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Nature and People in the Andes, East African Mountains, European Alps, and Hindu Kush Himalaya: Current Research and Future Directions

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Mountains are facing growing environmental, social, and economic challenges. Accordingly, effective policies and management approaches are needed to safeguard their inhabitants, their ecosystems, their biodiversity, and the livelihoods they support. The formulation and implementation of such policies and approaches requires a thorough understanding of, and extensive knowledge about, the interactions between nature and people particular to mountain social–ecological systems. Here, we applied the conceptual framework of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services to assess and compare the contents of 631 abstracts on the interactions among biodiversity, ecosystem services, human wellbeing, and drivers of change, and formulate a set of research recommendations. Our comparative assessment of literature pertained to the Andes, the East African mountains, the European Alps, and the Hindu Kush Himalaya. It revealed interesting differences between mountain systems, in particular in the relative importance given in the literature to individual drivers of change and to the ecosystem services delivered along elevational gradients. Based on our analysis and with reference to alternative conceptual frameworks of mountain social–ecological systems, we propose future research directions and options. In particular, we recommend improving biodiversity information, generating spatially explicit knowledge on ecosystem services, integrating knowledge and action along elevational gradients, generating knowledge on interacting effects of global change drivers, delivering knowledge that is relevant for transformative action toward sustainable mountain development, and using comprehensive concepts and codesigned approaches to effectively address knowledge gaps.

Keywords: *mountain biodiversity; mountain social–ecological systems; IPBES framework; literature assessment; global change.*

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Introduction

Mountains are remarkable for many reasons and represent areas of high conservation value (eg Messerli and Ives 1997; Körner and Ohsawa 2006). They are storehouses of biodiversity; support hundreds of millions of people with vital services (Grêt-Regamey et al 2012), both locally and in adjacent lowlands and urban areas (FAO 2015; Körner et al 2017); and hold an extremely rich cultural, ethnic, and social diversity (Wymann Von Dach et al 2016, 2018; Payne et al 2017). Yet mountains are increasingly exposed to changes in climate and land use, environmental pollution, large-scale political and socioeconomic transformations, and unsustainable management of natural resources. In the face of these growing challenges, effective policies and management approaches are needed to safeguard the natural assets that underpin human wellbeing in mountains and the essential capacity of mountain ecosystems and their biodiversity to support human populations in and beyond mountains.

The formulation and implementation of such policies and approaches requires a thorough understanding of the interactions between nature and people particular to mountain social–ecological systems. Previous mountain-specific assessments at global scale, such as the Millennium Ecosystem Assessment of Mountains Systems (Körner and Ohsawa 2006) and the thematic reports on mountain ecosystems from the Convention for Biological Diversity (Secretariat of the Convention on Biological Diversity 2003) contain useful knowledge. However, both are outdated and neither captures the salient interactions between individual components of mountain social–ecological systems. Much social and ecological knowledge required to support decision-making in mountains is also available in the mountain research community (Gleeson et al 2016) and among societal stakeholders and governmental institutions. However, the lack of a conceptual framework to organize this knowledge and present it to policymakers and other invested stakeholders has so far represented an obstacle in the sustainable management of mountain biodiversity and ecosystems and in developing sustainable development pathways. The use of the conceptual framework of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES; Díaz et al 2015) is therefore particularly relevant in this context. By unpacking biodiversity, nature's contributions to people (NCPs), human wellbeing, indirect and direct drivers, and their interrelations, the IPBES framework serves as a powerful conceptual tool. It specifically serves to guide data acquisition, align the conceptualization of mountain social–ecological systems to the conceptualization of the relationship between human and nature adopted globally, and facilitate the uptake of results and key messages (Martín-López et al 2019).

Here, we applied the IPBES framework in a comparative analysis of literature contents across mountain systems to detect regional patterns in the current state of research and knowledge about interactions between nature and people. Based on this comparative analysis and our literature assessment, which we summarize in the main text, we identify research opportunities. We focused on the Andes, the East African mountains, the European Alps (hereafter Alps), and the Hindu Kush Himalaya (hereafter Himalaya; Figure 1), where a lot of mountain research is currently performed (see Chakraborty 2019). We also specifically focus on biodiversity and ecosystems to complement recent literature focusing on NCPs (Martín-López et al 2019).

Methods

Elements of the IPBES framework

We addressed the ecological and social components that are the focus of the IPBES framework: biodiversity and ecosystems (nature), ecosystem goods and services (NCPs), human wellbeing (good quality of life), direct drivers, indirect drivers, and other institution and governance options (Díaz et al 2015). The categories of ecosystem goods and services we used in our analyses consisted of the NCPs adopted by IPBES (see Díaz et al 2018; for the lists of NCPs, see *Supplemental material*, Table S1: https://doi.org/10.1659/MRD-JOURNAL-D-19-00075.1.S1), and both the dimensions of human wellbeing and the direct and indirect drivers were taken from the Millennium Ecosystem Assessment (MEA 2005) and the IPBES assessments.

Data collection

Our analysis pertained to literature published between January 2015 and December 2018 that was available on Scopus (https://www.scopus.com). For each of the 4 mountain systems, the literature was first filtered to include only publications pertaining to nature and ecosystems. The resulting subset was then independently filtered 6 additional times for publications pertaining to (1) the state of nature, (2) direct drivers of change, (3) indirect drivers of change, (4) ecosystem services, (5) human wellbeing, and (6) (institutional) responses (see *Supplemental material*, Table S2 for the lists of search strings: https://doi.org/10.1659/MRD-JOURNAL-D-19-00075.1.S1). While we welcome the concept of NCPs, the literature we reviewed did not widely reflect it. We therefore also included the term "ecosystem services" in our search and applied it throughout the present text. In addition to peer-reviewed articles, we included the 4 IPBES regional assessments published in 2018 (https://www.ipbes.net/deliverables/2b-regional-assessments) and the fifth national reports to the Convention on Biological Diversity (CBD; https://www.cbd.int/nr5/default.shtml) for the 26 countries sharing parts of the 4 mountain systems. Relevant information included in the IPBES and the CBD reports was searched using the find function and the keywords "mountain," "montane," and "alpine," as well as the mountain systems' names. To avoid introducing a bias in the level of detail reported for each of the mountain systems, we did not include the report of the Hindu Kush Himalayan Monitoring and Assessment Programme (Wester et al 2019).

The literature assessment was performed by 1 scientist and on abstracts only. Evaluation of a random set of abstracts by 2 additional scientists served to test for the repeatability and objectivity of the evaluation. Following the IPBES framework, each abstract was tagged for information on biodiversity (5 species groups) and ecosystems (6 mountain ecosystems/biomes), ecosystem services (3 groups of ecosystem services and/or 18 NCPs), drivers (5 direct drivers, 6 indirect driver categories, 8 categories of institutional and practical responses), human wellbeing (6 dimensions of human wellbeing), and 5 categories of interactions (see *Supplemental material*, Table S3 for details: https://doi.org/10.1659/MRD-JOURNAL-D-19-00075.1.S1). Additional tags were attributed to abstracts referring to any of the 17 Sustainable Development Goals (SDGs) or the 20 Aichi targets. In the cases of ecosystem services, human wellbeing, SDGs, and Aichi targets, we recorded whether the code attribution was explicit (ie a given SDG was explicitly mentioned) or inferred (for example, all abstracts that mentioned the conservation value of biodiversity or ecosystems were tagged with life on land (SDG 15), even if the SDG itself was not explicitly mentioned). To detect interactions between SDGs, we applied network analysis tools (Dalampira and Nastis 2019; Egelston et al 2019; Lusseau and Mancini 2019) to a weighted data matrix in which each row contained a paper and each column represented a different SDG. For interpretation, we used the number of SDG references in each paper (degree centrality), the importance of each SDG for the whole network (eigenvector centrality), and the SDG co-occurrences within the literature sample. The analysis was run using the R packages igraph (Csardi and Nepusz 2006) and gplots (Warnes et al 2019).

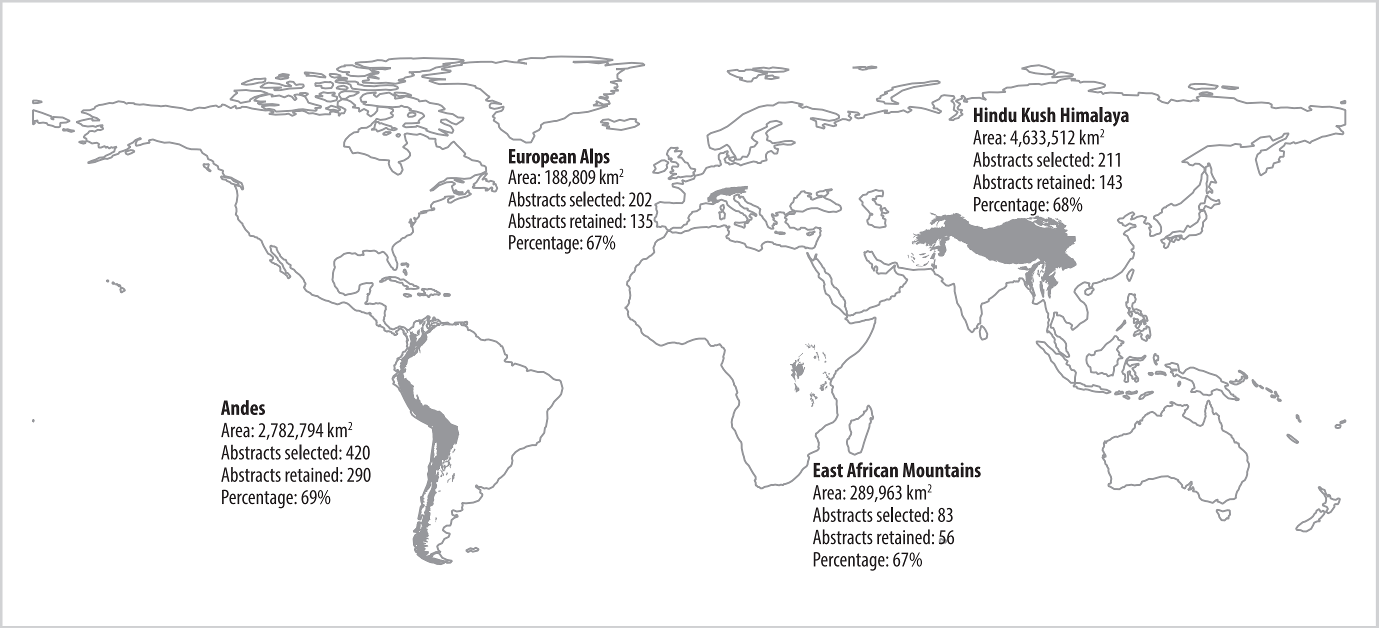
Results

Our search returned 916 peer-reviewed papers, of which we retained 631 (69%). The papers we excluded pertained to paleoecology or reported on newly discovered taxa. Based on our search criteria, 17 national reports to the CBD were retained in addition to the 4 IPBES regional assessments (IPBES 2018a, 2018b, 2018c, 2018d).

Comparative analysis of literature contents across mountain systems

The literature was most abundant for the Andes, followed by the Himalaya, the Alps, and the East African mountains (Figure 1). However, the Alps had the most publications per area (the area was calculated based on Körner et al 2011, 2017), with approximately 7.2 retained publications per 10,000 km^2, followed by the Himalaya (~2.2; the literature on the Hindu Kush Himalaya [143 publications retained] consisted primarily of literature pertaining to the Himalaya sensu stricto [129 publications retained]; the value we present is based on these 129 publications, which pertain to an area surface of approximately 595,000 km^2), the East

FIGURE 1 World map showing details of the 4 mountain systems included in the review (dark grey areas). The surface of each mountain system is based on Körner et al (2017). (Map by Mark Snethlage)



African mountains (∼1.9), and the Andes (∼1.0). Abstracts primarily addressed direct drivers, ecosystems, and ecosystem services (with both explicit and inferred information; Table 1). Fewer abstracts specifically referred to species, institutions, governance, and indirect drivers, and even fewer to human wellbeing. Explicit mentions of the SDGs and Aichi targets were rare, but about half of the papers discussed issues relevant to these development and conservation goals. These observations generally apply to the 4 mountain systems. Differences between systems included proportionally more papers addressing sustainable development in the Andes and the East African mountains than in the other 2 systems, and particularly few references to notions of human wellbeing in the Alps.

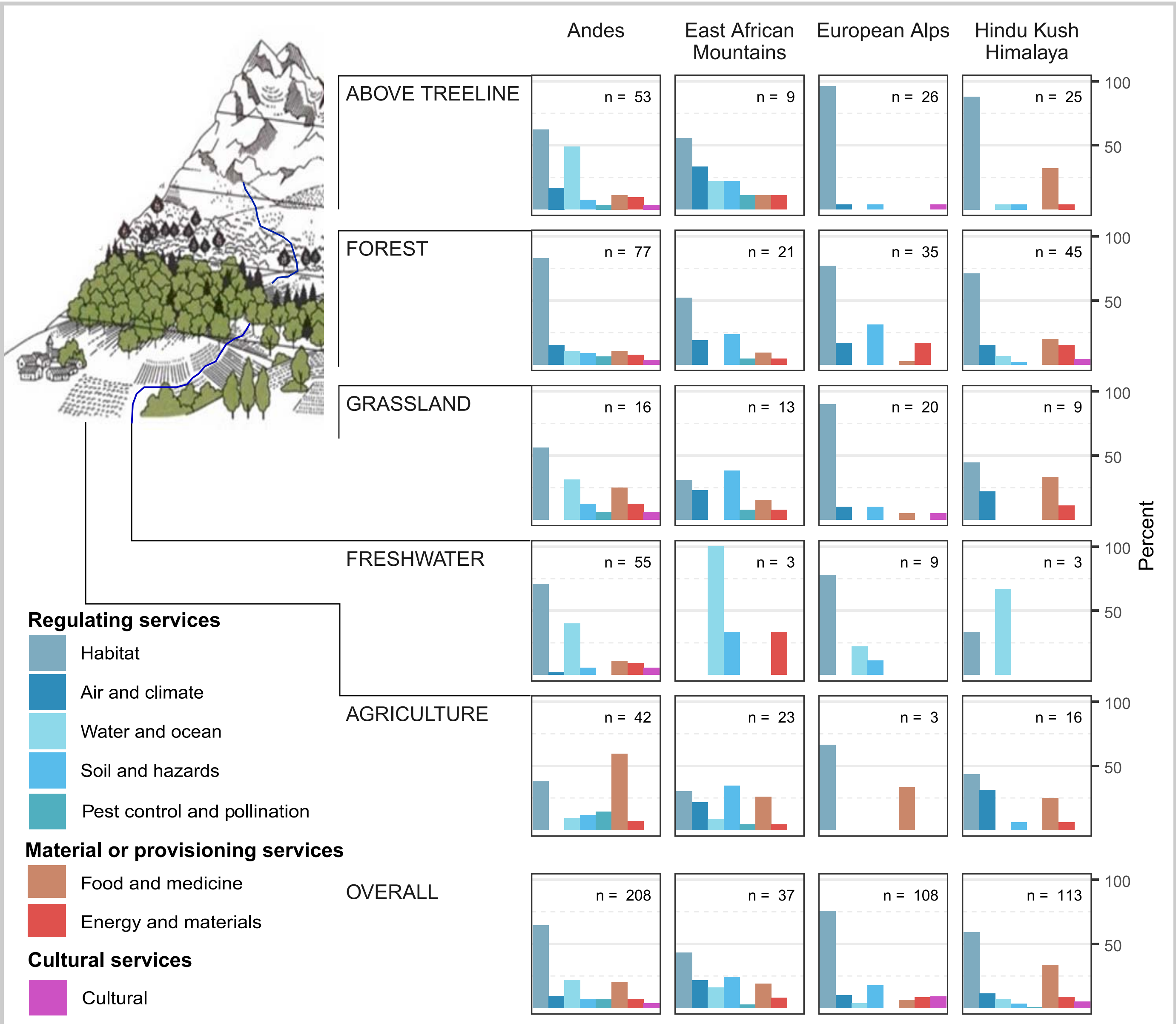
Biodiversity and ecosystems: The assessed literature presented large taxonomic gaps and did not offer enough systematic information on the state of and trends in biodiversity and ecosystems to perform a comparison. This was the case even though 3 of the 4 mountain systems overlap at least partly with 1 or more biodiversity hotspots (East African mountains: Eastern Afromontane biodiversity hotspot; Hindu Kush Himalaya: Himalaya biodiversity hotspot, Mountains of Southwest China biodiversity hotspot; Andes:

TABLE 1 Percentages of abstracts addressing individual dimensions of the IPBES framework, SDGs, and Aichi targets.[a)]

Individual dimensions	Andes (290)	East African mountains (56)	European Alps (135)	Hindu Kush Himalaya (143)
Species	58	54	63	51
Ecosystem	81	89	73	66
Ecosystem services (G)	78	79	90	78
Ecosystem services (D)	72	66	82	73
Direct driver	80	82	87	76
Indirect driver	10	14	15	8
Response	40	52	71	64
Human wellbeing	19	21	10	27
Interaction	21	21	88	35
SDGs	74	70	44	42
Aichi targets	28	66	49	51

[a)]Ecosystem services (G), ecosystem services—general (explicit or not, regulating, provisioning or cultural); Ecosystem services (D), ecosystem services—detailed (explicit reference to at least 1 nature's contribution to people); SDGs, 17 Sustainable Development Goals; Aichi targets, 20 targets of the Convention for Biological Diversity; Interaction, synergies, trade-offs, etc. Responses include legal and policy instruments, finance-based instruments, ecosystem management, etc. Numbers in parentheses indicate total number of abstracts assessed.

FIGURE 2 Percentage of references to given ecosystem services in individual ecosystems. n: total number of publications retained for a given combination of mountain system and ecosystem. (See *Supplemental material*, Table S1 for details on the ecosystem services: https://doi.org/10.1659/MRD-JOURNAL-D-19-00075.1.S1.) (Mountain drawing modified from Mayoux 1996)

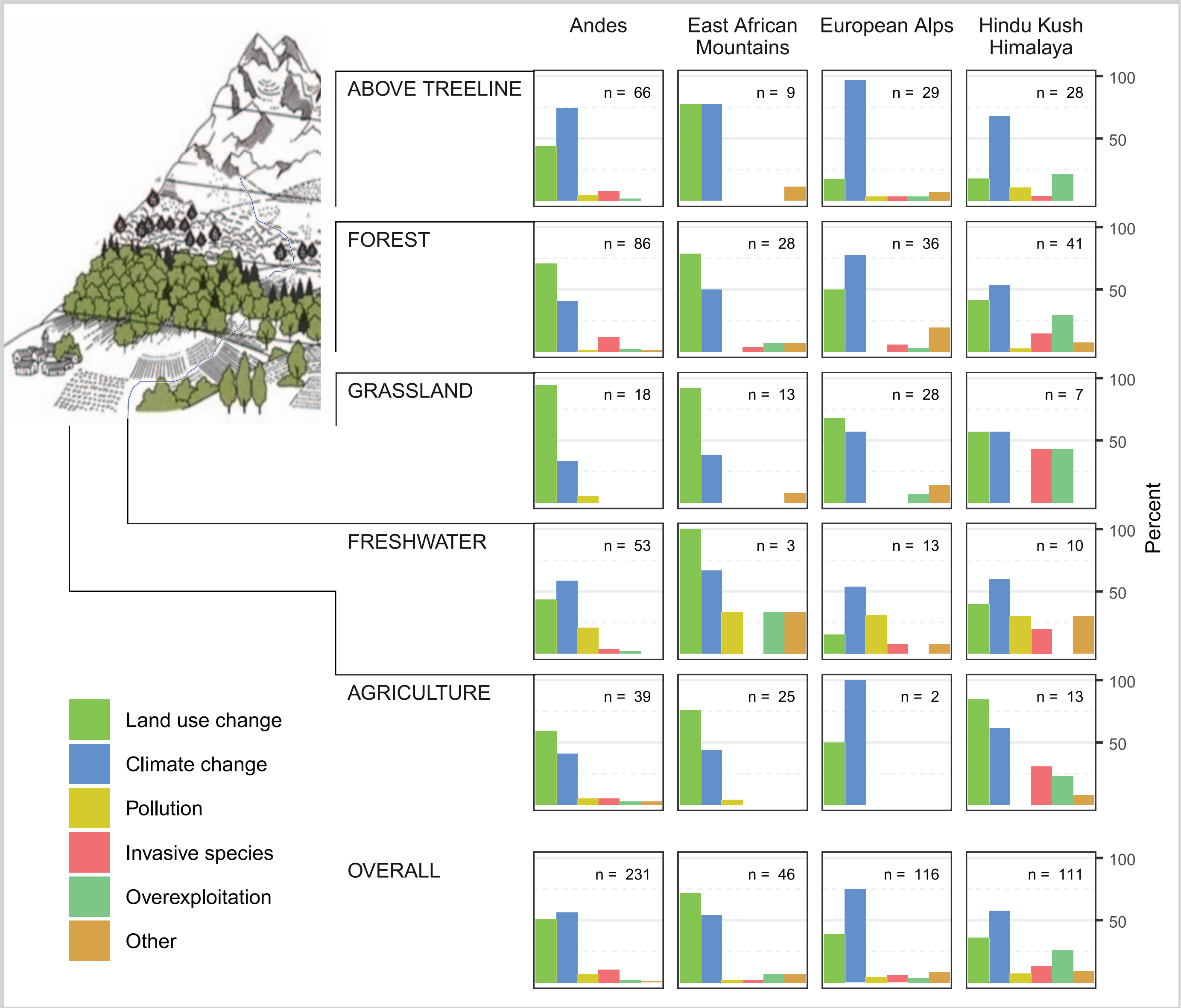


Tropical Andes biodiversity hotspot, Tumbes–Chocó–Magdalena biodiversity hotspot, Chilean Winter Rainfall–Valdivian Forests biodiversity hotspot). An additional challenge inherent to the literature on species and ecosystems was the widespread use of different measures and indicators of biodiversity and ecosystems (eg population size, range, cover, condition, alpha and beta diversity, phylogenetic diversity).

Ecosystem services: When we made no distinction between ecosystems within mountain systems (Figure 2, bottom row), "habitat" (see *Supplemental material*, Table S1 for the exact names of the ecosystem services: https://doi.org/10.1659/MRD-JOURNAL-D-19-00075.1.S1) stood out as the most frequently mentioned ecosystem service in the 4 mountain systems. When ecosystems were analyzed individually (Figure 2, upper rows), "habitat" was the most frequently reported service in ecosystems above the treeline as well as in forests. It remained the most frequently mentioned service provided by grasslands and freshwater ecosystems in the Andes and the Alps. In grasslands of the East African mountains, "soil and hazards" was reported more frequently, and in those of the Himalaya, it was "food and medicine." Ecosystem services associated with highly modified ecosystems (eg agricultural land) varied between systems, with "food and medicine" frequently referred to in the Andes in particular. Interestingly, abstracts pertaining to the East African mountains referred more systematically to a variety of ecosystem services.

Direct drivers of change: When we made no distinction between ecosystems within mountain systems (Figure 3, bottom row), climate change was the most frequently reported direct driver of change in the Alps and the

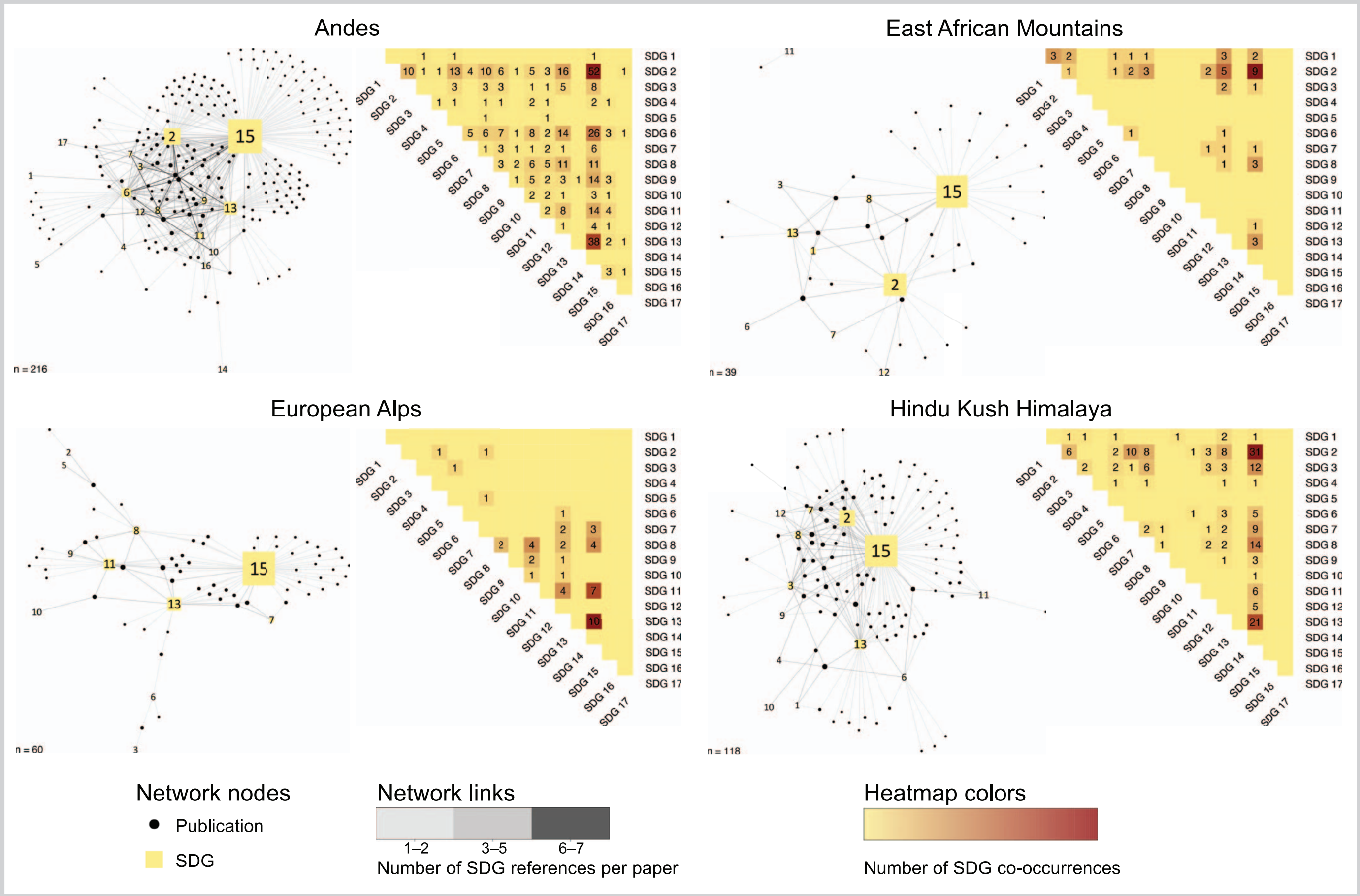
FIGURE 3 Percentage of references to given drivers in individual ecosystems. n: total number of publications retained for a given combination of mountain system and ecosystem. (Mountain drawing modified from Mayoux 1996)



Himalaya. In the Andes, the number of abstracts mentioning climate change and land use change was nearly equal, whereas in the East African mountains, more abstracts referred to land use change. Unlike in other mountain systems, literature pertaining to the Himalaya included a comparatively high number of abstracts discussing issues of overexploitation, in addition to climate change and land use change. When ecosystems were analyzed individually (Figure 3, upper rows), patterns were more nuanced. In this case, climate change was more systematically discussed in abstracts pertaining to ecosystems above the treeline and freshwater ecosystems, and land use change in abstracts pertaining to forests, grasslands, and agricultural land. These observations were essentially true for the Andes, the East African mountains, and the Alps, whereas in the Himalaya, comparatively more references to climate change were made across all but the highly modified (agricultural land) ecosystems. References to invasive species and overexploitation were most frequent across all ecosystems in the literature pertaining to the Himalaya, whereas only abstracts pertaining to freshwater ecosystems mentioned pollution, albeit in all 4 systems.

Institutions, governance, and other indirect drivers of change: Among the few references made to indirect drivers, economic drivers were reported most often, followed by demographic, cultural, and religious drivers. However, relative frequencies differed between mountain systems, with more frequent references to demographic drivers in the Himalaya and the East African mountains, and to economic drivers in the Andes and the Alps. For the Alps, references to demographic drivers were particularly few. The most frequently reported institutional responses pertained to "ecosystem and species management" and to "research and monitoring," followed by "legal, regulatory and policy instruments" and "planning." The occasional references to "economic and financial instruments" included specific measures such as payments for ecosystem services (especially for the Andes), subsidies,

FIGURE 4 Networks of Sustainable Development Goal (SDG) co-occurrences based on the literature review. The networks illustrate to which SDG(s) a publication refers. Each publication node (black dot) is linked to the SDG(s) to which it refers in its own text. The number of links from an individual publication to a specific SDG can vary between 1 (smallest black node) and 7 (largest black node). The SDG node size (yellow square) corresponds to the SDG eigenvector centrality and the SDG label size to the betweenness centrality. Both values indicate the structural importance of each SDG within the literature sample. The heat maps illustrate the SDG co-occurrence throughout each region's set of abstracts. The number of SDG co-occurrences ranges from 1 to 9 (East African mountains), 10 (European Alps), 31 (Hindu Kush Himalaya), and 52 (Andes).



and the promotion of income-generating activities. Other specific measures frequently described included the establishment and management of protected areas (PAs) (and other area-based conservation measures).

Sustainable Development Goals: Based on a network analysis, research pertaining to the SDGs was primarily mentioned in the literature on the Andes and the Himalaya (Figure 4). Moreover, more abstracts simultaneously referred to several dimensions of sustainable development in the Andes than in any other system. Across systems, life on land (SDG 15) was the goal to which most abstracts referred (Figure 4, large yellow square in all subplots). In the Andes, the East African mountains, and the Himalaya, zero hunger (SDG 2) and climate action (SDG 13) ranked second and third, whereas in the Alps climate action (SDG 13) ranked second and sustainable cities and communities (SDG 11) third. Zero hunger (SDG 2), sustainable cities and communities (SDG 11), and climate action (SDG 13) were often discussed together with life on land (SDG 15) (Figure 4, dark red colors in the heat maps).

Literature-based assessment

A summary of the literature assessment along the dimensions of the IPBES framework is provided in Table 2, and the full text of the assessment, including the references, is provided as supplementary material (see *Supplemental material*, Appendix S1: https://doi.org/10.1659/MRD-JOURNAL-D-19-00075.1.S1).

Discussion

We applied the IPBES framework to guide our collection of published literature on the interactions between nature and people in the Andes, the East African mountains, the Alps, and the Himalaya. Our deliberate focus on these 4 mountain systems enabled us to perform a comparative analysis of coded literature contents and to deliver a nuanced picture of current science. This comparative analysis revealed differences between mountain systems, and, in particular in the relative importance given in the literature to different drivers of change and to different ecosystem services. Different levels and trajectories of human-induced transformation between mountain systems call for caution in interpreting comparative results. Nevertheless, our analysis emphasizes the necessity of acknowledging mountain systems not only for their commonalities but also for their singularities and of formulating policy frameworks that account for differences

TABLE 2 Summary of the literature assessment performed along the dimensions of the IPBES framework. (Table continued on next page.)

Mountain system[a)]	IPBES dimension
	State of and trends in biodiversity and ecosystems
Andes (25)	Species diversity and levels of endemism are very high, particularly in the *páramo*, the *puna*, and the high peatlands and mountain forests. The *páramo* and *puna* remain the least transformed of the American biomes, despite trends towards their conversion in the north and locally significant reductions in their extent. Trends toward a decline in biodiversity, and in ecosystem condition and extent, are also reported in forests, with high extinction rates of endemic species in forest patches of Ecuador and the reduction in extent of many native mountain forests of Chile and Colombia, for example.
East African mountains (26)	The East African mountains are part of the Eastern Afromontane biodiversity hotspot and include the Albertine Rift and the Eastern Arc Mountains, 2 areas of biologically rich highland forests and moorland habitats. Both species richness and endemism levels are particularly high in the mountain cloud forests, and in the few ecosystems above the treeline. Yet important habitats for species of conservation value also include agroforestry and fallows, as well as freshwater habitats. Species-rich forests have been declining in coverage (>70% in the Eastern Arc) and condition, but the designation of most remaining forests as protected areas has slowed down decreases in coverage. Threats to ecosystems include the downgrading, downsizing, and degazettement of protected areas that already inadequately cover the distribution area of many species. Freshwater habitats are still in good condition in the higher reaches of the uplands but rapidly deteriorating on the mountain lower slopes.
European Alps (50)	Species richness is high in many taxonomic groups and particularly at the transitions between ecosystems (eg around the treeline). However, many species and functional groups are threatened in the long term, despite transient increases in the diversity of vascular plant species and the existence of local conditions (eg topographic complexity) that could enable persistence under warming climates. The cultural landscapes are increasingly homogeneous at local and polarized at larger scales. Declines in ecosystem condition are observed across all landscapes, including wooded pastures, species-rich seminatural grasslands, and traditional mixed-use (multifunctional) landscapes (eg larch grasslands). Changes in the vegetation are widespread and include greening in high alpine habitats, an increase of forest areas at the expense of grasslands on mountain slopes by up to 20%, range contractions by >40% for certain plant species, and changes in the treeline position. Above the treeline, glaciers have lost large proportions of their total area (~50%) and the hydromorphological regimes of mountain rivers and freshwater systems are rapidly changing, with numerous consequences for ecosystems and species.
Hindu Kush Himalaya (18)	Levels of biological diversity and endemism are extremely high (eg 9000 plant species in the Eastern Himalaya, 39% of which are endemic), notably in the Hindu Kush Himalaya biodiversity hotspot and in alpine grasslands. The Eastern Himalaya is also home to species-rich forests, including dry deciduous and cloud forests, which are particularly threatened high-biodiversity terrestrial ecosystems. To date, the frequency and the relative abundance of many alpine plant species in the Nepalese Himalaya are found to increase. Given the extent of the Hindu Kush Himalaya, the status of and trends in biodiversity and ecosystems as well as the patterns of greening vary considerably. Large variations also occur in the status of and trends in forest condition and extent. Where forest loss is relatively low (eg 7.4% since 1976 in Indian Western Himalaya and Bhutan), fragmentation is often high. The condition of many rangelands in the subalpine zones and of freshwater habitats has been deteriorating, with losses in productivity in subalpine grasslands and increasing eutrophication of water bodies.
	Ecosystem services
Andes (22)	The *páramo*, *puna*, and associated peat bogs, and also forests, glaciers, and freshwater ecosystems, provide a diversity of services that support about 105 million people in and around the mountains. In addition to water regulation, carbon sequestration, and grazing land for livestock, ecosystem services include recreation and tourism, cultural services, pollination, and seed dispersal. Mountain ecosystems are also an important source of plants used for medicine, food, firewood, and domestic tools. The central Andes (Bolivia, Peru) is 1 of the 7 key areas for the preservation of genetic diversity of crops and of their wild relatives.
East African mountains (20)	From a continental perspective, the East African mountains make the biggest relative contribution to the wellbeing, livelihoods, and socioeconomic development of millions of people in and beyond mountains. They are especially important for water regulation, groundwater recharge, soil conservation, climate regulation; as a resource for tourism; and for their cultural values. Aboveground forest carbon stocks are essential to mitigate climate change. At a regional scale, the Eastern Arc Mountains support a diversity of regulating and material ecosystem services including water regulation and provision, energy, agricultural products, timber, and NTFPs, many of which are paramount to individual regions' and countries' economic development. Under business as usual, projected climate change and overexploitation will severely affect the provision of these ecosystem services.

TABLE 2 Continued. (First part of Table 2 on page A7.)

Mountain system[a)]	IPBES dimension
European Alps (27)	The type of ecosystem services delivered has changed from primarily material to mainly regulating services, following different trajectories in different regions and according to different trade-offs within ecosystem service bundles. An additional change in the type of ecosystem services comes from societal evolution and an increasing demand for cultural services. Despite ongoing changes, many traditional landscapes still provide a diversity of services, such as timber, forage, space for recreation, biodiversity conservation, and carbon storage. Ecosystem services from forests specifically include increasingly valued non-timber services, such as protection against natural hazards. Managing these ecosystem services under ongoing and future change will require considering the valuation of services and the trade-offs between them.
Hindu Kush Himalaya (39)	Natural systems provide many ecosystem services to approximately one fifth of the total world population. Important regulating services, for the region and beyond, include the regulation of water flow and carbon storage. Besides regulating services, the region also provides many provisioning services important for local livelihoods, including fodder, firewood, timber, and NTFPs. A strong reliance on forest products and on traditional agroforestry systems is an important coping mechanism in the face of climate-related adversities. Cultural services (eg landscapes and ecosystems that attract tourists) can provide alternative income sources for local communities. Ecosystem bundles, including provisioning (food) and regulating (eg conservation and water regulation) services, are typically provided by traditional agroforestry landscapes based on land-sharing principles. These landscapes contribute to biodiversity conservation and complement the protected area network. Bundles include ecosystem services of both local and global value whose prioritization often results in trade-offs that need to be included in local management plans. Reported ecosystem disservices primarily take the form of human–wildlife conflicts.
	Direct drivers of change
Andes	
Land use change (19)	Land use change includes deforestation, changes in agriculture (grazing and conversion to pastures and cultures), rapid urbanization, and inappropriate forestry practices. Afforestation and agriculture particularly affect the high-mountain grasslands (*páramo* and *puna*) and their capacity to deliver ecosystem services. The conversion to cropland, drainage, and the construction of roads, dams, and other infrastructures are major threats to mountain wetlands and aquatic ecosystems.
Climate change (19)	Climate change interacts in complex ways with biodiversity because of altitudinal, latitudinal, and humidity gradients. Increasing temperatures particularly affect the glaciers, the *páramo*, the cloud forests, and the dynamics of freshwater ecosystems, with consequences for the provision of ecosystem services. Patterns and trends in precipitations are less clear and differ between the north and the south. Freshwater ecosystems are the most likely to suffer from decreases in precipitations in the south. Beyond the effects on ecosystems, climate change also affects the distribution of species (eg upward shift of species distribution) and ecological processes (eg pollination and the functioning of agroecosystems), calling for adaptation strategies.
Invasive species (5)	Alien and invasive species are an increasing problem at least in certain regions, particularly below the treeline, in freshwater ecosystems, and in agricultural areas.
Pollution (3)	Pollution is mostly a local issue affecting freshwater ecosystems, mainly around settlements, but the expanding mining sector and runoff of pesticides and fertilizers in agricultural areas represent increasing threats.
East African mountains	
Land use change (24)	Land use change is happening at an accelerating rate, primarily through deforestation and the degradation of forests and woodlands. Deforestation is often accompanied by, associated with, or the result of other anthropogenic disturbances, such as expansion of intensive crop cultivation and commercial plantations, mineral exploitation, large-scale commercial investments, the expansion of settlements, and renewable energy infrastructure. Consequences of anthropogenic disturbances include logging-induced landslides, negative impacts on large mammal species, increasing bushmeat hunting, high levels of fragmentation associated with reduced ecological connectivity, decreases in soil organic carbon and carbon stabilization, accelerated ecosystem cycles, and increasing water-related conflicts.
Climate change (6)	Climate change particularly affects ecosystems above the treeline and other high-montane ecosystems through increasing temperatures and wildfire, as well as glacier retreat. Lower montane ecosystems are primarily affected by changes in rainfall patterns.
Invasive species (3)	Certain nonnative tree species such as *Eucalyptus* spp. are already common and described as increasingly invasive, reaching remote locations such as the high-altitude remnants of native forests. Invasive species also include some introduced alien fish species.

 https://doi.org/10.1659/MRD-JOURNAL-D-19-00075.1

TABLE 2 Continued. (First part of Table 2 on page A7.)

Mountain system[a)]	IPBES dimension
European Alps	
Land use change (12)	Two important forms of land use change are land use intensification and land abandonment. This land use polarization has caused the degradation, loss, and fragmentation of many ecosystems (eg seminatural and larch grasslands, wooded pastures) with adverse effects on biodiversity. Additional forms of land use change are leisure and tourism. Tourism, via its infrastructures and the disturbances it engenders, has had important effects on alpine ecosystems. Similar impacts result from other types of infrastructures, including those for the production of renewable energies.
Climate change (30)	A systematic increase in temperature is the most discussed effect of climate change. Temperature increases influence alpine birds, vegetation, and ecosystems, both at high and at lower elevations, and affect the elevation range of alpine plant species and species' community composition, as well as vegetation phenology. They further lead to glacier retreat and the melting of permafrost, which in turn affect the quality of freshwater ecosystems and their associated biota and reduce slope stability, thereby increasing the risk of natural hazards. Other effects of climate change include changes in precipitation, droughts, and increased frequency, magnitude, and intensity of heatwaves and other extreme events.
Invasive species (6)	Alien species invasions are so far limited and the expansion of nonnative plant species and populations is small. However, in the face of climate change and land abandonment, and with the development of tourism and the increasing trade in ornamental species, the barriers to invasions and to the upward migration of nonnative plant species are gradually weakening.
Pollution (3)	Atmospheric deposition of nitrogen oxides and persistent organic pollutants are the main sources of pollution reported.
Hindu Kush Himalaya	
Land use change (16)	Land use change is reported for all mountain ecosystems and regions, including cold mountain deserts and freshwater ecosystems. It takes different forms, including marked increases in agriculture, scrubland, and urban areas. The progressive integration into globalized markets and better infrastructure results in shifts from subsistence to market-oriented agriculture and increasing rates of forest conversion. Yet agricultural land is also frequently abandoned. The region is concomitantly experiencing increasing tourism, urbanization, and infrastructure development.
Climate change (17)	Climate change is associated with different phenomena, including increases in temperature (up to 1.6°C per decade), ozone concentrations on the highest peaks, extreme events (eg extreme precipitation and increases in flooding events from melting glaciers), and variability in precipitation. Ongoing and predicted changes in climatic conditions are expected to have far-reaching consequences on natural ecosystems including glaciers as well as on ecosystem services and overall human wellbeing, but also on individual key conservation species and on trophic interactions between them, particularly in alpine areas. Effects of climate change on human wellbeing include increasing risks to traditional health care and food security caused by changes in the phenology of medicinal and agricultural plants. Climate change is likely to jeopardize the efficacy of protected areas.
Invasive species (8)	Invasive species are becoming an issue of concern as they are spreading and posing threats to the native flora, notably by suppressing the floral biodiversity of herbaceous species in forests. Major effects are on native scrublands and subtropical needle-leaved forests in the Western Himalaya. In the Indian Himalaya specifically, the advance of invasive species is recorded along riparian areas, in areas grazed by cattle, and in freshwater ecosystems. Invasive insects are increasingly recorded in the lower reaches of the Hindu Kush Himalaya and predicted to move to higher elevations as temperatures increase.
Pollution (8)	Levels of pollution vary. Sources include point sources and diffuse atmospheric deposition, solid waste, and high CO_2 concentrations, as well as atmospheric nitrogen deposition. Domestic sewage, effluents from industry, ill-managed tourism, and eutrophication are identified as the major sources of freshwater pollution.
All	
Overexploitation (14)	Besides increased game hunting in the East African mountains, overexploitation is a theme primarily in the Hindu Kush Himalaya, where hunting and gathering are threatening the biodiversity of many high-altitude wetlands, including the subcanopy vegetation. As many communities depend on livestock for their livelihoods, overgrazing is a widespread driver of change in different ecosystems including forests and above. Overexploitation, combined with deforestation, habitat fragmentation, the introduction of alien species, and increasing trade, affects specific biological resources with a cultural and local consumption value or a high market value. In the Indian Himalaya, as in other parts of the Hindu Kush Himalaya, overharvesting and habitat loss are the main drivers of decline in a number of medicinal and aromatic plants.

TABLE 2 Continued. (First part of Table 2 on page A7.)

Mountain system[a)]	IPBES dimension
	Governance, institutions, and indirect drivers of change (37)
All	The main indirect driver of change across the Andes, the East African mountains, and the Hindu Kush Himalaya is demographic growth. Additional factors include economic development as well as the lack of environmental education and awareness. Various governance and institutional mechanisms are developed within the context of national policy and law documents. These consist of economic and financial instruments, including payments for ecosystem services or direct subsidies; social and information-based instruments such as education, capacity building, and awareness raising; rights-based approaches and customary laws such as the use of traditional knowledge; and management-based instruments such as ecosystem-based adaptations and protected areas.

[a)]Numbers in parentheses correspond to the number of publications retained and cited in the full assessment. These numbers include references cited from the IPBES assessments and that occasionally pertain to work published before 2015. NTFPs, non-timber forest products; CO_2, carbon dioxide.

between and within mountain systems and contexts. The literature assessment (Table 2; and see *Supplemental material*, Appendix S1: https://doi.org/10.1659/MRD-JOURNAL-D-19-00075.1.S1) offered additional nuances and details that tend to be brushed over when attributing information to standardized categories.

Biodiversity and ecosystems

The limited amount of information on the status of and trends in species is in line with previous observations that species information is generally very incomplete, both taxonomically and geographically (Payne et al 2017; Crouzat et al 2019).

Ecosystem services

The assembled literature consistently highlights the diverse palette of ecosystem services that mountains provide (Grêt-Regamey et al 2012; Crouzat et al 2019) to millions of people locally, in surrounding lowlands, and beyond (Schirpke, Tappeiner, et al 2019). Importantly, both the structured content analysis and the assessment illustrate the tight coupling between individual services or service bundles and ecosystem types (Figure 2), which means that the loss or degradation of individual ecosystem types can jeopardize the capacity of entire mountain landscapes to deliver vital services. The long-term provision of ecosystem services therefore calls for governance and policy frameworks applying to entire mountain systems along elevational gradients that extend all the way into the lowlands. This is of particular importance in view of the predicted shifts in ecosystems' and species' ranges under global change, which was reported across the reviewed literature. In line with a previous review of current research on mountain ecosystem services (Martín-López et al 2019), regulating ecosystem services, in particular services related to habitat and water, received particularly high attention in the assessed literature. Yet these results also became more nuanced at the scale of individual ecosystem types. Our literature assessment, in particular, points to the importance of trade-offs between individual ecosystem services and bundles of services (eg between material services, such as energy provision, and nonmaterial ecosystem services, such as aesthetic landscape perception), specifically in the Alps and the Himalaya, and to the importance of acknowledging and accounting for these trade-offs in management plans.

Drivers of change

Current discourses in nature conservation and sustainable development tend to attribute declines in mountain biodiversity, ecosystem conditions, and ecosystem extent primarily to climate change. In line with this narrative and with current funding priorities, we found that climate change indeed received considerable scientific attention in the literature we assessed (Figure 3). However, analyses at the level of individual ecosystem types revealed that climate is more systematically mentioned as a driver of change in literature pertaining to ecosystems above the treeline and land use change in literature pertaining to ecosystems below the treeline. Yet variation existed between mountain systems, with literature on the impacts of climate change also pertaining to ecosystems below the treeline in the Alps, for instance. These patterns emphasize the importance of accounting for the succession of ecosystem types along elevational gradients when studying global change drivers in mountain systems in the Anthropocene and when formulating policies and management approaches. The prevalence of land use change across the broad selection of publications we screened gives it a higher importance than the one it receives in the literature on mountain ecosystem services (Martín-López et al 2019). Our literature assessment (Table 2; and see *Supplemental material*, Appendix S1: https://doi.org/10.1659/MRD-JOURNAL-D-19-00075.1.S1) added further nuances, for example by attributing different forms of land use change and climate change to different mountain ranges and ecosystem types and by highlighting the importance of interactions between drivers of change. Specific interactions included those between climate change and land use change, as well as between invasive species and other drivers (Carboni et al 2018; Shrestha and Shrestha 2019).

Institutions, governance, and other indirect drivers of change

In line with recent literature reviews (Martín-López et al 2019), the number of direct and inferred references to indirect drivers of change was also low in our assessment. References to indirect drivers pertained primarily to economic and demographic factors, with differences between mountain systems. Literature information on governance and policy frameworks covered various instruments but was most specific about PAs and financial instruments. The importance given to PAs in the literature reflects the role of PA designation as a flagship contribution toward safeguarding nature in mountains, despite major shortcomings including gaps in coverage and mismatches with areas of high conservation value (Rodríguez-Rodríguez et al 2011; Elsen et al 2018). The references to payment for ecosystem services schemes, particularly in the literature pertaining to the Andes and to a lesser extent to the East African mountains and the Himalaya, is consistent with their increasing application in these regions (see Martín-López et al 2019 for references).

SDGs and Aichi targets

The relatively higher number of references to notions of sustainable development in the Andes might reflect the importance of the holistic concept of *buen vivir* ("living well") in the political and scientific agendas of Bolivia and Ecuador, in particular (Vanhulst and Beling 2014), to which about half of the selected publications pertained. The importance of life on land (SDG 15) and climate action (SDG 13) in the assembled literature is in line with previous observations of an influence of life on land (SDG 15) on climate action (SDG 13) and vice versa (Ehrensperger et al 2019). It also supports previous calls for addressing environmental and climate issues together (Wymann Von Dach et al 2018). The importance of zero hunger (SDG 2) in the Himalaya, in turn, is exemplified by results from Nepal (Wymann Von Dach et al 2018). Differences in the importance of individual SDGs between mountain systems confirm the need for localized research and analyses at subnational and regional scale (Kulonen et al 2019), which can be facilitated by methods such as the SDG synergies approach (Barquet et al 2019). Context sensitivity is a main concern toward practical applications and the translation of findings on SDG interactions into concrete policy advice (Breuer et al 2019).

Methodology

The methodology we applied has some limitations. First, our literature assessment was based on a subset of articles published in English, of which we read only the abstracts. Accordingly, additional content pertaining to the various dimensions we assessed may have been included in the full articles. Second, with our focus on mountain biodiversity, the literature was first filtered to include only publications pertaining to nature and ecosystems. The output therefore reflects a topical prioritization of research on nature and people. Accordingly, comparatively many publications referred to or explicitly mentioned habitat ecosystem services and the SDG life on land (15), and the statistics on the numbers of publications assessed do not reflect the absolute number of publications addressing human wellbeing or governance and indirect drivers in mountains. A search without filters would have provided a more holistic view of ongoing research with a balanced emphasis for the social and societal components of the IPBES framework but would have yielded an unmanageable number of publications. Moreover, papers selected based on search terms for governance, indirect drivers, and dimensions of human wellbeing often do not establish an informative link with nature, biodiversity, and ecosystems.

Third, we might have missed a nonnegligible number of publications pertaining to the mountain systems of interest because of insufficient or inappropriate georeferencing. The inclusion of individual mountain ranges in the search string, which we did for the East African mountains with their relatively few individual mountain ranges (see *Supplemental material*, Table S2 for the lists of search strings: https://doi.org/10.1659/MRD-JOURNAL-D-19-00075.1.S1), would partly address this issue. However, given the number of mountain ranges in individual systems such as the Andes and the absence of a standardized hierarchy of mountain ranges within systems, this is impossible. Both better and more systematic georeferencing of papers based on meaningful standards and specific geographic search engines (eg JournalMap; http://www.journalmap.org) could help to overcome geographic biases in literature searches (Karl et al 2013).

Fourth, we also performed our comparative analysis on information that was not always explicit but inferred during the coding of the abstracts. In particular, as the SDGs were not included in the search terms, information pertaining to them was mostly inferred. However, this coding was performed for all 4 systems by the same person and the results were coherent with recent publications (Martín-López et al 2019). Fifth, our choice of search terms and of sampling method means that our results give information about ongoing research and not strictly about the actual relationship between nature and people. However, it is likely that the research priorities reflect, at least partly, real relationships.

Finally, the application of a biodiversity lens and, even more so, the adoption of the IPBES framework quite certainly influenced the type of knowledge we assessed. The IPBES framework serves as a powerful tool to guide and organize data acquisition with a focus on biodiversity, facilitate comparisons, deliver global recommendations, and enable the uptake of mountain-specific knowledge on biodiversity and ecosystems into global narratives. However, the adoption of standardized categories (eg of drivers or ecosystem services) in a general integrative framework (Díaz et al 2015) entails a certain loss of information. This information includes nuanced, detailed, and management- as well as policy-relevant information at pertinent scales, which is particularly needed in heterogeneous and complex mountain social–ecological systems. Accordingly, taking into account further conceptualizations of social–ecological systems, such as the conceptual model proposed by Klein et al (2019) or the general framework developed by Ostrom (2009), might grant access to more actionable forms of knowledge. This might particularly be the case for the model of Klein et al (2019). This model is specific to mountains and concentrates on some of their distinct characteristics, on particular paradoxes emerging from nonlinear interactions among these characteristics, and on the distinction between sustained and episodic drivers that affect mountain social–ecological systems at different temporal and spatial scales.

Research recommendations

Based on our comparative content analysis across mountain systems, as well as our assessment of the literature, we identify several opportunities to improve our knowledge and systematic understanding of the various components of the IPBES framework and of their interlinkages in mountains.

Recommendation 1: improving biodiversity information

- *Premise:* The lack of systematic information on the state of and trends in a wide range of species and species groups represents a challenge for the interpretation of how global change affects mountains and their wildlife, and for predicting future changes and informing future assessments. Importantly, it also represents a major challenge for reporting on the importance of biodiversity for ecosystem functions and services (Eisenhauer et al 2016) and for sustainable development (Blicharska et al 2019).

- *Direction:* We reiterate previous calls for a better geographic and taxonomic coverage in mountain biodiversity research (Payne et al 2017; Crouzat et al 2019) and encourage the informed choice and consistent use of specific measures and indicators of biodiversity and ecosystems. The systematic reporting on the link between nature and NCPs, which is key to informing biodiversity management, is contingent on detailed and standardized information on biodiversity.
- *Option:* The indicators adopted in the post-2020 global biodiversity framework of the CBD could be included and online platforms, such as the Mountain Portal of the Global Mountain Biodiversity Assessment (http://www.mountainbiodiversity.org), could serve as hosting infrastructures for such information.
- *Remark:* We acknowledge that considerable information on species and ecosystems resides in sources that we have not included here.

Recommendation 2: generating spatially explicit knowledge on ecosystem services

- *Premise:* The diversity of ecosystem services that mountains support or provide, and the importance of trade-offs between (bundles of) services, both within and between ecosystem types, were recurrent topics in the assembled literature. This illustrates the interest given to ecosystem services research in the mountain science community (see also Martín-López et al 2019).
- *Direction:* Given the need for spatially explicit knowledge about ecosystem service supply and demand, bundles, trade-offs, and flows (Schirpke, Candiago, et al 2019; Schirpke, Tappeiner, et al 2019) in environmental decision-making (Vannier et al 2019), we encourage this community to adopt standardized (eg Grêt-Regamey et al 2014) and transdisciplinary (Grêt-Regamey et al 2013; Scolozzi et al 2019; Vannier et al 2019) approaches to generate and deliver management-relevant knowledge on ecosystem services at scale.

Recommendation 3: integrating knowledge and action along elevational gradients

- *Premise:* Both the comparative content analysis and the literature assessment provided evidence for a tight coupling between ecosystem types and services as well as global change drivers.
- *Direction:* We recommend that mountain research account for the succession of ecosystem types along elevational gradients by adopting commonly used life zone classifications (eg Körner et al 2011) in appropriate study designs and in reporting study outcomes. Informed recommendations for the long-term management of mountain landscapes call for the integration of knowledge along elevational gradients to account for cascading effects of individual interventions and for the flow of goods, resources, and services along mountain slopes.
- *Options:* In this context, concepts and models of mountain social–ecological systems (Altaweel et al 2016; Klein et al 2019) and initiatives, such as Mountain Social Ecological Observatory Networks (Alessa et al 2018), the Zones Ateliers Alpes (http://www.za-alpes.org/) or the Trajectories project (https://trajectories.univ-grenoble-alpes.fr/), appear to be useful integration frameworks, both spatially and temporally, as well as in terms of methodologies, disciplines, and stakeholders (Alessa et al 2018; Grêt-Regamey et al 2019).
- *Remark:* Similar calls for a landscape perspective to account for the impact of upstream activities on downstream areas have recently been formulated (Makino et al 2019).

Recommendation 4: generating knowledge on interacting effects of global change drivers

- *Premise:* Although only a limited number of publications addressed more than 1 driver of change, the literature we assessed offered various examples that drivers of change rarely act alone.
- *Direction:* We join other authors (eg Martín-López et al 2019) in encouraging more research on the interactive effects of multiple drivers of change on mountain biodiversity and ecosystems, and indirectly on ecosystem services.

Recommendation 5: generating knowledge relevant for transformative action toward sustainable mountain development

- *Direction:* We encourage the generation of synthetic and "actionable knowledge" that guides future data collection, informs policy, affects negotiations, and supports decision-making and action on the ground.
- *Options:*
  - The IPBES framework could be used in combination with other (mountain-specific) conceptual models of social–ecological systems.
  - Upscaling syntheses, such as the present one, to the global scale could offer a baseline for developing global agendas toward sustaining the environmental commons (Messerli et al 2019) in mountains worldwide and for revisiting mountain work programs such as the one historically developed by the CBD (Conference of the Parties decision VII/27; https://www.cbd.int/decisions/?dec=VII/27).
  - Contributing with case studies, knowledge, and experiences to shared databases such as those developed by the land science community (World Overview of Conservation Approaches and Technologies, https://www.wocat.net/; Global Collaboration Engine, http://globe.umbc.edu/) or in the context of climate change adaptation (weADAPT, https://www.weadapt.org/) could support mitigation, innovation, and decision-making processes at scale.

Recommendation 6: addressing knowledge gaps by using comprehensive concepts and codesigned approaches

- *Premise:* Knowledge gaps need to be overcome by adopting standardized frameworks and novel approaches.

- *Direction:* We call for the use of comprehensive conceptual frameworks such as the one of IPBES (Díaz et al 2015) to improve interdisciplinary research and for the codesign of knowledge with stakeholders and actors engaged at the nexus between nature and people in mountains (eg Grêt-Regamey et al 2013, 2019; Vannier et al 2019).

Conclusion

Understanding the relationship between nature and people particular to mountain social–ecological systems is key to the formulation of long-term sustainable mountain development strategies. Our comparative analysis of literature contents across mountain systems allowed us to detect regional patterns in the current state of research and knowledge on the relationship between nature and people. It revealed considerable differences between mountain systems in the relative importance attributed in the literature to different elements of this relationship as well as gaps in knowledge. This led us to derive recommendations and options for mountain researchers to inform science-based and biodiversity-explicit management and sustainable development strategies for mountains.

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REFERENCES

Alessa L, Kliskey A, Gosz J, Griffith D, Ziegler A. 2018. MtnSEON and social–ecological systems science in complex mountain landscapes. *Frontiers in Ecology and the Environment* 16(S1):S4–S10. https://doi.org/10.1002/fee.1753.
Altaweel M, Virapongse A, Griffith D, Alessa L, Kliskey A. 2016. A typology for complex social-ecological systems in mountain communities. *Sustainability: Science, Practice, & Policy* 11(2):1–13.
Barquet K, Trimmer C, Sturesson A, Joyce B, Jambal D. 2019. *Piloting the SDG Synergies Approach in Mongolia*. Stockholm, Sweden: Stockholm Environment Institute.
Blicharska M, Smithers RJ, Mikusiński G, Rönnbäck P, Harrison PA, Nilsson M, Sutherland WJ. 2019. Biodiversity's contributions to sustainable development. *Nature Sustainability* 2(12):1083–1093. https://doi.org/10.1038/s41893-019-0417-9.
Breuer A, Janetschek H, Malerba D. 2019. Translating Sustainable Development Goal (SDG) interdependencies into policy advice. *Sustainability* 11(7):2092. https://doi.org/10.3390/su11072092.
Carboni M, Guéguen M, Barros C, Georges D, Boulangeat I, Douzet R, Dullinger S, Klonner G, van Kleunen M, Essl F, et al. 2018. Simulating plant invasion dynamics in mountain ecosystems under global change scenarios. *Global Change Biology* 24(1):e289–e302. https://doi.org/10.1111/gcb.13879.
Chakraborty A. 2019. Mountains as vulnerable places: a global synthesis of changing mountain systems in the Anthropocene. *GeoJournal*. Published 30 September 2019. https://doi.org/10.1007/s10708-019-10079-1.
Crouzat E, Zawada M, Grigulis K, Lavorel S. 2019. Design and implementation of a national ecosystem assessment – Insights from the French mountain systems' experience. *Ecosystems and People* 15(1):288–302. https://doi.org/10.1080/26395916.2019.1674383.
Csardi G, Nepusz T. 2006. The igraph software package for complex network research. *InterJournal, Complex Systems* 1695.
Dalampira E, Nastis SA. 2019. Mapping Sustainable Development Goals: a network analysis framework. First published: 02 July 2019. *Sustainable Development*. https://doi.org/10.1002/sd.1964.
Díaz S, Demissew S, Carabias J, Joly C, Lonsdale M, Ash N, Larigauderie A, Adhikari JR, Arico S, Baldi A, et al. 2015. The IPBES Conceptual Framework — connecting nature and people. *Current Opinion in Environmental Sustainability* 14:1–16. https://doi.org/10.1016/j.cosust.2014.11.002.
Díaz S, Pascual U, Stenseke M, Martín-López B, Watson RT, Molnár Z, Hill R, Chan KMA, Baste IA, Brauman KA, et al. 2018. Assessing nature's contributions to people. *Science* 359(6373):270–272. https://doi.org/10.1126/science.aap8826.
Egelston A, Cook S, Nguyen T, Shaffer S. 2019. Networks for the future: A mathematical network analysis of the partnership data for Sustainable Development Goals. *Sustainability* 11(19):5511. https://doi.org/10.3390/su11195511.
Ehrensperger A, de Bremond A, Providoli I, Messerli P. 2019. Land system science and the 2030 agenda: Exploring knowledge that supports sustainability transformation. *Current Opinion in Environmental Sustainability* 38:68–76. https://doi.org/10.1016/j.cosust.2019.04.006.
Eisenhauer N, Barnes AD, Cesarz S, Craven D, Ferlian O, Gottschall F, Hines J, Sendek A, Siebert J, Thakur MP, et al. 2016. Biodiversity–ecosystem function experiments reveal the mechanisms underlying the consequences of biodiversity change in real world ecosystems. *Journal of Vegetation Science* 27(5):1061–1070. https://doi.org/10.1111/jvs.12435.
Elsen PR, Monahan WB, Merenlender AM. 2018. Global patterns of protection of elevational gradients in mountain ranges. *Proceedings of the National Academy of Sciences of the United States of America* 115(23):6004–6009. https://doi.org/10.1073/pnas.1720141115.
FAO [Food and Agriculture Organization]. 2015. *Mapping the Vulnerability of Mountain Peoples to Food Insecurity*. Rome, Italy: FAO.
Gleeson EH, von Dach SW, Flint CG, Greenwood GB, Price MF, Balsiger J, Nolin A, Vanacker V. 2016. Mountains of our future earth: Defining priorities for mountain research — A synthesis from the 2015 Perth III conference. *Mountain Research and Development* 36(4):537–548. https://doi.org/10.1659/MRD-JOURNAL-D-16-00094.1.
Grêt-Regamey A, Brunner SH, Altwegg J, Christen M, Bebi P. 2013. Integrating expert knowledge into mapping ecosystem services trade-offs for sustainable forest management. *Ecology and Society* 18(3):34.
Grêt-Regamey A, Brunner SH, Kienast F. 2012. Mountain ecosystem services: Who cares? *Mountain Research and Development* 32(S1):S23–S34. https://doi.org/10.1659/MRD-JOURNAL-D-10-00115.S1.
Grêt-Regamey A, Huber SH, Huber R. 2019. Actors' diversity and the resilience of social-ecological systems to global change. *Nature Sustainability* 2(4):290–297. https://doi.org/10.1038/s41893-019-0236-z.
Grêt-Regamey A, Weibel B, Bagstad KJ, Ferrari M, Geneletti D, Klug H, Schirpke U, Tappeiner U. 2014. On the effects of scale for ecosystem services mapping. *PLOS ONE* 9(12):e112601. https://doi.org/10.1371/journal.pone.0112601.
IPBES [Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services]. 2018a. *The IPBES Regional Assessment Report on Biodiversity and Ecosystem Services for Africa*. Archer E, Dziba L, Mulongoy KJ, Maoela MA, Walters M, editors. Bonn, Germany: Secretariat of the IPBES.
IPBES [Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services]. 2018b. *The IPBES Regional Assessment Report on Biodiversity and Ecosystem Services for Asia and the Pacific*. Karki M, Senaratna Sellamuttu S, Okayasu S, Suzuki W, editors. Bonn, Germany: Secretariat of the IPBES.
IPBES [Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services]. 2018c. *The IPBES Regional Assessment Report on Biodiversity and Ecosystem Services for Europe and Central Asia*. Rounsevell M, Fischer M, Torre-Marin Rando A, Mader A, editors. Bonn, Germany: Secretariat of the IPBES.
IPBES [Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services]. 2018d. *The IPBES Regional Assessment Report on Biodiversity and Ecosystem Services for the Americas*. Rice J, Seixas CS, Zaccagnini ME, Bedoya-Gaitán M, Valderrama N, editors. Bonn, Germany: Secretariat of the IPBES.
Karl JW, Gillan JK, Herrick JE. 2013. Geographic searching for ecological studies: A new frontier. *Trends in Ecology and Evolution* 28(7):383–384. https://doi.org/10.1016/j.tree.2013.05.001.
Klein JA, Tucker CM, Nolin AW, Hopping KA, Reid RS, Steger C, Grêt-Regamey A, Lavorel S, Müller B, Yeh ET, et al. 2019. Catalyzing transformations to sustainability in the world's mountains. *Earth's Future* 7(5):2018EF001024. https://doi.org/10.1029/2018EF001024.
Körner C, Jetz W, Paulsen J, Payne D, Rudmann-Maurer K, Spehn EM. 2017. A global inventory of mountains for bio-geographical applications. *Alpine Botany* 127(1):1–15. https://doi.org/10.1007/s00035-016-0182-6.
Körner C, Ohsawa M. 2006. Mountain systems. *In:* Hasan R, Scholes RJ, Ash N, editors. *Ecosystems and Human Well-Being: Current State and Trends*. Washington, DC: Island Press, pp 681–716.
Körner C, Paulsen J, Spehn EM. 2011. A definition of mountains and their bioclimatic belts for global comparisons of biodiversity data. *Alpine Botany* 121:73–78. https://doi.org/10.1007/s00035-011-0094-4.
Kulonen A, Adler C, Bracher C, Wymann von Dach S. 2019. Spatial context matters in monitoring and reporting on Sustainable Development Goals: Reflections based on research in mountain regions. *GAIA – Ecological Perspectives for Science and Society* 28(2):90–94. https://doi.org/10.14512/gaia.28.2.5.
Lusseau D, Mancini F. 2019. Income-based variation in Sustainable Development Goal interaction networks. *Nature Sustainability* 2(3):242–247. https://doi.org/10.1038/s41893-019-0231-4.
Makino Y, Manuelli S, Hook L. 2019. Accelerating the movement for mountain peoples and policies. *Science* 365(6458):1084–1086. https://doi.org/10.1126/science.aay8855.
Martín-López B, Leister I, Lorenzo Cruz P, Palomo I, Grêt-Regamey A, Harrison PA, Lavorel S, Locatelli B, Luque S, Walz A. 2019. Nature's contributions to people in mountains: a review. *PLOS ONE* 14(6):e0217847. https://doi.org/10.1371/journal.pone.0217847.
Mayoux P. 1996. *Fleurs des Pyrénées faciles à reconnaître*. Rando Éditions.

MEA [Millennium Ecosystem Assessment]. 2005. *Ecosystems and Human Well-Being: Synthesis*. Washington, DC: Island Press.
Messerli B, Ives JD. 1997. *Mountains of the World: A Global Priority*. New York, NY: Parthenon Publishing.
Messerli P, Kim EM, Lutz W, Moatti JP, Richardson K, Saidam M, Smith D, Eloundou-Enyegue P, Foli E, Glassman A, et al. 2019. Expansion of sustainability science needed for the SDGs. *Nature Sustainability* 2(10):892–894. https://doi.org/10.1038/s41893-019-0394-z.
Ostrom E. 2009. A general framework for analyzing sustainability of social-ecological systems. *Science* 325(5939):419–422.
Payne D, Spehn EM, Snethlage M, Fischer M. 2017. Opportunities for research on mountain biodiversity under global change. *Current Opinion in Environmental Sustainability* 29:40–47. https://doi.org/10.1016/j.cosust.2017.11.001.
Rodríguez-Rodríguez D, Bomhard B, Butchart SHM, Foster MN. 2011. Progress towards international targets for protected area coverage in mountains: A multi-scale assessment. *Biological Conservation* 144(12):2978–2983.
Schirpke U, Candiago S, Egarter Vigl L, Jäger H, Labadini A, Marsoner T, Meisch C, Tasser E, Tappeiner U. 2019. Integrating supply, flow and demand to enhance the understanding of interactions among multiple ecosystem services. *Science of the Total Environment* 651:928–941. https://doi.org/10.1016/J.SCITOTENV.2018.09.235.
Schirpke U, Tappeiner U, Tasser E. 2019. A transnational perspective of global and regional ecosystem service flows from and to mountain regions. *Scientific Reports* 9(1):1–11. https://doi.org/10.1038/s41598-019-43229-z.
Scolozzi R, Schirpke U, Geneletti D. 2019. Enhancing ecosystem services management in protected areas through participatory system dynamics modelling. *Landscape Online* 73:1–17. https://doi.org/10.3097/LO.201973.
Secretariat of the Convention on Biological Diversity. 2003. *Status and Trends of, and Threats to, Mountain Biodiversity, Marine, Coastal and Inland Water Ecosystems: Abstracts of Poster Presentations at the Eighth Meeting of the Subsidiary Body on Scientific, Technical and Technological Advice of the CBD*. CBD Technical Series No. 8. Montreal, Canada: Secretariat of the Convention on Biological Diversity.
Shrestha UB, Shrestha BB. 2019. Climate change amplifies plant invasion hotspots in Nepal. *Diversity and Distributions* 25(10):1599–1612. https://doi.org/10.1111/ddi.12963.
Vanhulst J, Beling AE. 2014. Buen vivir: emergent discourse within or beyond sustainable development? *Ecological Economics* 101:54–63. https://doi.org/10.1016/j.ecolecon.2014.02.017.
Vannier C, Lasseur R, Crouzat E, Byczek C, Lafond V, Cordonnier T, Longaretti PY, Lavorel S. 2019. Mapping ecosystem services bundles in a heterogeneous mountain region. *Ecosystems and People* 15(1):74–88. https://doi.org/10.1080/26395916.2019.1570971.
Warnes G, Bolker B, Bonebakker L, Gentleman R, Liaw W, Lumley T, Maechler M, Magnusson A, Moeller S, Schwartz M, et al. 2019. gplots: *Various R Programming Tools for Plotting Data. R package version 3.0.1.1*. https://rdrr.io/cran/gplots/; accessed on 20 December 2019.
Wester P, Mishra A, Mukherji A, Shrestha AB, editors. 2019. *The Hindu Kush Himalaya Assessment – Mountain, Climate, Sustainability and People*. Cham, Switzerland: Springer International Publishing.
Wymann Von Dach S, Bachmann F, Borsdorf A, Kohler T, Jurek M, Sharma E. 2016. *Investing in Sustainable Mountain Development. Opportunities, Resources and Benefits*. Bern, Switzerland: Centre for Development and Environment.
Wymann Von Dach S, Bracher CP, Peralvo M, Perez K, Adler C. 2018. *Leaving No One in Mountains Behind: Localizing the SDGs for Resilience of Mountain People and Ecosystems*. Bern, Switzerland: Centre for Development and Environment and Mountain Research Initiative, with Bern Open Publishing.

Supplemental material

TABLE S1 Ecosystem services (nature's contributions to people) details.
TABLE S2 Search strings used for the literature selection.
TABLE S3 Values used in coding abstracts.
APPENDIX S1 Literature-based assessment.

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