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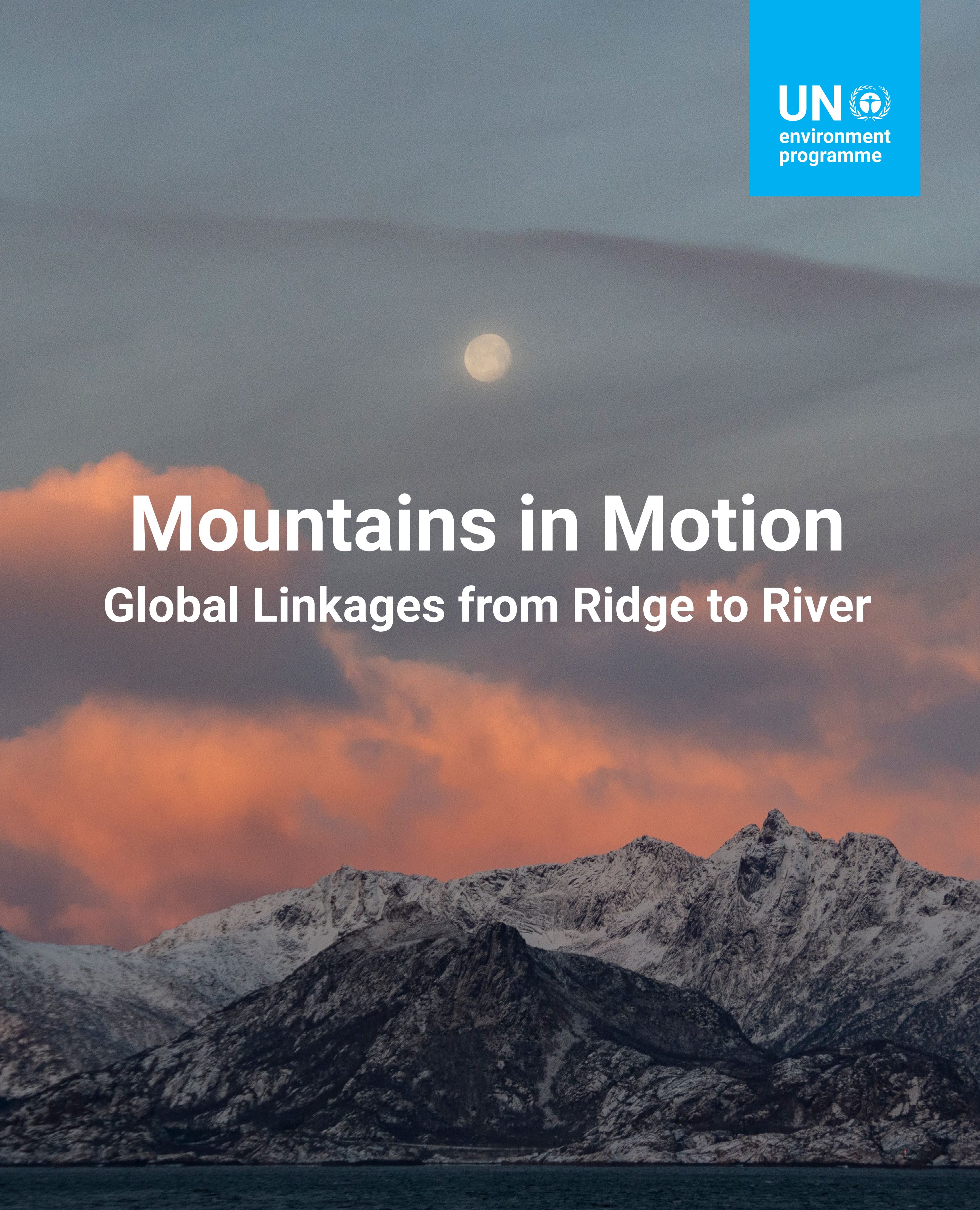

Mountains in Motion

Global Linkages from Ridge to River

GRID ARENDAL
A UNEP Partner

Mountains in Motion
Global Linkages from Ridge to River

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List of acronyms

AF: Adaptation Fund

BC: Black carbon

BRS Secretariat: Secretariat of the Basel, Rotterdam and Stockholm Conventions

CAMCA: Central Asian Mammals and Climate Adaptation project

CCAC: Climate and Clean Air Coalition

CBD: Convention on Biological Diversity

COP: Conference of the Parties

EAC: East African Community

EM-DAT: International Disasters Database

EPR: Extended Producer Responsibility

FAO: Food and Agriculture Organization of the United Nations

GBF: Montreal Kunming Global Biodiversity Framework

GCF: Green Climate Fund

GDP: Gross Domestic Product

GEF: Global Environment Facility

GlaMBIE: Glacier Mass Balance Intercomparison Exercise

GLOF: Glacial Lake Outburst Flood

GMBA: Global Mountain Biodiversity Assessment

IPBES: Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services

IPCC: Intergovernmental Panel on Climate Change

KBA: Key Biodiversity Area

LDN: Land Degradation Neutrality

m.a.s.l.: metres above sea level

NAP: National Adaptation Plan

NBSAP: National Biodiversity Strategies and Action Plan

NDC: Nationally Determined Contribution

PCB: Polychlorinated Biphenyls

PFAS: Per- and polyfluoroalkyl

POP: Persistent Organic Pollutant

UN: United Nations

UNCCD: United Nations Convention to Combat Desertification

UNDRR: United Nations Office for Disaster Risk Reduction

UNECE: United Nations Economic Commission for Europe

UNEP: United Nations Environment Programme

UNESCO: United Nations Educational, Scientific and Cultural Organization

UNFCCC: United Nations Framework Convention on Climate Change

USGS: United States Geological Survey

UN Tourism: United Nations World Tourism Organization

WMO: World Meteorological Organization

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Introduction

The triple planetary crisis of climate change, biodiversity loss, and pollution is the defining environmental and socio-economic challenge of our time. As a result, the ecological health and beauty of some of the most stunning environments on Earth are under threat, including mountain ranges, forests, and water basins.

Mountain ecosystems are critical intersections in global systems, dynamically linked to planetary health and human well-being far beyond their ridges. They function as water towers, supplying freshwater for downstream agriculture, energy, and urban centres, thereby inextricably linking ecosystem health to food, energy, and economic security. Furthermore, their vast carbon stocks and rich biodiversity provide essential global services for climate regulation, medicine, and agriculture, making their preservation a transboundary imperative that bridges environmental and developmental sectors.

This publication, Mountains in Motion, sheds a light on the interconnection of challenges to better understand the cascading effects of a changing climate and environmental conditions. Human-driven global warming causes rapid cryosphere decline and accelerates biodiversity loss by forcing some species to move to higher altitudes, and enabling invasive species to reach higher ground. Simultaneously, pollution, from long-range atmospheric deposition to local tourism waste not soundly managed, exacerbates ecosystem stress and may accelerate snow and ice melt.

Glacial retreat further releases contaminants, including heavy metals, affecting downstream water quality. These challenges form a feedback loop, where each crisis intensifies others, fundamentally undermining mountain ecosystem services and the prosperity and health of people that depend on them. Mountain regions have gained increasing attention at the international level in recent years, reflecting their critical role in biodiversity conservation, climate regulation, and water security. Despite ongoing efforts, there remains a need to strengthen countries' commitments, particularly within the framework of the Rio Conventions, where mountains are still often perceived primarily as geographical features rather than as strategic ecosystems that offer significant opportunities for investment in nature and in the livelihoods of communities who depend on them worldwide.

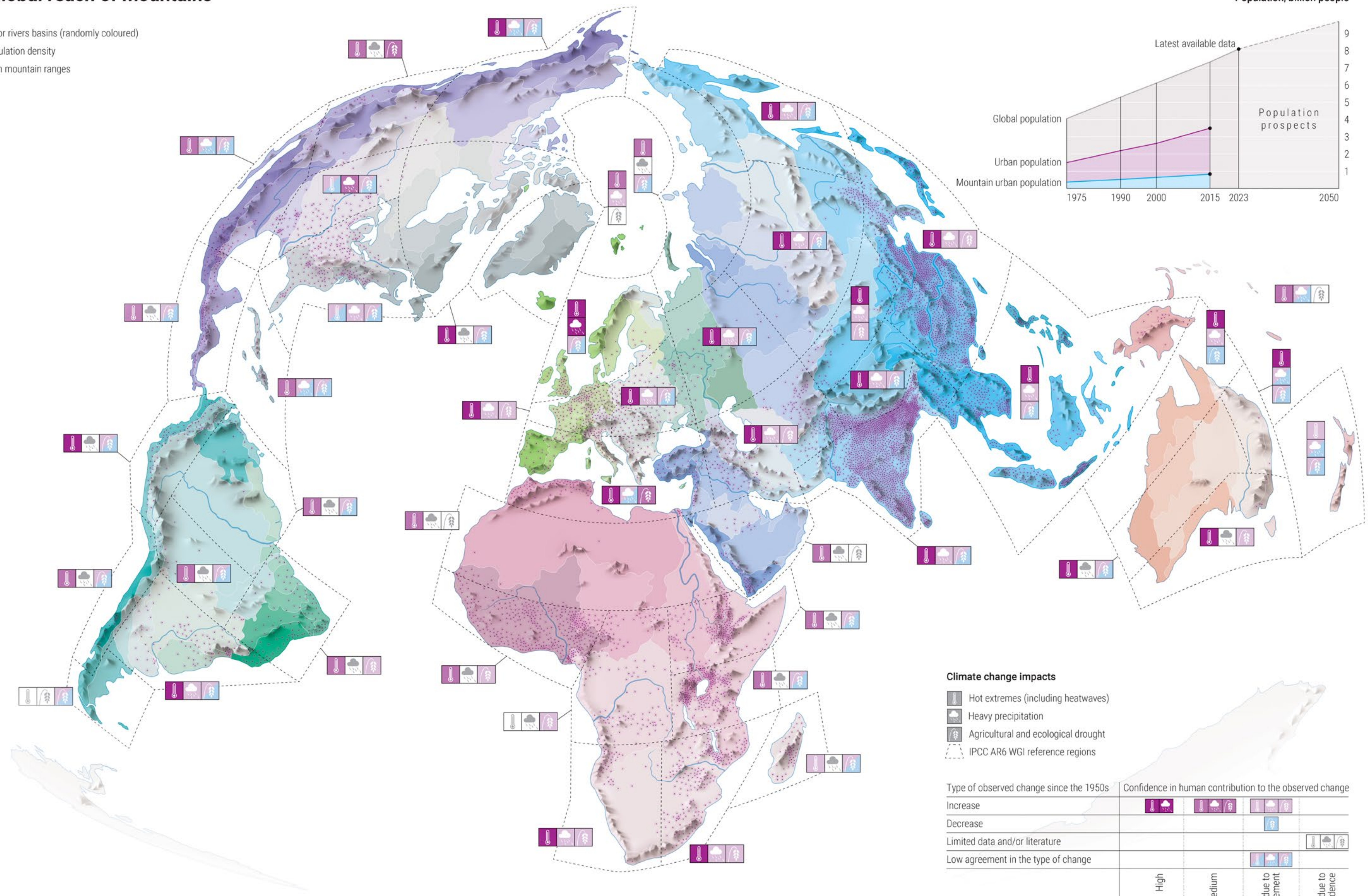
This report identifies links between the triple planetary crisis in mountain regions and the rest of the planet, moving beyond a siloed analysis. It leverages recent data from top-tier peer-reviewed journals, public databases and Rio convention reports, to quantify the "ridge-to-river" cascade of impacts, to build a compelling case for action. It provides a decision-making tool for translating science into policy-ready options, responding to future scenario modelling and mountain-specific indicators to mainstream these issues into climate, biodiversity, and development plans. Identified solutions recognize the key role of women, Indigenous Peoples and Local Communities and youth in shaping sustainable mountain futures.

This report is structured to guide the reader from understanding the challenges to identifying solutions. It begins by describing climate change impacts and trends in mountain regions, then analyses present and future challenges for biodiversity, describes the human-made pressures of pollution and land degradation, and examines international environmental governance in specific mountain regions. Throughout the report, map-based case studies illustrate the linkages between mountain regions and lowlands, supported by data that help to better grasp the challenges and solutions identified.

Alpine Kyrgyzstan. Photo: GRID-Arendal/Yannick Beaudoin

The global reach of mountains

- Major rivers basins (randomly coloured)
- Population density
- Main mountain ranges



Climate change impacts

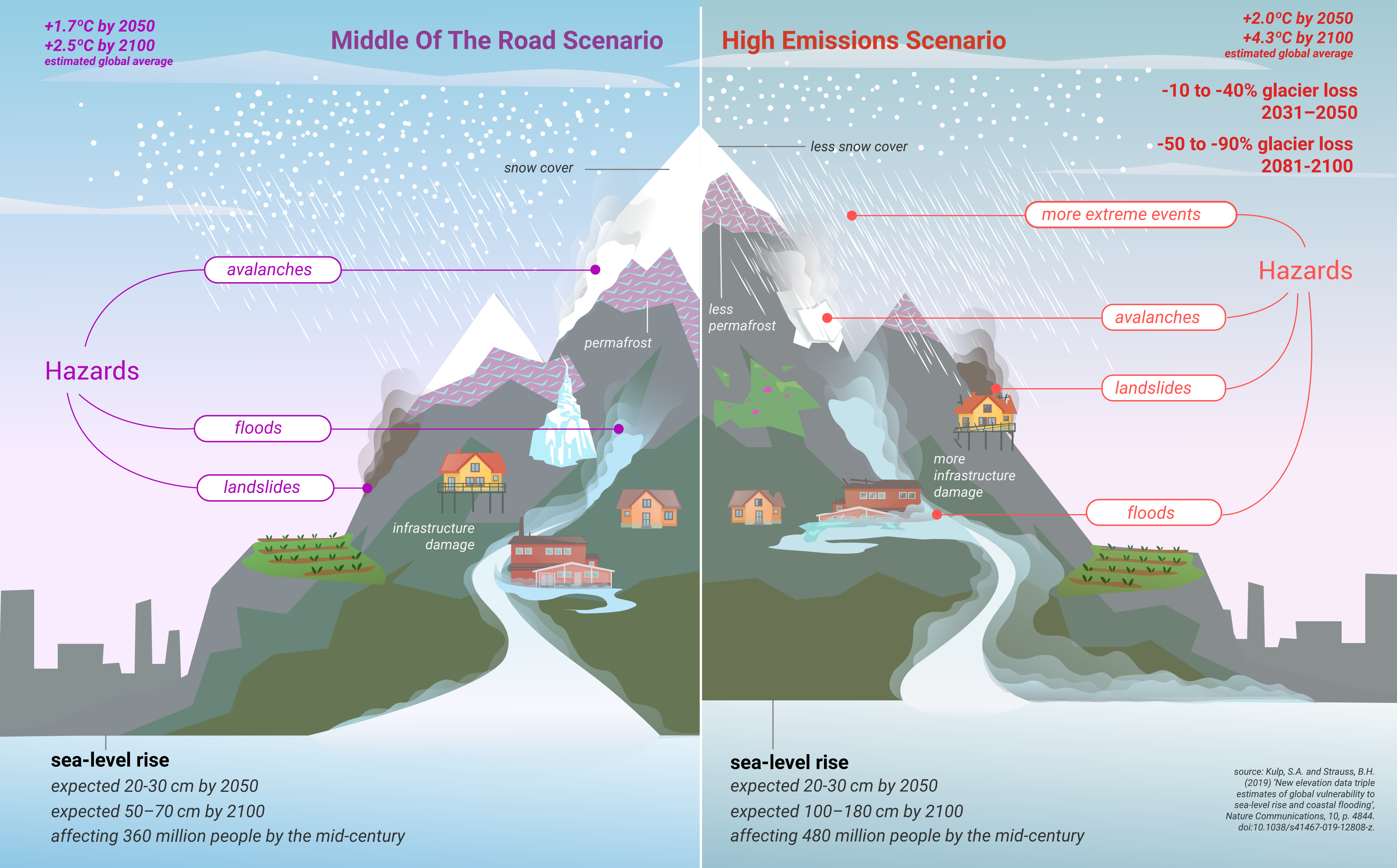
- Hot extremes (including heatwaves)
- Heavy precipitation
- Agricultural and ecological drought
- IPCC AR6 WGI reference regions

Type of observed change since the 1950s	Confidence in human contribution to the observed change			
Increase				
Decrease				
Limited data and/or literature				
Low agreement in the type of change				
	High	Medium	Low due to limited agreement	Low due to limited evidence

Map produced by Zoï Environment Network, February 2026
Source: LandScan Global 2024, Oak Ridge National Laboratory; HydroSHEDS; IPCC Sixth Assessment Report (AR6); UN Population Division; Human populations in the world's mountains: Spatio-temporal patterns and potential controls, Thornton JM, Snethlage MA, Sayre R, Urbach DR, Viviroli D, Ehrlich D, et al., 2022

Chapter 1: Changing mountain landscapes

The challenge of climate change



Climate change is fundamentally altering hydrological and climate regimes of mountain regions, intensifying risks for both people and ecosystems. Rising temperatures are disrupting historical precipitation patterns and accelerating the loss of the mountain cryosphere, which includes glaciers, snow cover, and permafrost. These hydrological shifts are amplifying the frequency and magnitude of natural hazards, such as glacial lake outburst floods, landslides, and avalanches.

When these hazards intersect with vulnerable human communities and sensitive natural systems, they trigger disasters, negatively impacting populations, destroying infrastructure, and irreversibly degrading critical mountain environments. This section examines this cascading chain of risks to inform effective resilience, and disaster risk reduction strategies.

Mountain cryosphere

Glaciers

Over the past two decades, glaciers have lost more ice than at any period since glacier monitoring began. Glacier mass has declined by nearly 39 per cent in Central Europe, 35 per cent in the Caucasus and Middle East, and 29 per cent in New Zealand, representing a total loss of 84 billion tons of ice (GlaMBIE 2025). Before reaching the ocean, glacial meltwater moves across valleys and diverse landscapes, supporting livelihoods but also generating growing risks, including flooding, for communities and critical infrastructure.

Furthermore, glaciers serve as archives holding a memory of past climate, preserving atmospheric aerosols that can be used as indicators for natural and societal changes as well as improving future climate projections (Legrand *et al.* 2025). These invaluable archives are now at increasing risk of being irreversibly lost. Lastly, glaciers fulfil crucial functions regulating local weather systems through their white surfaces reflecting sunlight, providing income to communities through eco-tourism and supporting cultural identities.

Snow cover

Snow plays a crucial role in maintaining glacier mass in mountainous regions, and functions as a temporary reservoir of water, regulating seasonal streamflow. Warmer temperatures affect snow cover to various extents in different mountains ranges, but a general trend seems to be emerging. Between 1982 and 2020, mountainous areas experienced a global decline in the snow cover duration of 15 days. There is also a seasonal shift, with snow cover extent declining in winter while increasing in spring (Notarnicola 2022). Moreover, global observations indicate the decline of snow cover in low altitude mountain regions (Adler *et al.* 2022).

There is considerable variability in snowfall between mountain regions, contributing to fluctuation in hydrological regimes. Interannual and interseasonal fluctuations in runoff patterns can have serious implications for agriculture and domestic water supply. With rising temperatures, snowfall is expected to decrease at lower elevations but increase at higher elevations. This can potentially increase avalanche activity, particularly wet and slush-like avalanches triggered by rain on snow events (Eckert *et al.* 2024). Lastly, snow cover also fulfils an important function for animal and plant life, providing shelter from wind and freezing temperatures.

Permafrost

Globally permafrost, ground continuously remaining below 0 °C, covers approximately 21 million km². This represents about 22 per cent of land surface and is mostly found in the Northern Hemisphere, whereas in the Southern Hemisphere it is restricted to the higher slopes of the Andes, New Zealand and Antarctica (Obu 2021). Permafrost thaw in Arctic and sub-Arctic regions has been studied extensively, with concerns over the release of greenhouse gases, such as methane, which may contribute to a positive feedback loop that exacerbates global warming (Natali *et al.* 2021).

In mountainous regions, permafrost thaw is primarily observed through reshaping the landscape sometimes generating natural hazards such as landslides, debris flows, and rockfalls. These hazards are largely due to the loss of cohesion between soil and rock particles as the ice holding them together melts, significantly increasing risks to infrastructure (Baral *et al.* 2023).

Hydrological consequences of permafrost thaw include the formation of new lakes, which are often threatened by instability in the mountain slopes especially in earthquake prone mountain regions. Landslides can contribute to formation of lakes when they form a natural dam in a river, increasing the risk of lake overflows, resulting in downstream flooding called Glacial Lake Outburst Floods (GLOFs). Additionally, permafrost thaw in mountain regions may have ecological effects, such as changes in soil moisture content and vegetation cover (Jin *et al.* 2021), although further research is required to fully understand these impacts.

How a shrinking cryosphere is influencing hazards in mountain regions

Given trends over the last decades, such as increased spring snowfall, accelerated glacier and snow melt, and extreme weather events, the disaster risk in mountain regions is projected to rise. With diminishing snow and ice cover, water is stored less in mountain aquifers, soils or wetlands. This leads to a projected increase in total and immediate runoff, increasing the likelihood of flood events (Yang *et al.* 2025).

Similarly, this shift in precipitation and runoff patterns towards spring and autumn seasons is more likely to induce summer drought. These conditions increase the exposure of mountains to water related hazards, including droughts and floods, with direct impacts on agriculture, tourism, and infrastructure-dependent businesses. The risk also evolved over time in relation to mountain populations which have increased from over 550 million in 1975 to about 1,050 million in 2015 according to the Global Mountain Biodiversity Assessment (GMBA) mountain area delimitation (Ehrlich *et al.* 2021). Population growth and expanding human activities in mountain regions heighten vulnerability by increasing exposure to natural hazards.

Air moisture in a warming climate

Elevation-dependant warming describes the significant change in atmospheric warming rate with elevation due to various feedback mechanisms, such as albedo and water vapor. According to Ombadi *et al.* (2023), for elevations above 2000 m.a.s.l., air moisture can increase by 15 per cent for each degree Celsius of warming. For comparison, at lower altitudes air moisture is commonly known to increase by 6.5 per cent for each degree Celsius of warming.

Increased air moisture content will likely exacerbate the extreme rainfalls intensity and thus increase the risks of rainfall induced hazards for mountain areas. Even though elevation-dependent warming in mountains is a known phenomenon, it remains poorly understood, with significant knowledge gaps related to sufficient quality and extent of data to improve climate models, that limit the ability to clearly assess its effects (IPCC 2019). The potential increasing frequency of hazards linked to earlier snowmelt combined with heavy rainfall such as wet-snow avalanches or rain-on-snow flood events poses additional risks to ecosystems including for plant and animal species that rely on snow cover for their survival (Notarnicola 2022).

Impact of disasters in mountainous areas

According to The International Disasters Database (EM-DAT), from 1985 to 2014, a total of 713 major hydro-meteorological disasters were recorded across the five mountain regions of African Mountains, Andes, Central Asia, European Alps, and Hindu Kush Himalaya. Those disasters include mass movements such as avalanches, landslides, and debris flows, as well as floods, storms, extreme temperatures, droughts, and wildfires. These events resulted in an estimated economic loss of US$ 57 billion and affected approximately 258 million

View over Lofoten from Matmora. Photo: GRID-Arendal/Peter Prokosch


Mountains near Kemin Kyrgystan. Photo: GRID-Arendal/Laurent Fouinat

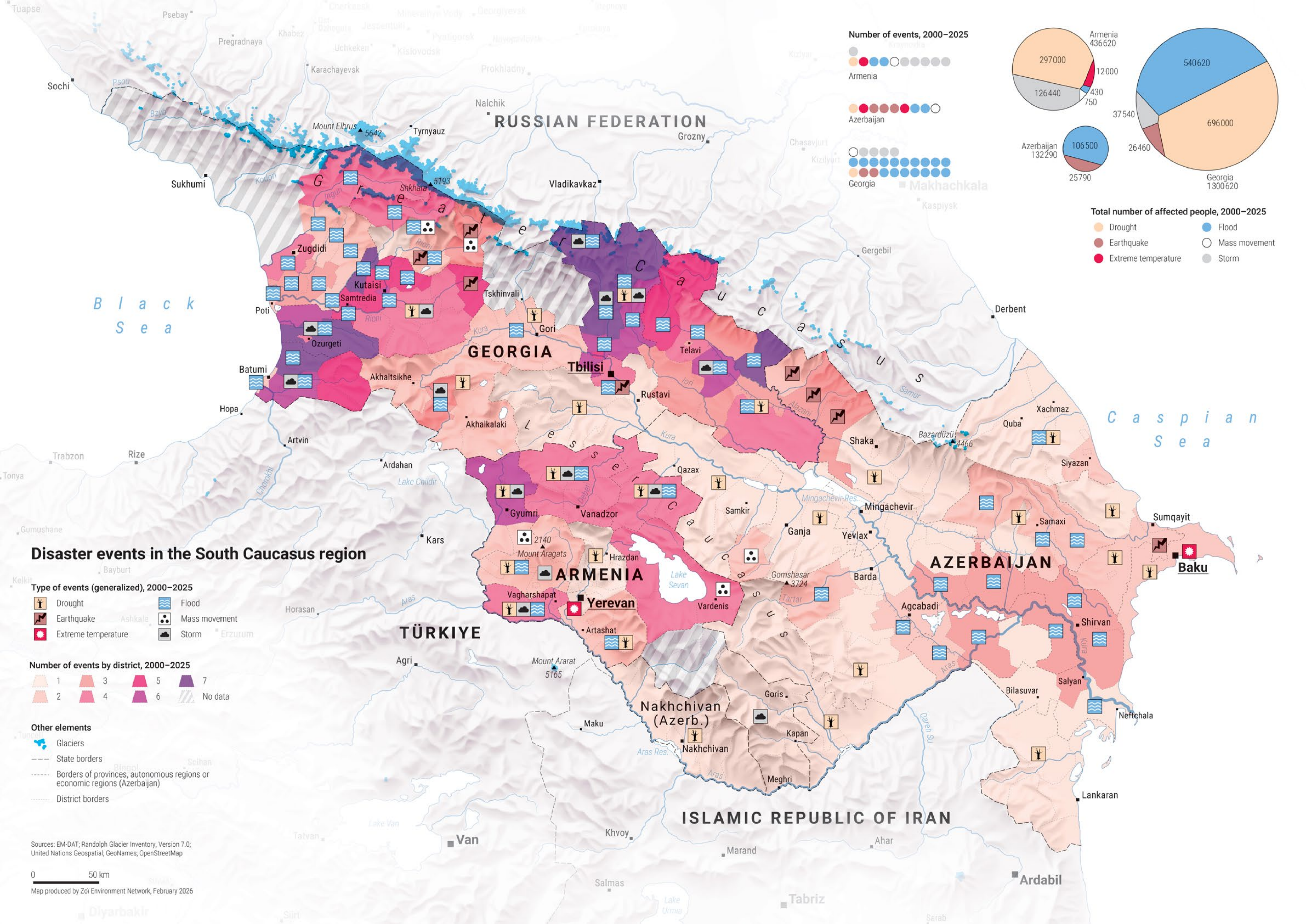
people, including nearly 40,000 reported casualties. This figure likely underestimates the true impact, as it does not account for smaller-scale events that also affect local populations and economies but for which data is lacking (Stäubli *et al.* 2018).

The frequency of weather- and climate-related disasters showed an increasing trend in the Hindu Kush Himalaya, the Andes, and the African Mountain regions. In contrast, no clear trend was observed in the European Alps or Central Asia, where such hazards occurred less frequently in countries with greater economic capacity for preparedness (Stäubli *et al.* 2018). However, frequency or intensity of events are not the main cause of fatalities but rather the vulnerabilities of people and infrastructure to such disasters (Adler et al. 2022). Looking ahead, the impact of natural hazards in mountain areas is expected to increase in regions where population growth and infrastructure development are expanding into exposed and vulnerable areas in addition to changing atmospheric conditions in a warmer climate.

Integrating risk assessment into land-use and infrastructure policy in mountains is critical to managing this escalating financial exposure. By 2050, climate change and development patterns could drive annual landslide losses alone to US$37 billion. The cost of landslides in addition to other hazards found in mountains represent a significant and yet preventable burden on public budgets, businesses, and communities (UNDRR 2025).

Disasters do not impact everyone in the same way, more prosperous communities with high degrees of social capital are inherently more resilient. Effects of disasters are shaped by existing vulnerabilities and inequalities, for example those related to gender, caste, class, ethnicity, disability, and place of residence. Women face heightened vulnerability before, during, and after disasters due to systemic disadvantages in nearly every aspect of life.

The unique challenges of mountain regions, including geographic isolation, reliance on climate-sensitive natural resources, and traditional social structures, intensify pre-existing vulnerabilities. As a result, women, elderly people, and marginalized groups face a disproportionately high burden from climate impacts and disasters. Growing population and migration due to climate change represent additional challenges for mountain regions. Effective policy must therefore move beyond a one-size-fits-all approach to target these amplified risks (Bano and Bengum 2024).



Disaster events in the South Caucasus region
Type of events (generalized), 2000–2025
Drought
Earthquake
Extreme temperature
Flood
Mass movement
Storm
Number of events by district, 2000–2025
1
2
3
4
5
6
7
No data
Other elements
Glaciers
State borders
Borders of provinces, autonomous regions or economic regions (Azerbaijan)
District borders
Sources: EM-DAT; Randolph Glacier Inventory, Version 7.0; United Nations Geospatial; GeoNames; OpenStreetMap
0
50 km
Map produced by Zoï Environment Network, February 2026
Number of events, 2000–2025
Armenia
Azerbaijan
Georgia
Total number of affected people, 2000–2025
Drought
Earthquake
Extreme temperature
Flood
Mass movement
Storm
Armenia
436620
297000
12000
430
750
126440
Azerbaijan
132290
106500
25790
Georgia
1300620
540620
696000
37540
26460
RUSSIAN FEDERATION
GEORGIA
ARMENIA
AZERBAIJAN
TÜRKIYE
ISLAMIC REPUBLIC OF IRAN
Nakhchivan (Azerb.)
Black Sea
Caspian Sea
Greater Caucasus
Lesser Caucasus
Lake Sevan
Mingachevir Res.
Aras Res.
Mount Elbrus 5642
Shkhara 5193
Bazardüzü 4466
Mount Aragats 2140
Gomshasar 3724
Mount Ararat 5165
Tbilisi
Yerevan
Baku
Sochi
Sukhumi
Nalchik
Tyrnyauz
Vladikavkaz
Grozny
Derbent
Gergebil
Zugdidi
Kutaisi
Samtredia
Poti
Ozurgeti
Batumi
Hopa
Tskhinvali
Gori
Telavi
Rustavi
Akhaltsikhe
Akhalkalaki
Artvin
Rize
Trabzon
Ardahan
Kars
Gyumri
Vanadzor
Hrazdan
Vagharshapat
Artashat
Vardenis
Qazax
Samkir
Ganja
Yevlax
Mingachevir
Shaka
Quba
Xachmaz
Siyazan
Samaxi
Sumqayit
Barda
Agcabadi
Shirvan
Salyan
Bilasuvar
Neftchala
Lankaran
Goris
Kapan
Meghri
Nakhchivan
Agri
Maku
Horasan
Khvoy
Marand
Ahar
Ardabil
Van
Salmas
Tabriz

How the cryosphere sustains downstream regions

Waterflow from high mountains is the result of glacial melt, snow melt, and rainfall, either directly or via aquifers. With warming temperatures and atmospheric conditions driving glacier loss, meltwater-derived runoff will experience a tipping point called peak water. This is the period of a maximum meltwater runoff, which will generally be followed by a subsequent decrease in meltwater contributions to the stream flow (Clason *et al.* 2023). Peak water has already been reached in 45 per cent of the largest water basins in the year 2017, and only water basins with large glaciers, which delay the onset, are yet to reach the peak water tipping point. Overall, one third of the largest river basins will experience over 10 per cent decreased runoff due to glacier mass loss by 2100 (Huss and Hock 2018; Hock *et al.* 2019).

Globally, the agricultural sector accounts for almost 28 per cent of GDP in low-income countries. In comparison, the agricultural sector accounts for 2 per cent of GDP in high-income countries (World Bank Data 2023). Meanwhile, irrigation accounts for 70 per cent of freshwater use from water resources worldwide (World Bank 2021). A reduction in water flow from mountain areas disproportionately impacts lower income countries and negatively affects food security from local to global levels. The relative contribution of glaciers to freshwater supply is highest close to the source and decreases with distance. Consequently, communities living in mountains will be more impacted by fluctuating river discharge compared to population living in lowlands.

Future water consumption is a critical factor to consider for managing water resources (Viviroli *et al.* 2020). Regardless of climate scenario, peak water is predicted to increase runoff only temporarily, given that rainfall is not projected to rise at a compensatory rate. Furthermore, growing human populations and economies in lowland areas that are dependent on mountains, for instance in South Asia and East Africa, will increase demands for freshwater for drinking purposes, food production, and industries. Peak water effects may compensate for some of those needs in the middle of the road scenario for climate change, at least for some time, but not sufficiently. Under such scenarios, the number of people depending on mountain runoff is predicted to reach 2.3 billion by 2050, representing 39 per cent of the total lowland population (Viviroli *et al.* 2020).

Sea-level rise and impact on coastal areas

It is estimated that water stored in mountain glaciers alone would contribute to approximately 50 cm of sea level rise. Mountain glaciers are the most sensitive to warmer temperatures and consequently the first to melt and have been experiencing high relative glacial loss since the beginning of the 21st century (GlaMBIE 2025). Comparatively, all ice stored in the polar regions could eventually contribute to an additional total of up to 65 metres of sea level rise, with 7 metres of water from the Greenland ice cap and 58 metres of water from the Antarctic icesheet (UNFCCC 2025).

Low elevation coastal zones consist of areas under 10 metres above sea level worldwide and are highly vulnerable to sea-level rise. These include a variety of natural and built environments, from small islands to megacities, located from the tropics to the poles in both the Global North and Global South (Magnan *et al.* 2022). In 2020, 900 million people, about 12 per cent of world population, were living in low elevation costal zones, representing an increase of 40 per cent since 2000 (Reimann, Vafeidis and Honsel 2023). These populations will face increasing exposure to flooding, erosion, and land loss as sea levels continue to rise.

View from Skrova towards East. Photo: GRID-Arendal/ Peter Prokosch

Mountain futures and resilience pathways in a warming climate

It remains crucial to monitor and assess glacier and cryosphere changes, filling knowledge gaps. This includes generating evidence about the functions and ecosystem services of emerging post-glacial ecosystems with key freshwater provisioning and biodiversity promotion functions (Bosson *et al.* 2023). Future monitoring should make proper and safe use of Earth Observation and Artificial Intelligence tools, coupled with locally owned citizen science and in-situ research.

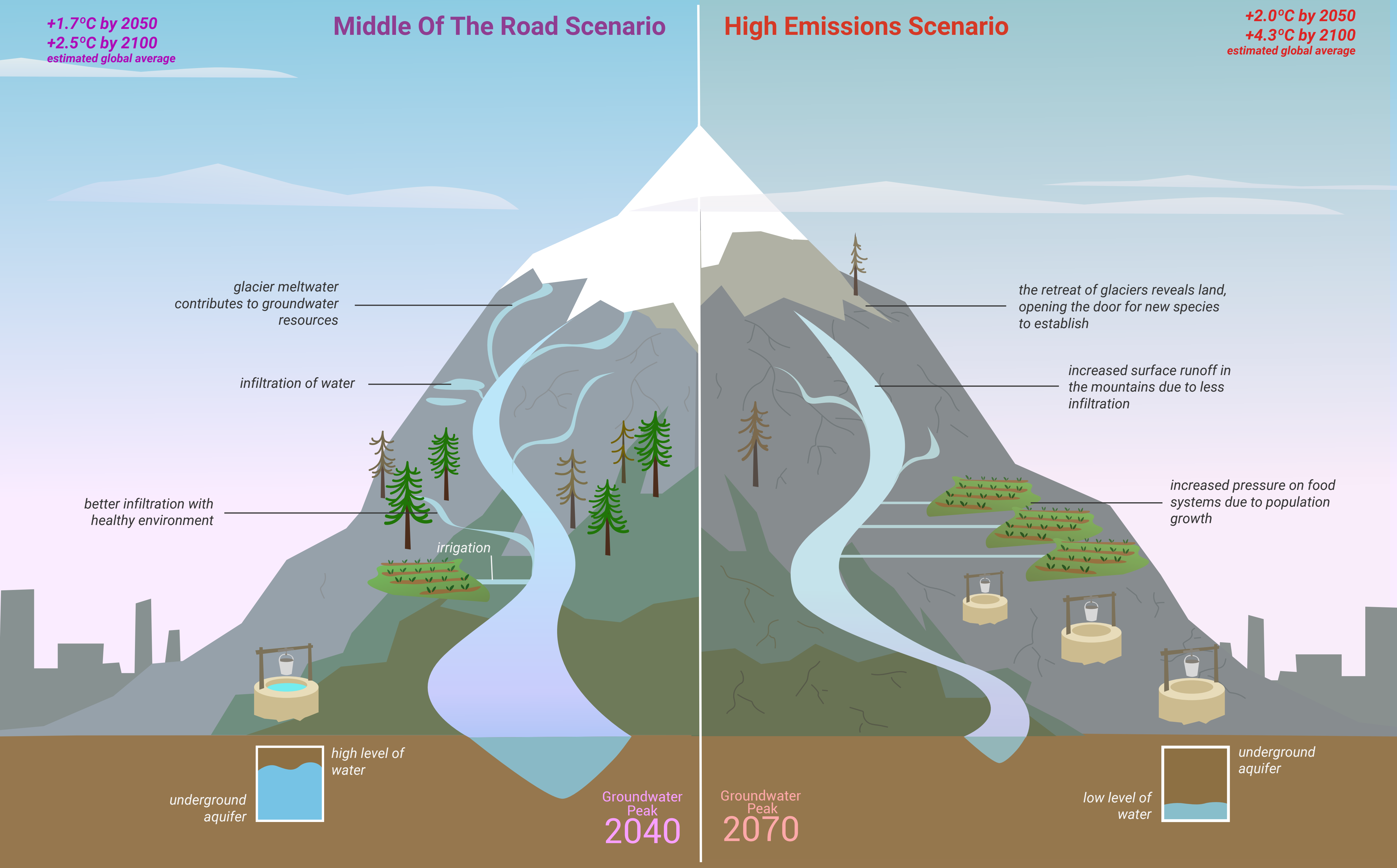
With regard to adaptation and resilience, public and private stakeholders need to develop, implement and scale community-owned adaptation measures, particularly in areas of sustainable irrigation and drought risk management (UNEP and GRID-Arendal 2022). This could include efficiency and water saving measures, such as drop irrigation and storing rainwater uphill through artificial ponds or so-called ice stupas. Further adaptation strategies may include alternative livelihoods that are less water intensive and ecosystem restoration. Policies should prioritize informing communities and creating knowledge networks and early warning systems; integrating riverine flood, glacial lake outburst floods (GLOFs), avalanche, and landslide risks into urban and settlement planning; and ensure that infrastructure is designed to withstand future climate impacts. This can be achieved using a combination of Nature-based Solutions, hazard zone maps, glacial lake monitoring, ecosystem-based buffers, as well as climate-adaptive construction techniques. Addressing disaster risks requires gender-responsive planning and policies and ensuring equal access to resources and decision-making for women and marginalised groups.

The socio-economic and cultural consequences of changing mountain ecosystems, including glacier loss, require systematic policy responses. This includes assessing and financing the economic costs associated with infrastructure damage and agricultural transformation. It also entails recognizing and supporting cultural responses, such as dedicated ceremonies to vanished glaciers, literature and artistic expression, and public events that reflect societal engagement with rapidly transforming mountain landscapes.

Sagarmatha National Park. Photo: GRID-Arendal/Peter Prokosch

Chapter 2: From peaks to aquifers

Mountain contributions to water systems



Mountains play a crucial role in the planet's water cycle as global water towers, from which up to 60 per cent of the world's freshwater originates (UN 2025). These elevated land masses act as barriers, forcing air and the moisture it carries to rise to higher altitudes, which creates condensation and eventually triggers elevation-induced precipitation either as snow or rain.

Once it reaches the ground, the water begins a journey that will ultimately return it to the ocean. However, the amount of time water remains on land can vary greatly depending on location and conditions. Water can be stored in the cryosphere, underground aquifers, or mountain lakes and wetlands for periods ranging from a few minutes to thousands of years before it eventually reaches the ocean or evaporates and re-enters the water cycle (USGS 2018).

Regulation of water infiltration in mountains

Snowmelt contribution

Snowfall in mountains can accumulate over time, and when atmospheric conditions allow it, the snowfall gets compacted and transforms into more permanent ice. The age of this glacial layer varies with depth, with some dating back several millennia. When snow cover eventually transforms to meltwater, it contributes gradually to streamflow by infiltrating soils and bedrock, ultimately supporting vegetation and recharging mountain aquifers.

The resulting active groundwater circulation can range from a few centimetres to over 100 metres in depth (Carroll *et al.* 2025). The flow of underground water is slower than on the surface and contributes to mountain stream runoff. Acting as a natural buffer during drought periods, it sustains mountain ecosystems, local communities, and regional economies. Mountain water resources provide essential downstream benefits by supporting pasturelands, maintaining forest habitats and biodiversity, and underpinning economic activities such as agriculture, mining and tourism. Considering that underground water aquifers globally contain 30 per cent of freshwater resources, it will become increasingly important under a warming climate, and given variable surface water flows, to safeguard these resources in mountain environments (UN 2025).

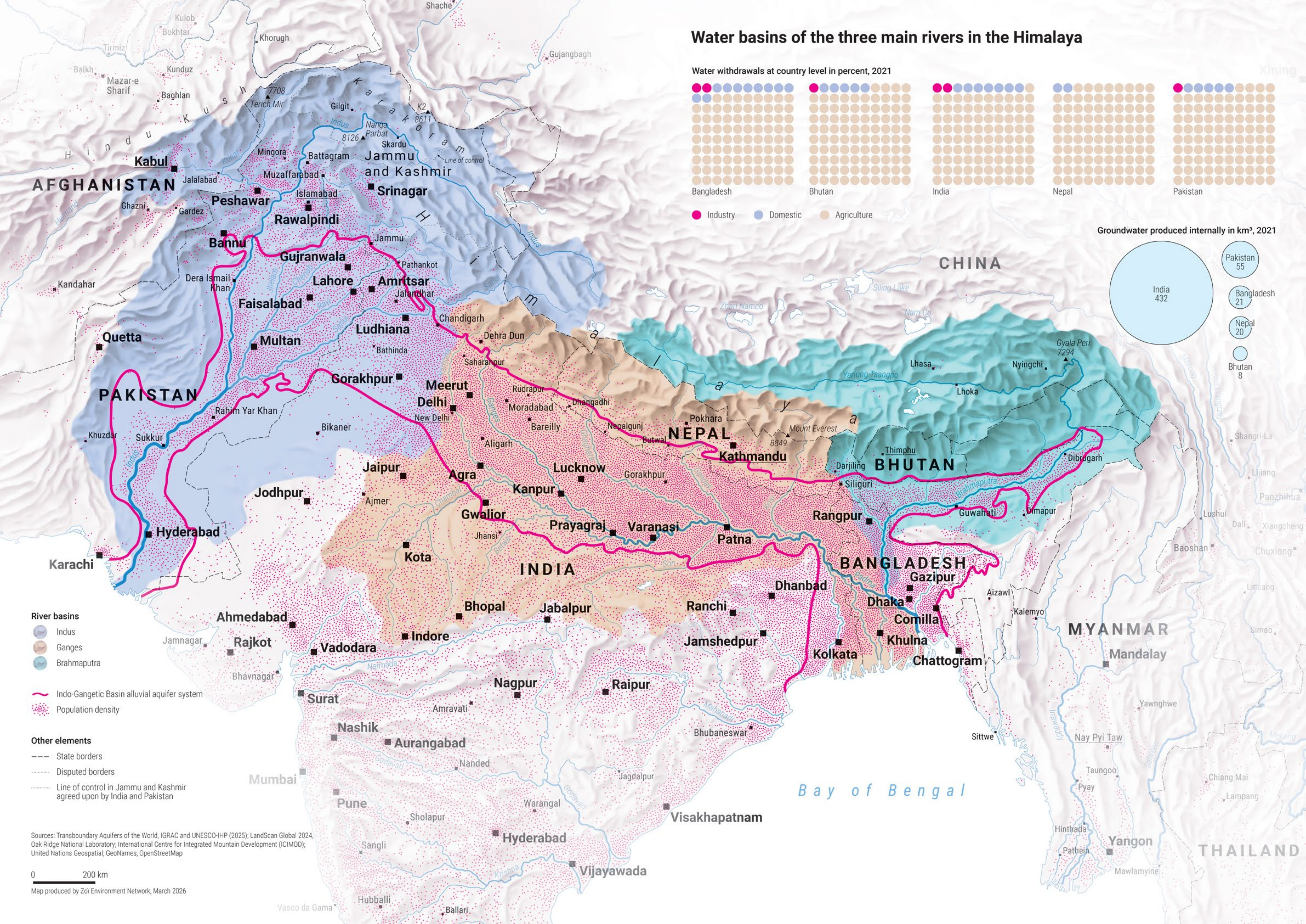
Underground water contributing to river flow

Under warmer climatic conditions, earlier and reduced snowmelt and increased spring precipitation accelerate surface runoff. This reduces water absorption by soils, limiting the recharge of aquifers and groundwater reservoirs, while increasing the risk of flooding (IPCC 2019). Rivers do not only rely on rainfall and surface runoff. A large share of their water, especially during dry seasons, comes from groundwater slowly feeding into rivers, known as baseflow. This baseflow is critical for maintaining river flows when rainfall is low and for supporting ecosystems, agriculture, and water supply.

Globally, baseflow feeds about 59 per cent of the world's rivers. In mountains, groundwater contributions to river flow are estimated by models to be from as little as 12 per cent to as much as 94 per cent, with this high variability explained mainly by different infiltration. However, observations suggest that about 21 per cent of global rainfall recharges groundwater (Xie *et al.* 2024).

With a warmer climate, forests are expected to use more water, leaving less available to seep into the ground and recharge underground reserves. As a result, groundwater storage is projected to decline, especially in dry years (Carroll *et al.* 2024). Forests are important contributors to mountain ecosystem services, amongst others stabilising soil and improving water infiltration. Consequently, policies that integrate forest management, water planning, ecosystem restoration and climate adaptation are essential to sustain reliable river flows from mountain regions.

Caucasus Mountains, Georgia. Photo: GRID-Arendal/Peter Prokosch



Water basins of the three main rivers in the Himalaya
Water withdrawals at country level in percent, 2021
Bangladesh
Bhutan
India
Nepal
Pakistan
Industry
Domestic
Agriculture
Groundwater produced internally in km³, 2021
India 432
Pakistan 55
Bangladesh 21
Nepal 20
Bhutan 8
River basins
Indus
Ganges
Brahmaputra
Indo-Gangetic Basin alluvial aquifer system
Population density
Other elements
State borders
Disputed borders
Line of control in Jammu and Kashmir agreed upon by India and Pakistan
Sources: Transboundary Aquifers of the World, IGRAC and UNESCO-IHP (2025); LandScan Global 2024, Oak Ridge National Laboratory; International Centre for Integrated Mountain Development (ICIMOD); United Nations Geospatial; GeoNames; OpenStreetMap
0
200 km
Map produced by Zoi Environment Network, March 2026
AFGHANISTAN
PAKISTAN
INDIA
NEPAL
BHUTAN
BANGLADESH
CHINA
MYANMAR
THAILAND
Jammu and Kashmir
Hindu Kush
Karakoram
Himalaya
Bay of Bengal
Kabul
Peshawar
Islamabad
Rawalpindi
Srinagar
Gujranwala
Lahore
Amritsar
Faisalabad
Ludhiana
Multan
Quetta
Gorakhpur
Meerut
Delhi
Hyderabad
Karachi
Jaipur
Agra
Jodhpur
Kanpur
Lucknow
Gwalior
Prayagraj
Varanasi
Patna
Kathmandu
Rangpur
Kota
Bhopal
Jabalpur
Ranchi
Dhanbad
Gazipur
Dhaka
Comilla
Khulna
Kolkata
Chattogram
Jamshedpur
Ahmedabad
Rajkot
Vadodara
Indore
Nagpur
Raipur
Surat
Nashik
Aurangabad
Mumbai
Pune
Hyderabad
Visakhapatnam
Vijayawada
Mandalay
Yangon
Lhasa
Thimphu
Guwahati
Siliguri
Mount Everest 8849
K2 8611
Nanga Parbat 8126
Line of control

Increasing groundwater abstraction

Niazi *et al.* (2024) analysed groundwater withdrawal across 235 major river basins worldwide under different socioeconomic and climate scenarios. Their findings show a recurring global pattern: groundwater use is expected to peak and then decline by the end of the 21st century. This decline is linked to falling economic returns as non-renewable groundwater pumping becomes increasingly energy-intensive and costly.

When global groundwater extraction reaches its peak, societies are likely to face additional challenges, such as increasing food prices, degraded aquatic ecosystems, land subsidence, and groundwater pollution. Proactive governance, sustainable water management, and early adaptation strategies will be essential to reduce these risks.

Links to ecosystem changes in mountains

The retreat of glaciers will expose newly deglaciated land that can subsequently be colonized by pioneer species. It is estimated that between 149,000 (± 55,000) km^2 to 339,000 (± 99,000) km^2 of land could become ice-free by 2100, corresponding to the land-areas of Nepal and Finland, respectively. Emerging post-glacial ecosystems will increasingly influence freshwater cycle through formation of new lakes, wetlands, grasslands and forests.

These environments will promote the accumulation of terrestrial biomass, the development of soils, and unconsolidated sediments, supporting local ecosystem services. If effectively managed, post-glacial environments can become carbon sinks, with estimated soil organic carbon stocks of 63.8 million tons under the middle of the road scenario and 84.5 million tons under the high emissions scenario (Bosson *et al.* 2023).

Pollution from poor sanitation, depletion of water sources, forest fires, mining and unsustainable agriculture can affect water availability and quality. Hence, industrial and energy development, as well as waste management in mountain areas needs to be carefully planned and managed to ensure high quality of mountain freshwater resources. In some mountain regions, such as the Andes, glacier retreat has led to the release of heavy metals into glacier-fed streams, leading to the acidification of some mountain rivers affecting both human health and biodiversity.

Mountain futures for sustainable mountain water

Enhancing groundwater infiltration in the world's mountain regions requires a multi-faceted strategy centred on Nature-based Solutions and community stewardship. The foundational approach is to restore and protect natural ecosystems, such as forests, grasslands, and wetlands, which increase soil permeability, slow runoff, and maximize the infiltration of rainfall and snowmelt to recharge aquifers. It will be important to use appropriate tree and plant species and techniques that favour soil permeability and groundwater discharge, avoiding mistakes of the past, such as the use of invasive trees that have even reduced water availability (FAO and UNEP 2023).

Ecosystem restoration and protection can be effectively complemented by tested adaptation approaches and solutions such as rainwater harvesting and water retention techniques. This includes small check dams, terraces, and contour trenches, which capture surface flow and allow it to percolate into the ground (UNEP and GRID-Arendal 2022). These interventions are supported by sustainable land and watershed management practices, such as conservation agriculture and agroforestry, which reduce soil compaction and protects critical recharge zones.

The success of these interventions depends on community-led and locally appropriate actions that integrate knowledge of Indigenous Peoples and Local Communities into the planning and management of these measures, ensuring they are culturally and ecologically suitable. To secure lasting impact, recharge strategies should be integrated into climate adaptation policies, promoting Nature-based Solutions as cost-effective, ecologically beneficial, and socially desirable components of national and regional water security strategies.

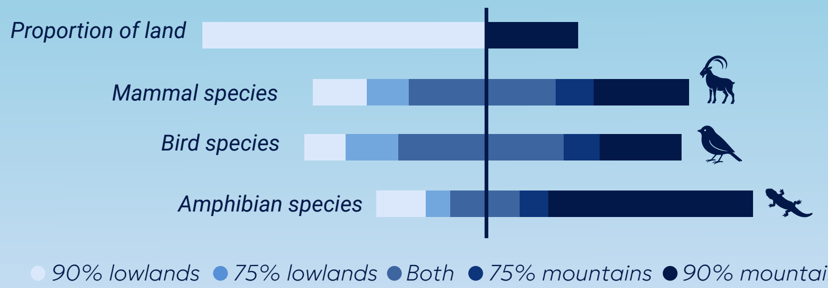
Nepal. Photo: GRID-Arendal/Rob Barnes

Chapter 3: Mountains as engines of biodiversity

Sustaining ecosystems and climate resilience

Proportion of species' range in mountains and lowlands

Mountain regions harbour approximately 87% of terrestrial global biodiversity.

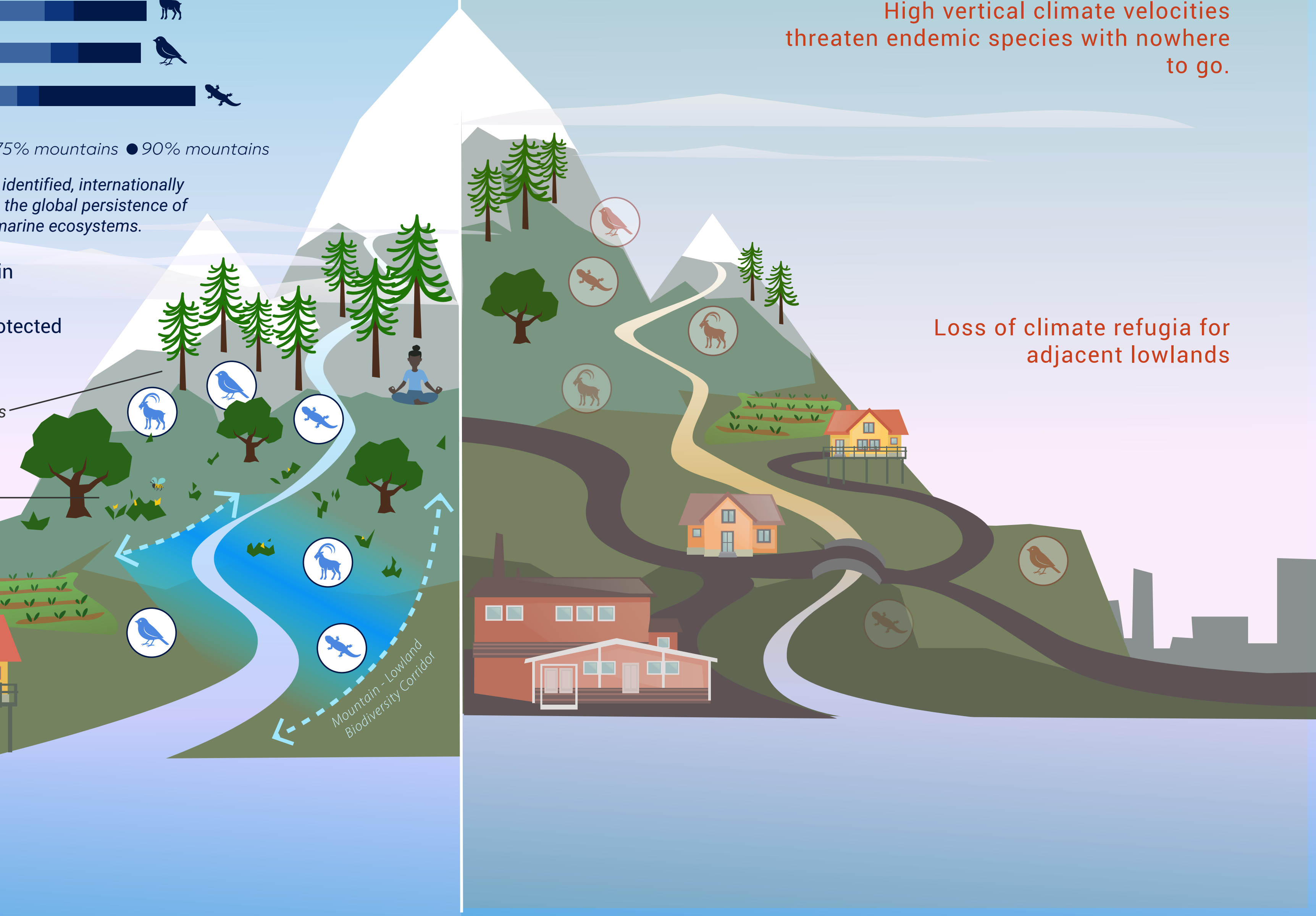


Key Biodiversity Areas (KBAs) are scientifically identified, internationally recognized sites that contribute significantly to the global persistence of biodiversity across terrestrial, freshwater, and marine ecosystems.

Over 40% of KBAs are found in mountain areas.

Only 17–19% of mountain areas are protected globally.

Mountains support downstream agriculture, clean water, and climate regulation.



Mountains harbour a disproportionately high percentage of global terrestrial biodiversity

Mountains contain more biodiversity than their geographic distribution would suggest. Their steep and varied landscapes create a wide variety of climates and habitats over short distances, allowing for a remarkable number of species to live side by side. Although mountains cover only a quarter of Earth's terrestrial area, they contain 85 per cent of the world's species of amphibians, birds, and mammals (Rahbek *et al.* 2019a). Their "stacked" climate zones make them powerful engines of biodiversity, and their unique conditions help explain why mountains are home to so many species found nowhere else (Rahbek *et al.* 2019b).

For example, the Makalu-Barun National Park in Nepal features an elevation gain of 8,000 metres and is home to over 3,000 different species of flowering plant, 315 butterfly, 43 reptile, 78 fish, and 88 mammal species in an area about the same size as London (1,500 km^2). New research also shows that mountain formation itself helps generate biodiversity over evolutionary and geological time scales, in both highlands and adjacent basins, making mountains global drivers of species diversity (Marder *et al.* 2025). Patterns vary widely between mountain ranges.

The Northern Andes, for instance, combine both extremely high local species richness with a high turnover in species composition along elevation gradients. This makes the region a uniquely important biodiversity hotspot that combines an exceptionally high number of species with strong ecological differentiation across altitudinal and climatic zones (Sonne and Rahbek 2024). As mountains create such unique conditions and drive long-term evolutionary processes, they also act as natural laboratories for understanding how species evolve and ecosystem's function (Wyckhuys *et al.* 2022), a history and unique natural resource well worth preserving.

Mountains as climate change sentinels

Until recently, it was assumed that species can respond to anthropogenic climate change by simply shifting their ranges to higher elevations to what is referred to as climate refugia. Many mountain regions are experiencing exceptionally high vertical climate "velocities" (Chan *et al.* 2024), with temperature bands, also called isotherms, shifting upslope. As global temperatures rise, climate zones are moving uphill, sometimes at up to 10 metres per year. This triggers a loss of high-altitude biodiversity that has nowhere else to go, with many species unable to move fast enough to keep up, especially those already living at the highest elevations. In the Ethiopian "Sky Islands", for example, endemic plants risk disappearing altogether (Kidane *et al.* 2019). This makes mountains early warning systems for biodiversity loss and climate change.

Mountains supply essential ecosystem services for people and nature beyond their boundaries

Mountains provide a range of mineral and freshwater resources and recreation opportunities. However, these services are highly vulnerable to climate change and biodiversity loss (Chakraborty *et al.* 2018), and the demand for water, food, timber, forage, and increasingly space for tourism activities is outpacing what mountains can supply. This demand often comes at the cost of other important ecosystem services such as climate regulation and natural hazard protection (e.g. landslides, floods, etc.) (Grêt-Regamey and Weibel 2020).

Other consequences include increased soil erosion, risk of insect pests, and a decrease in the supply of freshwater (Ioan *et al.* 2025). Some of the world's most important areas for biodiversity conservation, carbon storage, and clean water lie in major mountain chains such as the Andes, Alps, Hindu Kush Himalaya, and Caucasus (Jung *et al.* 2021). The health and benefits of downstream and downwind ecosystems, like river valleys and agricultural areas, directly depend on biodiversity upstream and upwind. Due to their high species richness, mountains also safeguard vital genetic resources, that allow species and ecosystems to adapt to changing environments.

This also applies to crops such as the thousands of potato varieties of the central Andes and wild Arabica coffee from Afromontane forests, making mountain ranges "living museums" of genetic diversity for many important commercial crops consumed all around the world (Payne *et al.* 2020). When mountain biodiversity declines, it affects water supply, food security, local livelihoods, cultural heritage, and global agriculture, while also impacting the ability of these ecosystems to adapt to climate change.

Himalaya Vulture (Gyps himalayensis), Sagarmatha National Park, Nepal. Photo: GRID-Arendal/Peter Prokosch

Why elevation gradients matter for conservation

Species in mountains face six times higher extinction risk than those in lowlands (Manes *et al.* 2021). The risk of extinction increases with higher elevation, especially for birds and amphibians, the two most endangered animal groups (White and Bennett 2015; Guirguis *et al.* 2023). Protecting entire elevation gradients is essential for species survival, yet most mountain ecosystems remain under-protected. Only 17–19 per cent of mountain ecosystems are protected globally (Sayre *et al.* 2020), and 40 per cent of mountain ranges have no protected areas (Jacobs *et al.* 2023). Although often perceived as "pristine" environments, half of the world's mountainous regions approach the global average for levels of human modification, and habitat fragmentation has reduced the ecological integrity of mountain ecosystems by up to 40 per cent (Theobald *et al.* 2024),

Many areas of Africa and South Asia hold significant potential for conservation gains, but socio-environmental conditions (e.g. status of the local economy, conflicts) often hinder the establishment of new protected areas (Mouillot *et al.* 2024). In addition, only a few protected areas cover full elevation gradients, even though such an approach would allow species to move upslope as climates change (Elsen *et al.* 2018). To survive climate change, species must be able to move up and down mountain slopes. Conservation efforts must therefore focus on protecting entire elevational pathways, not just isolated mountain tops.

Altitudinal migration: a missing link in connectivity

Many animals migrate to different elevations seasonally, but conservation plans rarely account for this and are often missing designated wildlife corridors that link low and high elevations (Jacobs *et al.* 2023). For example, during seasonal flooding, the Caquetá River basin pushes many species into higher parts of the Eastern Andes (Mosquerra-Guerra *et al.* 2025), and around 10 per cent of the world's bird species migrate along elevation gradients (Barçante, Vale and Alves 2017). For species that use both lowland and mountain habitats, protecting only one or the other leaves crucial gaps in their life cycles. Biodiversity corridors that connect adjacent high-altitude areas can provide potential safe havens across a wide range of latitudes and help species respond to seasonal changes and long-term climate shifts.

New habitats, new risks: Invasive species in mountains

Climate change, tourism, and land-use changes are accelerating the arrival of non-native, potentially invasive species in mountain ecosystems. In the recent decades, many mountain ecosystems have been less affected by invasive species because environmental conditions get harsher along the altitudinal gradient, limiting survival of non-native species (e.g. low temperatures, frequent frost, and short growing seasons). With warmer temperatures extending growing seasons reducing snow cover and frost frequency, barriers are weakening, allowing lower elevation species to survive, establish, and reproduce at higher elevations where they were previously unable to persist.

Land-use change, particularly the introduction of non-native tree plantations, can alter soil properties by changing soil acidity and reducing invertebrate diversity, thereby decreasing local soil biodiversity and carbon storage (Cifuentes-Croquevielle *et al.* 2020). In addition, as glaciers retreat, newly exposed land could become climate refugia for animals and plants at lower elevations. Evidence from research shows that while generalist species, including humans, will see their ecological niches expand, that of specialist species will retreat. This includes endemic species that are completely adapted to living on or near glaciers (Bosson *et al.* 2023; Ficetola *et al.* 2024).

Mountain futures for biodiversity-rich landscapes

Building resilience in mountain ecosystems requires integrated conservation, restoration, and governance strategies that fully recognise the central role, rights, and knowledge of Indigenous Peoples and Local Communities. Key strategies include expanding protected areas following Free, Prior and Informed Consent processes and creating ecological corridors to help species adapt to climate change; restoring degraded grasslands, forests and water catchments; and integrating biodiversity into land-use planning and agricultural practices to reduce fragmentation and unsustainable practices. In this regard, it is important to protect entire elevational pathways along isotherms, especially for migratory species. As a last resort, seed banks and animal biobanks can serve as a critical "biological insurance policy" for ecosystems by preserving a broad spectrum of genetic variants, ensuring that the specific traits are not lost forever but can be used for restoring or genetically rescuing populations. However, the technology is often expensive and taxonomic coverage is limited, including for mountain species.

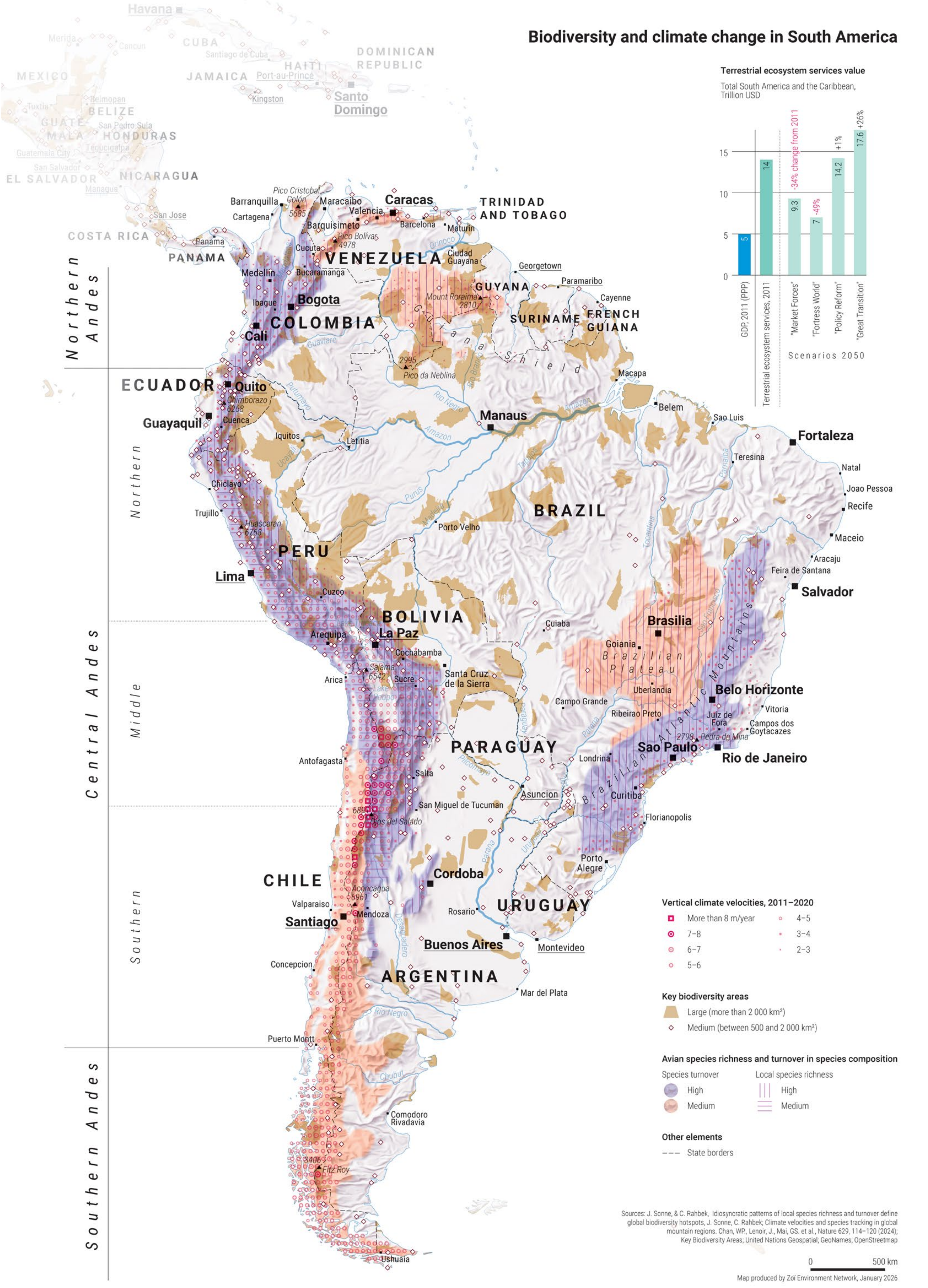
Any conservation or restoration measures should always consider the adaptation needs of communities living nearby, while ensuring that the adaptation measures themselves do not further compromise ecosystem health. Many Indigenous Peoples and Local Communities also maintain deep cultural, spiritual, and livelihood connections to mountain landscapes, and hold generations of knowledge about their species and seasonal dynamics.

Strengthening climate adaptation, with strategies that secure water resources, reduce climate-related risks and strengthen ecosystem and community resilience, is vital, alongside long-term monitoring to support evidence-based decision-making. The monitoring of biodiversity is crucial to fill knowledge gaps and keep track of conservation and adaptation impacts. Integrating technological advances in Earth Observation and Artificial Intelligence, coupled with traditional knowledge and citizen science, can cost-effectively increase public interest, understanding, and acceptance of conservation and adaptation measures.

Ensuring that both climate and biodiversity actions are integrated, rather than treated separately, is essential for effective and equitable mountain development policies, especially in regions where Indigenous Peoples and Local Communities depend directly on healthy ecosystems for their resilience. Finally, coherent policies across borders and sectors, combined with scaling up successful local initiatives, are essential to secure sustainable and effective outcomes for mountain ecosystems (Leadley *et al.* 2022).

Laukvikøyene Nature Reserve, Ramsar Site, Lofoten. Photo: GRID-Arendal/Peter Prokosch

Biodiversity and climate change in South America

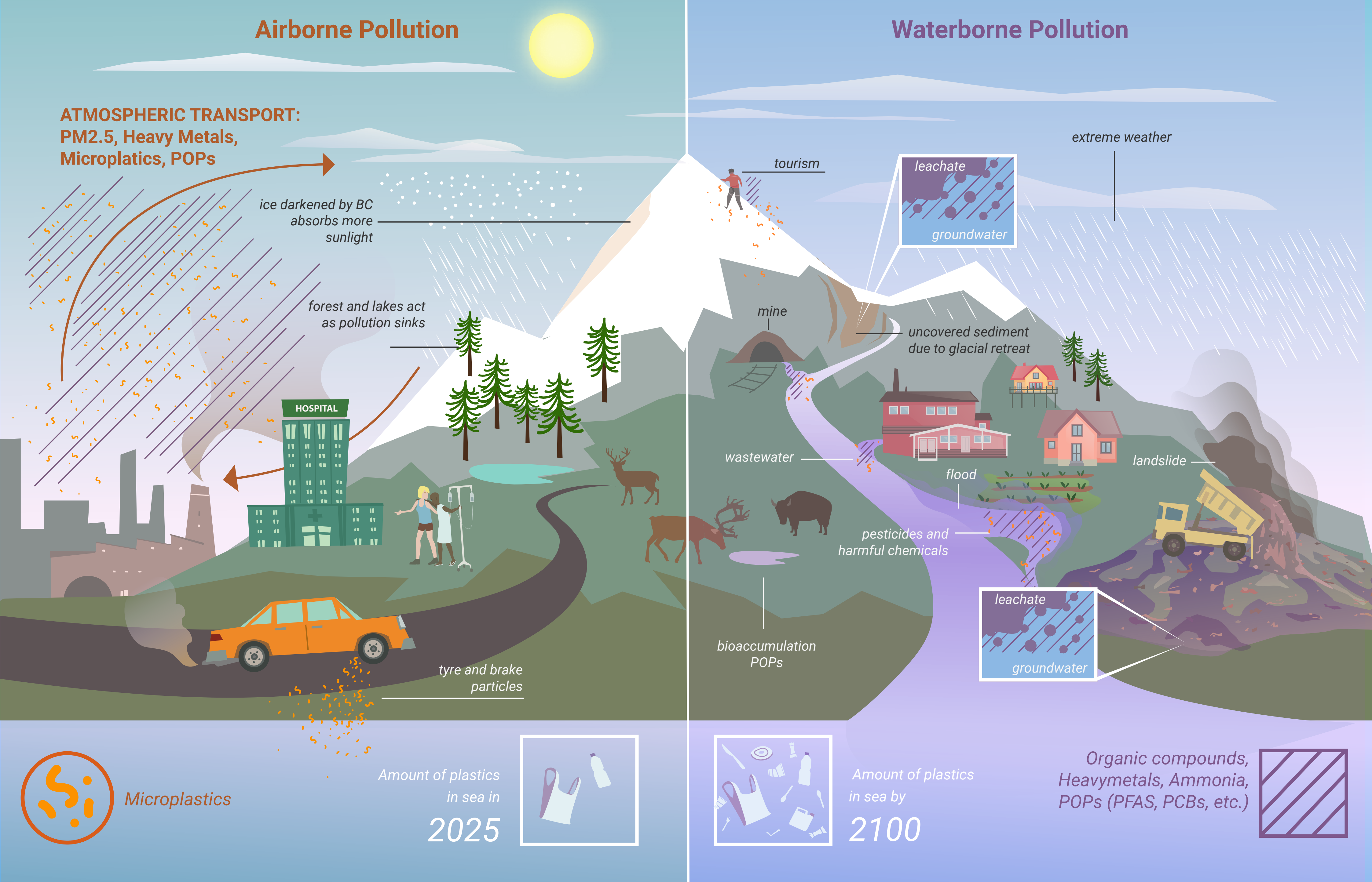


Sources: J. Sonne, & C. Rahbek, Idiosyncratic patterns of local species richness and turnover define global biodiversity hotspots, J. Sonne, C. Rahbek; Climate velocities and species tracking in global mountain regions. Chan, WP., Lenoir, J., Mai, GS. et al., Nature 629, 114–120 (2024); Key Biodiversity Areas; United Nations Geospatial; GeoNames; OpenStreetmap

Map produced by Zoï Environment Network, January 2026

Chapter 4: From sky to streams

Mountain pollution pathways



Plastic waste dumped near a river in Pakistan. Photo: GRID-Arendal/Anonymous Photographer

Pollutants are carried through several ways including groundwater, living organisms, and human use. There are two major pathways, air and water, into and out of high-altitude landscapes, embedding mountains within broader regional and global systems. Their vulnerability is amplified by steep topography, fragile ecosystems, and high climatic sensitivity and complex meteorological conditions that influence pollution transport, dispersion and accumulation.

Pollutants originating in lowland areas such as persistent organic pollutants (POPs), including polychlorinated biphenyls (PCBs), dioxins, furans and brominated flame retardants, and other air contaminants can be transported to the highest altitudes by wind. In turn, pollution generated within mountain environments can flow downstream, linking the health of peaks and valleys in inseparable ways.

Climate change accelerates these risks: glacier retreat, permafrost thaw, and extreme weather events can suddenly release long-stored pollutants, producing contamination pulses that threaten biodiversity, ecosystem services, and human health with impacts cascading downstream beyond mountain regions. These interlinked processes make clear that pollution in mountains is not a local challenge but a global concern.

Reducing pollution in mountain environments requires actions that address both upstream drivers and local management capacity. Despite the presence of some large urban areas, mountain regions are mostly remote, steep, and sparsely populated. This makes conventional waste and pollution control systems designed for densely populated lowland settings not always practical. Tailored solutions must therefore prioritize waste prevention, local resource recovery, and circular approaches adapted to mountain geographies (BRS Secretariat and GRID-Arendal 2022).

In addition, coordinated management across watersheds and airsheds is essential, as pollution is transported from high-altitude landscapes to downstream communities and ecosystems and vice-versa (UNEP 2021). Strengthening governance at the level of mountain municipalities, protected areas, and river basins can enable integrated planning for waste, water, and atmospheric pollution management, while fostering regional cooperation and shared monitoring systems (UNEP 2023).

Waterborne pollution

Underground water contributing to river flow

Mountain environments are increasingly affected by a range of waterborne pollutants linked to land use change, household waste mismanagement, and industrial activities. Expanding agriculture, infrastructure, mountain urbanization, increasing tourism, and settlements in and around mountain regions intensify waste generation, placing pressure on limited waste management systems (Schmeller *et al.* 2022).

Trends of modern consumerism have altered waste generation in mountain communities. Traditional materials are often being replaced by single-use products, many of which are made of plastic packaging, which are difficult to collect and recycle and impose new challenges on local communities. Remote communities are faced with large amounts of waste including from plastics, electronic devices, batteries, paints, oils and others that are challenging to manage in an environmentally sound manner. Many communities do not have access to proper waste management practices, leading to littering and pollution of land and waterways. Waste collection rates in mountain regions are typically low, accounting for 30 to 60 per cent in low-income countries, and 50 to 80 per cent in middle income countries (Scheinberg, Wilson and Rodic-Wiersma 2010).

Waste separation at source is uncommon, as circular waste management practices have limitations in remote areas. In some mountain cities, waste is disposed of in open dumpsites as opposed to engineered sanitary landfills. In addition, uncontrolled solid waste disposal in rivers and creeks has been reported in some studies. Open dumping in mountain environments poses additional risks, as dumping sites are often located near watercourses due to scarcity of land, with the potential to pollute water that is used by large populations downstream.

Mismanaged waste and extreme weather events

Climate change intensifies the environmental risks associated with waste mismanagement, as extreme weather events such as flash floods, landslides, and debris flow can mobilise pollutants previously stored in soils, landfills, and waste deposits, suddenly releasing large contaminant loads into river systems (Crawford *et al.* 2021). The result is a greater threat to aquatic ecosystems, drinking water supplies, coastal environments and the oceans (Touma *et al.* 2022).

Landfills in steep or remote terrain are particularly vulnerable. Leachate can seep into groundwater and rivers, especially when practices do not follow environmentally sound waste management guidelines. Growing populations, both permanent and seasonal, contribute to increased plastic pollution, much of it entering waterways via poorly managed solid waste disposal (Huang *et al.* 2024). Even modern engineered sanitary landfills, designed with impermeable liners, eventually allow some leachate to escape. The leachate has shown to contain organic compounds, heavy metals, ammonia, per- and polyfluoroalkyl (PFAS), polychlorinated biphenyls (PCBs), and dioxins amongst others (Tolaymat *et al.* 2023).

One of the main connections between mountains and lowland areas is via rivers. While they provide essential water, they also transport pollution such as plastics, including microplastics, chemicals used in agriculture and other contaminants downstream. Illegally used chemicals are of particular concern. Industrial activities such as mining may release heavy metals and processing residues through tailing dams into mountain streams, and hydropower reservoirs can trap mercury in sediments, creating long-term contamination risks (Maus *et al.* 2022).

These pollutants eventually flow downstream, mixing with additional sources before reaching the oceans, where they contribute to pollution, bioaccumulation and biodiversity loss (Beard *et al.* 2022; UNESCO 2025). Microplastics are additional contaminants, increasingly found in remote ecosystems. While microplastic research has increased in recent years and generated significant volumes of data, there is a lack of a robust, open access, and long-term aggregation of this data (Nyadjro *et al.* 2023).

As a key component of mountain ecosystems, high-mountain lakes are recognized indicators of global change. Pastorino *et al.* (2022) review the limited evidence on microplastics in high-mountain lakes and argue these systems are sensitive "sentinels" of broader environmental change. A literature search found only nine studies, mostly on the Tibetan Plateau, focusing on water and sediments, consistently reporting microplastics as fibres and fragments dominated by polypropylene and polyethylene. Tourism and transportation are identified as the principal sources, with snowfall and rainfall acting as key deposition events.

Mountain Tourism

Mountain tourism varies greatly between countries but is estimated to represent between 9 per cent and 16 per cent of total international tourist arrivals, which is equivalent to a range of between 195 and 375 million international arrivals (FAO and UN Tourism 2023). In popular destinations, waste generation can reach several kilograms per person per day, far exceeding local management capacity. The growth in tourists visiting popular mountain regions and the accompanying waste issues can be staggering.

For example, the Mount Everest region in Nepal has seen an exponential increase in visitors from 20 in 1964 to approx. 52,000 in 2019. Up to 140,000kg of solid waste is estimated to remain after 60 years of expeditions (Kelliher 2014). Without sustainable waste management solutions, such as waste prevention, reduction, reuse, recycling, and final disposal in environmentally sound manner, tourism will continue to be a significant pollution driver in mountain catchments (Alfthan *et al.* 2016). Tourism should contribute to the protection, not the degradation of mountain landscapes (UN Tourism and UNEP 2021). Governments and protected-area authorities can, for instance, establish carrying capacity frameworks to limit visitor numbers during ecologically sensitive seasons, and implement "pack-in, pack-out" requirements for trekking and mountaineering expeditions (UNEP 2023). Tourism businesses can also be required to participate in waste take-back and cost-sharing schemes that support local waste services (UNEP 2021).

Certification systems for low-impact tourism operators, combined with community-based monitoring, can encourage stewardship while strengthening local economies. Environmental education and visitor guidance campaigns can further reduce littering, improve waste sorting, and promote respect for local cultural and ecological values (UN Tourism and UNEP 2021).

Airborne pollution

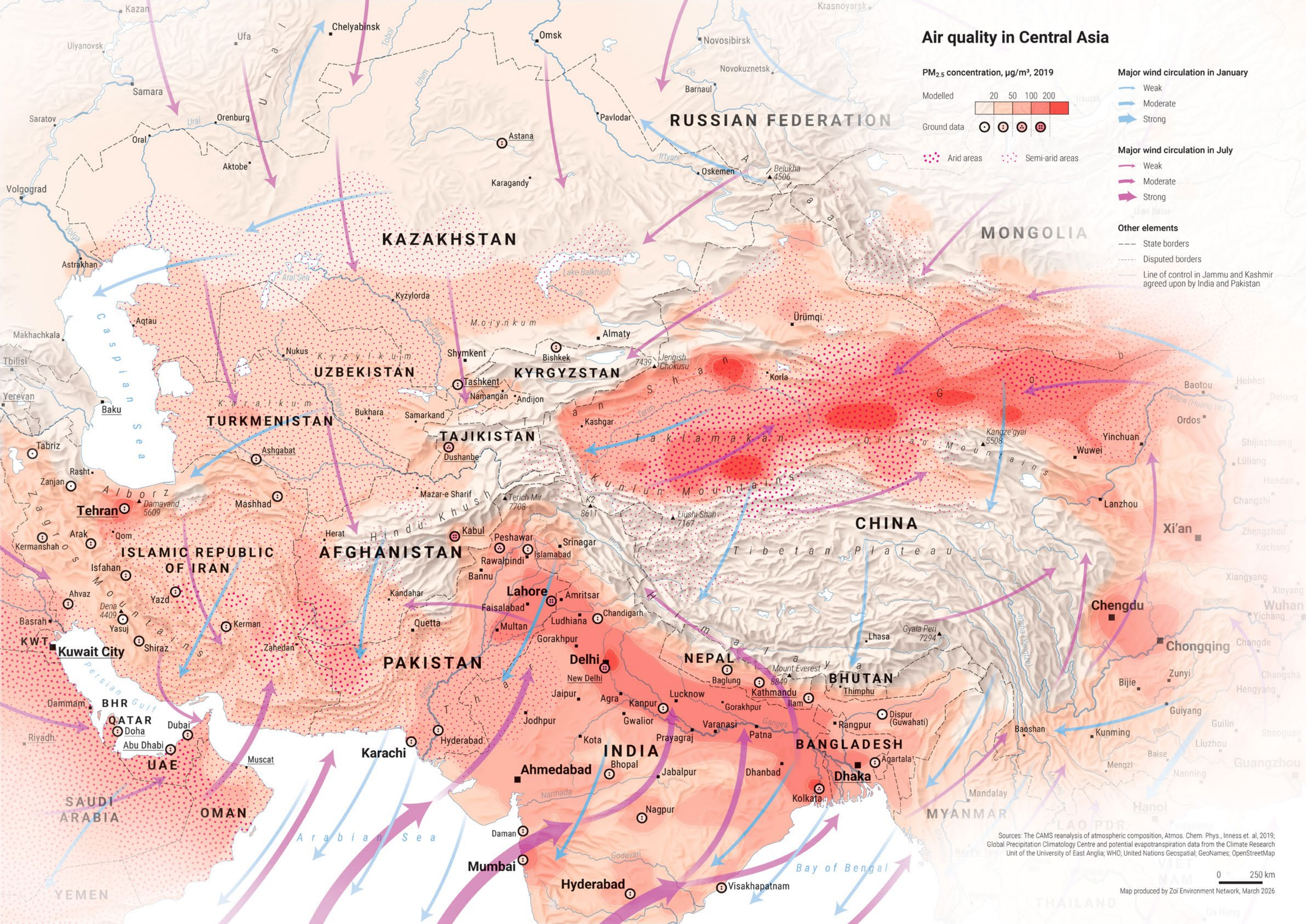
Mountain valleys are especially vulnerable to air pollution because of the landscape and the way air moves in these areas (Shukurov and Marakulina 2021). These environments are also useful for studying how pollutants travel and change as temperature, vegetation, and climate vary with elevation. Daily wind patterns can carry pollutants uphill, and because higher elevations are colder and receive more rain or snow, these pollutants are deposited and build up there over time (Daly and Wania 2005). In many valleys, a weather pattern called temperature inversion, where warm air forms a layer above cooler air, can trap pollutants close to the ground. This means pollution can linger longer, increasing exposure for both local ecosystems and the people living there (Chemel and Burns 2015). Major sources of airborne pollution include urban centres and industrial zones, with emissions from coal- and oil-fired power plants, vehicle exhaust, particulates from tire and brake wear, and manufacturing processes releasing fine particulate matter (PM2.5), heavy metals, and microplastics. Such sources combined with episodic events such as forest fires or crop residue burning can contribute to poor air quality sometimes over long distances. Women and youth are especially affected by health risks associated with open fire cooking and unchecked burning of waste.

Black carbon (BC) and particulates

Black carbon produced mainly from coal and oil combustion, residential sector and vehicle exhaust, is a powerful short-lived climate pollutant with about one to two weeks lifespan in the atmosphere (Clean Air Fund 2025). When black carbon settles onto snow and ice, it absorbs sunlight and reduces surface reflectivity, which accelerates melting across mountain and polar regions. Ice-core evidence shows that black carbon levels increased sharply in the mid-19th century with industrial growth and expanding fossil-fuel use (Kang *et al.* 2020).

Today, black carbon concentrations in snow and ice are generally 10–100 times higher in mid-latitude mountain regions than in the polar regions, with the highest levels found in older, melting glacier ice where black carbon accumulates over repeated melt seasons. On the Tibetan Plateau, for example, black carbon in surface snow and ice accounts for roughly 20 per cent of the observed melt-season reduction in reflectivity, contributing to stronger warming at the surface (Singh 2021). Globally, this effect increases glacier melt by around 20 per cent and shortens seasonal snow cover by several days. In short, black carbon emissions are concentrated around densely populated, fossil-fuel-dependent regions, where prevailing winds transport soot to nearby mountain snowfields.

Global simulations of atmospheric transport of microplastic particles produced by road traffic, tire wear particles, and brake wear particles show high transport efficiencies of these particles to remote regions. The fine fraction (PM2.5) of both tire wear particles and break wear particles persists in the atmosphere for about four weeks on average, long enough for intercontinental transport. By contrast, coarse particles fall out much sooner, about eight days for PM10 tire wear particles. As a result, the highest surface levels cluster over major source regions, such as the Eastern USA, Europe, and Southeast Asia, while the fine fraction can still reach remote places (Evangeliou *et al.* 2020; Allen *et al.* 2019).



Air quality in Central Asia
PM2.5 concentration, µg/m³, 2019
Modelled
20 50 100 200
Ground data
Arid areas
Semi-arid areas
Major wind circulation in January
Weak
Moderate
Strong
Major wind circulation in July
Weak
Moderate
Strong
Other elements
State borders
Disputed borders
Line of control in Jammu and Kashmir agreed upon by India and Pakistan
RUSSIAN FEDERATION
KAZAKHSTAN
MONGOLIA
UZBEKISTAN
KYRGYZSTAN
TURKMENISTAN
TAJIKISTAN
AFGHANISTAN
ISLAMIC REPUBLIC OF IRAN
PAKISTAN
CHINA
NEPAL
BHUTAN
BANGLADESH
INDIA
MYANMAR
SAUDI ARABIA
OMAN
UAE
QATAR
BHR
KWT
YEMEN
Caspian Sea
Aral Sea
Lake Balkhash
Persian Gulf
Arabian Sea
Bay of Bengal
Taklamakan
Tibetan Plateau
Kunlun Mountains
Qilian Mountains
Tian Shan
Hindu Khush
Himalaya
Karakum
Kyzylkum
Moiynkum
Alborz
Zagros Mountains
Thar
Altai
Gobi
Kazan
Ulyanovsk
Ufa
Samara
Saratov
Orenburg
Oral
Aktobe
Volgograd
Astrakhan
Makhachkala
Tbilisi
Yerevan
Baku
Aqtau
Chelyabinsk
Omsk
Novosibirsk
Novokuznetsk
Barnaul
Krasnoyarsk
Pavlodar
Astana
Karagandy
Oskemen
Belukha 4506
Kyzylorda
Almaty
Bishkek
Shymkent
Tashkent
Namangan
Andijon
Nukus
Bukhara
Samarkand
Dushanbe
Ashgabat
Mashhad
Mazar-e Sharif
Herat
Kabul
Kandahar
Quetta
Peshawar
Islamabad
Rawalpindi
Srinagar
Bannu
Lahore
Amritsar
Faisalabad
Multan
Ludhiana
Chandigarh
Gorakhpur
Delhi
New Delhi
Jaipur
Agra
Jodhpur
Gwalior
Kanpur
Lucknow
Varanasi
Patna
Prayagraj
Kota
Bhopal
Jabalpur
Ahmedabad
Dhanbad
Kolkata
Dhaka
Agartala
Rangpur
Dispur (Guwahati)
Thimphu
Kathmandu
Baglung
Ilam
Mount Everest 8849
Lhasa
Gyala Peri 7294
Nagpur
Mumbai
Daman
Hyderabad
Visakhapatnam
Karachi
Tehran
Damavand 5609
Tabriz
Rasht
Zanjan
Qom
Arak
Kermanshah
Isfahan
Yazd
Kerman
Zahedan
Shiraz
Yasuj
Dena 4409
Ahvaz
Basrah
Kuwait City
Dammam
Doha
Abu Dhabi
Dubai
Muscat
Riyadh
Ürümqi
Korla
Kashgar
Jengish Chokusu 7439
K2 8611
Terich Mir 7708
Liushi Shan 7167
Kangze'gyai 5508
Wuwei
Yinchuan
Lanzhou
Xi'an
Baotou
Hohhot
Ordos
Chengdu
Chongqing
Bijie
Zunyi
Guiyang
Kunming
Baoshan
Mandalay
Volga
Ural
Tobol
Ishim
Irtysh
Ob
Syr Darya
Amu Darya
Tarim
Indus
Ganges
Narmada
Godavari
Yellow (Huang He)
Yangtze
Jinsha (Yangtze)
Sources: The CAMS reanalysis of atmospheric composition, Atmos. Chem. Phys., Inness et. al, 2019; Global Precipitation Climatology Centre and potential evapotranspiration data from the Climate Research Unit of the University of East Anglia; WHO; United Nations Geospatial; GeoNames; OpenStreetMap
0 250 km
Map produced by Zoï Environment Network, March 2026

Mountain futures for clean environments

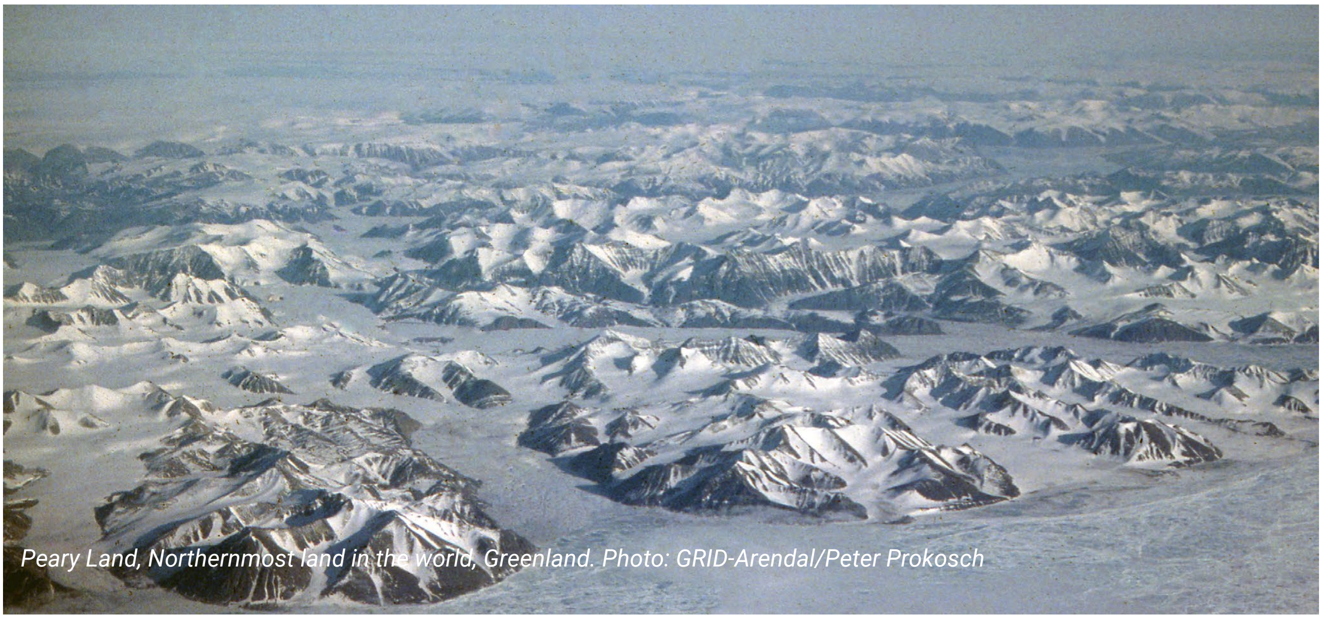
Reducing waste at the source is the most effective way to protect fragile mountain ecosystems. This includes a circular economy approach, aiming to prevent waste before it is created. Effective waste management with a circular economy approach in mountainous areas depends on adopting terrain-appropriate collection strategies, including decentralized systems, community-level segregation, and transport solutions designed for steep, remote, and weather-constrained environments along with appropriate technical strategies for its management.

Under a high-emissions scenario without specific policies in place, global plastic pollution is projected to increase three- to four-fold by 2100, as economic growth outpaces waste management (Yan *et al.* 2024), creating a runaway pollution crisis that affects even the most remote regions. Establishing extended producer responsibility (EPR) policies that require companies to take back packaging and products, particularly plastics, batteries, and electronic waste, can significantly reduce the waste burden placed on remote and high-altitude communities (BRS Secretariat and GRID-Arendal 2022).

Encouraging reuse systems, such as refillable drinking bottles, shared returnable containers for food and beverages, or rental and repair models for trekking and outdoor gear, helps lower waste volumes while supporting local livelihoods and tourism economies (UNEP 2023). Where recycling is feasible, micro-scale resource recovery centres can cluster collection, sorting, and safe storage of recyclable materials for periodic transport to regional processing facilities, helping to overcome logistical constraints in steep and sparsely connected terrain. Special attention in this context should be given to active participation and decision-making of women and youth. These measures should be paired with dedicated financial mechanisms, such as national EPR funds, green procurement frameworks, or tourism-based levies earmarked for waste services, to ensure sustainable financing for mountain waste management (UNEP 2021).

Targeted measures to reduce black carbon and road-based particulate emissions offer rapid co-benefits for climate, water security, and public health (UNEP and WMO 2011). Transitioning to clean household energy and improved cookstoves in mountain settlements can substantially reduce local soot emissions while improving indoor air quality and reducing health risks (UNEP 2019).
Shifting vehicle fleets toward electric public and shared transport, combined with low-emission zones in mountain valleys, directly reduces PM2.5 and black carbon emissions from road transport (CCAC 2021).

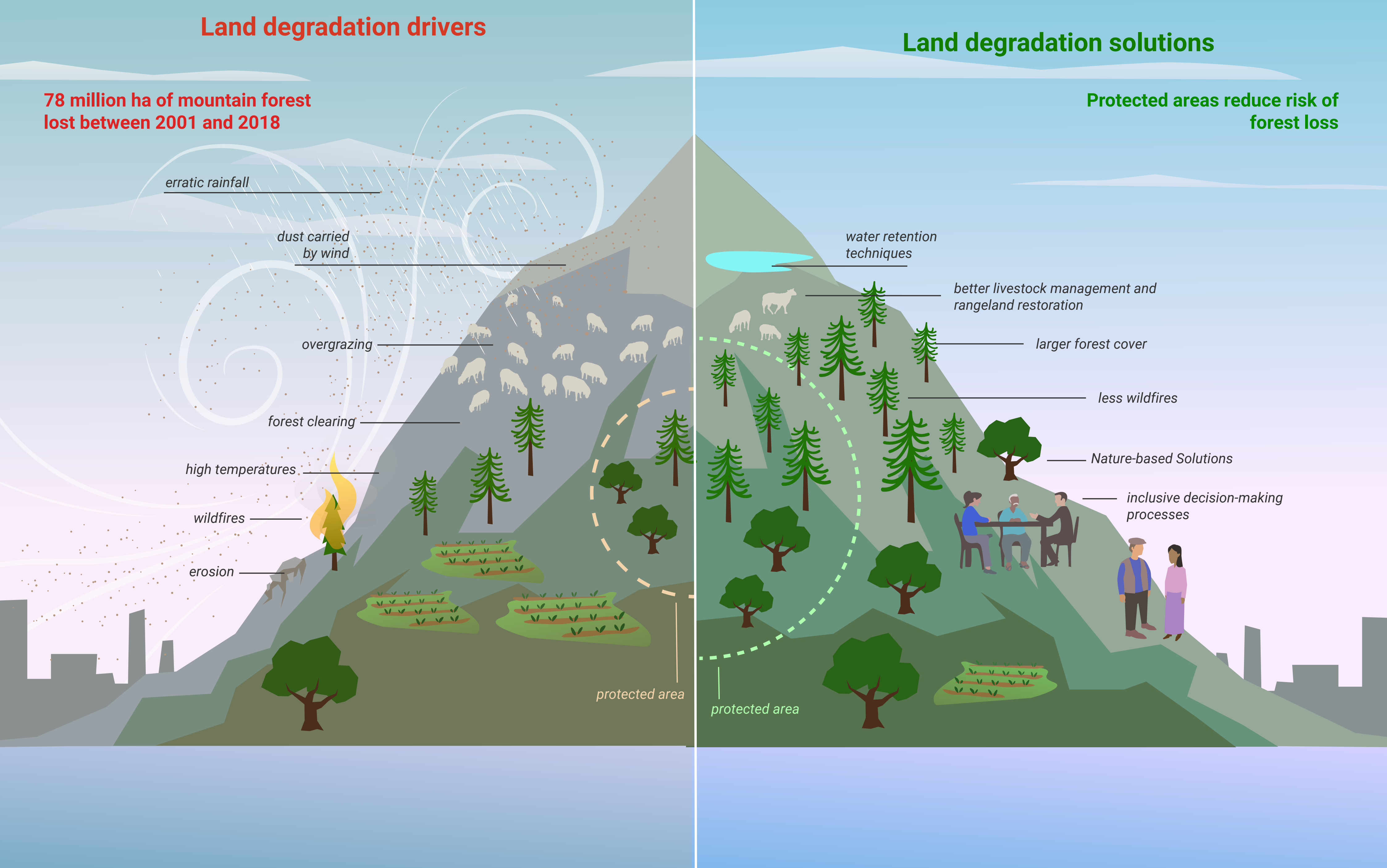
Installing snow- and ice-monitoring stations that track black carbon and microplastic deposition provides crucial data for identifying pollution sources and evaluating policy effectiveness in high-altitude cryosphere regions (UNEP, GRID-Arendal and Global Mountain Safeguard Research Programme 2022). Because many airborne contaminants originate far beyond mountain borders, regional cooperation on transboundary air pollution control remains essential to protecting mountain ecosystems and downstream communities (UNECE 2020).



Peary Land, Northernmost land in the world, Greenland. Photo: GRID-Arendal/Peter Prokosch

Chapter 5: Land degradation in mountains

Challenges and pathways for prevention




Sheep grazing in Vashlovani National Park. Photo: GRID-Arendal/Peter Prokosch

Land degradation is defined by the United Nations Convention to Combat Desertification (UNCCD) as the reduction or loss of the biological and economic productivity of land and its constituents: soil, water, and biodiversity. Affecting all types of land, land degradation can be observed directly on the surface through increased erosion processes, and below the surface through alterations in the soil's physical, chemical, and biological properties. Drivers of land degradation can be natural or indirect, but most are related to human activities (UNCCD 2022).

Overgrazing

Although "greening" of high-altitude grasslands is predicted with warmer temperatures (Zhang *et al.* 2025), regional evaluations suggest that overgrazing may counteract or even outpace these potential gains. This has been shown in the high-altitude Qinghai-Tibet Plateau where stronger grassland carrying capacity has been coupled with more serious overgrazing (Wang *et al.* 2025), and a higher presumed risk of erosion and reduction in species composition, soil quality, and productivity. In the mountain grasslands of the French Alps, drought was found to trigger land degradation by inhibiting a potential increased biomass productivity in summertime (Corona-Lozada *et al.* 2019).

The impact of livestock grazing on the health of grasslands, especially in dry regions, is a major environmental debate. The effect of grazing depends heavily on the local climate and biodiversity. In warmer or wetter conditions, grazing tends to have negative conserquences on biomass productivity, leading to lower soil carbon storage, increased erosion, and reduced plant growth. Conversely, in cooler conditions with a high diversity of plants, grazing can often have positive effects on the ecosystem. However, most often, site-specific parameters such as temperature, rainfall patterns, and plant diversity are the most critical factors that determine the impact of grazing on ecosystem services (Maestre *et al.* 2022).

Despite the pressing challenge of grassland degradation, evidence confirms that restoration is achievable with timely intervention (Bardgett *et al.* 2021). To effectively combat this issue, adopting a multi-faceted strategy is essential. This begins with elevating policy recognition of grasslands' critical roles in climate mitigation, food security, biodiversity, and sustainable livelihoods. Interventions must be grounded in local ecological and institutional contexts, particularly in mountain rangeland systems where climate variability, grazing pressure, and biodiversity conservation objectives intersect. This is especially relevant in Central

Asian highlands, where grasslands simultaneously support pastoral livelihoods and serve as key habitats and movement areas for wild ungulates. Results from the application of the Participatory Rangeland and Grassland Assessment methodology in Kyrgyz Republic demonstrate that areas with stable or improving productivity values may simultaneously experience declining soil organic carbon stocks, increased erosion risk, and shifts in species composition due to prolonged and concentrated grazing pressure (Sharpe *et al.* 2022). Following the collapse of long-distance seasonal livestock mobility after the Soviet period, many accessible pastures have been subject to year-round use, while remote summer pastures remain underutilized, creating spatial imbalances in grazing intensity (Isakov and Thorsson 2015; Hoppe *et al.* 2016).

Field-based assessments combined with herder perceptions further indicate that climatic stressors such as increasing aridity, altered precipitation patterns, and reduced snow cover duration interact with overgrazing to accelerate land degradation processes in high-altitude grasslands (Sharpe *et al.* 2022). Importantly, these pressures impact both livestock production and the forage resources of wild ungulates, which share the same rangelands and compete for limited grazing areas, especially in critical seasonal pastures and ecological corridors.

This highlights the limitations of grazing management approaches that focus exclusively on livestock carrying capacity without accounting for wildlife needs and climate-driven variability. Responding to this challenge, the Central Asian Mammals and Climate Adaptation (CAMCA) initiative provides a practical example of how restoration-oriented, multi-functional rangeland management can be operationalised.

Within a newly established ecological corridor in the Kyrgyz Republic, wildlife considerations have been integrated into community-level grazing management by embedding corridor-specific grazing regimes at the pasture-unit scale. This includes reserving a defined share of available forage for wildlife, e.g., applying a "leave 40 per cent" rule in corridor pasture units, recalculating carrying capacity under both climate-related biomass projections and biodiversity requirements, and negotiating seasonal livestock redistribution to reduce grazing pressure in priority wildlife areas.

Mountain forest loss

Mountain forests in some parts of the world have been comparatively less affected than lowlands by human activity due to steep slopes and high elevations with difficult access for humans. In previous centuries, extensive deforestation occurred, leading to numerous environmental problems. Since the early 2000s, however, forests in several places have been increasingly cleared for timber, wood products, and new forms of agriculture such as boom crops and plantations. Between 2001 and 2018, around 78 million hectares of mountain forest were lost, representing about 7 per cent of the global total. Tropical mountains, especially in South Asia, have seen the fastest losses, mainly due to shifting cultivation, commodity farming, and commercial forestry. Overall, Asia, South America, Africa, Europe, and Australia all experienced accelerated mountain forest loss, while North America and Oceania were exceptions (He *et al.* 2023).

Mountain forests play a crucial role in maintaining soil health, stabilizing land often reducing effects of disasters, and regulating water and climate. Tree roots bind soil and break up compacted layers, reducing erosion and improving structure, while forest canopies and undergrowth act as natural barriers against wind and rainfall. Forests enhance water management by promoting infiltration and recharging groundwater. They also support nutrient cycling, improving soil fertility and long-term productivity. Forests can also mitigate climate change by sequestering carbon and create stable microclimates that protect soil from extreme temperatures and dryness, reducing the risk of land degradation.

At the global scale, including regions other than mountains, the presence of protected areas is an effective tool to reduce the forest loss. However, between 2000 and 2015 only 30 per cent of protected areas have prevented forest loss, and in 71 per cent of protected areas the forest loss was simply reduced (Yang *et al.* 2021). At the same time, resolving forest tenure rights in favour of local communities, especially women groups, and Indigenous Peoples shows much promise for protecting forests and advancing restoration in many areas if enabling conditions and improved governance can be put in place. Predictions show that if forest loss rates double outside protected areas, 20 per cent of them could lose over 5 per cent of their forest cover by 2036, with significant losses predicted in iconic mountain parks. This includes mountain areas, such as Khan Khentii Mountain national park in Mongolia losing 8.6 per cent or the Virunga National Park in the Congo basin potentially losing 7.9 per cent of forest cover (Burivalová *et al.* 2021).

Wildfires in mountains

Wildfires are a natural part of many ecosystems, helping maintain healthy forests and landscapes. However, climate change, along with shifts in population and land use, is altering wildfire patterns and risks. Fire seasons are becoming longer, starting earlier and lasting later, which increases the damage (UNEP 2022). Wildfires can threaten lives and livelihoods, disrupt local and national economies, and have lasting social and environmental impacts.

Beyond the immediate danger to human life, fires can cause health problems, destroy infrastructure such as power lines, roads, and water systems, and degrade key ecosystem services, including water supply, biodiversity, nutrition, and carbon storage. Wildfires can have major impacts on water security. Forests normally act like a sponge and filter, regulating the quantity and quality of water for downstream communities and aquatic ecosystems. After severe fires, this natural function is weakened. Fires also directly affect soil, altering its structure, moisture retention, and nutrient content, and reducing microbial life and seed banks (Agrawal *et al.* 2025; UNEP 2022). Water flows more quickly over bare, unstable soils, increasing erosion and the risk of flooding and landslides in mountainous regions.

Globally, satellite data show that total burned area declined between 2000 and 2013, largely due to human factors such as population distribution and land management, as well as climate conditions such as precipitation and temperature. Moderate emissions scenarios suggest that this decline may continue. However, under high-emissions scenarios, fire activity is expected to rise, particularly at high latitudes and in mountainous regions, where fires are spreading to higher elevations that were previously less fire-prone.

Warmer, drier conditions are lengthening fire seasons, and extreme fires are becoming more frequent in many regions (Jones *et al.* 2024). Strengthening understanding of wildfire behaviour and trends under a changing climate, along with targeted fuel management and improved fire monitoring, will be critical for protecting communities, ecosystems, and infrastructure from escalating wildfire risks (UNEP 2022).

Wildfire near Osoyoos Lake, British Columbia, Canada. Photo: Envato Elements/wirestock


Gorakshep, Sagarmatha National Park, Nepal. Photo: GRID-Arendal/Wenzel Prokosch

Land degradation and linkages with the lowlands

One of the by-products of desertification processes is the creation of fine particles of dust. While long-range transport of dust via high-atmospheric currents is a well-known phenomenon, accelerating desertification and degradation in many lowland areas have resulted in increased dust dispersion to mountain areas. Dust light enough to be carried by the wind can fall on the snow and ice layers, which reinforces a negative climate feedback loop whereby albedo is diminished increasing snow and glacial melt (Dong *et al.* 2020).

To ensure food security in mountain regions, sustainable land management must be implemented more widely. In many parts of the world, pastoralism, a traditional land management practice that benefits from indigenous knowledge, is often overlooked, which may contribute to rangeland degradation. As a result, rangelands have a reduced capacity to provide ecosystem goods and services, including supplying meat and dairy products to populations well beyond mountain areas.

Adapted management practices should be applied at local, national, and regional levels to support mountain livelihoods, maintain biodiversity, combat invasive species, and enhance carbon sequestration to reach countries land neutrality targets. Such practices include rotational grazing, livestock mobility, adaptive governance, and gender-inclusive approaches (UNCCD 2024). Mountain ecosystems are impacted by distant processes iincluding the global driver of urbanisation (IPBES 2019). The expansion of cities consumes nearby cropland, pushing agriculture into new areas, intensifying resource demand, and creating urban heat islands. This rising consumption also fuels the demand for materials, exacerbating challenges like plastics pollution. Climate migration from lowlands with warmer temperatures to mountain regions is expected to increase in the short term further pressuring mountain ecosystems.

Additional challenges in mountain regions are amongst others, mining activities which can destabilise slopes, damage fragile soils, and degrade water quality, increasing risks for local communities and downstream users. At the same time, population growth and expanding settlements place growing pressure on limited land, forests, and water resources, often pushing development into hazard-prone areas. These challenges are compounded by weak enforcement of land-use and environmental regulations, allowing unsustainable practices to persist and undermining long-term safety, ecosystem services, and water security.

Village near Nkuringo, Uganda. Photo: GRID-Arendal/Laurent Fouinat

Mountain futures for thriving mountain landscapes

Achieving land degradation neutrality in mountain regions requires preventing new degradation while restoring already degraded land through integrated, Ecosystem-based and people-centred approaches. Priority actions include protecting and restoring forests, grasslands, wetlands and alpine ecosystems to stabilize slopes, reduce erosion and maintain soil fertility. Sustainable land and soil management practices such as terracing, agroforestry, conservation agriculture and improved grazing management further promote healthy mountain landscapes. Applying ecosystem-based approaches is important to link land restoration with climate adaptation, water regulation and disaster risk reduction.

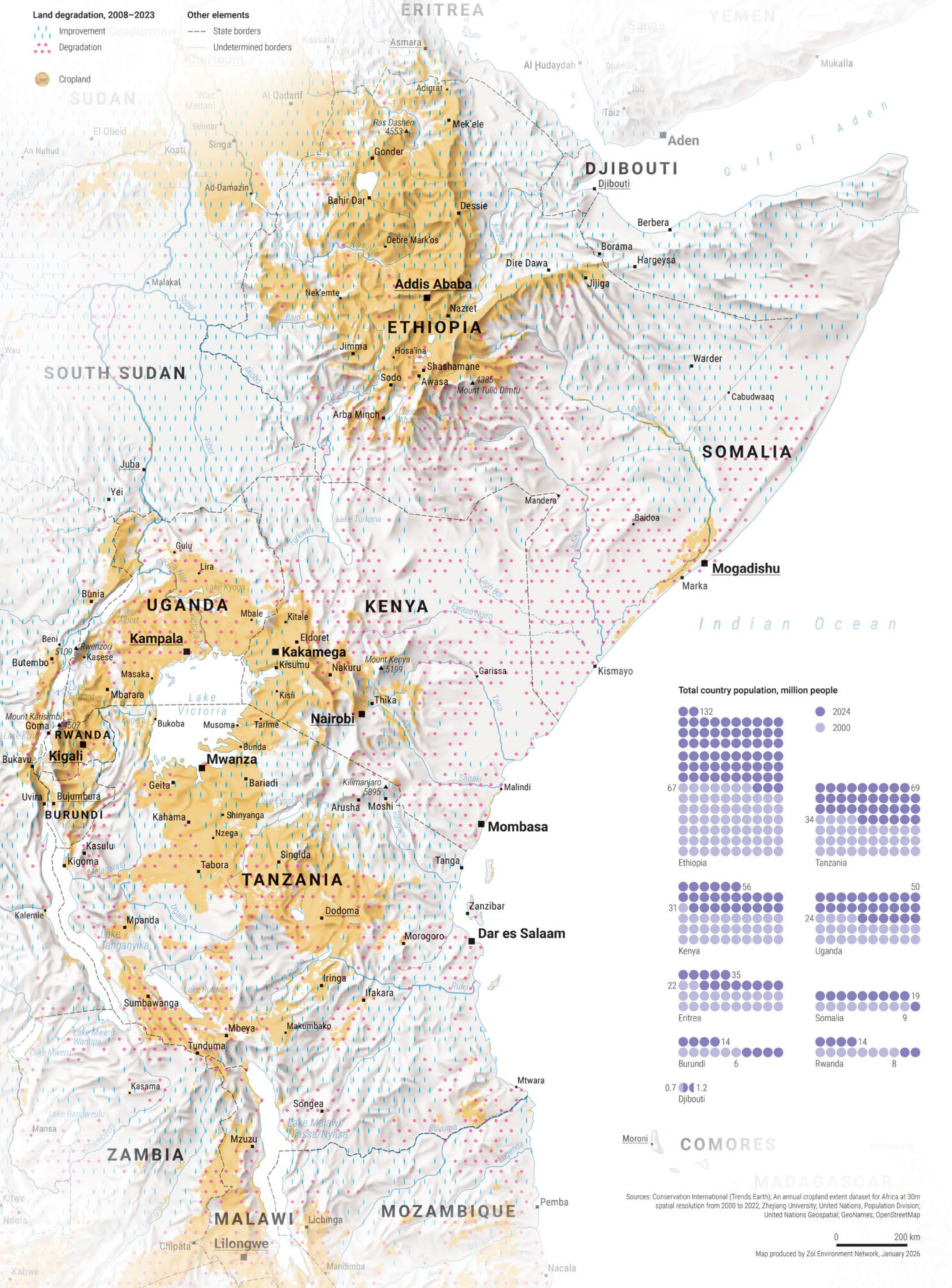
Empowering local communities, especially women, youth, and Indigenous Peoples, securing land tenure, and integrating traditional knowledge are essential to ensure long-term stewardship of fragile mountain landscapes. These actions must be embedded in national development, climate and biodiversity policies, supported by adequate financing and robust monitoring systems, to safeguard mountain ecosystems and the critical services they provide to billions of people downstream. Efforts should focus on supporting mountain populations and reducing their dependence on weather patterns for agriculture and drinking water, while promoting improved land management to mitigate degradation, erosion, and forest loss.

Women are often the primary managers of mountain resources and the main actors in agriculture which underlines the need for women's improved access to resources and productive assets, including land, economic and financial services.

Although protected areas play an important role in conserving forests, they alone are not sufficient. Stronger national strategies, developed in coordination with neighbouring countries, are needed to amplify impact and ensure more effective forest protection and management. Mountain ecosystem restoration should be a foundational pillar of national strategies, as it underpins the success of other solutions (FAO and UNEP 2023). To underpin these efforts, standardized assessment methods must be developed to consistently measure degradation and track progress.

Furthermore, fostering stakeholder collaboration is essential to negotiate trade-offs and create mosaic landscapes that serve multiple needs. This should be supported by robust, standardized monitoring and reporting systems to build an evidence base for scaling effective practices. Finally, actions such as harnessing scientific and technical innovation and integrating solutions like rotational grazing to reduce pressure of livestock on the landscape, with socio-economic approaches that respect local tenure and economies, ensures that restoration is both effective and equitable at a meaningful scale.

Land degradation in East Africa



Sources: Conservation International (Trends.Earth); An annual cropland extent dataset for Africa at 30m spatial resolution from 2000 to 2022, Zhejiang University; United Nations, Population Division; United Nations Geospatial; GeoNames; OpenStreetMap

Map produced by Zoï Environment Network, January 2026

Chapter 6: International environmental governance of mountains under the Rio Conventions

UNEP Conference, Nairobi. Photo: GRID-Arendal/Maria Dalby

Mountains and the triple planetary crisis

Scientific evidence shows that mountains are vulnerable to multiple environmental risks associated with climate change, water scarcity, pollution, biodiversity loss, and land degradation. The importance of mountains was first formally recognized internationally at the United Nations Conference on Environment and Development in 1992. Chapter 13 of the Agenda 21 Action Plan was dedicated to sustainable mountain development stressing the importance of mountain environments at global, regional and local levels; protecting natural resources including water; enhancing the livelihoods of communities and Indigenous Peoples; and promoting international cooperation on mountains.

Key developments since 2000 include the:

- *Establishment of the Mountain Partnership secretariat, a voluntary alliance established in 2002.*
- *Adoption of the Framework Convention on the Protection and Sustainable Development of the Carpathians (Carpathian Convention), which unites 7 Carpathian countries of Central and Eastern Europe (2003).*
- *Inclusion of mountains in the United Nations Sustainable Development Goals of the 2030 Agenda (Target 6 of SDG 6, Targets 1 and 4 of SDG 15), as well as a variety of initiatives, promoting sustainable mountain development.*
- *Intergovernmental Panel on Climate Change (IPCC) publications: Special Report on the Ocean and Cryosphere in a Changing Climate (2019), and the Working Group II Cross-Chapter Paper 5: Mountains of the Sixth Assessment Report (2022).*
- *Declaration of the International Year of Mountains 2022 (UNGA/RES/76/129) and Five Years of Action for the Development of Mountain Regions 2023-27 (UNGA/RES/77/172).*
- *Proclaiming the International Year of Glaciers' Preservation 2025 co-facilitated by the United Nations Educational, Scientific and Cultural Organization - UNESCO and World Meteorological Organization - WMO, (UNGA/RES/77/158)*
- *United Nations Environment Assembly 7 Resolution on the preservation of glaciers and the broader cryosphere, particularly in mountain regions in 2025 (UNEP/EA.7/Res.10).*

These efforts have significantly helped to raise awareness and increase knowledge about mountain ecosystems and communities as a global issue, their role, and to support sustainable management of natural resources, social, and economic development.

The conservation and sustainable development of mountain systems are essential for achieving commitments and global targets under all three Rio Conventions. Elevating the role of mountains in global climate and biodiversity agendas is essential to ensure these vital regions receive the attention and resources they urgently require. Embedding mountain-specific actions within national instruments, international policy frameworks and financial mechanisms helps countries meet global commitments, mobilises resources, and ensures that mountain conservation contributes measurably to global biodiversity and climate goals, while ensuring benefits that extend far beyond mountain borders.

Better understanding the challenges faced by mountain and associated ecosystems within the triple planetary crisis is an opportunity to develop joint and coordinated approaches for improved international environmental governance. By doing so, it can help generate positive spillover effects across economic sectors, social well-being, human security, and support progress toward achieving the 2030 Agenda.

Mainstreaming mountains in the Rio Conventions

The ‘Rio Conventions’ describe the three conventions which emerged from the United Nations Conference on Environment and Development, also known as the ‘Earth Summit’, held in Rio de Janeiro in 1992. They include the Convention on Biological Diversity (CBD), the United Nations Framework Convention on Climate Change (UNFCCC), and the United Nations Convention to Combat Desertification (UNCCD). After more than 30 years, mainstreaming of mountain ecosystems and communities remains relevant for major international environmental governance frameworks and for achieving sustainable development in mountain areas.

In 2022, the Conference of the Parties of the CBD adopted the Kunming-Montreal Global Biodiversity Framework (GBF), which has 23 action-oriented global targets calling to halt and reverse biodiversity loss before 2030. The agreed targets provide an overarching framework supporting the restoration, protection and sustainable use of terrestrial ecosystems, including mountains. There is also an ongoing initiative to revitalize the CBD Programme of Work on Mountain Biological Diversity to help implement the GBF in mountain regions and align activities.

The UNFCCC has led to the adoption of the Paris Agreement in 2015, which set the goal of holding the global temperature increase to well below 2°C, pursuing efforts to limit it to 1.5°C. Recently, momentum for mountain areas has accelerated in this regard. The first Global Stocktake (UNFCCC 2023) recognized the vulnerability of mountain regions and the need for stronger adaptation measures.

The same year saw the re-establishment of the like-minded negotiating group “Mountain Group”, officially comprised of Armenia, Kyrgyzstan and Tajikistan. At the sixtieth session of the Subsidiary Body for Scientific and Technological Advice (SBSTA 60), the Expert Dialogue on Mountains and Climate Change in 2024 brought together Parties, Indigenous Peoples, scientists, and regional platforms to share region-specific challenges and solutions.

The dialogue reinforced momentum generated by the Nairobi Work Programme, which introduced a thematic focus on mountains, high-latitude areas and the cryosphere in 2022 to strengthen knowledge-sharing and inform adaptation planning. The process recognises benefits of mountain conservation and restoration, the role of Ecosystem-based approaches in mountain regions for reducing climate change risks and providing multiple co-benefits, as well as urged to reduce climate impacts on mountain ecosystems. While the UNCCD's goal of land degradation neutrality (LDN) and the set of 19 principles governing its implementation process first introduced in 2012 do not specifically address mountains, the goal is directly relevant to these areas, as mountain slopes are particularly vulnerable to erosion and degradation.

Status of the mountain agenda under the Rio Conventions: Five case studies

To identify options for strengthening international environmental governance of mountains under the Rio Conventions, five case studies have been undertaken, organised by regions: Andes, Caucasus, Central Asia, East Africa, and Hindu Kush Himalaya.

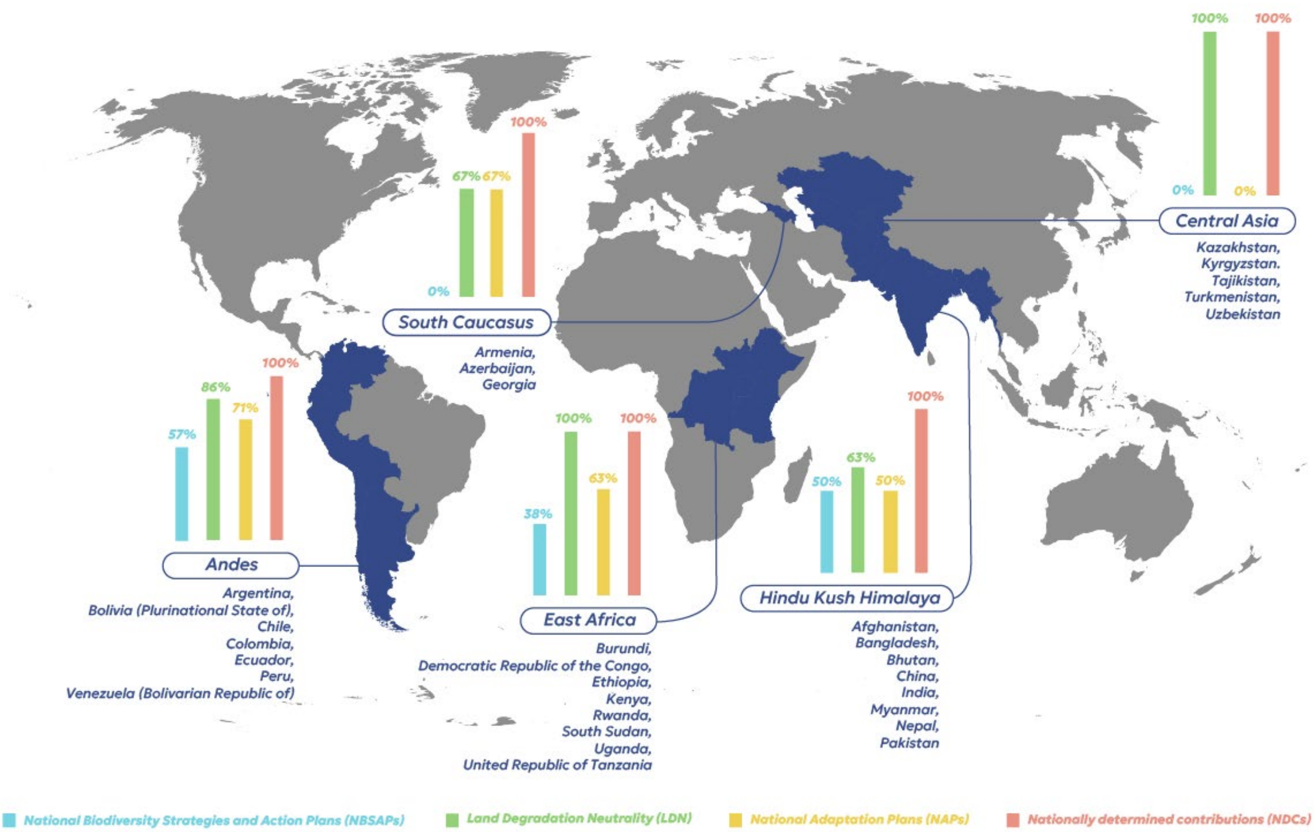
The regions were selected as they represent major mountain ranges in developing and middle-income countries. Each case study presents a status of national submissions under the Rio Conventions and mapping of the mountain agenda in national commitments and strategies. The reviewed documents include Nationally Determined Contributions (NDCs) and National Adaptation Plans (NAPs) under the UNFCCC, submissions defining Land Degradation Neutrality (LDN) targets under the UNCCD, and National Biodiversity Strategies and Action Plans (NBSAPs) under the CBD. These submissions communicate national commitments and strategies under the three Rio Conventions and provide details of the national implementation of the international frameworks.

The mapping shows a 100 per cent submission rate for NDCs in all regions, while NBSAPs have the lowest submission rates across all regions at the time of writing, reaching a maximum 57 per cent in the Andes region. One of the possible explanations is that the Kunming-Montreal Global Biodiversity Framework was adopted only in 2022, and countries are still in the process of formulating their NBSAPs.

Further analysis* identified the examples of commitments and strategies supporting the mountain agenda in countries' submissions. The examples of mountain-related goals, targets,

The analysis is based on 63 submitted documents from the selected countries that were available in English. These were examined using qualitative text analysis guided by the question: How do countries communicate strategies and commitments supporting the mountain agenda in national submissions under the 'Rio Conventions'? The key words used to identify the relevant strategies and commitments included 'mountain', 'mountains', and 'mountainous'.

Overview of submissions under the Rio Conventions (on 9 October 2025)



indicators, and measures were identified in all submissions NDCs, NAPs, LDN reports, and NBSAPs. This demonstrates that all three 'Rio Conventions' and their policy tools integrate mountain specific considerations.

The most compelling examples found in submissions are presented under three overarching categories:

1. Conservation and restoration of mountain ecosystems to enhance resilience and carbon sequestration

- Creation and expansion of specially protected natural areas (e.g. in Azerbaijan NAP)
- Protected areas coverage to reach 12 per cent, aligned with SDG 15.1. (Georgia LDN)
- Indicator for NBSAP Target 8, which aims to strengthen knowledge of climate–biodiversity linkages, enhance carbon sequestration, and reduce emissions: Number of research studies conducted on the impacts of climate change on mountain biodiversity (Bhutan NBSAP)
- Conservation of biodiversity and ecosystems including mountains, forests, watersheds (Ethiopia NAP)
- Target to protect and restore 10,000 ha of mountain ecosystems (Uganda NDC)
- Restore bare hills and protect mountainous areas (Uganda NBSAP)
- Protection and restoration of water-related ecosystems including mountains (Nepal LDN)

2. Integrating mountain ecosystems into climate adaptation strategies

- Mainstreaming of climate adaptation into mountain ecosystems services and policies; management of disaster risks caused by climate change for mountain ecosystems (Azerbaijan NAP)
- Climate change adaptation of the most vulnerable ecosystems including mountains (Georgia NDC)
- Mountain ecosystem conservation as an adaptation option (Ethiopia NAP)
- Investment in vulnerable ecosystems such as mountains to foster adaptation to climate change (Kenya NDC 3.0)
- Mountain ecosystems as a cross-cutting matter of adaptation within adaptation priorities and goals (Kyrgyzstan NDC 3.0)
- Four priority adaptation programmes on mountains (Nepal NAP)

3. Integrating mountain considerations into national policies and the 2030 Agenda for Sustainable Development

- Comprehensive management plan of 'mountain, river, forest, grassland, and lake' (China LDN)
- National Forest Policy Implementation Strategy (2021-2031) supports sustainable forest ecosystems management in particular the biodiversity hotspots in the Eastern Arc Mountains and coastal forests (United Republic of Tanzania NBSAP)
- Development plans for management of mountain ecosystems (Azerbaijan NAP)
- Aligning LDN target with SDG 15.1 (Georgia LDN)
- Aligning the LDN target with SDG 6 (Nepal LDN)

Several important environmental actions have been financed by multilateral donors such as the Global Environment Facility (GEF), Adaptation Fund (AF), and Green Climate Fund (GCF), yet access to climate finance remains uneven across mountain regions. The Hindu Kush Himalaya region has to date received by far the largest proportion of multilateral adaptation funding at 65 per cent (US$ 1.798 billion), followed by the Andes with 15 per cent (US$ 428 million), Central Asia with 11 per cent (US$ 300 million), and East Africa with 9 per cent (US$ 250 million).

Funding for mountain-specific projects mainly comes from multilateral climate funds, such as the GEF, the GCF, and the Least Developed Countries Fund, while broader adaptation funding is largely provided through bilateral aid (Zoi Environment Network 2023).

Mountain futures for strengthening international environmental governance of mountains

While the case studies demonstrate that countries recognize the importance of mountain ecosystems and communities in safeguarding these environments, further efforts are needed to integrate upstream considerations systematically into national strategies and commitments. Recent conceptualisation of the triple planetary crisis, as well as a common platform for the Rio Conventions provides a framework to address climate change, biodiversity loss, pollution and land degradation, in a coordinated manner.

Pollution in mountain areas can be addressed effectively through coordination with existing multilateral environmental agreements focused on chemicals and waste. New mechanisms such as the Intergovernmental Panel on Chemicals, Waste and Pollution provide additional opportunities to address clean mountain environments. These considerations set the stage for strengthening international environmental governance of mountains and translating global commitments into practical, regionally adapted, actions.

Coordination across conventions and national reporting

Effective international and regional environmental governance of mountains requires improved coordination for national implementation of multilateral environmental agreements and other relevant instruments. Joint monitoring, reporting, and evaluation across the Rio Conventions can track progress on mountain ecosystems, identify gaps and needs, and maximise the impact of national efforts.

The need to reduce reporting burdens and build on synergies was also recognized in recent CBD and UNFCCC COP decisions. Integrating these synergies into NAPs, NBSAPs, and LDN targets can align national commitments, goals, and targets, avoiding fragmentation and increasing consistency in addressing environmental issues in mountainous areas. International governance of mountains should prioritize the efficient use of scarce resources, while adopting climate-nexus approaches that emphasize the interconnectedness of climate, biodiversity, water, land, and human systems, thereby maximizing implementation synergies across the Rio Conventions.

Developing and strengthening existing regional programmes, initiatives and mechanisms

Regional integrated programmes offer an important mechanism for translating international commitments, such as those under the GBF or Paris Agreement, into tailored actions that support buy-in from decision-makers. By focusing on building resilience in mountain ecosystems and communities, such programmes can integrate local knowledge, address transboundary risks, and provide solutions adapted to regional contexts.

Prominent examples include the Carpathian Convention Biodiversity Framework, the EAC Climate Change Policy, the Greater Virunga Transboundary Collaboration, Andean Mountain Initiative, and Alpine Convention Climate Action Plan 2.0 to name a few.

Improving access for national and local stakeholders to climate and innovative finance including dedicated support for nexus approaches

Large multilateral funds such as the AF, GCF and GEF need to follow the developments and decisions under the respective Rio Conventions to mainstream issues and themes of addressing environmental challenges in mountain ecosystems and communities in respective programming and funding decisions. The adaptation funding gap is estimated to rise to 365 billion US$ in 2035 (UNEP 2025), which includes substantial investments needs in fragile mountain areas.

For Indigenous Peoples and Local Communities, more accessible funding mechanisms such as small grants provide important opportunities and avenues for resilience and environmental action in mountains. Looking ahead, more innovative and diversified sources of finance, including public-private partnerships, tourism levies, philanthropy, and community funds, should be mobilized to address the environmental challenges facing mountain communities.

Additional opportunities for resource mobilization lie in bioeconomy, biodiversity credits and payments for ecosystem services. The UNEP Finance Initiative brings together banks, insurers and investors to catalyse action in support of the much-needed transformational actions and nexus approaches.

Conclusions: Motion for change

Mountains are vital planetary life-support systems inextricably linked to global stability, sustainability, and human well-being, not isolated realms. As this linkages report demonstrates, the impacts of climate change, biodiversity loss, land degradation, and pollution are interlinked and cascading and they do not respect national and geographic boundaries. The cryosphere's decline dictates water security for billions downstream, while the loss of mountain biodiversity undermines ecological resilience across continents. Pollution affects the health of people, plants and animals, whereas measures to tackle land degradation carry important livelihood, nature and carbon sequestration co-benefits.

Accelerated action on sustainable mountain futures is essential because climate change, land degradation and rapid socio-economic change are already pushing natural and human systems close to their adaptive limits, a situation that would be exacerbated under a middle of the road climate scenario and potentially catastrophic in a high-emissions pathway. In such scenarios, rising temperatures, accelerated glacier loss, water scarcity, extreme events and ecosystem collapse may exceed the capacity of ecosystems and communities to adapt incrementally, undermining livelihoods, food and water security, and long-term development gains.

Adaptation in mountains is therefore not only a technical challenge but a transformative one: it requires deep cultural, socio-economic and institutional change, including shifts in land-use practices, livelihood strategies, governance arrangements and risk management systems. These transformations take time, sustained investment and strong institutions, and delays in action will increase costs, reduce options and heighten the risk of irreversible losses and damages for mountain populations and downstream societies alike.

Investing in the protection and sustainable management of mountain ecosystems and strengthening the resilience of Indigenous Peoples and Local Communities is therefore not merely a local, national, or regional concern, but a strategic global imperative. These investments generate amplified returns by safeguarding the critical ecosystem services that underpin whole economies and societies.

Water Security: Mountains provide freshwater to more than 60 per cent of people on Earth. Protecting the watersheds through forest conservation, waste management, restoration and sustainable land-use is fundamental for agriculture, industry, energy and cities far beyond the peaks and valleys themselves. Climate Resilience: Mountain ecosystems act as carbon sinks, regulators of local weather and unique refugia for biodiversity. At the same time, they are sensitive to climate risks and disasters. Their conservation is a powerful Nature-based Solution for climate mitigation and adaptation, helping to buffer surrounding regions against extreme weather events and climatic shifts.

Climate Resilience: Mountain ecosystems act as carbon sinks, regulators of local weather and unique refugia for biodiversity. At the same time, they are sensitive to climate risks and disasters. Their conservation is a powerful Nature-based Solution for climate mitigation and adaptation, helping to buffer surrounding regions against extreme weather events and climatic shifts.

Regional Stability and Cooperation: The transboundary nature of mountain resources, particularly water, presents a powerful opportunity for cooperation. The Rio Convention framework provides a basis for countries to consider how they can contribute to global goals while addressing regional priorities. By ensuring stable water supplies, sustaining livelihoods, and fostering dialogue, collaborative mountain governance can build trust and reduce the potential for conflict between nations that share these vital basins. This makes mountains critical landscapes for building long-term resilience, cooperation, and regional stability.

Sagarmatha National Park, Nepal. Photo: GRID-Arendal/ Peter Prokosch

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