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Opportunities for research on mountain biodiversity under global change

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Mountains worldwide host very rich biodiversity, are home to hundreds of millions of people, and provide billions of upland and lowland inhabitants with vital ecosystem services. By altering mountain ecosystems and their biodiversity, global change modifies this picture substantially. We concisely review current knowledge and knowledge gaps on mountain biodiversity, ecosystem services, and human well-being under global change. We argue that our ability to understand, predict, and sustainably manage mountain biodiversity and to support human well-being requires concerted research efforts in natural and social sciences and comparative analyses of biological and social–ecological systems within and across mountain ranges. Specific examples illustrate how the Global Mountain Biodiversity Assessment will continue to support these efforts in the future.

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Introduction

Because of their global occurrence across all latitudes [1••] (Figure 1) and the steep, small-scale environmental and climatic gradients characterizing them, mountains offer unique 'experiments by nature' for studying the mechanisms driving the evolution and maintenance of biodiversity and ecosystem functions in a changing world [2]. Yet, mountains are not only storehouses of biodiversity and intriguing study systems for natural scientists. Mountains and their biodiversity also serve as water suppliers and climate regulators [3], and support hundreds of millions of livelihoods locally (0.5–1.2 billion people in mountains only [1••,4]), and an even higher number in adjacent lowlands and urban areas, with vital ecosystem services [5]. Moreover, mountains around the world harbour an extremely rich ethnic and cultural diversity and are home to both extremely poor and marginalized inhabitants as well as to communities achieving high levels of life quality [6,7]. Mountains therefore offer complex and fascinating study systems for social sciences and take a prominent position in international science and policy agendas [4,6,8].

In recent years, natural and social scientists have increasingly participated in common initiatives [9] (e.g. Global Network of Mountain Observatories, G.N.O.M.O) and conferences (e.g. Perth III: Mountains of Our Future Earth) to work toward a holistic understanding of mountain systems. Accordingly, within the mountain research community, biases in thematic coverages toward natural sciences tend to decrease [10]. Yet, numerous opportunities still exist for interdisciplinary research on the socio-economic role of mountain biodiversity in a changing world and on the importance of biodiversity in achieving the United Nations' sustainability agenda in mountain regions.

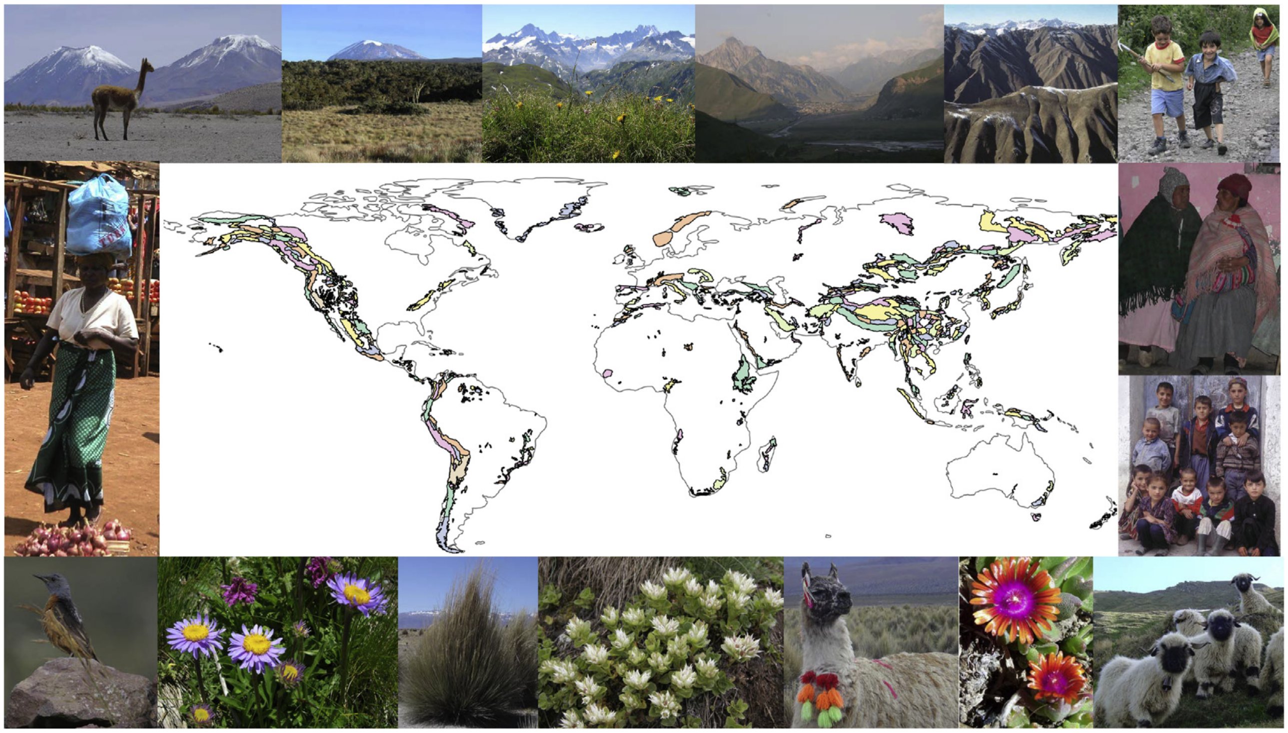
Here we concisely review the state of knowledge on mountain biodiversity, ecosystem services, and human well-being in the light of global change. We then identify open research questions and outline future activities of the Global Mountain Biodiversity Assessment (GMBA)[1] in its role as a platform to foster international and cross-disciplinary collaboration on the assessment, conservation, and sustainable use of mountain biodiversity.

Global change in mountains

Climate change, land-use change, pollution, overexploitation, and alien invasive species are considered the most important drivers of biodiversity change [7]. Indications of climate change in mountains include increases in

[1] GMBA was formerly a DIVERSITAS project and is now a Future Earth global research project.

Figure 1



The >1000 mountain ranges of the world (central map [1••]) vary in their biophysical, geomorphological, socioeconomic, cultural, and political characteristics and in the extraordinary floristic and faunistic diversity they host. For their individuality and their worldwide distribution, mountains offer unique study systems for unravelling the tight relationship between biodiversity and human well-being. Top (left to right): mountains in Bolivia, Tanzania, Switzerland, Georgia, and Central Asia; right (top down) and left: mountain inhabitants of Georgia, Bolivia, Pamir, and Tanzania; bottom (left to right): mountain biodiversity of Georgia, Switzerland (incl. sheep), Bolivia (incl. lama), Tanzania, and South Africa. Pictures from V. Ralph Clark, Erika Hiltbrunner, Christian Körner, Eva Spehn, and Niklaus Zbinden.

temperatures above global averages (e.g. 0.5–0.7 °C per decade in the Alps [11] and the Colombian Andean Central mountain range [12]), changes in precipitation patterns (e.g. less in the summer and more in the winter in the Alps [11], more unusually heavy rainfalls in the Andes [12]), decreases in snow cover duration, changes in cloudiness and relative humidity, and the melting of glaciers [11,13]. Land-use changes include an increase in the intensity of land use and concomitant overexploitation (e.g. in (sub)tropical mountain ranges [14] and temperate mountain grasslands at and above the treeline [15]), a decrease in the intensity of land use accompanied by land abandonment and emigration (e.g. in temperate mountains [16]), and a higher likelihood of farmland abandonment in mountainous than in non-mountainous regions across the world [17]. Levels of pollution in mountains, including rates of nitrogen (N) deposition, are largely unknown (but see [18] for N deposition in the southern Rocky mountains). Occurrences of biological invasion are currently considered to be limited at the highest elevations [19] but observations of rapid upwards spread of non-native species in the Alps highlight that invasions into native alpine communities are likely to represent a growing pressure [20]. Evidence for the impacts of land-use change on climate (e.g. decreased cloud occurrence and precipitation with increasing deforestation at Mt Kilimanjaro [21]) suggests that coupled models will likely reveal additional interactions between global change drivers in mountains.

Beyond warming, detailed information about temporal changes in climate exists only for a subset of indicators and mountain ranges worldwide (e.g. European Alps [11], Sierra Nevada (Spain) [22], Rocky Mountains [23], Sierra Nevada (United States), see G.N.O.M.O), notably because of the general paucity of high-elevation observation stations. Accordingly, extrapolating climate patterns across scales and over time is difficult [24,25]. Remote sensing offers promising new approaches to obtain data [26], and emphasis on the validation of these data for high-elevation regions will greatly improve their robustness and usability for the modelling of trends and risks, and for the prediction of climate-induced changes in mountain biodiversity, ecosystem services, and human well-being. Additionally, targeted efforts to tackle the trade-offs between the spatial and temporal resolution at which remote sensing data are collected (i.e. high resolution at very local scale and dense time intervals versus lower resolution at large spatial, but also temporal scale) and to fill data gaps with new missions (e.g. within the Copernicus Earth Observation Programme) will reduce measurement errors and uncertainties in the models for which these data are used. Both additional data and improved models will contribute to a better understanding of the complex and profound effects of, and interactions between, climatic variables [27], microclimate [28], changes in land cover and land use [29], N deposition [18,30], and biological invasions in mountains.

Mountain biodiversity

A comprehensive biological inventory of the world's mountains does not exist. Available data, mostly on plants, suggest that mountains support high (endemic) species numbers and half of all global biodiversity hotspots [2,31]. About 4% of all flowering plants are found in the alpine belt alone, which covers only 2.6% of the terrestrial land area outside of Antarctica [2]. Complex patterns of taxonomic diversity along altitudinal gradients are driven by combinations of biotic, abiotic, topographic, ecological (e.g. facilitative interactions), and evolutionary factors and processes [32••,33•,34]. Direct responses of high-elevation species to climate change detected in monitoring and resampling studies include an upward migration of subalpine and lower alpine species into ecologically suitable habitats [35], which leads to transient increases in diversity at higher altitude [36]; changes in vegetation structure and composition toward thermophilization [37] and homogenization [38]; and shifts toward earlier phenologies [39]. Effects of land-use changes and pollution include a decrease in diversity with land abandonment followed by forest regrowth below the treeline [40] and with increasing N deposition [18,30]. Effects of global change derived from computational simulations and species distribution models include upward migration of native and invasive species [41]; losses of habitat, range, and genetic diversity [27,42]; decreasing population size and constrained evolutionary responses [43••]; and changes in biotic interactions [39]. However, varying responses, notably to temperature increases, across taxa [44••], communities [45], and mountain ranges [46] illustrate that patterns are by no means general. Moreover, it has been argued that the high geological and topographical diversity of mountains and the resulting small-scale heterogeneity have so far buffered mountain organisms against climate change effects and are of great value for the conservation of mountain ecosystems [28].

Research on distribution and richness patterns in mountains and on the effects of global change is plentiful. Yet, overcoming current biases toward terrestrial ecosystems, vascular plants [47,48], and single-taxa studies (but see [44••,46]) and considering all — including rare — taxa [49,50] is necessary for achieving a better mapping of global mountain biodiversity, a better understanding of both the interactions between species and ecosystem types and the relationships between biodiversity and ecosystem services, and a better-informed prioritization in conservation. With the online mountain portal (www.mountainbiodiversity.org), GMBA supports the collation of data from all taxonomic groups (including largely understudied species such as fungi [51•] and soil microorganisms [52]), and all ecosystems types (e.g. alpine streams [53]). Additionally, increasing the number of monitoring programs specifically designed to answer well-defined research questions [54] and inform both local-scale and global-scale models and scenarios will contribute to a more accurate assessment of the simultaneous impact of multiple global change drivers on mountain biodiversity and ecosystems at various spatial and temporal scales (e.g. [55•]). GMBA sees its primary role in the long-term ecological research and monitoring community as a catalyst in the formulation of tractable questions in mountain biodiversity and global change research, and in the establishment of scientifically robust monitoring and research programs. These programs should enable the detection, documentation, and understanding of global change impacts on various facets of mountain biodiversity and ecosystems at local and global scale. Finally, both additional work on genetic, phylogenetic, as well as intraspecies and interspecies functional diversity (e.g. [56,57•,58]) and the application of eco-evolutionary (e.g. [43••]) as well as modern community ecology theories (e.g. network or metacommunity theory [32••]) will serve to improve our understanding of the mechanisms governing the historic evolution of biodiversity patterns and our ability to predict the response of species, communities, and ecosystems to drivers of global change. By bringing together different communities of research and practice to work on common questions, GMBA strives to promote added-value between fields of expertise.

Ecosystem services

Because of their topography, climate, and biodiversity, mountains support a variety of ecosystem services that contribute substantially to lowland and upland economies and livelihoods [5]. These include the provision of food, feed, fibre, and water, the regulation of natural hazards, carbon sequestration, pest and disease control, pollination, and the support of cultural identity [59,60]. Yet, the capacity of mountain ecosystems to provide such key services is at risk: climate-mediated and socio-economically driven land-use changes have already influenced the provisioning of ecosystem services and impacted human populations at all elevations (e.g. [59–62]). For example, land conversion in the Western Andean Range caused a 16% decrease in the overall capacity of the landscape to deliver ecosystem services over 50 years [63] and declining groundwater in the mountains of Oman has led to water shortages for domestic supply [59]. Effects on the provision of ecosystem services of climate change alone [64,65] or in combination with land-use change [66•] are well-illustrated by recent results from trait-based and other models (e.g. forest dynamics [65]). The future provision of ecosystem services requires mountain ecosystems to cope with global change, which in turn depends on the maintenance of ecosystem functions provided by communities of species [66], and ultimately on the intactness of biodiversity [67]. From the perspective of socio-economic and political sciences, it requires alternative policies and governance structures for mitigating impacts and enhancing sustainable management practices [68].

The challenges associated with performing field experiments in slow-growing mountain ecosystems, and especially in remote or difficult terrain, are obvious and not easy to overcome. Accordingly, research on the biological importance of various facets of biodiversity — including taxonomic, functional, and phylogenetic diversity — for ecosystem functioning and services in mountains progresses slowly. Empirical evidence is needed to show that general results on biodiversity-ecosystem services relations collected in different ecosystems [69] and on many taxa [49,50] apply to mountain ecosystems as well. As the supply of, and demand for, ecosystem services result from an interplay between social and ecological systems [70••], strengthened collaborations across the fields of biological and social sciences and an integration of the socio-economic and ecological perspectives are indispensable. The difficulties associated with different theories, conceptual backgrounds, and types as well as amounts of available data are numerous but methods such as generalized models appear promising for the quantitative study of social–ecological systems (e.g. [71]). In its function as a platform for interdisciplinary and transdisciplinary science, GMBA is dedicated to facilitating integrated studies on pathways to sustainable development that warrant the necessary provision of ecosystem services, are economically and ecologically efficient, socially acceptable, and politically feasible.

Human well-being

Biodiversity supports human well-being in many ways [7], either directly through enhanced ecosystem functions and services or indirectly by increasing the resilience of such functions to global change [72]. Yet, the importance of biodiversity for human well-being is often merely implied, even though explicitly formulating and quantifying this relationship is key to concomitantly achieving the United Nations Sustainable Development Goals (SDGs; [70••,73••]) and several of the Strategic Goals of the Convention on Biological Diversity. Given the diversity of vital ecosystem services mountains provide to human populations, most notably drinking water, food and feed [5], timber, non-timber forest products, medicinal plants, wild crop relatives [70••], and the stability of slopes [2], the value of mountains and their ecosystems for human well-being is immense [74]. Yet because of a scarcity of policy-relevant knowledge and often as-yet unarticulated policy needs, sustainable mountain development remains a challenge [6].

The vulnerability of mountain people to food insecurity has been assessed globally [4,75]. However, understanding which geographic, cultural, socio-economic, and biological factors promote tight biodiversity-human well-being relations in mountains requires a qualitative and quantitative assessment of the relationship between mountain biodiversity, ecosystem services, and several aspects of human well-being (e.g. health, security, cultural identity) along environmental, social–ecological, and governance gradients, as well as within and across mountains. A recent conceptual framework for assessing the context-dependent relationship between nature and people at various scales is that adopted by the Intergovernmental Platform on Biodiversity and Ecosystem Services [70••]. By unpacking biodiversity, ecosystem services, human well-being, indirect and direct drivers, and their interrelations, this framework is appropriate for collecting knowledge relevant for the evaluation and interpretation of interactions between biodiversity and human well-being, also in mountains. This conceptual framework, combined with tools to identify synergies and trade-offs between SDGs related to biodiversity and to human well-being, offers a plethora of opportunities in mountain biodiversity and sustainable development research. By initiating research efforts on biodiversity-related opportunities for sustainable development in mountains that efficiently combine various approaches in natural and social sciences (e.g. surveys, observational studies, and computational simulations for spatiotemporal extrapolations), GMBA is contributing to achieving tangible progress in our understanding of the nexus between biodiversity and human well-being in mountains globally.

Scale

The notion of spatial scale is both particularly relevant and challenging in mountains. The global distribution, recognition, value, and importance of mountains justify their promotion as 'global common good' [76]. Simultaneously, the sharp biologically and socio-economically relevant gradients in topography and bioclimatic conditions that characterize them, their very regional specificities, and their role for local societies justify their promotion as 'glocal common good' (as opposed to 'global') [77]. Scale strongly influences processes and patterns [24,25], data acquisition [78], modelling, as well as mapping of social–ecological systems [79]. Accordingly, conducting research across multiple scales can help and is needed to uncover novel patterns or processes [80]. Upscaling information from local and fine-grained to global and coarse-grained resolution usually leads to an increase in the extent and a decrease in the resolution of the data [81], while downscaling results in the opposite [82]. In both directions, predictions are associated with errors and uncertainties, which likely are particularly large in highly heterogeneous landscapes such as mountains. Notions of temporal scales become particularly important in the context of social–ecological systems research and in the study of the multiscale behaviour of these complex adaptive systems [83]. In such systems, 'fast' variables (e.g. ecosystem services such as crop production) are of primary concern to ecosystem users. Their dynamics are strongly influenced by 'slow' variables, that is, other system variables that generally change more slowly (e.g. soil fertility), which in turn respond to external drivers (e.g. levels of precipitation, erosion) that vary at a specific temporal scale.

Increasing our understanding of spatial and temporal processes and patterns at multiple scales is considered a key area of future research in mountain landscape ecology [84]. As ecological and social processes do not operate at the same scales, linkages at various levels must be developed [85]. In models of (social)–ecological systems, estimates of ecological functions and ecosystem services can substantially differ between fine-resolution and coarse-resolution analyses, as in the case of carbon sequestration, flood regulation, agricultural production, timber harvest, and scenic beauty in mountain ecosystems of Europe and the U.S. [86]. An additional objective on the GMBA science roadmap is to contribute to a better understanding and consideration of the role and importance of scale for data collection and usage in mountain biodiversity and global change research.

Conclusion

We identify research avenues toward advancing mountain biodiversity and global change science, for overcoming the historical fragmentation in mountain research, and for contributing to the science-policy debate on the sustainable management of the biological resources underpinning human well-being in mountains and beyond. We argue that interdisciplinary and transdisciplinary progress toward a unified understanding of the nexus between biodiversity, ecosystem functions and services, and human well-being in mountains, and of its evolution under global change, requires a concerted effort from natural and social scientists, the monitoring of context-relevant variables over time and along a spatial continuum, and more funding. In its role as facilitator and catalyst of mountain biodiversity research, GMBA aims at supporting these research efforts through continuous networking, information exchange, and co-design with scientists and stakeholders.

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Conflict of interest statement

The authors declare no conflict of interest.

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