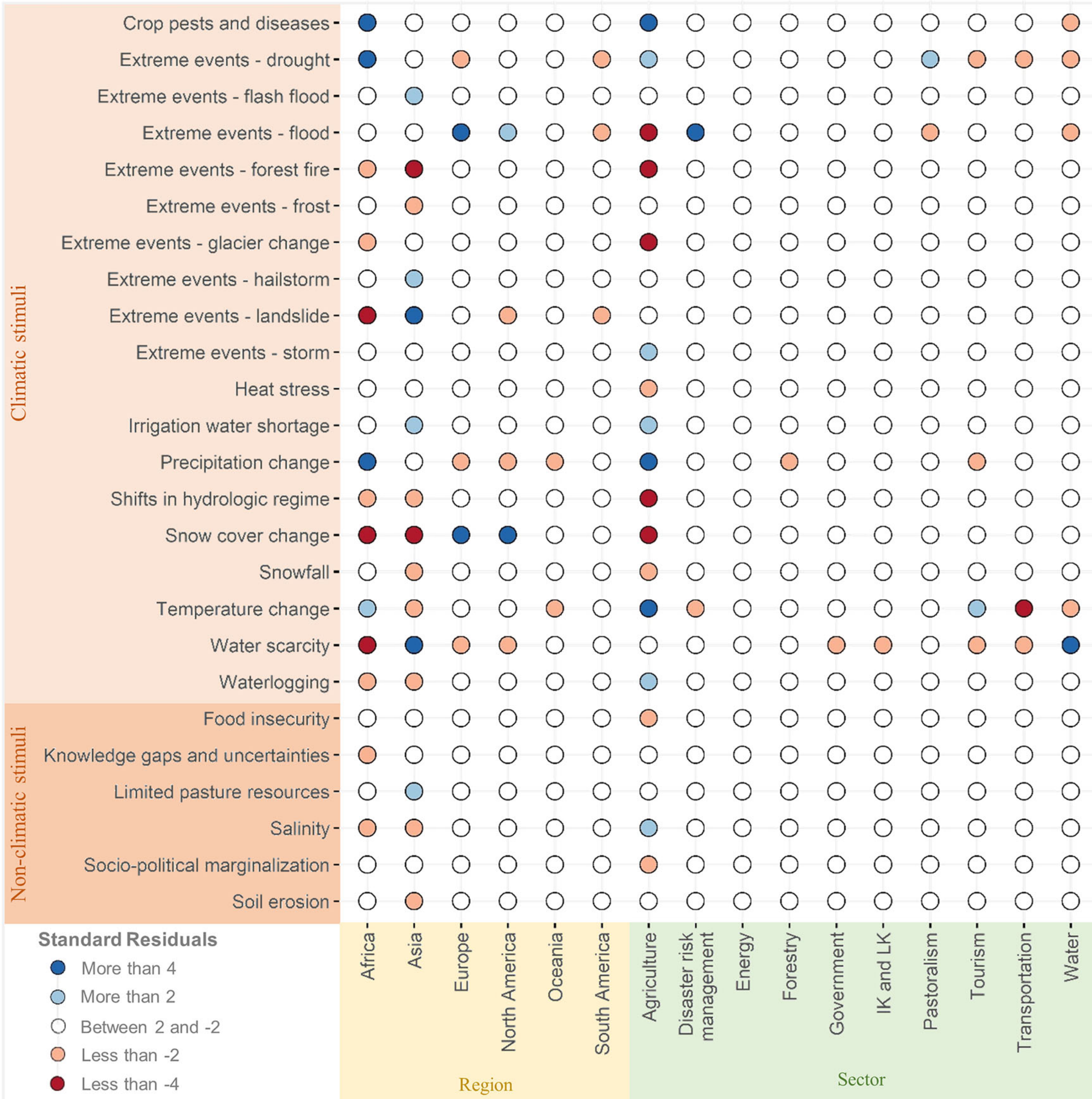

Fig. 5 | Stimuli triggering adaptation responses by region and sector. Chi-square test illustrates residuals as the difference between observed and expected frequencies for each combination. Standard residuals below −2 and above 2 are considered significant ($P < 0.05$). Positive residuals (blue) indicate a higher-than-expected frequency, while negative residuals (red) indicate a lower-than-expected frequency. Observations with expected frequency below 5 are considered insignificant (see Supplementary Tables 15–16).

(41%) and Africa (26%). This distribution aligns with the adaptation patterns identified in prior mountain-focused reviews[17,23,38]. This geographical imbalance is partly due to the fact that majority of the global mountain population lives in countries of the Global South, with 53% in Asia and 23% in Africa[11]. The assessment further reveals agriculture as the highest reported sector, followed by water and disaster-risk management. This distribution is consistent with previous findings[17,40].

Adaptation responses in mountainous regions share several similarities with those in non-mountainous regions, such as coastal, desert, Mediterranean, and polar areas. In mountainous regions, strategies such as agroforestry, change of sowing/harvest dates, community partnership and collaborative engagement, crop diversification, drought-tolerant varieties, early warning systems, environmental restoration and reforestation, livelihood diversification, soil and water conservation practices, water resource management and water-efficient irrigation systems, are commonly adopted. These strategies aim to address key risks arising from precipitation changes, temperature changes, water scarcity, snow cover change and extreme events like droughts, and landslides. Similarly, in deserts and semi-arid regions, adaptation focuses on water management[41], drought-tolerant crops[42], and early warning systems[43] to combat water scarcity and desertification. Both regions emphasize drought-tolerant varieties to build resilience against climate variability. In the Mediterranean region, adaptation measures such as water-efficient irrigation[44], mulching[45], ecosystem restoration[46], and drought-tolerant species[47] align with mountainous strategies like agroforestry, water and soil conservation. These approaches reflect a shared focus on sustainable land and water management. Similarly, in polar regions, adaptation responses include altering harvest activities[48], integrating indigenous and local knowledge for resource management[49], and prioritizing restoration and conservation efforts[50]. These strategies reflect the community resource management approaches seen in mountainous areas. These similarities highlight how, despite distinct geographical and climatic challenges, mountainous and non-mountainous regions adopt overlapping strategies—such as nature-based solutions, early warning systems, diversification, and community-led initiatives—to address interconnected climate risks, underscoring the need for cross-regional and multi-sectoral adaptation solutions.

Apart from similarities, mountainous and non-mountainous regions also exhibit significant differences due to the distinct stimuli or risks they face and their unique geographical and socio-economic contexts. In mountainous regions, key stimuli such as glacier change, landslides, snow cover change, and irrigation water shortages drive specific adaptation strategies like expansion of irrigation infrastructure, agroforestry, and changes in sowing or harvest dates to address water scarcity and precipitation changes. In contrast, non-mountainous regions, such as coastal cities, focus on stimuli like sea level rise, flooding, and saltwater intrusion, leading to adaptation measures such as sea walls[51], and mangroves and marshes to reduce mortality and damages due to storm surges[52]. Similarly, in deserts and semi-arid regions, drought and desertification, soil erosion are primary stimuli, prompting adaptations like rotational grazing[53], insurance and saving programmes for cost savings[54]. Polar regions, facing rapid ice melt and ecosystem shifts, prioritize changes to survey and monitoring design[55], hazard mapping[56], use of new technologies[48], to address risks to infrastructure and community livelihoods.

In terms of adaptation types across the mountainous regions, behavioural/cultural responses were the most prevalent, followed by technological/infrastructural responses, with ecosystem-based and institutional adaptations being less common. This finding also aligns with that of McDowell et al.[23], where behavioural/cultural adaptations were overwhelmingly dominant, followed by ecosystem-based and technological/infrastructural adaptations. Despite the recognized importance of ecosystem-based adaptation as a low-cost anticipatory adaptation response[15], it appears underrepresented in our findings and concentrated in rural settlements. Challenges remain in mainstreaming ecosystem-based adaptation across sectors and securing adequate adaptation finance[15]. The underutilization of ecosystem-based adaptation, especially in mountain regions, underscores the need to integrate it across various sectors and promote its use in urban areas as well. Such integration could enhance the overall effectiveness of adaptation strategies.

Our findings indicate that behavioural/cultural responses are most prevalent in Africa and Asia. These responses are closely associated to agriculture and pastoralism sectors and are predominantly reactive. These responses are concentrated in rural settlements and highlights a significant gap in anticipatory responses. This finding aligns with other evidence suggesting that rural areas in the Global South often experience high poverty, inadequate infrastructure, heavy reliance on agriculture, with limited attention from national policymakers[57]. Despite these challenges, these communities leverage their extensive local knowledge and experience to tackle climatic stressors[57]. Notably, the majority of responses in the IK and LK sector were concentrated in Asia and Africa, primarily related to rural settlements. This aligns with evidence from the systematic map on indigenous knowledge, which shows a focus in regions such as East Africa and the Himalayas, with most studies also centered on rural areas[58,59]. Additionally, our findings reveal that technological and infrastructural responses were the least common in both the IK and LK sector and the pastoralism sector. These sector-specific patterns highlight a critical need for increased technological and infrastructural investment and support, particularly in these sectors, to effectively manage stressors.

Our findings also identify the most commonly reported climatic stimuli as precipitation change, temperature change, and drought. Key non-climatic stimuli include economic stress, soil erosion, and reduced soil fertility. These findings align with prior reviews, which report that the leading stimuli motivating adaptation are drought (69%), precipitation variability (57%), and extreme heat (37%)[23]. Similarly, the non-climatic stimuli for adaptation include economic stress (37%) and other environmental changes, such as soil erosion and deforestation (29%)[17].

Timely adoption of responses is crucial to prevent irreversible damage and to advance efforts towards poverty reduction[16]. Any delay in adopting coordinated global efforts for anticipatory responses will diminish the opportunity to secure a sustainable future for all[15]. However, institutional responses are more common in urban areas and are mostly anticipatory, reflecting structured planning and governance mechanisms. The limited representation of institutional responses in Africa highlights challenges in governance and institutional capacity, which may hinder the implementation of comprehensive adaptation strategies. Enhancing institutional support and capacity in these regions could improve the effectiveness of adaptation efforts. Most adaptation responses in global mountain regions are reactive (48%) to specific stimuli. This observation is also consistent with previous studies, which highlights that responses in mountain regions predominantly react to specific stimuli and are often not based on scientific information about climate change[17,23,38]. This can be partially due to resource constraints including research fundings in these regions.

The distribution of agencies funding such researches exhibits notable regional disparities. Government funding is more prevalent in the Global North, while NGOs play a slightly larger role in the Global South. This trend may reflect the differing priorities and capacities between regions, with governments in the Global North typically having more resources and infrastructure to support research, whereas NGOs in the Global South stepping in to fill gaps left by limited governmental support. Additionally, our findings highlight a significant lack of private sector involvement in funding climate change adaptation research in mountain regions. This absence could be partially attributed to the private sector's focus on more immediate, profit-driven concerns rather than long-term adaptation strategies, which may be perceived as less immediately profitable[60]. This gap also underscores a potential opportunity for enhancing funding diversity and increasing private sector engagement to support adaptation efforts.

Our findings demonstrate that multi-sectoral responses, particularly those involving multiple livelihood options, early warning systems, and community partnerships and collaborative engagement, cover a broad range of sectors and are driven by various climatic and non-climatic stimuli. For instance, multiple livelihood options span agriculture, disaster risk management, IK and LK, pastoralism, tourism, and water sectors. Similarly, early warning systems combine sectors such as agriculture, disaster risk management, government, IK and LK, transportation, and water. However, no multi-sectoral responses were identified in the energy sector. This could be due to the limited number of papers in our review that focus on the energy sector, likely because we only included peer-reviewed articles published in English. Information from technical reports, review papers, non-English articles, or other sources may reveal additional insights. Nevertheless, coordinated multi-sectoral responses having broad coverage of sectors may enhance resilience and offer effective strategies against environmental stressors. In contrast, single-sector responses were narrowly focused, targeting specific challenges within individual sectors. Examples include the expansion of irrigation infrastructure and fertilizer application in the agriculture sector. Similarly, in disaster risk management, constructing stone walls and using sandbags provide localized protection against hazards. In pastoralism, pastoral migration and changes in migration patterns reflect adaptive strategies tailored to livestock management. These single-sector approaches may be easier to implement due to their targeted nature and clear sectoral focus, but they may lack the holistic approach needed to address interconnected challenges.

The current state of research on climate change adaptation in global mountainous regions reveals a growing body of evidence, particularly from Asia and Africa, where the majority of adaptation responses have been documented. Studies predominantly focus on reactive, behavioural, and cultural adaptations, especially in rural settlements, with agriculture and water emerging as the most addressed sectors. Multi-sectoral responses, such as multiple livelihood options and early warning systems, are increasingly recognized for their potential to address interconnected risks. Despite these developments, deficiencies persist, including an overreliance on peer-reviewed, English-language literature, which excludes valuable insights from grey literature and non-English sources. Ecosystem-based adaptations are underutilized, and anticipatory and institutional responses are scarce, particularly in rural areas of the Global South. Moving forward, future research should prioritize geographical inclusivity, incorporate non-English and grey literature, and emphasize anticipatory and institutional responses, especially in underserved regions. Greater private sector engagement and a focus on urban settlements are also essential to address the unique challenges of mountainous regions. By addressing these gaps and trends, future research can support more sustainable climate change adaptation in global mountain regions.

In conclusion, addressing the varying needs of each sector and region is essential for effective climate change adaptation. Enhanced support for technological and infrastructural development in IK and LK and pastoralism is crucial, where responses are predominantly reactive. Strengthening institutional support in regions with less government involvement, such as Africa, can support more effective climate action. Increased governmental funding, along with technological and infrastructural investments, is needed to support communities in rural settlements, who often rely on traditional methods and lack access to advanced adaptation resources. Expanding anticipatory responses in sectors such as agriculture and IK and LK, will improve overall adaptation effectiveness. This comprehensive analysis also highlights the need for multi-sectoral responses that consider regional capacities, sectoral priorities, and settlement types to build resilience globally.

Methods

Review Protocol

To identify relevant articles documenting adaptation responses we followed the guidelines for systematic review, adhering to the established reporting standards outlined in ROSES[61]. The summary of the documents screened at various stages of the review is presented in Fig. 6.

Research question

We structured the review according to the established standards for formulating research questions and conducting searches in systematic reviews[61,62] employing a PICoST approach: population (P), interest (I), context (Co), study design (S) and time (T). The population encompasses all human population in global mountain regions affected by climate change. The activity of interest is adaptation responses. We examined adaptation responses across global mountains context, and specifically targeted adaptation activities directly aimed at reducing risk, exposure or vulnerability, even if later identified as maladaptation. We focused solely on empirical research articles, excluding reviews, conference papers, book chapters and other non-journal document types. Furthermore, we focused on empirical literature encompassing qualitative or quantitative analyses and all study designs, published within the timeframe from 2012 to 2022 (see Supplementary Table 3).

Scoping

To ensure comprehensive coverage of relevant documents, we conducted preliminary scoping by leveraging five predetermined publications to formulate search terms and refine the search string (see Supplementary Method 1). Instead of replicating the search strings, we utilized these papers to identify potential search terms and gain a better understanding of the terminology commonly used in this field. This process guided the development of unique search strings for this protocol (see Supplementary Table 1).

Identification

Search strings were developed for the Scopus and SciDirect databases. Additionally, Google Scholar was selected as an additional database. The searches focused on documents that combined three concepts: climate change, adaptation responses and mountainous region. The identification of documents in these three databases have resulted in a total of 1497 articles.

Screening

The objective of screening was to compile a database of papers published between 2012 and 2022 focusing on actions taken by individuals in response to climate change or environmental conditions attributed or theorized to be linked, at least in part, to climate change in mountain regions. Adaptation is defined as 'the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities'[63]. Conceptual or theoretical contributions were treated as non-empirical and therefore excluded. To be eligible for inclusion, documents had to explicitly document adaptation actions theorized or conceptually linked to risk or vulnerability reduction. The inclusion and exclusion criteria for screening are summarized in Supplementary Table 2. All 1497 selected articles underwent screening, with only 924 articles advancing to the third step of eligibility.

Eligibility

This step involved the manual examination of the retrieved articles by the reviewers to ensure alignment with the specified criteria[64]. The list of 924 articles identified underwent an initial filtering process, which entailed a double review of titles and abstracts. This process aimed to exclude any articles that did not meet all three core criteria: mountain, adaptation and climate change. During this stage, 673 articles were excluded for various reasons, including mainly focus on vulnerability, constraints to adaptation, and resilience rather than adaptation, focus on plant phenological changes, studies conducted in non-mountainous region, emphasis on review rather than empirical data, and publication in the form of conference proceedings. Consequently, this selection process resulted in 251 pertinent studies. Furthermore, during the screening of full-text articles, an additional 53 studies were excluded. Upon closer examination, it became evident that the content of these studies did not align with the three criteria of our review, despite initial impressions from the titles and abstracts. Therefore, these studies were disregarded, leaving 198 studies for further review.

Quality appraisal

To ensure the quality of the article content, Journal Citation Report - Impact Factor (IF) for the year 2022 was checked[65]. Articles published in journals with an IF equal to or higher than 1.5, were automatically considered to have acceptable quality. Articles published in journals with an IF <1.5 or without an IF, as well as all book chapters, were excluded from the subsequent analysis process, resulting in the exclusion of 47 articles. Among these excluded articles, 14 had an IF below 1.5, 31 did not have an IF and 2 were book chapters. Thus, 151 articles remained eligible for review.

Coding and data extraction

After quality appraisal stage, 151 articles were deemed potentially eligible for data extraction. However, an additional filtering step was undertaken during data extraction to ensure the documents contained sufficient full-text information to extract relevant data. Consequently, 33 articles were excluded from the analysis due to being review articles (5 articles), studies in non-mountainous regions (2 articles), publication before the inclusion year (1 article), climate-related content without adaptation focus (16 articles), adaptation planning without empirical evaluation (4 articles), and conceptual or theoretical papers (5 articles). After these exclusions, 118 articles remained eligible for review (see Supplementary Method 2). The methods for data extraction and the development of the codebook questions were guided by our key research questions. These questions included both closed and restricted-answer questions as well as open-ended questions. To ensure the reliability of our coding process, we adopted a qualitative consensus approach[66]. In the initial phase, two coders collaboratively coded 10 studies. The process was done iteratively to reach a common consensus and stipulate a clear coding guideline. They coded each study sequentially, engaging in detailed discussions to resolve discrepancies and align their interpretations. This iterative process continued until the coders achieved consistent agreement, as demonstrated by assigning identical codes for variables—such as adaptation response types, funding agencies, multi-sectoral nature, and climatic/non-climatic stimuli. Once consensus was established, the remaining studies were divided between the coders for independent coding. During this phase, any uncertainties or disagreements were resolved through collaborative discussions to ensure consistency. In this study, an adaptation response is categorized as sector-specific if it predominantly addresses challenges or offers solutions within the specified

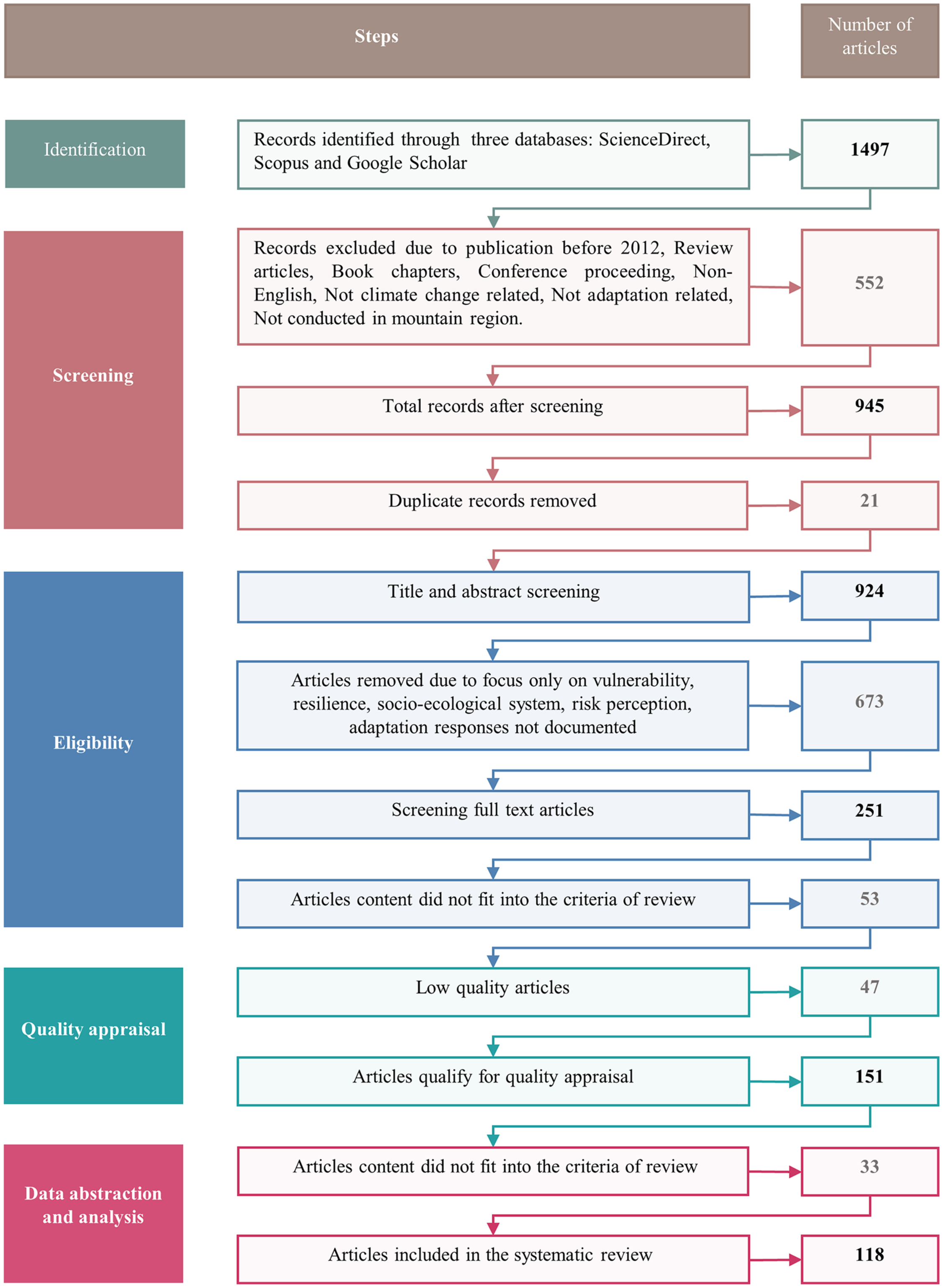

Fig. 6 | ROSES diagram. Screening process for reviewing articles of climate change adaptation in global mountain regions. Numbers in grey indicate articles removed after a screening step.

primary sector mentioned in the research article. This classification is derived from the sectors documented in the 118 research articles. Within this context, an adaptation response is identified as sector-specific based on its central focus on issues pertinent to the primary sector. For example, it is considered water-related if it addresses challenges related to water resources, including but not limited to floods, droughts, extreme rainfall events, groundwater depletion, and other hazards or interventions related to water, as discerned within the context of the respective adaptation response. Furthermore, multi-sectoral adaptation response refers to adaptation strategies shared across two or more sectors, integrating efforts in sectors such as agriculture, water, and disaster risk management, to collectively address the interconnected challenges posed by climate change. The unit of analysis for the database is discrete adaptation response.

Analysis

All analyses were conducted using R statistical software, MS Excel and JavaScript. We merged the database with our additional coding regarding multi-sectoral adaptation, their research funding agency and stimuli, adaptation response type, settlement and timing. This process resulted in a data frame containing various categorical variables, for which we computed descriptive statistics. Initially, we cross-tabulated each adaptation response with the sector, settlement, region, response type and timing. In instances where records mentioned more than one category per variable (such as multiple adaptation responses), each record was treated as multiple observations, resulting in new rows in the data frame. We then employed the chi-square test of independence to determine whether certain variable combinations occurred more or less frequently than expected if the null hypothesis were incorrect[67]. We calculated the residuals to identify which category combinations contributed the most to the chi-square test results. These tests were performed for various variable combinations, such as sector–region combinations, settlement–region combinations and settlement–sector combinations within regions. We classified adaptation type responses according to the IPCC AR6 outline. A full codebook, containing all variables is available in Supplementary Table 4. Additionally, papers could be assessed as 'indeterminate' or 'ambiguous' if they provided insufficient information on certain element such as settlement type and timing of adaptation, respectively.

Limitations

The findings of this study should be interpreted with several considerations in mind. Similar to other studies in this field[4,67,68]. We focused solely on evidence from peer-reviewed empirical studies, excluding comments, review articles, and book chapters. However, it is crucial to acknowledge that many field responses to climate change adaptation may not be captured in peer-reviewed literature and are often documented in grey literature, which can be challenging to systematically assess[4,69,70]. Additionally, our review is biased towards English-language literature due to our search criteria, potentially leading to an underrepresentation of evidence from non-English speaking countries. Future studies should aim to include non-English literature and different sources of grey literature to complement our findings. Including languages other than English in future studies would address this limitation and improve our understanding of global mountain adaptation[71]. Furthermore, while we categorized adaptation responses into 'sector-specific' and highlighted several important sectors, our analysis is not exhaustive. A reanalysis of documents in global mountain regions could focus on sectors not covered in this study. Evaluating the adaptation-related work of major regionally focused institutions such as the International Centre for Integrated Mountain Development and the Instituto de Montaña would contribute to a more comprehensive understanding of adaptation efforts in mountainous regions.

Data availability

The dataset used to create all figures is available online (https://doi.org/10.6084/m9.figshare.28684316). The dataset contains categorical variables contained in an Excel file. There are no accession codes. This dataset also contains sector and categories of adaptation responses.

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Author contributions

Ritika Kapruwan, Atishaya Kumar Saksham, Sharad Tiwari and Rajiv Pandey conceptualized the review. Ritika Kapruwan, Atishaya Kumar Saksham, James D. Ford, Jan Petzold, Graham McDowell and Stefan Schneiderbauer contributed to the Introduction. Ritika Kapruwan, Atishaya Kumar Saksham, James D. Ford, Jan Petzold, Graham McDowell, Sharad Tiwari and Rajiv Pandey contributed to the Results. Ritika Kapruwan, Atishaya Kumar Saksham, James D. Ford, Jan Petzold, Graham McDowell and Samuel Rufat contributed to the Discussion. Ritika Kapruwan, Atishaya Kumar Saksham and James D. Ford contributed to the Methodology. Ritika Kapruwan and Atishaya Kumar Saksham coordinated inputs and contributed to all the figures. Jan Petzold, Samuel Rufat, Stefan Schneiderbauer and Rajiv Pandey contributed to some of the figures. Ritika Kapruwan and Atishaya Kumar Saksham led the writing, and all authors reviewed and edited the manuscript before submission.

Competing interests

The authors declare no competing interests.

Additional information

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