nature climate change

Article https://doi.org/10.1038/s41558-024-02221-w

Perceived climate change impacts and adaptation responses in ten African mountain regions

Received: 16 April 2023

Accepted: 27 November 2024

Published online: 6 January 2025

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Mountain regions are particularly vulnerable to climate change impacts. Yet, little is known about local adaptation responses in African mountain regions, especially if these are incremental or transformational. First, using household questionnaires, we interviewed 1,500 farmers across ten African mountain regions to investigate perceived climate change impacts and adaptation responses. Second, through a reflective process involving all co-authors, we identified: (1) main constraints and opportunities for adaptation, and (2) if adaptation was incremental or transformational. Questionnaire data show that farmers in all sites perceive multiple impacts, and that they mostly respond by intensifying farming practices and using off-farm labour. We established that, while several constraints were shared across sites, others were context specific; and that adaptation was mostly incremental, but that certain attributes (for example, social capital) made three sites in East Africa slightly more transformational.

Temperature changes are more rapid in mountain environments than at lower elevations[1], changes which negatively affect not only glaciers and water budgets, but also crop yields, livestock and human diseases[2]. African mountain regions, especially across East Africa, have also observed an increase in extreme weather events (floods and droughts), which have had severe social, ecological and economic impacts[3]. In African mountain regions, as in other regions with complex topography, considerable uncertainty exists about the local consequences of ongoing climate change, because of the limited spatial resolution of global or regional climate models[4]. For such regions, field observations from subsistence-oriented communities can help to not only document the multiple fine-scale environmental consequences of climate change, including those relevant to local communities[5], but also provide the insights needed to design effective adaptation responses[6]. Indeed, the potential contribution of local knowledge from subsistence-oriented communities to climate research is increasingly being acknowledged, particularly in data-deficient regions of the world[7–9].

Recent synthesis works on climate change adaptation in Africa[10–12] have overlooked mountain regions, although the IPCC Assessment Report 6 chapter on mountains highlights the increase in climate change impacts over recent decades with observable and serious consequences for people and ecosystems across the mountains of the world, particularly in Africa[13]. African mountain regions, with

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Table 1 | Key contextual information on the ten mountain regions studied

Site	Main ethnic group	Adults	Farm size (ha)	Large animals (%)	Farming (%)	Staple crop	Cash crop	House owner (%)	Radio owner (%)	No education (%)	CC literate (%)	ILK sown seeds (%)
Bamboutos (Cameroon)	Bamiléké	4.3	1.4	60% pigs	69% farming	Maize, beans, Irish potato	Irish potato	91	65	21	57	100
Itombwe (Democratic Republic of the Congo)	Nyindu	4.6	1.9	96% cows	99% farming	Maize and Irish potato	NA	100	67	82	24	100
Kigezi (Uganda)	Bakiga	2.6	1.7	67% pigs	100% farming (33% coffee)	Maize, beans, Irish potato	Coffee/ Irish potato	95.4	64	6.6	49	95
Bale (Ethiopia)	Oromo	5.8	0.54	90% cows/ goats	97% farming (88% coffee)	Maize, teff, mung bean	Coffee/ sesame	95	78	86	79	11.3
Mt Kenya (Kenya)	Meru	2.9	1	88% cows/ goats	99% farming (44% coffee)	Maize, beans, Irish potato	Coffee/ banana	100	100	2	82	82
Aberdare (Kenya)	Kikuyu	3.4	2.4	90% cows/ goats	96% farming (40% coffee)	Maize, beans, Irish potato	Coffee/ tea	100	99	2.6	81	68
Kibiria (Burundi)	Bantu[a]	2.7	0.5	37% cows/ pigs	100% farming	Maize, beans, Irish potato	Tea	92	71.3	66.6	96	98
Nyungwe (Rwanda)	Bantu[a]	1.8	0.74	54% cows/ pigs	60% farming	Beans	Beans	100	44	29	90	53.3
Kilimanjaro (Tanzania)	Chagga	2.9	2.3	87% cows	60% farming (8.5% coffee)	Banana, maize, beans, yams	Coffee	100	97	1	99	NA
Udzungwa (Tanzania)	Hehe	3.9	3.9	55% goats/ pigs	60% farming	Maize, beans, millet	Irish potato/ onions	97.3	45	8	98	NA

Data were obtained from the semistructured questionnaires. Adults, average adults per household. Large animals, percentage of respondents owning large domestic animals (n=150 respondents per site). Farming, percentage of respondents practicing staple crop farming (or coffee farming). The following also refer to percentage of respondents per site: house owner, no education, climate change (CC) literate and indigenous and local knowledge (ILK) used to determine when to sow seeds. NA, not available. [a]Refers to both Hutu and Tutsi ethnic groups of Bantu origin, as differentiating between these two is politically unacceptable in these countries.

228 million people, have the second highest population density in mountain regions of the world (after Asia), and it is projected that this population will continue to increase under all shared socio-economic pathways (SSP) scenarios, contrary to, for example, Asian mountain regions. The report also warns that with warming >1.5 °C, and related changes in rainfall, adaptation becomes more and more urgent in mountain regions. Yet knowledge of where and how climate change adaptation is happening in African mountain regions remains extremely limited[13].

As the effects of climate change become more severe, it is recognized that if African countries, and their diverse peoples, are to adapt to predicted climate change impacts, incremental adaptation (characterized by responses that seek to maintain the essence and integrity of a system) might not be sufficient, and transformational adaptation (a shift in characteristic features and functions of socio-ecological systems) will be necessary[14,15]. However, most available case studies in Africa show incremental modes of adaptation rather than transformational ones[15,16]. Detailed comparative case-study analysis can help to identify the wider processes of change that can overcome barriers to transformational adaptation[17]. Such analyses have, to date, focused on African lowlands rather than on the continent's mountain regions[15,17].

Here, we first explore both climate change impacts as perceived by local subsistence-oriented communities, and their adaptation responses, in ten African mountain regions located in Central and East Africa (Table 1 and Extended Data Fig. 1), using focus-group discussions (FGDs) with village elders and a semistructured questionnaire administered to 1,500 smallholder farmers (150 per study site; Methods). Following ref. 18, we provided a list of potential: (1) climatic changes observed, (2) impacts in the biophysical domain and (3) adaptation responses, which were narrowed down to those relevant for each study area according to FGDs participants' views, with only those being included in the semistructured questionnaire (for example, questions about coffee were only relevant to five sites where this crop was cultivated). The collection of locally relevant, but cross-culturally comparable, information using a common protocol allows the simultaneous identification of common trends and context-specific singularities of individual sites[18].

Second, through a reflective and analytical process involving all co-authors, we determined for each site: (1) main constraints and opportunities for adaptation adapting the IPCC guidelines[19], and (2) if adaptation was incremental or transformational, applying the framework of ref. 15 (Methods). Through this comparative analysis, we demonstrate that there are general patterns across mountain regions in perceived climate change impacts and local adaptation responses, but also that there are some context-specific effects, which should be considered if we are to help mountain communities better adapt to climate change impacts and initiate transformational pathways that secure sustainable development. This work contributes to recent calls to better integrate indigenous and local knowledge (ILK)—defined as the understandings, skills and philosophies developed by societies with long histories of interaction with their natural surroundings[20]—to climate research[21,22] and to better document adaptation responses in data-deficient Central Africa[16,22].

https://doi.org/10.1038/s41558-024-02221-w

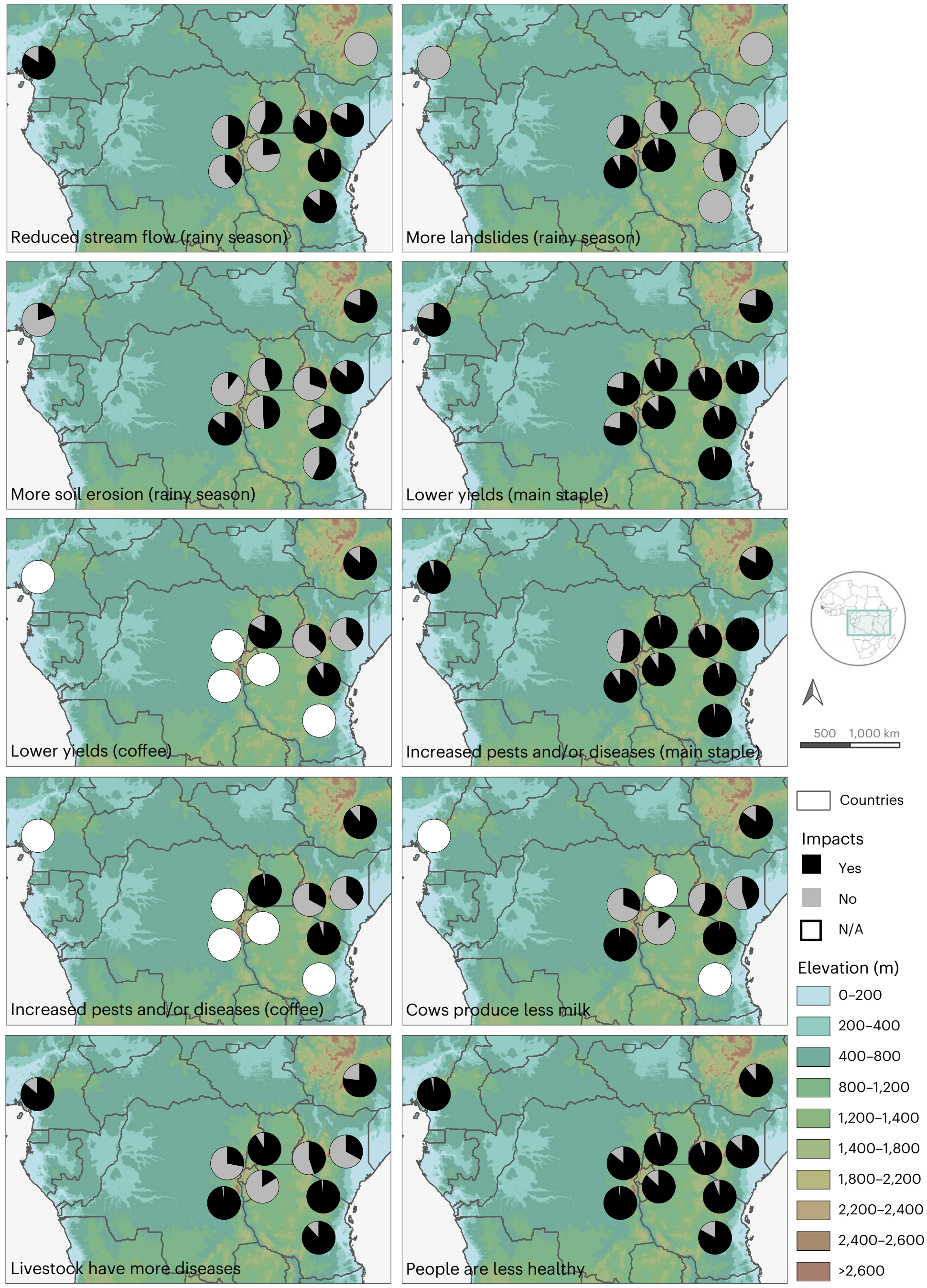

Fig. 1 | Climate change impacts perceived in the ten mountain regions studied. Data show the percentage of respondents per site reporting each impact ($n = 150$ respondents per site). For perceived climatic changes, see Extended Data Fig. 2. Note that responses relate to predetermined questions and that not all impacts were asked at each study site, as some were identified as not applicable in a given site by focus-group participants (Methods). Figure created using QGIS v.3.28.15. Elevation data from NASA (https://www.un-spider.org/links-and-resources/data-sources/digital-elevation-model-srtm-1-arc-second-30m-nasa-nga). Country boundaries from ICPAC, accessed through https://open.africa/dataset/africa-shapefiles.

Perceived climate change impacts

Seven climate change-related impacts were reported by numerous respondents to the household questionnaires in nearly all (9 out of 10) sites, including reduced stream flow, reduced crop yields and cow milk production, increased soil erosion, increased crop and livestock diseases and reduced human health (Fig. 1). An increase in landslides was reported in five sites, and lower coffee yields were also reported in each of the five coffee-growing sites studied (Fig. 1). These impacts were mostly related to nine different climatic changes, which were reported by most respondents in nearly all (9 out of 10) sites, including increased temperatures, reduced fog, changes in rainfall amount and distribution, an increase in extreme droughts, fewer hailstorms and increased wind strength during the rainy season (Extended Data Fig. 2). An increase in extreme floods and less frost, were also cited by respondents in seven sites (Extended Data Fig. 2).

Most of these impacts have been documented by previous work in East African mountains[13,23], but we now extend these impacts to mountain regions in Cameroon, Democratic Republic of the Congo and Burundi. Previous studies on African mountains seldom identified reduced human health as a climate change impact (for example, ref. 23), although this is well-documented in, for example, Mexico, Colombia or Nepal[24–26]. Our study respondents related reduced human health to

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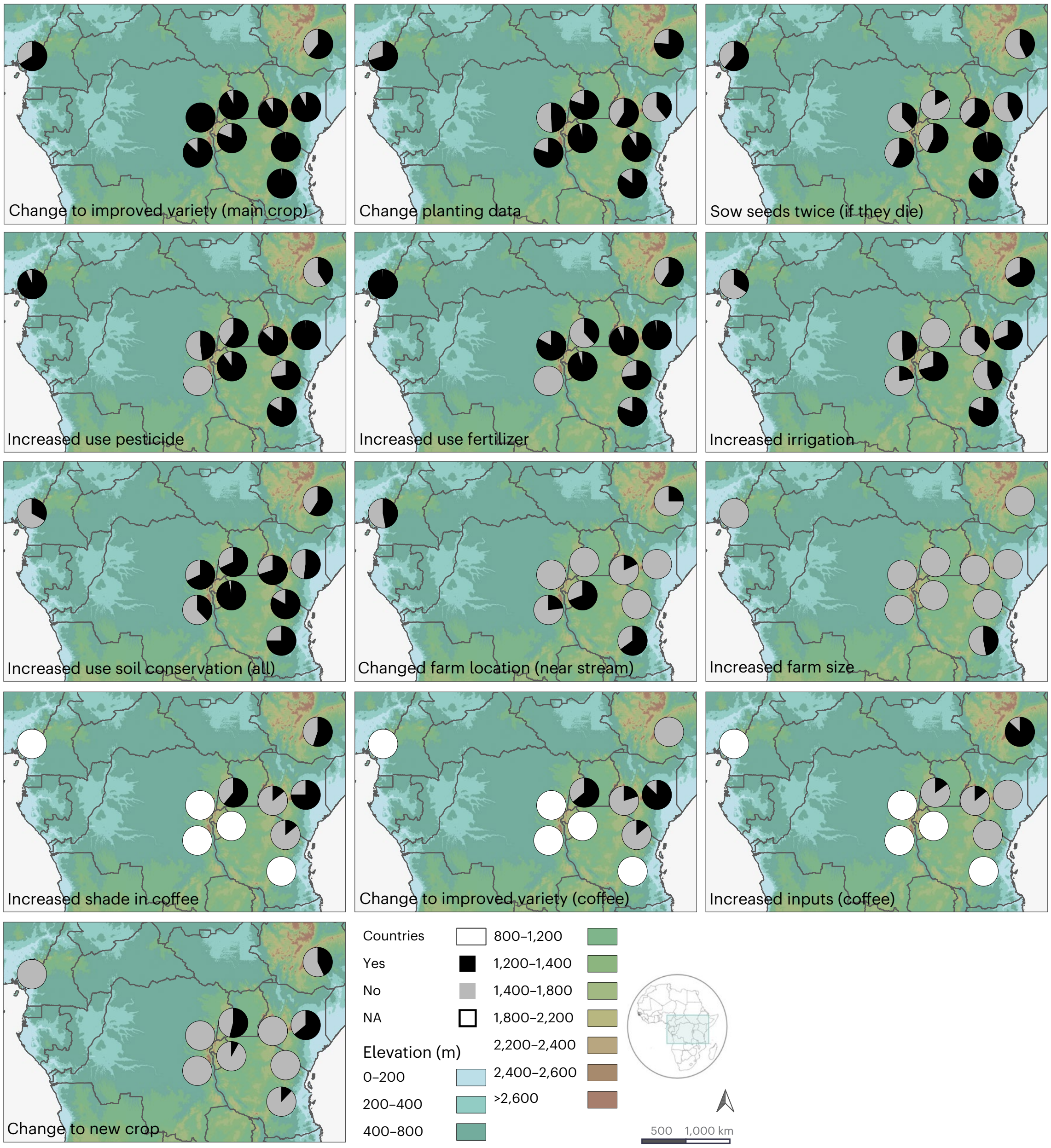

Fig. 2 | On-farm adaptation responses used in the ten mountain regions studied. Data show the percentage of respondents per site reporting each adaptation response ($n = 150$ respondents per site). For off-farm adaptation responses, see Extended Data Fig. 3. Note that responses relate to predetermined questions, and that not all responses were asked at each study site, as some were identified as not applicable in a given site by focus-group participants (Methods). Figure created using QGIS v.3.28.15. Elevation data from NASA (https://www.un-spider.org/links-and-resources/data-sources/digital-elevation-model-srtm-1-arc-second-30m-nasa-nga). Country boundaries from ICPAC, accessed through https://open.africa/dataset/africa-shapefiles. New crops refers to: millet (Udzungwa), Irish potatoes (Bale, Kigezi), banana (Bale, Mt Kenya), pineapple (Kigezi), sweet potatoes, cassava, or wheat (Kibira). NA, not available.

an increase in malaria prevalence and influenza (Kibira, Burundi), respiratory diseases (Aberdare, Kenya) or waterborne diseases (cholera, typhoid, dysentery; Udzungwa, Tanzania), something which requires further investigation.

The reported widespread reduction in fog also requires further examination. ‘Reduced fog’ is the consequence of rising cloud base (and/or reduced overall cloud incidence) in mountain regions which is known to be driven by increased temperatures[27,28]. In some ecosystems, fog can be an important source of water, substantially extending the length of the growing season for plants[27]. This could also apply to crops, as some FGD participants noted “these days the fog disappears very early in the morning in the dry season, which negatively affects the growth of maize seeds” (farmer comment in Bale Mountains, Ethiopia). The IPCC chapter on mountains[13] mentions that risks to livelihoods and economy from changing mountain water resources are low in Central Africa and moderate in East Africa; but this chapter only considers changes in rainfall, glaciers and groundwater, not fog. It is increasingly acknowledged that relying on information gathered by instrumental meteorological measurements falls short of providing a comprehensive view of ongoing, locally experienced climate change impacts[29,30]. Our results support such a statement, highlighting that mountain farmers in Africa are faced with multiple impacts simultaneously, and that most of these impacts are widespread across mountain regions.

Local adaptation responses

Eight on-farm and one off-farm adaptation responses were reported by most respondents to the household questionnaires in nearly all (9 of 10) sites, including changing planting dates, sowing seeds twice

Table 2 | Key attributes explaining (un)likelihood of transformational change processes for adaptation at the study sites

Study site	Change agents	Learning and pathways to change	Scope and scale	Indications of sustainability of change	Overall grade
BAM	Farmers themselves, no external support, no farmers' associations	Limited learning, no room for experimenting due to ongoing conflict	Limited to some individuals	Limited sustainability of change	0
ITO	Farmers themselves, no external support, no farmers' associations	Limited learning, no room for experimenting due to ongoing conflict	Limited to some individuals	Limited sustainability of change	0
NYU	NGOs and government extension services present	Limited learning among actors, limited room for experimenting due to government policies and law enforcement.	Limited to government choices (strong law enforcement). Externally driven commercially oriented agricultural change	Weak linkages between national and local goals, issue of food insecurity	0.5
KIB	NGOs and government extension services present, and some farmers' associations	Limited learning among actors	Limited to some individuals or villages (if NGO). Externally driven commercially oriented agricultural change	Weak linkages between national and local goals	1.0
KIG	Some NGOs present, and some farmers' associations	Limited learning among actors	Limited to some individuals	Limited sustainability of change	1.0
ABE	NGO support in two villages, change agents mostly individuals, farmers' associations present	NGOs support knowledge exchange, farmers engaged in experimenting	Individual level mostly, wealthier farmers have more options	Change driven by farmers keen to try new adaptation responses	1.0
UDZ	NGOs and government extension services present, farmers' associations present	Limited knowledge exchange among actors	Individual level mostly, wealthier farmers have more options	Change driven by farmers keen to try new adaptation responses	1.0
BAL	Government extension services present	Limited learning among actors but extensive social networks spread interventions	From individual to village level	Change driven by multiple actors and extensive social networks, opportunity for linkages between national and local goals if learning among actors is strengthened	1.5
KEN	Top farmers have an important role, NGO supports organic coffee certification (one village), farmers' associations present	Top farmers allow for knowledge exchange, strong social capital among Meru, farmers engaged in experimenting	From individual to village level, changes beyond agriculture	Change driven by farmers keen to try new adaptation responses, strong social capital	2.0
KIL	NGOs and government extension services present, farmers' associations present	Limited knowledge exchange among actors, but farmers engaged in experimenting (high education, remittances from younger urban generations), strong social capital (for example, irrigation system)	From individual to village level, changes beyond agriculture	Change driven by farmers keen to try new things, strong social capital	2.0

Data were identified through a reflective process involving all co-authors (Methods). Framework adapted from ref. 15, excluding the overall grade which we created and categorized from 0 (only incremental) to 5 (very transformational). ABE, Aberdare Range (Kenya); BAL, Bale Mountains (Ethiopia); BAM, Bamboutos Mountains (Cameroon); ITO, Itombwe Mountains (Democratic Republic of the Congo); KEN, Mount Kenya (Kenya); KIB, Kibira (Burundi); KIG, Kigezi Highlands (Uganda); KIL, Mount Kilimanjaro (Tanzania); NYU, Nyungwe (Rwanda); UDZ, Udzungwa Mountains (Tanzania). NGO, non-governmental organization.

if they die, changing to improved crop varieties, increasing use of soil conservation techniques, irrigation, fertilizer, pesticide and veterinary care; and diversifying into off-farm labour (Fig. 2). With regard to coffee, changing to improved varieties, increasing use of pesticides or shade of coffee plants were reported in most of the five coffee-growing sites studied. Seven other on-farm and six other off-farm adaptation responses were also reported by respondents, some of which were only cited in one study site: for example, increasing farm size in Udzungwa (Tanzania), diversifying into timber trade in Mt Kenya or diversifying into mining in Itombwe (Democratic Republic of the Congo) (Fig. 2 and Extended Data Fig. 3). Despite high climate change literacy (defined as a combination of having heard of the concept of climate change and the knowledge and acceptance of its anthropogenic cause; Methods), most (>80%) respondents in seven sites used only ILK to determine when to sow their seeds (Table 1). However, ILK will become less useful to farmers in the future, as climatic patterns such as rainfall distribution continues to change from the patterns observed in the past and shared from one generation to the next[31,32].

We also investigated if perceiving a greater number of climatic changes influenced adaptation responses, using mixed-effects models (Methods). In Uganda, it has been shown that farmers with better skills on climate tracking (for example, recall of rainfall patterns which align with meteorological data available), tend to achieve higher crop yields; most likely making better on-farm decisions, such as timing of planting[32]. We found that there was no significant overall relationship between the proportion of climatic changes observed and the proportion of adaptation responses enacted (slope = −0.028, 95% confidence interval (CI) = −0.160–0.112) (Extended Data Fig. 4). Household wealth was a stronger driver of adaptation. Overall, poorer households performed fewer adaptation actions than average-wealth ones (difference = −0.039, 95% CI = −0.077–−0.002), while richer households tended to perform more actions than average-wealth ones (difference = 0.031, 95% CI = −0.033–0.087), although this last effect differed markedly between sites, with clear differences in Bale (Ethiopia), Bamboutos (Cameroon) and Mt Kilimanjaro (Tanzania), but not at the other sites (Extended Data Fig. 4). Site itself was also an important factor influencing adaptation responses. In general, in sites with the lowest proportion of adaptation responses, households tended to be poorer (for example, even richer households in Itombwe in Democratic Republic of the Congo were rather poor), while sites reporting more adaptation were often richer (for example, Mt Kilimanjaro in Tanzania), although some poorer sites also reported high adaptation

Table 3 | Main three constraints (–) and opportunities (+) identified for the study sites

	Constraints (number of sites)	Opportunities (number of sites)	BAM	ITO	KIG	NYU	KIB	BAL	KEN	ABE	KIL	UDZ
Physical aspects												
Land is limited	7				–	–	–	–	–	–	–	
Road infrastructure is limited (market access)	3		–	–	–							
Water is limited/is abundant	2	4		+			+	–	+	–	+	
Economic aspects												
Lack access to credit	8		–		–		–	–	–	–	–	–
Governance/institutions												
Limited capacity to self-organize/ organized already	2	5	–	–			+		+	+	+	+
Existing national agricultural policies	1					–						
External actors present and perceived as helpful		6			+	+		+		+	+	+
Knowledge, awareness, technology												
Lack of skills in new technologies	4						–	–			–	–
Aware of climate change impacts		9	+		+	+	+	+	+	+	+	+
Mobile communications available		7	+		+		+		+	+	+	+
Human resource												
Entrepreneur-experimenting skills exist		3							+	+	+	
Other												
Violent conflict limits options	2		–	–								

Data were obtained through a reflective process involving all co-authors (Methods). Note that in some sites either two or four were agreed upon, instead of three. Site abbreviations as in Table 2.

(Extended Data Fig. 4). Collectively, these analyses are consistent with household wealth acting as a constraint to adaptation (discussed below), alongside other site-dependent effects.

Overall, results show that African mountain farmers respond to climate change impacts by using multiple adaptation responses, most of which focus on intensifying farming practices. In most mountains, adopting new crop varieties was combined with increasing use of inputs (fertilizer and pesticides) and soil conservation techniques, as shown before[33], and was supported by external actors (Table 2). In Itombwe (Democratic Republic of the Congo), extension services and inputs are not available (owing to violent conflict and lack of road infrastructure to bring inputs), and, still, over 80% of the farmers used improved varieties, highlighting the high penetration of improved maize seeds in the African continent, even into remote mountain regions. Overall, most adaptation responses reported are behavioural rather than technological, infrastructural or ecosystem-based, as shown for mountain regions elsewhere[34].

Climate change impacts are unlikely to be the only driver of intensifying farming practices; other contributors could be decreasing farm sizes related to increasing human population density in mountain regions (Table 1), global market drivers and national agricultural policies (for example, in Rwanda, the government requests farmers to focus on improved varieties of maize and beans, rather than traditional crops with low export value such as sweet potato, cassava or sorghum[35]). Regardless of the drivers, the ecological and economic sustainability of intensifying farming practices should be further investigated, as several study respondents highlighted that increasing use of chemical fertilizers/pesticides has sometimes led to water pollution, and there were cases of dis-adoption of improved varieties due to the requirement of also using 'expensive' inputs when cultivating such varieties.

Despite the observed similarities in the on-farm adaptation responses used across sites, important differences were found in the off-farm responses implemented, mostly driven by context-specific differences. Notably, the drivers of engaging with a given off-farm adaptation response were not necessarily the same across sites. For example, in Mt Kenya farmers engaged with vegetable and fruit production because of high access to urban markets, while in Bale (Ethiopia) this was driven by a livelihood diversification programme supported by the government, and in Nyungwe (Rwanda) this was related to little government regulation on vegetable/fruit farming compared to regulations on staple crops or animal rearing (and therefore higher income opportunities). Context-specific differences also affected the lack of adoption of certain adaptation responses, particularly in the two sites affected by violent conflicts: in Bamboutos (Anglophone Cameroon) farmers were unwilling to invest in animal rearing as animals can be easily stolen by rebels, and in Itombwe (eastern Democratic Republic of the Congo) few farmers invested in soil conservation techniques as they were likely to abandon their villages (and farms) during increased periods of violent conflict.

The IPCC chapter on mountains[13] mentions that across continents, adaptation responses in mountains mainly focus on the use of early warning systems and the diversification of livelihood strategies, in particular tourism. Yet, increased use of early warning systems or engagement with tourism, were not cited in any of the ten sites studied. Early warning systems are not available in most sites studied, and where they are (for example, Mt Kenya), respondents said that radio forecasts were not accurate, so they did not use them. Concerning tourism, even if most study sites contain National Parks visited by tourists, there are not enough job opportunities for all farmers to engage in this industry, particularly if they do not speak English/French or have certain skills.

Temporary outmigration is also a form of adaptation for climate-vulnerable households in rural areas in Africa, as shown in Uganda or Tanzania[36]. However, others have shown that extreme temperature and rainfall shocks caused no increase in rural temporary outmigration[37], as several sociodemographic, economic and political

BOX 1

Priorities for climate change adaptation in mountain regions of Africa

(1) Improve access to credit, technical skills and markets: It is widely acknowledged that these are widespread constraints to smallholder farmers' adaptation to climate change[33]. We emphasize that there are multiple pathways to addressing these issues, and innovative solutions could comprise multiple actors, such as the private sector[16] or some community members as shown by 'elite farmers' in Mt Kenya in this study, which facilitated access to both new skills and technologies. Access to markets is not just related to physical infrastructure (for example, roads), but also awareness of market prices and types of markets and cultural values (for example, symbolic value of some crops or animals[44]). While physical infrastructure largely depends on government interventions, other actors such as NGOs or extension services can help address awareness of market prices using mobile phones and cultural values, by engaging with farmers more closely. Product certification (for example, organic coffee certification) could also be an option, as this can increase economic benefits and compensate for lower yields, contributing to farmers' climate change adaptation[45], as we observed in Mt Kenya.

(2) Increase knowledge exchange among actors: Knowledge exchange among actors (for example, local farmers and extension services) benefits the transformational adaptation process[15], but this is still not the norm in most mountain contexts. Often, a new technology is presented as a one-off (for example, seeds from improved crop varieties are distributed) and the farmer has no opportunity to ask questions once he/she tries the new technology and challenges arise (as our study respondents highlighted). Apart from supporting farmers throughout the 'new technology' learning process, farmers can also help design adaptation responses better adapted to their cultural values and contexts. For example, bananas are a staple crop in both Mt Kenya and Mt Kilimanjaro, but our study respondents highlighted that there is limited access to improved varieties of banana.

(3) Consider national policies and governance: In Rwanda, agricultural intensification policies have raised crop yields, and the conventionally measured poverty rates have fallen, but these policies appear to be exacerbating rural landlessness, inequality and food insecurity, particularly for the poorest households[46]. While these policies directly promote some adaptation responses such as improved crop varieties, they also indirectly promote others (for example, diversifying into vegetable farming), as our results have shown. Thus, the multiple effects of such national policies should be considered at the local scale, by taking into account that farmers are not a homogeneous group, particularly in the culturally diverse mountain regions. Concerning governance, special attention should be paid to the nuanced effects of violent conflicts. There are multiple types of violent conflicts, such as civil wars, sectarian, territorial disputes, political instability or transitional terrorism, which can affect farmers adaptation responses differently. Not only important infrastructure such as bridges or dams may have been destroyed, but also state services such as early warning systems may be lacking[47]. Less obvious impacts such as imposition of movement restrictions can also severely disrupt farming[48], as well as the reduced opportunities for livelihood diversification during violent conflicts (for example, tourism)[49]. More research attention and external support should be given to conflict-affected regions, particularly in mountain regions.

factors affect migration[38]. Temporary outmigration was not identified as a form of adaptation in any of our study sites (during the FGDs used to narrow down the list of potential adaptation strategies). While limited employment opportunities in urban areas and limited economic resources available for migration are likely to limit rural outmigration, high place attachment seems to be another key factor, as farmers explained "our land, even if small, has fertile soils and it is not affected by severe droughts like in other parts of the country" (farmer comment during FGD in Kigezi, Uganda). Other studies have highlighted how place attachment limits smallholder farmers' outmigration in rural areas[39].

Constraints and opportunities

Through a reflective and analytical process involving all co-authors (including at least one with long-term expertise in each site), together with information from FGDs and the IPCC list of constraints and opportunities for adaptation[19], physical (for example, access to land) and economic (for example, access to credit) aspects were identified as the main constraints to adaptation in most sites, with governance aspects and knowledge, awareness and technology, also cited in some sites (Table 3). A recent overview of adaptation gaps in mountain regions[34] also noted that soft limits (issues which could be tackled, such as economic constraints, knowledge, awareness and technology) limited adaptation. In our study, some aspects considered as constraints in some sites could be considered opportunities in others (for example, water for irrigation). Two aspects not included in the IPCC list of main constraints[19] or in the overview of adaptation gaps in mountain regions[34] were also identified in the FGDs: violent conflict (cited in Cameroon and Democratic Republic of the Congo) and strict national agricultural policies (cited in Nyungwe, Rwanda). This highlights the importance of engaging with local farmers, through, for example, open questions in FGDs, to investigate their constraints to adaptation, as local context(s) might be quite diverse.

The opportunities most relevant across sites were found to be awareness of climate change impacts and mobile phone communication (Table 3), factors widely known to be key to smallholder farmers' climate change adaptation[33]. Mobile phone communication, which is increasingly available even in remote areas across the African continent at an affordable cost (accessible in all sites studied except in Democratic Republic of the Congo) increases potential access not only to weather forecasts and technical information (for example, on new pests), but also to markets and mobile financial services. Presence of external actors and entrepreneurial skills were also identified as opportunities in several sites (Table 2), the latter with comments such as: "if you have the chance to try something new, you try it, but if you are not happy with the outcome, you stop that and maybe try something else next growing season" (farmer comment in FGDs in Mt Kenya). Although smallholder farmers tend to be risk averse, which leads to limited investment and adoption of new technologies[40], our results show that in some sites (with greater market integration and farmers' access to education), entrepreneurship is not rare.

Incremental rather than transformational adaptation

After applying the framework of ref. 15, co-authors considered that in all sites adaptation was more incremental than transformational, but also that some sites were slightly more transformational than others (Table 2 and Extended Data Fig. 5). Some of the 'towards transformational' attributes were shared across sites (for example, knowledge exchange among actors, strong social capital, farmers engaged in experimenting), but not all (for example, change agents). In Mt Kenya, for example, 'elite' farmers and strong social networks among Meru farmers were key for innovation and knowledge dissemination. Elite farmers refer to rich farmers who not only have better access to information, technology and inputs (for example, improved seeds, fertilizer and pesticide), but also are keen to advise their fellow farmers by, for example, providing improved seeds to trial. In Mt Kilimanjaro (Tanzania), multiple actors, strong social networks and the fact that most Chagga farmers have invested in educating their children—who now work in urban areas and can provide remittances, information and market access to their relatives in the mountains—can explain the experimental nature of the farmers in this mountain and the diversity of adaptation responses they use. In Bale Mountains (Ethiopia), it was the presence of government extension services and strong social networks which helped spread (and diversify) adaptation responses. These differences in 'towards transformational' attributes, highlight that there are multiple pathways towards transformation processes[15]. Overall, our findings on mountain regions are aligned with previous work on the African lowlands showing that farmers' adaptation in the continent is still mostly incremental[15–17]; and with the observation that most adaptation in mountain regions across the world is incremental in nature[13,34].

We identify three key priorities for moving forward farmers' climate change adaptation in mountain regions in Africa and beyond (Box 1). These recommendations are drawn from key insights that emerged from this study, combined with our collective reflection on the similarities and differences across the ten mountain contexts studied. While the first priority—credit, technical skills and markets—refers to well-known soft limits to adaptation relevant beyond mountain regions, the other two priorities are particularly important in mountain regions, known to suffer from socioeconomic and political isolation and marginalization and changes in governance[41]. The last priority (the nuanced effects of violent conflicts) was not mentioned before (see refs. 15,16) and can be extremely important in some mountain contexts. Thanks to our study approach (involving FGDs with village elders), we were able to identify such issues. Indeed, the importance of coproduction, of connecting researchers with diverse societal actors to collaboratively and iteratively produce knowledge, action and societal change, is increasingly recognized[42,43]. Although the approach we used was rather solutions-oriented[43], and we only engaged local actors in part of the process, it helped start a more participative process. Mountain regions, which are not just environmentally but also culturally complex systems[41], could especially benefit from more coproduction approaches, to help multiple actors design appropriate pathways to the transformational changes needed in the face of increasing climate impacts.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-024-02221-w.

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https://doi.org/10.1038/s41558-024-02221-w

Methods

Field data collection and analysis

We selected ten study sites in mountain regions (both mountains and highlands, as defined by ref. 13) covering a wide range of ecological contexts (for example, different elevation or annual rainfall), socioeconomic contexts (for example, different livelihood strategy or market access) and political contexts (different countries). Site selection was also affected by security situation on the ground (for example, ongoing conflict in Anglophone Cameroon) and previous engagement in the area by local partners facilitating fieldwork. In each study site (Extended Data Fig. 1), four villages located at different elevations were selected. These villages were selected by local partners facilitating fieldwork based on accessibility, given the limited resources available for this research. In each village, we first conducted exploratory FGDs with four or five elders. After we explained the aim of the study to the village chief, he explained it to the elders (mostly male, typically >60 years of age), and some decided to participate on a voluntary basis. These FGDs were used to adapt a common semistructured questionnaire to each study context and to build trust among community members. The common (for all ten sites) semistructured questionnaire included a long list of potential (1) climatic changes observed, (2) impacts in the biophysical domain and (3) adaptation responses (from ref. 50) which were narrowed down to those relevant for each study area, according to FGDs participants. During the FGDs we also gathered information on agents of change promoting adaptation responses in the village (the government, NGOs or local communities without external support) and on perceived constraints for further adaptation.

Then, in the same villages, we conducted semistructured questionnaires to 37 or 38 randomly selected households aiming to interview about 50% males and 50% females of the main decision-making couple (if more than one generation lived together) ($n = 150$ in total per study site). In each village, households were selected by walking the main road (or footpath as defined by local inhabitants) and selecting every third household to the right. If the household head was not available, the next-door neighbour was targeted. We first interviewed the household head who opened the door (male or female), until we reached the targeted sex quota for that village, and then we asked to interview the other sex in the subsequent households. We acknowledge that there are preferred methods for selecting households (for example, randomly from a list), but a register of households was unavailable in several study sites. The 'main road' approach might have led to interviewing richer households in more market-integrated contexts (for example, in Mt Kilimanjaro). As the main focus of our research was on differences across sites (and not within sites), we consider this a minor issue, but future research should investigate differences across households within study sites.

The questionnaires used addressed household characteristics and assets, climatic changes observed, impacts in the biophysical domain, adaptation responses used to cope with or adapt to observed changes and impacts (Supplementary Information). They also included climate change literacy, defined as a combination of climate change awareness (having heard of the concept of climate change) and the knowledge and acceptance of its anthropogenic cause. Climate change literacy, combined with climate information services that are demand driven and context specific (for example, for agriculture) can be the difference between coping and informed adaptation responses[51].

The methodological approach and the questionnaire used follow the guidelines of the project 'Local Indicator of Climate Change Impacts', a project focused on providing data on the contribution of local and indigenous knowledge to climate change research[50]. We adjusted the framework proposed by ref. 52, in which changes in the climate itself and the effects of climate change observed (in the physical, biological and social systems) are differentiated. We adhere to the Framework Convention on Climate Change[14] and use 'climate change' to refer to a change in the state of the climate that can be identified by changes in the mean and/or the variability of its properties, and that persists for an extended period. Similar to ref. 8, we use the term 'local perceptions of climate change' to refer to reports provided by local peoples about changes in the climatic system (temperature, precipitation and wind).

The exploratory FGDs and the household questionnaires were carried out in the languages Ngombale (Bamboutos), Rukiga (Kigezi Highlands), Kinyarwanda (Nyungwe), Kirundi (Kibira), Oromo (Bale Mountains), Swahili (Itombwe, Mount Kenya, Aberdare, Mount Kilimanjaro and Udzungwa) and were facilitated by some co-authors between November 2020 and January 2022. All study participants (FGDs and household questionnaires) were selected on a voluntary basis and were first informed that the study aimed to better understand climate change impacts and adaptation practices. Free, prior and informed consent was orally secured after reading a consent form in the local language, which clarified the study aim, voluntary participation, confidentiality and procedure for withdrawal from the study.

In each study site, data gathering was led by a researcher from the same ethnic group studied, who had previously worked in the study area targeted: someone who could be considered an insider. Because of this, and also because of the use of a standardized questionnaire and the engagement in reflexive practice during eight webinars used to coordinate results interpretation across sites, we consider that researchers' positionality across sites was rather uniform. Owing to the predominance of agriculture-based livelihoods and historically sedentary settlements and culture, throughout the paper we refer to our study respondents as farmers, but we acknowledge multiple livelihood strategies. We also refer to our study respondents as subsistence-oriented farmers, because even if some cultivate cash crops (coffee; Table 1), the proportion of their farms allocated to coffee is smaller than the proportion allocated to staple crops.

To investigate differences across study sites, the main unit of analysis was percentage of respondents per study site. Initially, we explored differences in the responses within one study site related to sex of the respondent using paired t-tests but these were non-significant, probably because most of the females interviewed were married and were not female-headed households (those without a husband or adult male relative living with them). Thus, we do not include sex-based analysis in this manuscript. We also investigated if: (1) perceiving more climatic changes or (2) household wealth, influenced adaptation responses, using mixed-effects models. For each study site and respondent, we calculated the proportion of potential climatic changes, impacts and adaptation responses reported. Changes, impacts and adaptations that did not apply to a site (for example, reduction in frost in sites that would not normally experience frost) were excluded from the calculation of proportions. We used hierarchical models to evaluate within and between site variation in adaptation responses. To do this, we fitted linear mixed-effects models using the lme4 R package v.1.1-31 (ref. 53) which modelled the proportion of adaptations as a function of the proportion of climatic changes and household wealth category as fixed effects, study site as a random effect, with both proportion of climatic changes and household wealth allowed to vary among random effect levels (fitting a random slope model). This treatment was especially important for wealth, as it is a relative index for each site so categories differ more in less equal societies, but it also allowed the effect of climatic changes observed to vary between sites. The response variable was the proportion of possible adaptations observed in a household (that is, varying from zero to one). We used a Gaussian error distribution for the hierarchical model as the response variable was approximately normally distributed, and reviewed diagnostic plots to ensure that model assumptions of normality and homoscedasticity of residuals were met. Confidence intervals for linear model coefficients were obtained through parametric bootstrapping.

In each study site, households were classified into three wealth categories (poor, average and wealthy) on the basis of a wealth index created from ten asset indicators specific to each study site[54,55], identified during the FGDs. For a list of assets used in each site, see Supplementary Information, section B. Assets that varied most across the households in that site (>25% of households did not own them) were weighted 0.25 greater than those more commonly found.

Constraints and opportunities

Throughout the 18 month research project, bimonthly webinars were organized with all co-authors (including at least one with long-term expertise in each site), to share findings and reflections across study sites. During the eighth webinar, we realized that some constraints identified at some sites, could be considered opportunities in other sites. Therefore, we reframed our approach to also consider opportunities. First, study site leaders (both student who led the fieldwork and the professor with years of experience working on that site) used the information on constraints mentioned during the FGDs to identify the top three constraints at their site (those cited most often), according to the list provided in ref. 19, which groups constraints into broad categories (for example, physical aspects and economic aspects). Second, they identified the top three opportunities (adapting the list in ref. 19), reflecting on the data gathered during the field campaign and their own knowledge of the site. Although we requested site leaders to identify three of each, some identified two to four in some sites, as they considered some to be equally important, or only one to be relevant. Note that even if not cited in one site, some constraints and opportunities might still apply, they were just not considered as the top three most important by the study site leaders. Third, we combined the information from the ten sites to identify general constraints and opportunities across mountain regions, those cited in most sites.

Transformational adaptation

Before the last webinar, we requested study site leaders (co-authors) to reflect on transformational adaptation at their study site, by applying the framework of ref. 15. This framework considers five aspects (change agents, learning with engagement, generalizability of pathways, impacts across scales and sectors and sustainability of change) to determine if change is incremental or transformational. During the last webinar, through a process of collective qualitative assessment, the case studies were allocated points along the incremental to transformational continuum. The process analysis throws light on ways that characterize change, reflecting on ongoing social dynamics and multiple dimensions to think about transformational change, rather than deciding whether a particular change is transformational or not[15], as it is known that incremental changes may aggregate over time to become transformational. During this last webinar, we also reflected on these findings to identify key priorities for moving forward climate change adaptation in African mountain regions and beyond—summarized in Box 1.

Study limitations

We report a range of adaptation responses, which can help inspire adaptation options in other mountain regions. However, we did not investigate which are complementary or substitutions, nor their effectiveness or long-term sustainability, aspects which require further investigation, as highlighted by ref. 16. We focused on climate change impacts as the main challenge to farmers' livelihoods, but population change, new technologies, globalization, agricultural policies and social change are all exerting increasing influence on rural smallholder farmers[56], and should also be considered when designing future adaptation interventions. Also, because of financial constraints, we did not engage local actors to reflect on transformational adaptation processes; this step was carried out by co-authors only. To imagine, initiate and maintain transformational change, we recommended engaging with local actors in a deliberative process in the future. Engaging national actors in the deliberative process in the future is also recommended to address systemic issues that constrain adaptation[43].

Ethics statement

The research was approved following an ethical review at the University of York. Informed consent was obtained from all research participants before entering the study. State permissions were obtained from the relevant authorities in each country: Tanzania—the Tanzania Commission for Science and Technology (COSTECH) (2019-68-NA-2018-205); Kenya—the National Commission for Science, Technology and Innovation (NACOSTI) (NACOSTI/P/21/11045); Rwanda—the National Council for Science and Technology (NCST) (no number given); Uganda—the Uganda National Council for Science and Technology (UNCST) (NS282ES); Ethiopia—the authorities of the Oromia regional state (no permit number given); Burundi—the Faculty of Sciences, University of Burundi (no permit number given); and Democratic Republic of the Congo—the Faculty of Sciences of the Université Officielle de Bukavu (001/FS/VDR/BZI/UOB/2021-2022). At the local level, traditional authorities (for example, village chiefs and paramount chiefs) were consulted before starting this research, explaining study objectives, methods and potential benefits of the findings. We followed the guidelines on ethical research of the British Sociological Association[57] when conducting interviews.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

Source data are provided with this paper. These data are also available via Figshare at https://doi.org/10.6084/m9.figshare.27320790.v1 (ref. 58).

Code availability

R code to produce mixed-effects models and the associated figure is available via Zenodo at https://doi.org/10.5281/zenodo.14004312 (ref. 59).

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Acknowledgements

We are deeply grateful to our study participants, who graciously shared their time, energy and stories. We thank our field assistants and facilitators for making this research possible and D. I. Mutaganzwa for helping to gather the data in Rwanda. We acknowledge funding from the Mountain Research Initiative (MRI) through the Synthesis Workshops funding programme for MRI Community-led Activities (to A.C.-S., N.Z.-C. and B.A.K.), the Mountain Sentinels Fellowship 2021 (to B.M.) and the UK Research and Innovation's Global Challenges Research Fund (UKRI GCRF) through the Development Corridors Partnership project (project no. ES/P011500/1, to R.A.M.).

Author contributions

A.C.-S. and N.Z.-C. conceived the study and designed the methodological approach. Data were collected by A.B.A., G.K.R.B., R. Batumike, K.R.K., F.M., B.M., A.N., R.O.K.T. and I.T. A.C.-S. and N.Z.-C. led the data analysis and wrote the manuscript, with contributions from all co-authors. M.J.P.S. led the statistical analysis. All co-authors read and approved the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Extended data is available for this paper at https://doi.org/10.1038/s41558-024-02221-w.

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41558-024-02221-w.

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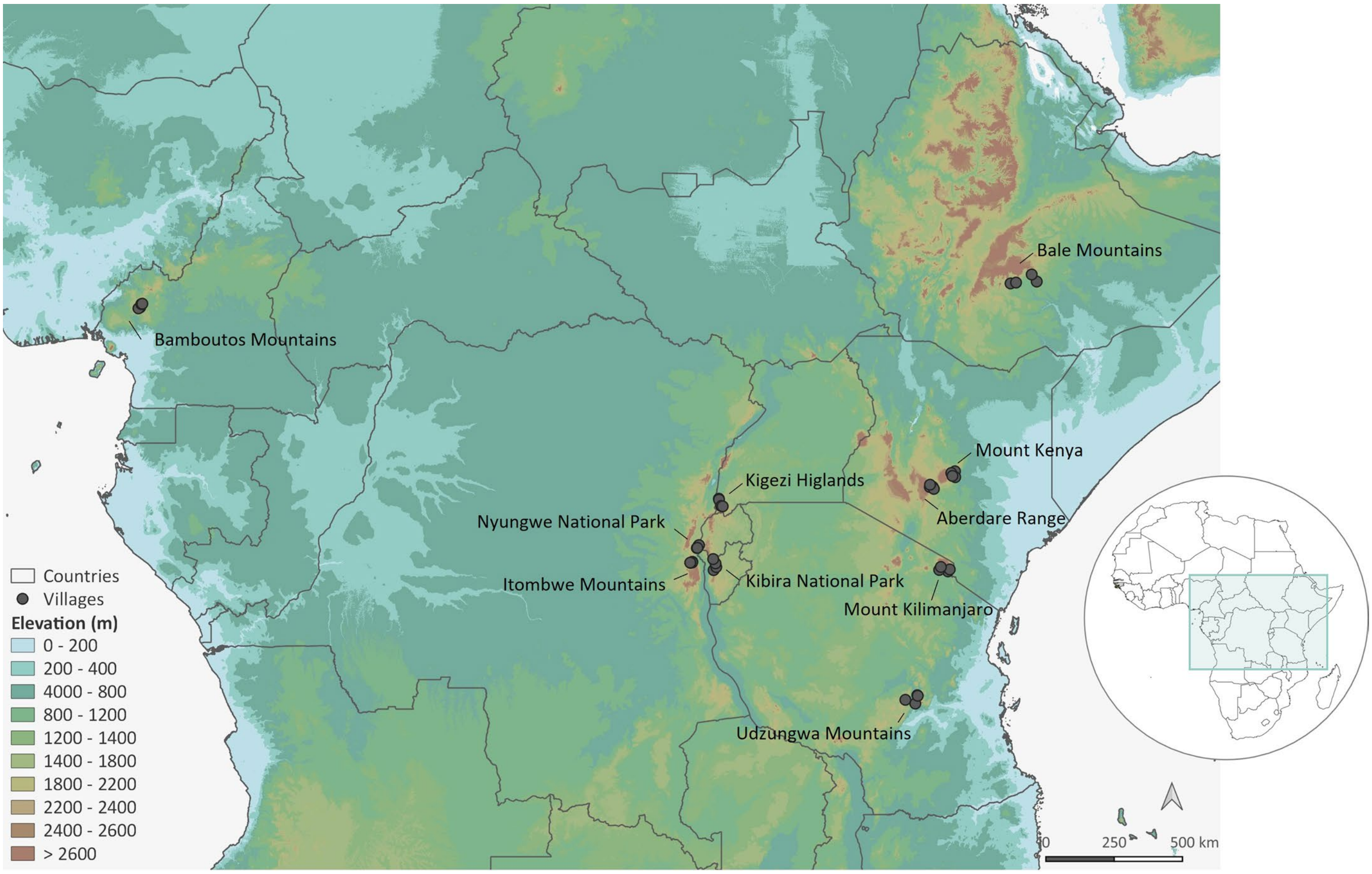
Peer review information *Nature Climate Change* thanks Nicholas Simpson and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

 https://doi.org/10.1038/s41558-024-02221-w



Extended Data Fig. 1 | Map of the ten mountain regions studied. Map of the ten mountain regions studied across tropical Africa, including locations of villages sampled. Figure created using QGIS version 3.28.15. Elevation data from NASA (https://www.unspider.org/links-and-resources/data-sources/digital-elevation-model-srtm-1-arcsecond-30m-nasa-nga) Country boundaries from ICPAC, accessed through https://open.africa/dataset/africa-shapefiles.

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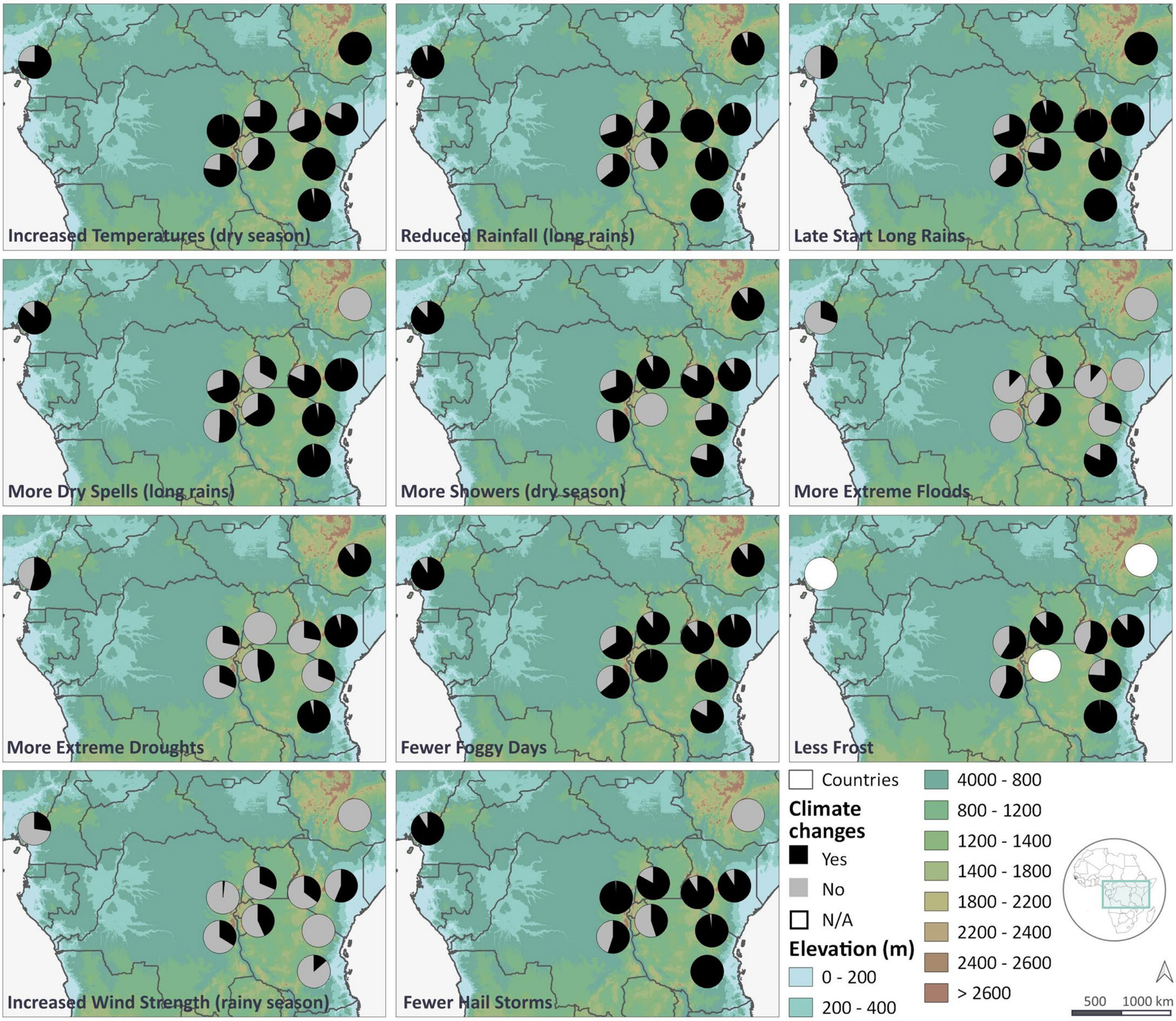

Extended Data Fig. 2 | Climatic changes reported in the ten mountain regions studied. Climatic changes reported in the ten mountain regions studied with regard to percent of respondents per site reporting each impact (n = 150 respondents per site). Note that responses relate to predetermined questions, and that not all responses were asked at each study site, as some were identified as not applicable in a given site by focus-group participants (see Methods).

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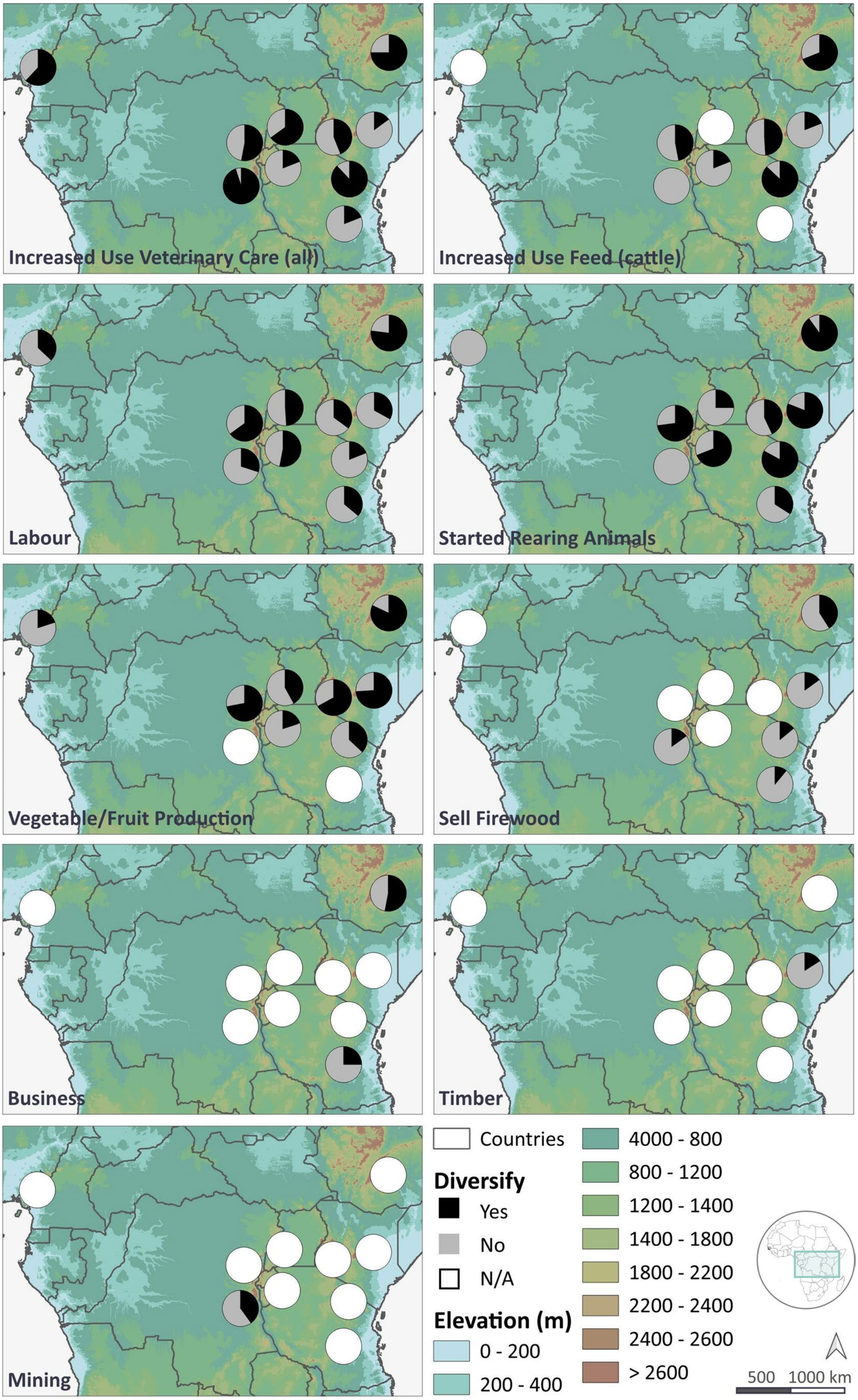
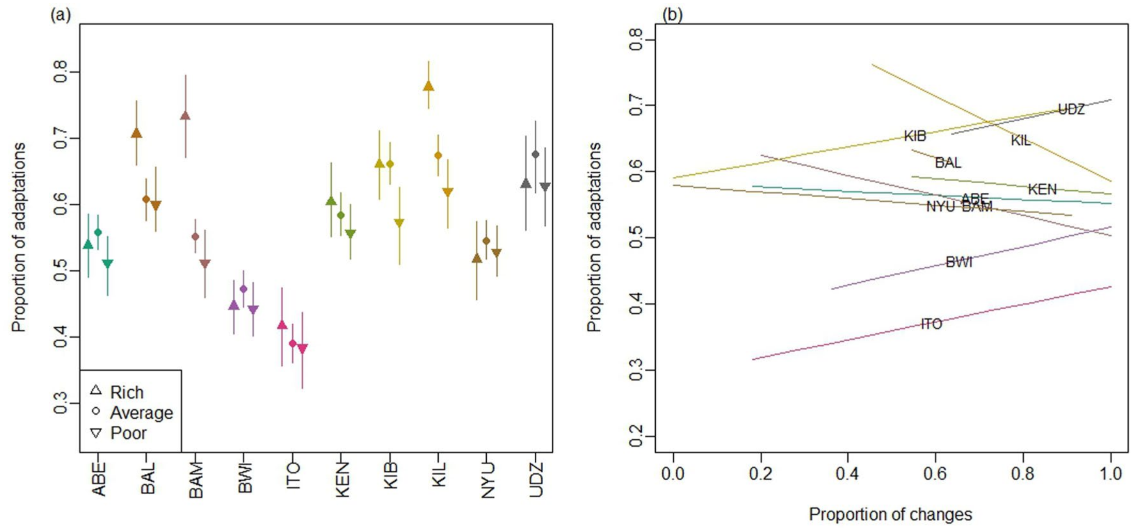
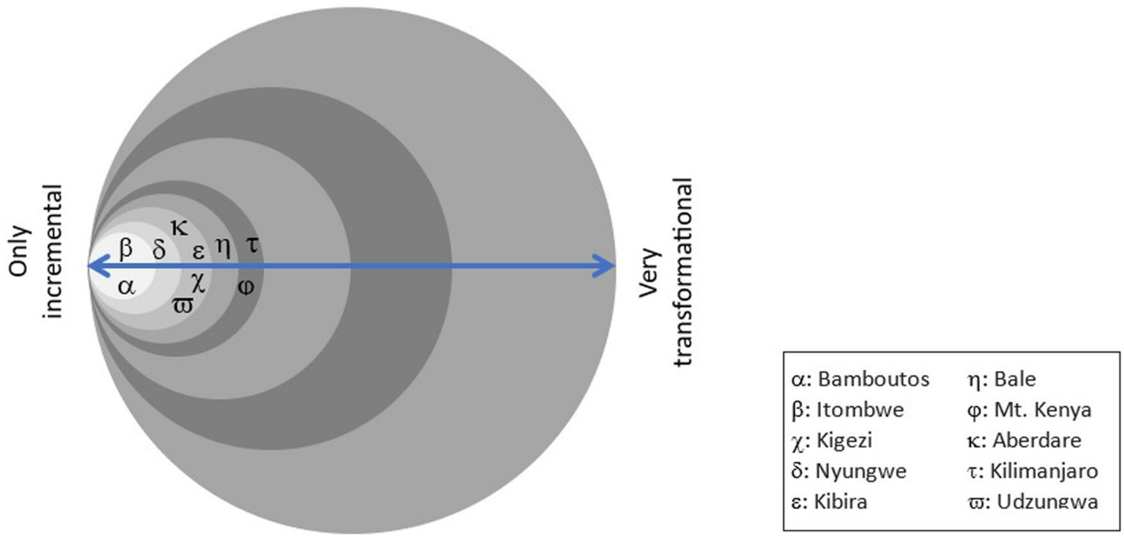


Extended Data Fig. 3 | Animal rearing and off-farm adaptation responses used in the ten mountain regions studied. Animal rearing and off-farm adaptation responses used in the ten mountain regions studied with regard to percent of respondents per site reporting each adaptation response (n = 150 respondents per site). Note that responses relate to predetermined questions, and that not all responses were asked at each study site, as some were identified as no applicable in a given site by focus-group participants (see Methods).



Extended Data Fig. 4 | Influence of site, household wealth and proportion of climate changes observed on the proportion of adaptation responses. Influence of site, household wealth and proportion of climate changes observed on the proportion of adaptation responses used by each household. Graphs show effects estimated from a linear mixed effects model of adaptation as a function of wealth, climate changes observed (fixed effects, both allowed to vary amongst random effect levels), with site as a random effect. (**a**) Predicted adaptations for each wealth group in each study site. Points show predicted means, with arrows showing 95% confidence limits, with climate changes observed held at the dataset-wide mean. (**b**) Modelled relationships between proportion of climate changes observed and proportion of adaptation responses used by each household in each study site. Relationships are produced for the average wealth group. Colours as in (a). Letters showing site names are plotted for the mean proportion of changes and proportion of adaptations for each site. BAM: Bamboutos Mountains (Cameroon), ITO: Itombwe Mountains (DRC), KIG: Kigezi Highlands (Uganda), NYU: Nyungwe (Rwanda), KIB: Kibira (Burundi), BAL: Bale Mountains (Ethiopia), KEN: Mount Kenya (Kenya), ABE: Aberdare Range (Kenya), KIL: Mount Kilimanjaro (Tanzania), UDZ: Udzungwa Mountains (Tanzania). N = 150 respondents per site.

https://doi.org/10.1038/s41558-024-02221-w



Extended Data Fig. 5 | Overview of the relative location of the ten mountain regions studied along an incremental-transformational pathway. See Table 2 for key attributes explaining (un)likelihood of transformational change processes.

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Last updated by author(s): Oct 29, 2024

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☐	☒	A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons
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☐	☒	For null hypothesis testing, the test statistic (e.g. *F*, *t*, *r*) with confidence intervals, effect sizes, degrees of freedom and *P* value noted *Give P values as exact values whenever suitable.*
☒	☐	For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
☒	☐	For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
☒	☐	Estimates of effect sizes (e.g. Cohen's *d*, Pearson's *r*), indicating how they were calculated

Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	No software was used.
Data analysis	We performed all analyses in R v.4.2.2 , and we used the lme4 R package version 1.1-31

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio guidelines for submitting code & software for further information.

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Source data to generate figures and tables is available from
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Research involving human participants, their data, or biological material

Policy information about studies with human participants or human data. See also policy information about sex, gender (identity/presentation), and sexual orientation and race, ethnicity and racism.

Reporting on sex and gender	Sex was considered in study design: we aimed to interview about 50% males and 50% females of the main decision-making couple (if more than one generation lived together) (n=150 respondents in total per study site). Sex was determined based on self-reporting. Initially, we explored differences in the responses within one study site related to sex of the respondent using paired t-tests but these were non-significant, probably because most of the females interviewed were married and were not female-headed households (those without a husband or adult male relative living with them). Thus, we do not include sex-based analysis in this manuscript. Source data is disaggregated by sex.
Reporting on race, ethnicity, or other socially relevant groupings	Neither race nor ethnicity were recorded during interviews. However, we discuss ethnicity in the manuscript in relation to different cultures affecting adaptation strategies, citing main ethnic groups found in each study site. In each study site households were classified into three wealth categories (poor, average, wealthy) based on a wealth index created from ten asset indicators specific to each study site [5654,5755], identified during the FGDs. Source data provides information on wealth groups.
Population characteristics	See above
Recruitment	In each village, households were selected by walking the main road (or footpath as defined by local inhabitants) and selecting every third household to the right. If the household head was not available, the next-door neighbour was targeted. We first interviewed the household head who opened the door (male or female), until we reached the targeted sex quota for that village, and then we asked to interview the other sex in the subsequent households. We acknowledge that there are preferred methods for selecting households (e.g. randomly from a list), but a register of households was unavailable in several study sites. The 'main road' approach might have led to interviewing richer households in more market-integrated contexts (e.g. in Mt Kilimanjaro). As the main focus of our research was on differences across sites (and not within sites), we consider this a minor issue, but future research should investigate differences across households within study sites.
Ethics oversight	The research was approved following an ethical review at University of York. Informed consent was obtained from all research participants before entering the study. State permissions were obtained from the relevant authorities in each country: Tanzania - the Tanzania Commission for Science and Technology (COSTECH) - (number 2019-68-NA-2018-205); Kenya - the National Commission for Science, Technology and Innovation (NACOSTI) (number NACOSTI/P/21/11045); Rwanda - the National Council for Science and Technology (NCST) (no number given); Uganda - the Uganda National Council for Science and Technology (UNCST) (number NS282ES); Ethiopia - the authorities of the Oromia regional state (no permit number given); Burundi - the Faculty of Sciences, University of Burundi (no permit number given); DR Congo - the Faculty of Sciences of the Université Officielle de Bukavu (number 001/FS/VDR/BZI/UOB/2021 -2022). At the local level, traditional authorities (e.g. village chiefs, paramount chiefs) were consulted before starting this research, explaining study objectives, methods and potential benefits of the findings. We followed the guidelines on ethical research of the British Sociological Association [54] when conducting interviews.

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

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Behavioural & social sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	We used mixed-methods, a combination of exploratory focus-group discussions (FGDs, four per study site) and semi-structured household questionnaires (150 per study site). We focused on 10 study sites, so we had 40 FGDs and 1500 questionnaires in total.
Research sample	The research sample is smallholder farmers in ten rural mountain regions of Africa (Burundi, Cameroon, DRC, Ethiopia, Kenya, Rwanda, Tanzania and Uganda). We interviewed 150 households per study site, selected from 4 different villages (37-38 per village). These include about 50% males and 50% females of the main decision-making couple in the household. With regard to age, we did not gather information about their ages but all respondents were > 18 years old. This sample size (150 respondents per mountain) was selected following the guidelines of the project Local Indicator of Climate Change Impacts, (see [Reyes-García et al. 2021]). We acknowledge that 150 respondents might not be representative for understanding differences within one study site, but as our study aim was to document patterns across study sites, we think this number is appropriate.
Sampling strategy	In each village, households were selected by walking the main road (or footpath as defined by local inhabitants) and selecting every third household to the right. If the household head was not available, the next-door neighbour was targeted. We first interviewed the household head who opened the door (male or female), until we reached the targeted sex quota for that village, and then we asked

	to interview the other sex in the subsequent households. 150 respondents is the minimum recommended by the guidelines of the project Local Indicator of Climate Change Impacts, (see [Reyes-García et al. 2021]). We acknowledge that 150 respondents might not be representative for understanding differences within one study site, but as our study aim was to document patterns across study sites, we think this number is appropriate.
Data collection	Pen and paper were used for data collection. No other person was present except participant and researcher. The researcher was blind to study hypothesis during data collection.
Timing	Data collection took place between November 2020 and January 2022, about 1 month per study site (no gap within one study site).
Data exclusions	No data were excluded from the analysis.
Non-participation	No participants dropped out or declined participation.
Randomization	Participants were not allocated into experimental groups.

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

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☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology and archaeology
☒	☐ Animals and other organisms
☒	☐ Clinical data
☒	☐ Dual use research of concern
☒	☐ Plants

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging

Plants

Seed stocks	N/A
Novel plant genotypes	N/A
Authentication	N/A