Chapter 2

Mountain biodiversity under change

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Mountains worldwide, as defined by their ruggedness, height, and climate, share an important biological characteristic: they are cradles and sanctuaries of the world's biodiversity (Rahbek et al., 2019). They are home to an approximate one-third of terrestrial species diversity (Körner, 2004) and encompass around half of the 34 world's "biodiversity hotspots" (Chape et al., 2008)—areas of particularly rich, unique, and often threatened biodiversity—and 30% of its so-called key biodiversity areas—areas that significantly contribute to the global persistence of biodiversity (Fig. 2.1, UNEP, GRID-Arendal, GMBA, & MRI, 2020). Mountains around the world are known for their high levels of endemism (Körner, 2004; Noroozi et al., 2018) and they are the origin of many crop species farmed and consumed all around the globe (Brush, 1998). For example, about 5000 varieties of wild Arabica coffee (*Coffea arabica*) are growing in the southern Ethiopian Afromontane cloud forests (Price et al., 2011), and an immense diversity of potato, quinoa, and Phaseolus-bean cultivars, as well as the ancestor of corn (Teosinte), originate from South- and Central-American mountains.

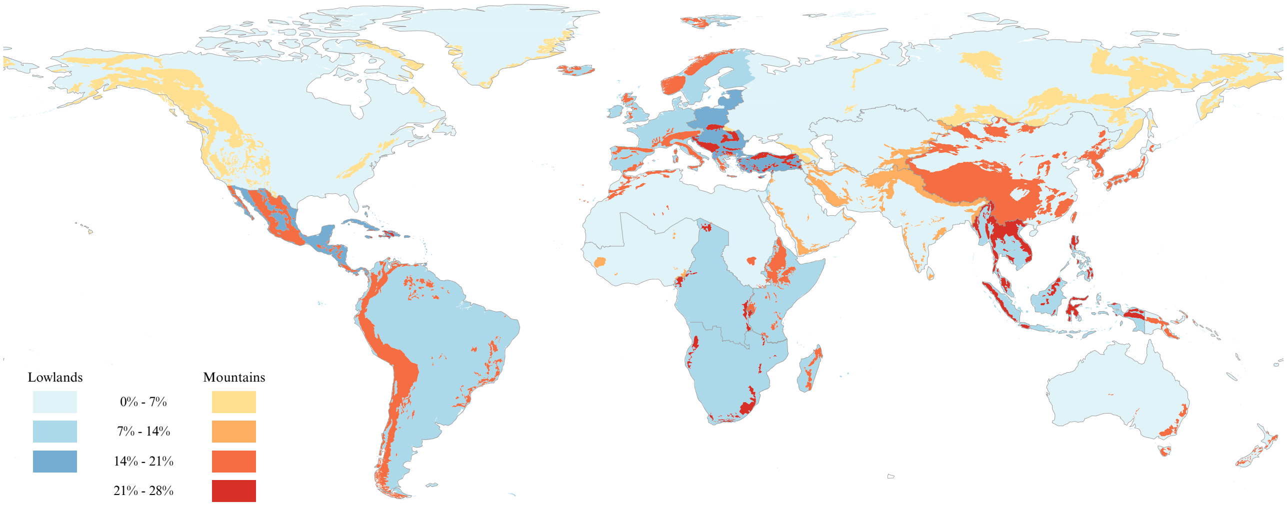

FIGURE 2.1 This map shows the percentage of land area covered by terrestrial key biological areas (KBAs) in mountainous (*orange-red colors*) and non-mountainous (*blue colors*) regions. For nonmountainous regions, the percentage coverage is calculated for the 16 IPBES subregions (IPBES, 2015, 2018). For mountainous regions, percentage coverage is calculated for each mountain range included in the latest release of the GMBA mountain inventory. *Credit and Copyright: Map by Mark Snethlage and Jonas Geschke, GMBA (2020), first published in UNEP, GRID-Arendal, GMBA, & MRI. (2020). Elevating mountains in the post-2020 Global Biodiversity Framework 2.0. https://www.gmba.unibe.ch/unibe/portal/microsites/micro_gmba/content/e426548/e426554/e935475/e935488/Post-2020_Agenda_Elevating_Mountains.pdf.; ArcGis Countries WGS84 (2015). Available at: https://hub.arcgis.com/datasets/a21fdb46d23e4ef896f31475217cbb08-1. BirdLife International (2019). Digital boundaries of Key Biodiversity Areas from the World Database of Key Biodiversity Areas. Developed by the KBA Partnership: BirdLife International, International Union for the Conservation of Nature, American Bird Conservancy, Amphibian Survival Alliance, Conservation International, Critical Ecosystem Partnership Fund, Global Environment Facility, Global Wildlife Conservation, NatureServe, Rainforest Trust, Royal Society for the Protection of Birds, Wildlife Conservation Society and World Wildlife Fund. September 2019 Version. Available at: http://www.keybiodiversityareas.org/.*

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Mountain biodiversity under global change

The present-day distribution of mountain species and their high diversity and endemism constitute a snapshot in time (Payne, Hoorn, et al., 2020) that holds the memory of millions of years of changes (Antonelli et al., 2018; Flantua et al., 2020; Hoorn et al., 2013; Muellner-Riehl et al., 2019). The most important drivers of diversification are elevational gradients, the associated rapid change in climatic conditions over short distances, and pronounced contrasts in life conditions due to topography (Körner, 2004; Körner, 2021a; Scherrer & Körner, 2011). Yet in recent history, it is primarily direct human action that has shaped mountain landscapes worldwide (Körner & Ohsawa, 2005; Payne, Hoorn, et al., 2020, Payne, Snethlage, et al., 2020; Spehn et al., 2006). Actions and drivers include overexploitation of natural resources, pollution (e.g., by reactive nitrogen), the introduction of nonnative species, and changing land use practices. Humans have traditionally converted pristine montane forests into pastures and hay meadows, thereby creating many stable and highly diverse "cultural agricultural landscapes" (for the European Alps see Bätzing, 2015). Yet, over the course of thousands of years in certain cases (Noroozi & Körner, 2018) and very recently in others (see Payne, Snethlage, et al., 2020), land use has become destructive, livestock farming increasingly unsustainable, and the impacts of touristic or hydro-technological infrastructures increasingly severe. The abandonment of sustainable land use practices have had particularly profound consequences, including the loss of diverse and multifunctional cultural landscapes (e.g., Hiltbrunner et al., 2014; Körner & Spehn, 2002; Payne, Snethlage, et al., 2020; Spehn et al., 2006; Tasser et al., 2017).

At a global scale, warming—with its associated effects on glaciers (Hock et al., 2020) and snow (Hock et al., 2020; Notarnicola, 2020), altered precipitation regimes, and an increase in extreme events such as flooding and droughts, add to the already existing tensions created by the mismanagement of land. Noteworthy, mountains of Europe and North America experienced an episode of warming by approximately 2 K only a few thousand years ago. During this so-called Atlanticum epoch, the elevation of the treeline in these regions was 200−250 m higher than today (Tinner & Lotter, 2006; see summary in Körner, 2012, 2021a) and glaciers almost vanished, with no obvious lasting impact on biodiversity. A novel 200 m shift of the treeline and further glacier losses will cause land cover shifts: the predicted glacier melting would open 126,000 km^2 of new land for alpine life, yet, approximately 1.4 million km^2 of current naturally treeless, alpine terrain would become upper montane forest (Körner, 2021a). Hydrological consequences in water-limited forelands would be severe and add to the locally important consequences of reduced snow cover duration in mountain regions such as the Alps and the Rocky Mountains (Vorkauf, Marty, et al., 2021; Vorkauf, Kahmen et al., 2021). In contrast, land abandonment caused species-rich pastures to convert into monotonic shrubland within 40 years, also preventing the return of montane forests (Hiltbrunner et al., 2014), and man-lit and drought-enhanced fires destroyed much upper montane forests worldwide (e.g., Mount Kilimanjaro; Hemp, 2005).

Demographic and economic growth, the progressive integration of individual mountain regions into globalized markets, and limited environmental education and political awareness all accelerate the already ongoing changes (e.g., Payne, Snethlage, et al., 2020).

Across the world's mountains, global warming has caused an upslope shift in various species including large mammal (Büntgen et al., 2017), plant, bird, and butterfly species (e.g., Pauli et al., 2012; Roth et al., 2014; Rumpf et al., 2019; Steinbauer et al., 2018). Since soils cannot track them, these shifts can cause species to experience soil conditions that do not correspond to their specific preferences. Yet, extinctions that can be strictly associated with climatic change have so far not been reported (Körner & Hiltbrunner, 2021). Climate-related shifts in abundance may result in local species' disappearance in mountain regions that are small and not high enough. Upslope shifts of the treeline position, in turn, are an inevitable consequence of climatic warming, but it is often hard to separate advances due to land use abandonment from those related to climate (Körner, 2021b). Additional changes in mountain ecosystems include "greening" (Carlson et al., 2017; Filippa et al., 2019; Rumpf et al., 2022) and shrub encroachment, which are both commonly associated with a reduction in biodiversity (Payne, Snethlage, et al., 2020). At the individual species level, changes in phenology such as earlier-than-average budburst in alpine plant taxa increase the risk of desynchronized organismic interactions and of exposure to late frost events, although high freezing tolerance and clonal growth might serve as effective buffers against major damage (Körner, 2021a; Möhl et al., 2022; Vorkauf et al., 2021). Yet, the most critical impacts of global change are those affecting soils. Given that soils take thousands of years to develop, their degradation and gradual erosion represents an ultimate ecosystem collapse with no option for repair (Körner, 2021a).

Mountain biodiversity and human well-being

Mountain biodiversity supports numerous ecosystem functions and underpins many of the services that mountain ecosystems provide (Grêt-Regamey et al., 2012; Larigauderie et al., 2012; Martın-López et al., 2019; Payne, Snethlage, et al., 2020).

At local scale, mountain species are commonly indispensable (Obrecht et al., 2021; Payne, Spehn, et al., 2020) as a source of building materials, energy, medicinal products, and food as well as for securing infrastructures through slope stabilization. On Mount Kilimanjaro, for example, inhabitants mostly depend on species-rich mountain forests for the supply of fuelwood and medicine (Bär et al., 2017). By stabilizing soils and covering the ground, a high diversity of mountain species and diverse land cover types further contribute to protecting watersheds and are thereby critical for securing the clean water on which people depend for private, agricultural, and industrial consumption. For example, most of the water needed for the more than 1.5 million inhabitants of Quito in Ecuador comes from the mountainous Condor Bioreserve (Bovarnick et al., 2010; Ziegelmayer et al., 2004), the Uluguru mountains are essential in supplying water to Tanzania's fast-growing capital Dar es Salaam (Encalada et al., 2019), and Mount Kilimanjaro is the primary source of water for the 42,200 km^2 large Pangani river basin (Hemp, 2005; Sébastien, 2010). Yet, ongoing land cover changes threaten the ability of mountain ecosystems and their biodiversity to serve as the fabric of millions of peoples' lives and affect human populations at all elevations and worldwide. For example, over the last 50 years, land conversion in the Western Andes has decreased the landscape's overall capacity to fulfill essential ecosystem functions by approximately 16% (Balthazar et al., 2015).

Mitigation

Mountain ecosystems require particular protection (UNEP, GRID-Arendal, GMBA, & MRI, 2020), not the least given how important their intactness is for the safety of people down their slopes. Nowhere else do people and their infrastructures depend more on erosion control than in steep terrain. Moreover, because of their steep climatic gradients and their topographic diversity, hardly any other terrestrial ecosystem occurs on earth where as much terrestrial biodiversity (i.e., species and intrasepcific genetic diversity) can be protected per unit area as in mountains. Yet, despite the importance of intact mountain biodiversity as a pillar of sustainable development and the teleconnection between mountains and commonly densely populated forelands (Körner & Ohsawa, 2005; Obrecht et al., 2021; Secretariat of the Convention on Biological Diversity CBD, 2018), mountain ecosystems are still largely underprotected and we are not on track to achieve the 2030 goal set out in the United Nations Agenda 2030 of "ensuring the conservation of mountain ecosystems, including their biodiversity" (Ly et al., 2023). Mountain-specific indicators have to be defined for relevant goals and targets of the Kunming-Montreal Global Biodiversity Framework of the Convention of Biological Diversity (see UNEP, Grid-Arendal, GMBA & MRI, 2021) to galvanize efforts across nations and governments (Díaz et al., 2020) to protect mountains and restore their ecosystems—in particular the commonly most affected montane belt (montane forests or intact substitute agro-ecosystems). In that context, the conservation of mountain soils and of the diversity of taxa required to ensure ecosystem integrity in steep terrains is key.

Comparative mountain research has repeatedly been challenged by the existence of various mountain definitions (Körner et al., 2021; Körner and Urbach, in Box 1.1) and a lack of consensus among mountain scientists regarding what belongs to mountains and their forelands. The Global Mountain Biodiversity Assessment (GMBA, https://www.gmba.unibe.ch) addressed this challenge by providing a standardized (Körner et al., 2017; https://ilias.unibe.ch/goto_ilias3_unibe_cat_1000515.html, https://doi.org/10.7892/boris.106896) and a hierarchical (Snethlage et al., 2022; https://earthenv.org/mountains; https://doi.org/10.48601/earthenv-t9k2-1407) inventory of the world's mountains for comparative research. The adoption of such a tool does not prevent the use of individual definitions when appropriate and based on a clear understanding of what these definitions mean and imply, but it serves as a baseline layer of named mountain units that can be cropped to clearly defined and justified boundaries. When used together with a relevant mountain definition and the bio-climatological characterization of life conditions in mountains developed by GMBA (Körner et al., 2011, 2017), these data make it possible to identify the climatic conditions under which people are currently living in mountains, and to develop scenarios for the future. As a platform for international and cross-disciplinary mountain biodiversity science, the GMBA network further plays an instrumental role in catalyzing mountain biodiversity research through topical working groups, synthesis publications, and topical events, in promoting access to mountain biodiversity data through data and information portals such as the Mountain Portal, and in facilitating the science-policy dialog.

Conclusion

The importance of mountain biodiversity for the security and well-being of people living in and near mountains is enormous. A high diversity of plant functional traits serves as an insurance against slope erosion and a high diversity of species underpins ecosystem functions and services, economic, esthetic, ethical, and cultural values, and thus human well-being. Therefore upslope biodiversity is essential for life in mountains, but unsustainable land use practices have already severely degraded the montane belt and are exerting high pressures on all mountain ecosystems. Given the overproportioned biological richness of intact mountain ecosystems and their vital role for human life, their conservation and sustainable management needs to be a societal and political priority.

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