Towards a set of Essential Biodiversity Variables for assessing change in mountains globally

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Abstract

Mountain regions harbor unique and rich biodiversity, forming an important part of our global life support system. This rich biodiversity underpins the ecological intactness and functioning of mountain ecosystems, which are imperative for the provision of key ecosystem services. A considerable amount of data are required to assess ecological intactness and ecosystem functioning and, given the profound anthropogenic pressures many mountain regions are being subjected to, are urgently needed. Yet data on mountain biodiversity remain lacking. The Essential Biodiversity Variables (EBVs) framework can help focus efforts related to detecting, investigating, predicting, and managing global biodiversity change, but has not yet been considered in the context of mountains. Here, we review key biological processes and physical phenomena that strongly influence mountain biodiversity and ecosystems, and seek to elucidate their associations with potential mountain EBVs. We identify seven mountain-relevant EBVs of high relevance: *Species composition, Species abundance, Species distribution, Ecosystem fragmentation, Ecosystem extent, Ecosystem heterogeneity* and *Ecosystem functional type*. Our proposed set of mountain-relevant EBVs can help ensure that the most critical drivers and responses of mountain biodiversity change are well tracked and understood. If implemented, the selected EBVs can contribute to relevant information for management and policy interventions that halt mountain biodiversity loss and maintain functional mountain ecosystems.

Keywords:

Essential Biodiversity Variables (EBVs); mountains; monitoring; global change; ecosystems; biodiversity; Earth Observations; GEO Mountains

Introduction

Biodiversity loss and its impact on ecological intactness is a global challenge. Repeated calls have been made to generate and share relevant data to monitor changes and support the effective conservation, management, and sustainable use of ecosystems worldwide. To respond effectively to biodiversity loss, the harmonization of biodiversity monitoring approaches and improving access to the corresponding datasets have been recognized as being of great importance, leading to the concept of Essential Biodiversity Variables (EBVs) (Geijzendorffer et al. 2016, Hoffmann et al. 2014, Jetz et al. 2019, Pereira et al. 2010). In short, EBVs can be considered a minimum set of fundamental biodiversity measurements that are required to detect and report on biodiversity change (O'Connor et al. 2020, Pereira et al. 2013, Pettorelli et al. 2016).

EBV datasets take the form of spatio-temporal layers (or data cubes) that characterise the state of biodiversity, and from which specific biodiversity indicators or metrics can be computed (Hardisty et al. 2019, Schmeller et al. 2017). Besides their use in science and for the visualization and communication of change in biodiversity, such indicators are extremely useful and regularly applied in policy-oriented biodiversity assessments. Two global biodiversity initiatives, the Intergovernmental Science-Policy Platform for Biodiversity and Ecosystem Services (IPBES) (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services 2019, Schmeller and Bridgewater 2021), and the Kunming-Montreal Global Biodiversity Framework of the United Nations – aim to identify and address the key drivers of biodiversity loss. For that policy related work, a strategy on how the complex ecological processes and the resulting biodiversity changes can be more effectively monitored and communicated to policy makers is needed (Geijzendorffer et al. 2016).

EBVs were initially conceived to be globally applicable, with no distinction between domains (terrestrial, freshwater, and coastal/marine) or ecological settings (e.g. mountains, wetlands, tundra, and deserts). Whilst this brings clear benefits of consistency and comparability, generic EBVs may not be well suited to provide relevant information on biodiversity and its changes within specific domains and ecological settings. Here we explore the relevance of the EBV concept in a mountain context, where both the need for biodiversity data collection and the associated difficulties are well established.

Nevertheless, there are several reasons why more and well-targeted biodiversity data from mountain environments are still needed. First, because of the sharp change in climatic and life conditions in mountains they host a uniquely high diversity of species (Körner 2004), of which a high proportion are endemic (Rahbek et al. 2019) as a result of the biogeographic isolation under which mountain populations of plants and animals have evolved. Second, mountain biodiversity fulfils many important functions, including slope stabilisation or drinking water storage and hydrological regulation (Körner 2004). Third, mountain biodiversity is essential to sustainable development (Payne et al. 2020c) and repeated calls have been made to recognize the importance of mountain biodiversity and its protection in international agendas. However, despite political commitments towards the safeguarding of mountains (e.g. the 2030 Agenda for Sustainable Development and its 17 Sustainable Development Goals (SDGs), including mountain-specific SDG targets: https://sdgs.un.org/topics/mountains), mountains and their biodiversity continue to be subjected to multiple anthropogenic pressures. These pressures include climate and land-use change, pollution, the rapid spread of invasive species, the over-exploitation of natural resources, and demographic change (Comer et al. 2022, Payne et al. 2020a, Schmeller et al. 2022, Thornton et al. 2022a). Their impacts have already induced major responses across mountain socio-ecological systems (Mayer et al. 2022, Payne et al. 2020c) and are associated with high risks for ecosystem health as well as human health and well-being (Adler 2022, Schmeller et al. 2020, 2022).

The challenges associated with biodiversity data collection in mountains arise primarily from remoteness and topography. Remoteness affects accessibility, logistics, and costs. Accordingly, despite the development of certain successful *in situ* observation programmes and networks such as GLORIA (Grabherr et al. 2000), MIREN (Haider et al. 2021), and the iLTER (Haase et al. 2016), the coordinated coverage of *in situ* biodiversity monitoring efforts in mountains remains limited. Despite recent improvements in remote sensing technologies, the spatial resolutions of the resultant products are often insufficient in mountains (Pettorelli et al. 2016, Randin et al. 2020, Rumpf et al. 2022). Additional challenges associated with data collection arise from the fact that many responses of mountain species and ecosystems to drivers may be non-linear or involve tipping points. For instance, biodiversity declines are likely to accelerate when different drivers are mutually amplifying, e.g. rising temperatures coupled with drought (Chen et al. 2011), or fish introduction and chemical pollution in aquatic ecosystems (Machate et al. 2022), calling for the adaptation of monitoring schemes. Likewise, species-specific traits such as body size (Brose et al. 2008, 2006) and phenology (Barnosky et al. 2012), as well as shifts in species distributions (Parmesan and Yohe 2003, Steinbauer et al. 2018, Balint et al. 2011, Engler et al. 2011), may provide early indications of critical changes in biodiversity and ecosystems (Schmeller et al. 2018); appropriate monitoring is required if such changes are to be detected in a timely fashion (Figure 1).

In summary, given past and ongoing changes in mountain ecosystems and their biodiversity as well as predicted future changes, there is an urgent need to improve their monitoring and assessment. The numerous challenges associated with biodiversity data collection in mountain environments call for the identification and prioritization of biodiversity-related variables for the world's mountains that are possible to be measured in such settings. By enabling the detection of biodiversity change (Pereira et al. 2010, Schmeller et al. 2015, 2017), EBVs can serve as an early warning of irreversible changes in ecosystems (Schmeller et al. 2018) and provide a useful initial reference framework from which to prioritize the measurement of biodiversity variables that hold particular importance in a mountain context. A set of mountain EBVs could therefore increase the relevance and efficiency of biodiversity data collection, while considering local requirements (Kühl et al. 2020), improve coordination, collaboration and information exchange. It will further improve reporting and forecasting of biodiversity change, and hence enhancing mitigation and adaptation efforts (Thornton et al. 2021b). At the same time, mountain EBVs must accommodate diverse data collection efforts and stakeholder groups (Bingham et al. 2017, Kühl et al. 2020), and evolve with ongoing progress in measurement technologies (Randin et al. 2020).

The establishment of a globally applicable and coherent approach that harmonizes existing approaches and data, identifies future monitoring priorities, and meets mountain-specific observational requirements should help considerably to address existing deficiencies in data coverage and biodiversity assessment-relevant information (Figure 1).

Key biological and biophysical processes that determine or influence mountain biodiversity

Our contribution builds upon a workshop hosted by the Mountain Research Initiative as a contribution to the Global Earth Observation (GEO) Network on Observations and Information in Mountain Environments (GEO Mountains), held in February 2020. At the workshop, extensive discussions were held amongst 23 global experts, following a similar approach taken to identify and propose relevant Essential Climate Variables ECVs in mountains (Thornton et al 2021). For EBVs, we first identify and review several key processes and associated phenomena which determine or strongly influence mountain biodiversity. We then proceed to explore the extent to which candidate mountain EBVs could provide information pertaining to those key processes. Importantly, the candidate EBVs were not limited to those already included in the general framework (Pereira et al. 2013), but additions were made where deemed necessary, such as EBVs on community productivity, treeline position, evapotranspiration and soil carbon stock. Finally, a subset of high-priority mountain-relevant EBVs was selected based on their combined informativeness in relation to the key processes (Figure 2).

Ultimately, we identified 12 biological, biophysical, and abiotic key processes that exert a strong influence on mountain ecosystems. These key mountain processes are changes in: *1) species distribution; 2) biotic interactions; 3) species traits; 4) genetic processes; 5) taxonomic composition; 6) functional composition; 7) soil erosion; 8) disturbances; 9) nutrient dynamics; 10) water quantity and quality dynamics; 11) carbon dynamics; and 12) ecosystem distribution.* We then proceeded to assess the relationship of these key processes on distribution, composition, and condition of mountain biodiversity at genetic, species, and ecosystem levels.

Changes in species distribution areas

The geographic ranges of species and their changes through time are fundamental ecological characteristics (Gaston and Fuller 2009). From a conservation perspective, information on species distributions underlies almost every aspect of biodiversity management (Franklin 2010), with geographic range, for example, being used as a predictor of extinction risk in the International Union for Conservation of Nature (IUCN) Red List. Although climate is often considered to be the main determinant of species distribution (Thomas et al. 2006, Woodward 1987), geographic distributions are also locally structured by extinction and colonization events arising from spatial variation and interactions between demographic rates, local population persistence, the distribution of suitable habitats, dispersal and interspecific interactions (Pulliam 2000). Many species outposts, which in mountain environments often are located at their cold limits, are reacting strongly to climate warming and are thus acting as sentinels of climate change impacts.

In the short term, rapid changes in species abundance and distribution are likely to result from the direct effects of climatic factors on species phenology, growth rate and demography (Chuine 2010). In the longer term, altered temperature and precipitation regimes will also offer (temporally limited) opportunities for some species to shift their range and colonize new, higher elevation areas, thereby altering the community compositions, functions and services of mountain ecosystems (Alexander et al. 2018, 2015). In accordance with general distribution trends, range shifts and declines of species in mountain habitats have already been observed (Freeman et al. 2018, Lenoir et al. 2010, Rumpf et al. 2018). However, many of these changes occur at rates that lag expected rates, and there is considerable variation in change rates between species (Alexander et al. 2018). Changes in species distribution with different strategies within and among montane belts inevitably lead to considerable changes in community functional trait composition that might have major consequences for montane ecosystem functioning (Winfree et al. 2015). This is especially relevant in mountains, since functional redundancy is considered to be lower than in lowland ecosystems (Körner 2004).

Changes in community taxonomic composition

The composition of a biotic community is the assemblage of taxa and their abundance within a given area. Community composition depends on both abiotic habitat conditions (i.e., abiotic filtering) and biotic interactions between co-occurring individuals of the same species, different species, or organism groups. Beyond tropical mountains, with increasing elevation and in topography-influenced habitats such as ridges and snow beds, abiotic factors, especially climatic ones like temperature, increase in relative importance over biotic ones as drivers of community composition (Normand et al. 2009, Randin et al. 2009). The composition of alpine and subnival ecosystems is strongly determined by low-temperature stress. The relaxation of this abiotic filter, therefore, leads to a change in species abundance and compositional community changes (Nagy and Grabherr 2009, Pauli and Halloy 2019, Rumpf et al. 2018, Steinbauer et al. 2018).

Because animal and plant communities in mountains are composed of species with different climatic niches, shifts in species composition can indicate directional changes, for example shifts towards more warmth-demanding communities (i.e. thermophilization; Gottfried et al. 2012) following changes in thermal or soil moisture conditions. Besides such abiotic drivers, which also include disturbances and nutrient dynamics, changes in community composition are strongly related to biotic processes such as biotic interactions, adaptation, and species range shifts. Changes in community composition are expected to occur more rapidly than species' range shifts since species turnover over time is preceded by changes in the abundance of resident species (Lamprecht et al. 2018, Rumpf et al. 2018).

Changes in genetic and phenotypic diversity

Species are composed of genetically differentiated populations that can evolve and change over time. Genetic diversity – the variation in genetic composition within and across populations – is therefore a fundamental dimension of biodiversity, determining species composition and ecosystem functioning. How contemporary genetic diversity is maintained and partitioned within species depends primarily on the movement among populations (gene flow), the emergence of new mutations, random demographic processes (e.g. genetic drift), and adaptive processes (e.g. natural selection). As high-elevation ecosystems are more isolated than low-elevation ones, genetic differentiation between isolated populations of the same species might be more pronounced in mountains as compared to lowlands (Steinbauer et al. 2016, Valbuena-Ureña et al. 2018).

The steep environmental gradients in mountains can impose strong selection on populations to adapt to local conditions despite being connected by gene flow (Halbritter et al. 2018, Keller et al. 2013, Clausen et al. 1948). The great spatial heterogeneity of mountain landscapes means that local adaptation can occur at fine scales (Fischer et al. 2011, Hamann et al. 2016). Mountains can thus host high levels of (adaptive) genetic diversity within small areas. In increasing the fitness of local populations, adaptation is important for population persistence and the extent of species distributions, especially in a mountain context under strong climate change impacts. By affecting the performance of populations and their capacity to persist or spread to new habitats, the capacity for plasticity is an important trait for coping with environmental heterogeneity in mountains (Gruber et al. 2013, Ligarreto et al. 2011). Phenotypic plasticity also plays a crucial role in adaptation and functional diversity within communities (Körner 2004), and consequently in the survival and competitive abilities of species and the functioning of ecosystems in the context of rapid climate change (Schmeller et al. 2022).

Changes in species interactions

Species are embedded in more or less complex ecosystems in which they interact with various competitors, natural enemies, mutualists, and commensalists. These interactions are key regulators of population sizes and dynamics, and strongly govern individual species' distributions as well as the composition of local communities. Species interactions are also the basis for ecosystem functioning (Tylianakis et al. 2011). In mountains, competition with warm-adapted species, rather than warm temperatures themselves, is thought to restrict many alpine plants to cooler, high elevation environments (Alexander et al. 2018, Paquette and Hargreaves 2021, Vittoz et al. 2009). More generally, competition is thought to strongly shape community assemblies at lower elevations, while positive interactions ("facilitation") become more prevalent at higher elevations (Callaway et al. 2002). Facilitation can be especially important in arid mountain regions, where "nurse plants" provide shelter for more heat- and drought-sensitive species (Anthelme et al. 2014, Bucher and Rosbakh 2021).

Nonetheless, competition certainly plays a key role for both plant (Brooker 2006, Lyu and Alexander 2022) and animal populations (Chan et al. 2019) at high elevations.

Other types of interaction also vary with elevation. For example, herbivory pressure tends to decline with increasing elevation (Rasmann et al. 2014). As a consequence some high elevation plants are less able to cope with herbivory (Pellissier et al. 2012), and hence with grazing pressure from livestock. Similarly, pollinator abundance is lower at higher elevations, meaning that plants typically rely on a smaller number of more generalist insects to provide pollination services (Inouye 2020). These distribution patterns are highly relevant for the future biodiversity of mountains because they imply that changes in biotic interactions might mediate some impacts of environmental change on mountain biodiversity (Alexander et al. 2018). The effects of changing environmental conditions on biodiversity may not be exclusively negative. For example, novel herbivores might help promote diversity by preferentially feeding on dominant high elevation plants, and so help subordinate species to persist despite climate warming (Descombes et al. 2020).

Changes in functional trait composition

Functional trait composition refers to the distribution of intra- and interspecific traits, life forms and strategies among and between co-occurring species in a community or food web (McGill et al. 2006). Functional traits comprise any morphological, behavioural, physiological, or phenological features that define the performance of individuals under specific environmental conditions (Violle et al. 2007). In mountains, plants and animals possess specialized traits to survive temperature extremes, the high fraction of ultraviolet light, short growing periods and frequent strong winds. These environmental adaptations, via functional traits, are closely linked to niche partitioning, species interactions and community composition (Villéger et al. 2008). Therefore, the changes in functional traits can be used to infer mountain species responses to the changes in their (a)biotic environments, species interactions and community assembly process (‘response’ traits; Villéger et al. 2008). Changes in functional traits also have effects on mountain ecosystem services such as carbon sequestration and water runoff (‘effect’ traits; Fernandez and Kennedy 2015, Hébert et al. 2016). Temporal shifts in functional traits at population, species, or community levels can be used to monitor and predict the effects of global change on alpine biodiversity (Byamungu et al. 2021, Gallagher et al. 2013, Yin et al. 2020). They allow changes in crucial mountain ecosystem services and functions such as productivity, carbon sequestration, resource efficiency and soil stability to be inferred (Lavorel and Grigulis 2012).

Changes in nutrient dynamics

Due to their essential role in biochemical processes, nutrients constrain the function and shape of ecosystem community structure. Nutrient influences can be magnified at higher elevations (Dantas de Paula et al. 2021), and by the high spatio-temporal variability of nutrients in such settings. In response to the unique challenges posed by the physical nature of mountain environments, soil-plant systems have developed various strategies to deal with limited nutrient availability in space and time. Nitrogen (N) and phosphorus (P) in particular underpin the fundamental processes of metabolism, growth and reproduction and are therefore required in large amounts by all organisms.

The apparent scarcity of N and P in alpine systems is rarely due to low abundance, but is more frequently a consequence of their reduced biological availability. Competition for these nutrients can be high, as can the range of strategies and adaptations to access or maximise nutrient uptake. Critical N loads for alpine systems have rarely been explored (Bowman et al. 2012), and the interactive effects of climate change are poorly understood (Matteodo et al. 2016). Since high mountain soils are commonly nutrient-poor, anthropogenic fertilisation effects, especially when combined with climate warming, can have a strong impact on species composition (Staude et al. 2022).

Unlike N, phosphorus has no gaseous phase, and so all P in mountain systems is derived either from local erosion of bedrock or mineral matter (mineral dissolution), local introduction from livestock, dust or aerosol deposition, or in precipitation. P dynamics can create high functional diversity within alpine environments and furthermore have the potential to rapidly alter ecosystem processes through community turnover induced by climate or land use change. With respect to general nutrient cycling, snow in particular plays an important role in many mountain environments (Edwards et al. 2007, Litaor et al. 2005, Venn and Thomas 2021). Changes in snow cover persistence and snowmelt timing as a consequence of climate change are likely to increase the nutrient stress on alpine communities (Baptist et al. 2010). Snow and ice-related specialisms may become more limited in extent, and snow-free periods in winter may enhance nutrient limitations, creating greater temporal variance in ecosystem processes whilst many systems begin to homogenise in spatial terms.

Changes in carbon dynamics

Mountain carbon dynamics are strongly heterogeneous in space and time (Fu et al. 2015, Körner 2021). Nevertheless, specific adaptations and constraints in mountain ecosystems make it possible to infer the functioning of mountain carbon cycling. The net difference between photosynthesis and plant respiration dictates the total carbon eventually stored in plant biomass. Plants in high mountain regions are often temperature limited (Li et al. 2018) and therefore often have higher respiration rates

(Larigauderie and Körner 1995) and slower growth rates (Fu et al. 2015) than lowland plants.

Generally, particulate organic matter (POM) in mountain soils is structurally complex and difficult to break-down (Chomel et al. 2016), and consequently constitutes a high proportion (~20%–60%) of the total organic matter (Budge et al. 2011, Leifeld et al. 2009, Saenger et al. 2015). POM is decomposed by soil microorganisms into dissolved organic matter. Organic matter decomposition in mountains is also temperature-limited (Schinner 1982), which contributes to a build-up of soil organic matter (Hagedorn et al. 2019). However, as mountain soil microbes produce cold-adapted enzymes that work efficiently at low temperatures (Jing et al. 2018, Margesin et al. 2009), even minor warming could cause a large increase in POM decomposition, possibly altering mountain soil carbon stocks (Benbi et al. 2014) enhanced nutrient (e.g., nitrogen) availability (Chen et al. 2020, Kudernatsch et al. 2008) may further increase decomposition.

Changes in water dynamics and quality

Hydrological conditions in mountainous terrain, both at the surface and in the subsurface, exhibit considerable spatial and temporal variability across a range of scales (Thornton et al. 2021b, 2022b). In many regions, snowmelt, ice-melt and groundwater discharge sustain mountain stream and river flows through dryer and hotter periods or seasons. As such, these water sources play a crucial role in ensuring ecological streamflow and supporting in-stream ecosystems (Somers and McKenzie 2020, Thornton et al. 2021a). Many mountain streams and torrents, especially lower order ones, are ephemeral or intermittent, and host biota that are adapted to or can tolerate such conditions (Stubbington et al. 2017). Mountain lakes, wetlands, and many alpine meadows often hold particularly high ecological importance (Gandarillas et al. 2016, Hayashi 2020, Ortiz-Álvarez et al. 2018).

Extreme hydrological events can cause major ecological disturbances (Herbst and Cooper 2010) via elevated sediment concentrations (Cover et al. 2010), increased input of micropollutants to acute toxic levels (Machate et al. 2022), or through changes to channel morphology (Molnar et al. 2010). Outside such extreme events, water quality is primarily controlled by lithology and subsurface water residence times and flow pathways. Indeed, certain hydro-chemical conditions can support exceptionally high levels of biodiversity (Cantonati et al. 2020). Mountain forests are able to sustain high rates of evapotranspiration under drought conditions (Mastrotheodoros et al. 2020), and spatio-temporal patterns of near-surface soil moisture strongly influence terrestrial species distributions (Giaccone et al. 2019). Climate change is likely to affect all aforementioned aspects of mountain hydrological systems. Other crucial hydrological variables for biodiversity such as water temperatures will likewise respond (Michel et al. 2020).

Changes in ecosystem distributions

Earth's land- and seascapes are composed of ecosystems. Ecosystems are generally recognized as comprising distinct physical environments and their associated biota (Bailey 1996, Sayre et al. 2020b). The organismal makeup of an ecosystem is a function of both the basic environmental drivers (e.g., climate, substrate type, etc.) that determine which organisms can occur there based on tolerances and life history requirements. Other factors such as geographic isolation, disturbance regime, glacial histories, and evolutionary history also play an important role (Dirnböck et al. 2011, Hewitt 2001, 2004, Schönswetter et al. 2005). Many topographically isolated mountain systems only have highly fragmented alpine areas, but outstandingly high proportions of small-ranged species, resulting in exceptionally high extinction risks (Mendoza-Fernández et al. 2022).

In mountains, the structuring factors drive rapid modification of macro-climates to meso- and micro-climates and barriers to dispersal of propagules (Pepin et al. 2015). Reactions to these changes, however, depend on the temperature and hydrological tolerance of species. The differences in reaction time and movement abilities will disassociate existing communities, the basis of ecosystems. Hence, changes through elevation-dependent climate warming (Palazzi et al. 2019, Pepin et al. 2022, Rangwala and Miller 2012) and its effects on the cryosphere (e.g. snow phenology; (Wang et al. 2022) and hydrosphere is predicted to result in changes in ecosystem distribution (Wang et al. 2022). As ecosystem distribution and redistribution are closely linked to functional composition and species distribution these processes will see increased pressures and changes with increasing climate change impacts (Chiang et al. 2014).

Identifying mountain relevant EBVs

Based on our review of key mountain processes, their interactions, feedback mechanisms, and major abiotic influences, we proceeded to first identify those existing EBVs that hold high relevance in mountains (Figure 2). We then identified several additional candidate EBVs that could help advance our understanding of mountain biodiversity change. We thus considered the following 15 variables as candidate EBVs in a mountain context: *Allelic Diversity, Species Abundance, Species Distribution, Species Growth (Morphology), Movement, Phenology, Species Composition, Community Productivity (Net Primary Production), Ecosystem Composition by Functional Type, Ecosystem Extent, Ecosystem Fragmentation, Ecosystem*

Heterogeneity, Evapotranspiration, Soil Carbon Stock and *Treeline Position* (Table 1). Thereafter, we developed a consensus ranking that represents the perceived importance of each EBV with respect to the information content that their corresponding datasets could cumulatively provide with respect to all key biological processes and their abiotic influences.

To relate the 12 key mountain processes with our 15 candidate mountain EBVs, we constructed a table characterising the strength of their bi-directional pairwise dependencies. In this way, we were able to distinguish between EBVs that are related to individual or multiple processes (Figure 2). From this, we derived an aggregated information power (AIP) score, thus prioritizing those candidate EBVs which support the understanding of multiple processes over those more specific EBVs that are associated to a smaller number of processes. In this expert elicitation approach, we sought parsimony in the selection of variables for presumed reduction in monitoring costs. The 12 biological, biophysical and abiotic processes were weighted equally.

The selected processes that drive the functioning of mountain ecosystems through their impacts on biodiversity on the different biological levels (from genetic to ecosystem) formed the basis of our scoring system. As alluded above, we assigned scores based on the perceived importance of the information that could be provided by each candidate mountain EBV to understand the key mountain processes and influences. We applied four categories: no importance (Score 0), low importance (Score 1), medium importance (Score 2) and high importance (Score 3). Below, using allelic diversity as an example, we illustrate this scoring system:

Low importance (Score 1): Allelic diversity contributes to the key ecological/biophysical process, but low allelic diversity may not have a negative impact on the process and in turn it itself is impacted little by the key process in question;

Medium importance (Score 2): Allelic diversity contributes to the key process, but does not drive it alone, nor is allelic diversity solely driven by the key process in question;

High importance (Score 3): Allelic diversity is imperative for the key process to operate, and the key process under question is itself strongly driving allelic diversity.

Our reasoning follows the logic that, for instance, levels of allelic diversity strongly and directly result from population genetic processes, and equally allelic diversity itself shapes population genetic processes (and so the combination received a score of 3). On the other hand, population genetic processes are one of many factors influencing species abundance (Score 2), and will therefore also influence community composition, but the contribution of population genetic processes relative to other processes is likely to be much weaker at the community scale (Score 1). Biotic interactions can strongly regulate species abundances at local scales (Score 3), and therefore also influence biodiversity patterns at larger scales and regulate ecosystem processes to a greater or lesser extent. However, the contribution of biotic interactions at larger scales, for example to species distributions, may be reduced relative to other factors (Score 2), or might not need to be considered to understand some ecosystem properties such as ecosystem fragmentation (Score 1). We followed the same approach and logic throughout our assessment (i.e., for the other candidate variables). These importance scores were added to the count of the number of processes to which a candidate mountain EBV contributes information, leading to the enumeration of the AIP score.

We subsequently selected the highest AIP scoring EBVs and checked their interdependence to assess whether some EBVs themselves inform other EBVs (Figure 2). For this we used a second scoring system, from 0 to 4. A score of 4 would indicate that two EBVs are entirely redundant, a score of 3 highly redundant, 2 redundant, 1 little redundant, 0 not redundant (i.e. fully independent).

The consensus building process

Our assessment was based on the consensus agreement of all experts (N = 23). Based on the AIP distribution (Figure 3), we identified the seven most informative candidate mountain EBVs. A noticeable step in the AIP distribution was observed at the value of 29, and therefore this was chosen as the importance or informativeness threshold for a candidate variable to be considered a priority mountain EBV. The seven variables are: *Species composition, Species abundance, Ecosystem fragmentation, Ecosystem extent, Ecosystem heterogeneity, Species distribution* and *Ecosystem functional type* (Figure 3).

Among these seven selected mountain EBVs, our interdependence analysis shows some redundancy of species abundance, species composition, ecosystem composition by functional type and ecosystem heterogeneity (Table 2). Ecosystem heterogeneity depends on nearly all other EBVs and could easily be deduced from other EBVs, once their corresponding data are available and standardised.

The policy relevance of mountain EBVs – ways forward

Our assessment yielded seven mountain-relevant EBVs, three of which relate to species and community levels (*Species abundance, Species distribution, Species composition*), and four to the ecosystem level (*Ecosystem composition by functional type, Ecosystem extent, Ecosystem fragmentation, Ecosystem heterogeneity*). We suggest that data collection regarding these EBVs should be prioritized to effectively document and evaluate on-going and extensive changes in mountain biodiversity and key mountain processes. Among the proposed set of EBVs, ecosystem heterogeneity captures a particularly high number of mountain processes (N = 11/12), and is highly linked with six other EBVs. This variable has a high potential to be monitored by remote sensing, which would allow large scale and relatively rapid data acquisition and high temporal resolution (Rocchini et al. 2016, Turner et al. 2015).

The three species-level EBVs (composition, distribution and abundance) are globally applicable and are also of high interest in a mountain context. In lowlands, these EBVs are generally well informed (Schmeller et al. 2018) and efforts need to be stepped up in mountains to provide equally high-quality data (Jetz et al. 2019). The three ecosystem structure related EBVs (extent, fragmentation, and heterogeneity), and the EBV in the ecosystem function class (ecosystem composition by functional type) are intended to provide standardized characterizations of different dimensions of ecosystem extent and condition. These EBVs can be informed by remote sensing, and in light of the continued increase of the spatial resolution of remote sensing data (Pettorelli et al. 2016, Skidmore et al. 2021), we recommend to increase efforts to quickly operationalize these EBVs to document environmental changes in mountains.

Although most of the EBVs in our mountain set are universal, specific requirements or attributes of the respective measurements may differ considerably between mountainous and non-mountainous terrain, as well as within individual mountainous areas. Data from those approaches might be difficult to compare and compile over larger spatial scales, potentially introducing substantial biases in mountain biodiversity assessments. In particular, higher spatial resolution is typically required in mountainous terrain to capture the dominant scale of variability due to the spatial compression of climate life zones. As such, mountain EBVs may not provide a one-fits-all solution to the urgent need to inform environmental governance about ongoing threats to global mountain ecosystems.

Recent years have seen major developments in the global landscape with regards to biodiversity and conservation policy. Perhaps most notably, the 15th Conference of Parties to the UN Convention on Biological Diversity in 2022 saw the adoption of the Kunming-Montreal Global Biodiversity Framework (GBF). The GBF, as well as the ecosystem accounting framework of the United Nations System for Environmental and Economic Reporting (UNSEEA), require national level reporting of some of our proposed mountain EBVs, such as ecosystem extent and condition.

The set of mountain-relevant EBVs proposed here can thus potentially be seen as a part of a broader framework which includes variables related to both climate (Thornton et al. 2021b) and society. Datasets corresponding to these complementary variables that explicitly consider the specificities of mountain areas and could eventually represent potentially powerful information pools to identify the status and predict the evolution of mountain systems more broadly. In this sense, we hope that our proposed mountain EBVs will encourage collective reflection on both “establishing a culture of integration in biodiversity monitoring” (Perino et al. 2022), and considering biodiversity as a key component of mountain social-ecological systems. To realise this vision, further convergence and agreement is needed, and new monitoring programs may need to be co-designed to elucidate the integrated nature of mountain system dynamics.

This integration should not merely be data-oriented in purpose, but rather should recognise, work with, and interrelate the monitoring efforts made by diverse groups of stakeholders, where different motivations, resources, agendas, and mandates inevitably shape the legacies of these efforts (Kühl, et al 2020). As a network initiative, GEO Mountains is working towards this integration goal for the multiple and diverse components of mountain social-ecological systems. In addition, the Global Mountain Biodiversity Assessment (GMBA) links experts and data regarding all aspects of mountain biodiversity, contributing also to GEOSS and GEO Mountains. These scientific community-led efforts are, in turn, consistent with and respond to the Group on Earth Observations' own priorities in support of societal benefit areas, whereby Earth observations play a key role in decision making at all scales (Pettorelli et al. 2016). Such efforts are therefore well placed to ensure that the necessary specifications and/or translations of global agendas to guide appropriate coordinated monitoring efforts in mountains, including data integration and interoperability, are taken up at all levels. Meanwhile, our existing relationships with other networks, such as the World Network of Mountain Biosphere Reserves (https://www.mountainbiosphere.org) could provide an excellent opportunity for the framework to be implemented and refined.

Ultimately, the common language and means for data integration that can be facilitated through mountain EBVs should not only facilitate important scientific advances and monitoring efforts, but also support the science-policy dialogues upon which this type of collaborative work depends.

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Table 1: The full set of candidate mountain EBVs. The table gives the name of the candidate EBV, its definition, the EBV class as defined by GEO BON (Pereira Henrique Miguel et al. 2013), and important references for the EBV definition.

	Definition	**EBV class**	**References**
Allelic diversity	The average number of alleles per locus in a population of a given species and is an indicator of genetic differentiation.	Genetic composition	(Allendorf 1986, Pereira et al. 2013, Schmeller et al. 2018)
Species abundance	The number of individuals, the biomass or surface coverage of a species within a local population or a biological community at a given point in time.	Species populations	(Jetz et al. 2019, Schmeller et al. 2018, Turak et al. 2017)
Species distribution	The arrangement of a biological taxon in time and space.	Species populations	(Jetz et al. 2019)
Species Growth	The variation in species growth over space and time.	Species traits	(Cunningham and Read 2003)
Movement	Behaviour related to the spatial mobility of organisms, such as dispersal and migration.	Species traits	(Hawkes 2009)
Phenology	The presence, absence, date of appearance, or duration of seasonal recurring activities of organisms.	Species traits	(Schmeller et al. 2018, Tang et al. 2016)
Species Composition	The presence/absence and abundance of species in ecological assemblages.	Community composition	(Jetz et al. 2019)
Community productivity (Net Primary Production)	The rate at which energy is transformed into organic matter, primarily through photosynthesis.	Ecosystem functioning	(Melillo et al. 1993)
Ecosystem composition by functional type	The diversity of the functional traits in ecological assemblages.	Ecosystem functioning / Community composition	(Paruelo et al. 2001)

Ecosystem extent	The horizontal (spatial) distribution of discrete ecosystem units.	Ecosystem structure	(Payne et al. 2020b, Sayre et al. 2020a)
Ecosystem fragmentation	A measure of the emergence of spatial discontinuities (fragmentation) in an ecosystem.	Ecosystem structure	(Reed et al. 1996, Saunders et al. 1991, Sayre and Hansen 2017)
Ecosystem heterogeneity	The degree of variability of the ecosystem in space and time.	Ecosystem structure	(Cadenasso et al. 2006, Schmeller et al. 2018)
Treeline position	The spatial position of the low-temperature determined treeline.	Ecosystem structure/traits	(Bader et al. 2021, Paulsen and Körner 2014)
Evapotranspiration	Net flux in water from the land surface to the atmosphere, including evaporation from water bodies, bare soil, and leaves, as well as transpiration by vegetation.	Ecosystem traits	(Goulden and Bales 2014)
Soil carbon stock	Organic and inorganic carbon stored in the soil, resulting from the balance between soil carbon inputs and outputs.	Ecosystem traits	(Sjögersten et al. 2011)

Figure legends:

Figure 1: The conceptual framework of the present study, linking the different levels of biodiversity to key mountain processes. The different biodiversity levels, from genes to ecosystem, can be measured with a variety of Essential Biodiversity Variables (EBVs) through space and time (Pereira et al. 2013). These EBVs can provide information on several key mountain processes, such as water or nutrient dynamics, population genetic processes, and ecosystem redistribution, because these processes change ecosystems and biodiversity. We elucidate the relationships between EBVs and key mountain processes to define a set of EBVs that are most relevant for mountain contexts. Such an EBV set will improve data coverage and biodiversity assessment-relevant information for mountain biodiversity and will aid the global policy arena in decision making (e.g. the United Nations Environmental Programme).

Figure 2: Approach in evaluating candidate mountain EBVs. We first reviewed which key mountain process exist (see the review section of our article), identified relevant EBVs from the list put forward by Pereira et al. (2013) and complemented this list with additional candidate mountain EBVs. We then crossed the information of key mountain processes and the ability of candidate EBVs to inform those processes. By calculating the AIP (see Material and Method section for details), we selected the seven most informative candidate mountain EBVs. The final step of our work was to understand how the different EBVs are interrelated and which ones might be most useful to operationalize with priority. Find more details in the main text.

Figure 3: List of Essential Biodiversity Variables and the key mountain processes they inform. The table illustrates the main conclusions of our expert-

based assessment of importance of the candidate variables to provide information regarding the key biological, biophysical, and abiotic processes. This assessment yields two important results: 1) the importance of each candidate mountain EBV in providing information regarding every key mountain process (no importance (Score 0), low importance (Score 1), medium importance (Score 2), high importance (Score 3)), and 2) the degree to which individual candidate EBVs inform multiple processes (defined as *N* processes). These two dimensions of information power are captured as an aggregate importance score (AIP) for each candidate EBV, where the importance score is added to the number of processes each candidate EBV informs.

Figure 1:

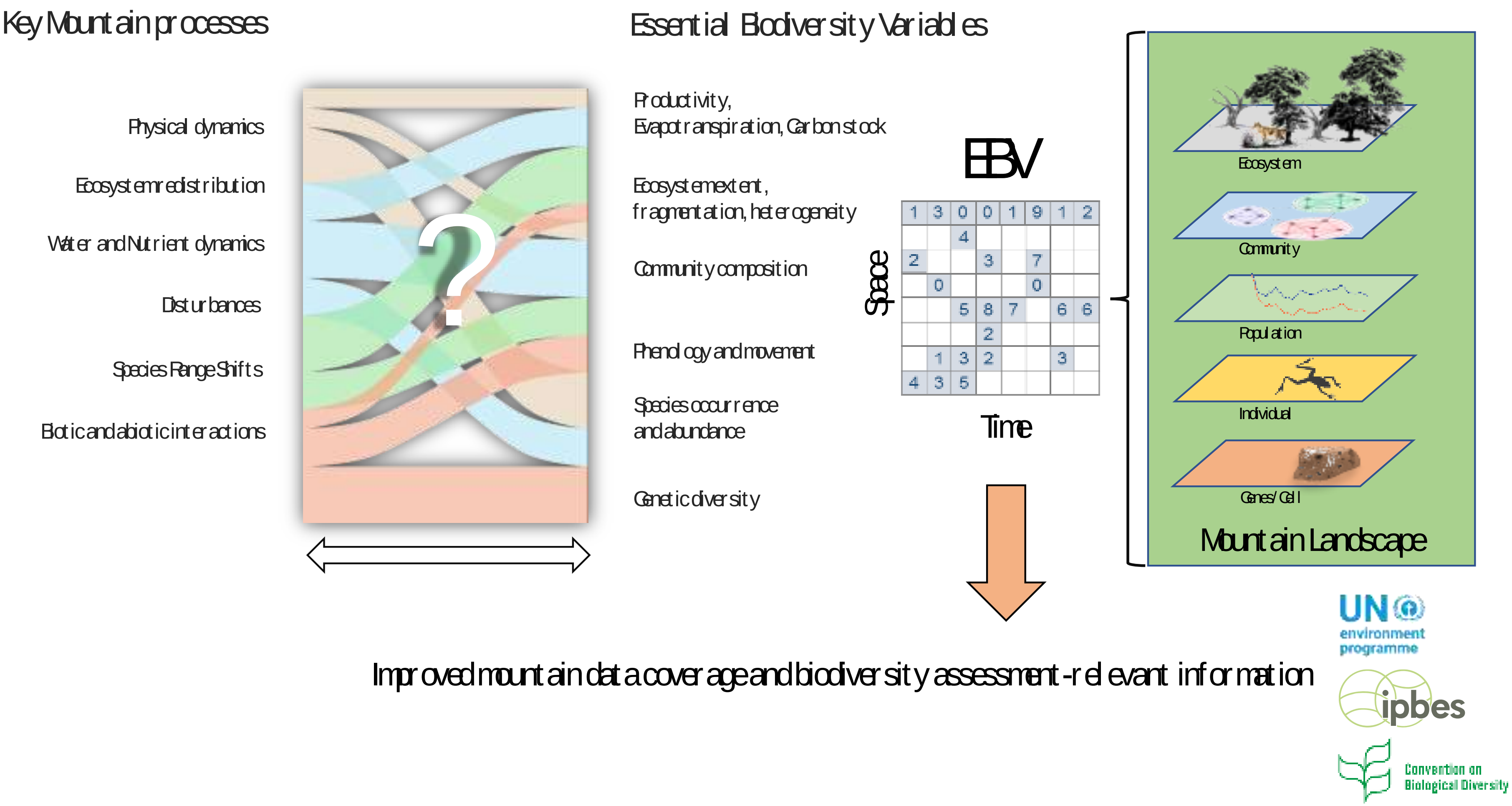
Key Mountain processes
Physical dynamics
Ecosystem redistribution
Water and Nutrient dynamics
Disturbances
Species Range Shifts
Biotic and abiotic interactions
Essential Biodiversity Variables
Productivity,
Evapotranspiration, Carbon stock
Ecosystem extent,
fragmentation, heterogeneity
Community composition
Phenology and movement
Species occurrence
and abundance
Genetic diversity
EBV
Space
Time
Ecosystem
Community
Population
Individual
Genes/Cell
Mountain Landscape
Improved mountain data coverage and biodiversity assessment-relevant information
UN environment programme
ipbes
Convention on
Biological Diversity

Figure 2:

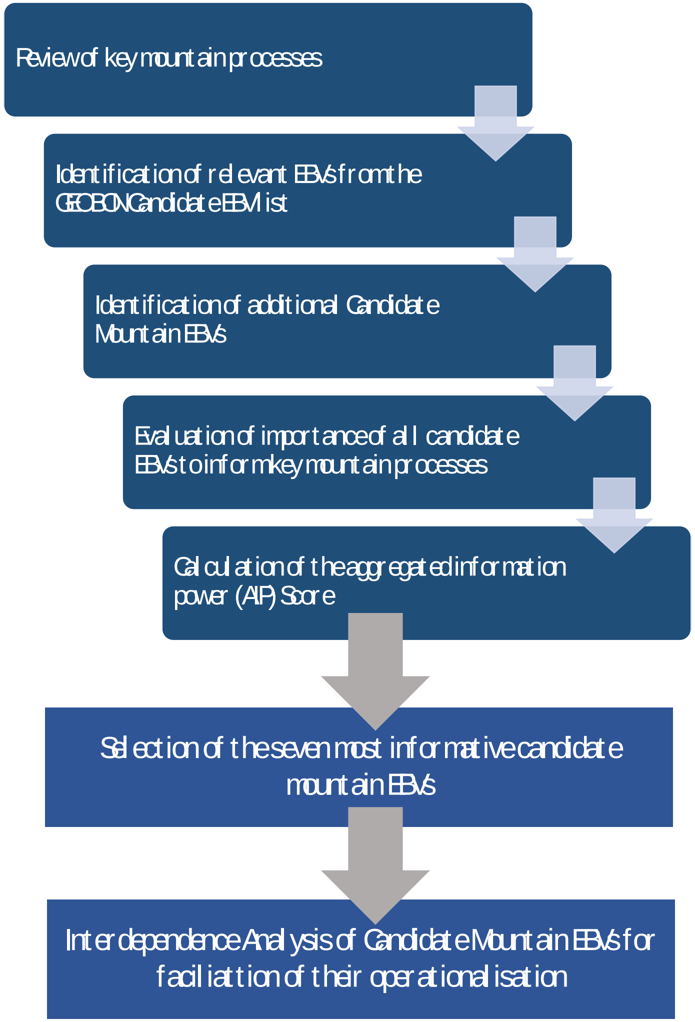
Review of key mountain processes
Identification of relevant EBVs from the GEOBON Candidate EBV list
Identification of additional Candidate Mountain EBVs
Evaluation of importance of all candidate EBVs to inform key mountain processes
Calculation of the aggregated information power (AIP) Score
Selection of the seven most informative candidate mountain EBVs
Interdependence Analysis of Candidate Mountain EBVs for faciliation of their operationalisation

Figure 3:

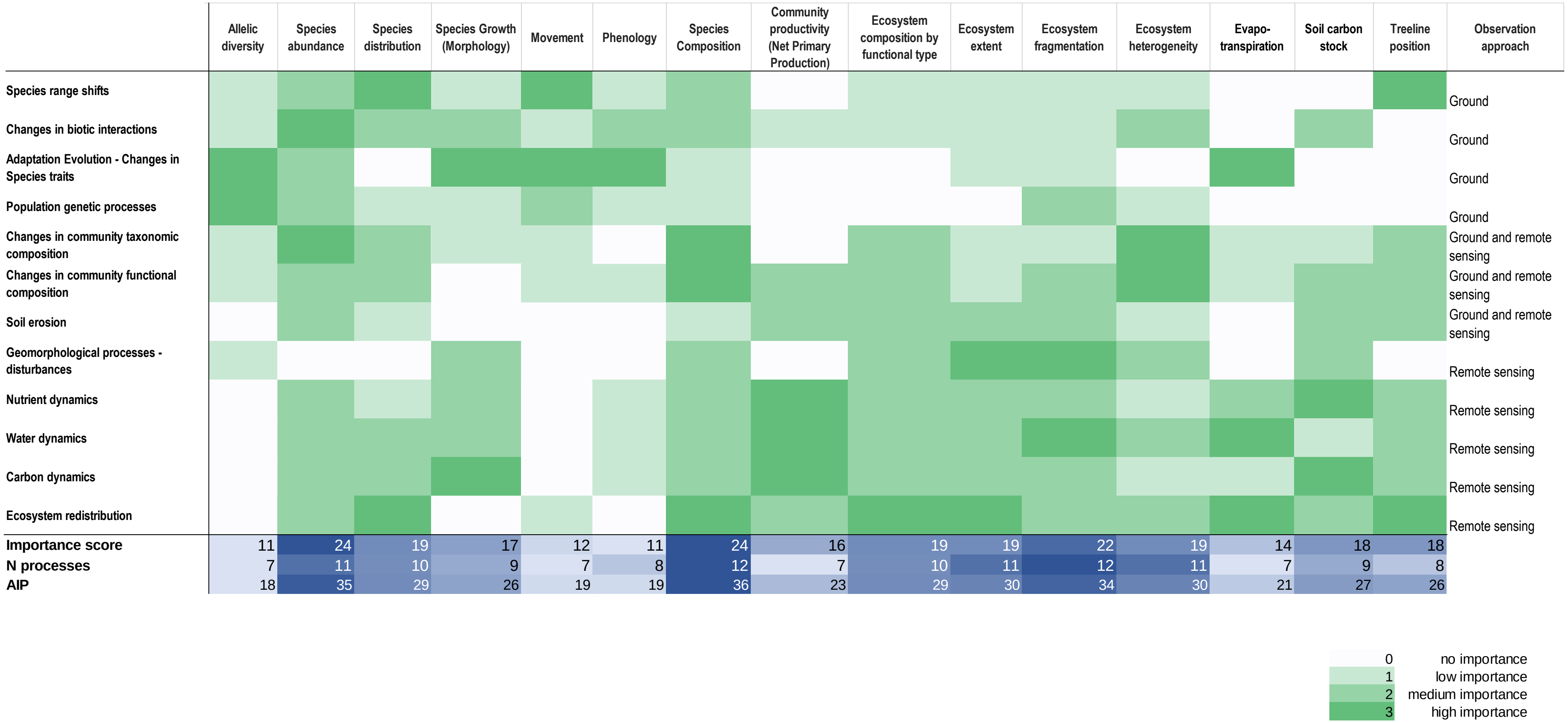
Allelic diversity
Species abundance
Species distribution
Species Growth (Morphology)
Movement
Phenology
Species Composition
Community productivity (Net Primary Production)
Ecosystem composition by functional type
Ecosystem extent
Ecosystem fragmentation
Ecosystem heterogeneity
Evapo-transpiration
Soil carbon stock
Treeline position
Observation approach
Species range shifts
Changes in biotic interactions
Adaptation Evolution - Changes in Species traits
Population genetic processes
Changes in community taxonomic composition
Changes in community functional composition
Soil erosion
Geomorphological processes - disturbances
Nutrient dynamics
Water dynamics
Carbon dynamics
Ecosystem redistribution
Ground
Ground
Ground
Ground
Ground and remote sensing
Ground and remote sensing
Ground and remote sensing
Remote sensing
Remote sensing
Remote sensing
Remote sensing
Remote sensing
Importance score 11 24 19 17 12 11 24 16 19 19 22 19 14 18 18
N processes 7 11 10 9 7 8 12 7 10 11 12 11 7 9 8
AIP 18 35 29 26 19 19 36 23 29 30 34 30 21 27 26
0 no importance
1 low importance
2 medium importance
3 high importance

Table 2: Interdependence of the candidate mountain EBVs. Impact from top EBV on left EBV (upper triangle), impact from left EBV on top EBV (lower triangle). Empty circle = no redundancy (=fully independent), one quarter = low redundancy (score = 1), demi circle = redundant (score = 2), three quarter = highly redundant (score = 3), black circle = fully redundant (score = 4). See also Schmeller et al. (2018).

	Species abundance	Species distribution	Species Composition	Ecosystem composition by functional type	Ecosystem extent	Ecosystem fragmentation	Ecosystem heterogeneity
Species abundance		◑	◑	◑	◑	●	●
Species distribution	◑		●	●	◕	◔	◕
Species Composition	●	●		●	◔	◔	●
Ecosystem composition by functional type	◕	●	●		◔	◔	◕
Ecosystem extent	◔	◑	◔	◔		◔	◑
Ecosystem fragmentation	◔	○	○	◔	◑		●
Ecosystem heterogeneity	●	●	●	●	◑	●	