Alpine Botany
https://doi.org/10.1007/s00035-021-00265-8

SHORT COMMUNICATION

Mountain definitions and their consequences

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Received: 11 June 2021 / Accepted: 14 July 2021

Abstract
Mountains are rugged structures in the landscape that are difficult to delineate. Given that they host an overproportional fraction of biodiversity of high ecological and conservational value, conventions on what is mountainous and what not are in need. This short communication aims at explaining the differences among various popular mountain definitions. Defining mountainous terrain is key for global assessments of plant species richness in mountains and their likely responses to climatic change, as well as for assessing the human population density in and around mountainous terrain.

Keywords Biodiversity · Biogeography · Elevation · Geographical information systems · Alpine ecology

Biological aspects of mountain definitions

Whether an area belongs to mountains or not is a matter of definition and has substantial conservational and biogeographic implications. Despite often demanding climatic conditions, life in mountains, on average, is far more diverse than would be expected from the land area that they cover, and biodiversity of vertically structured land clearly exceeds that in nearby flat terrain in lowlands (Mutke and Barthlott 2005; Körner 2021). Not surprisingly, a third of all terrestrial protected areas include mountains (Körner and Ohsawa 2005). But, what is it that we call a mountain?

The central feature of mountains is the inclination of land, causing gravity in interaction with geology to structure the landscape, with the resulting topography, in turn, interacting with climate (solar radiation, wind, snow distribution and allocation of water and substrate) to create a rich habitat diversity. It is this habitat diversity that explains plant species richness in mountains (Körner 2004). Whatever mountain definition one choses, ruggedness of terrain (i.e., the elevation range within a defined gridded reference window) has to be the starting point. Both ruggedness and the rapid change of elevation (and thus climate) over short distances have repeatedly been addressed as the main determinants of climatic change effects on mountain biota (Loarie et al. 2009; Scherrer and Körner 2011). Taxa inhabiting rugged terrain are less at risk of losing habitats under climatic change than taxa that are confined to lowland terrain with no suitable habitats nearby to escape (Körner 2021). It is thus key for mountain biodiversity assessments to objectively identify mountain terrain and to quantify its extent in a reproducible way, employing geographical information systems such as in the Map of Life project (Jetz et al. 2012).

Inventories of mountain terrain published in this journal (Körner et al. 2011, 2017) arrived at 12.5% of the global land outside Antarctica belonging to mountainous terrain. This represents half of an earlier estimate (Kapos et al. 2000) and about one third of an even larger (30%) fraction of land recently attributed to mountainous terrain (Karagulle, et al. 2017; Sayre et al. 2018; Price et al. 2019). Catchment-based concepts, in turn, consider half of all land area to be influenced by mountains (Viviroli et al. 2020). It is very difficult for the biological research community to understand this diversity of statistics for what seems to be a common sense issue.

Here, we offer the shortest possible explanation of the different mountain concepts and their practical consequences when it comes to defining which fraction of biota or human population is associated with mountainous terrain. We show that no definition is right or wrong but that they differ in the extent of terrain included that falls outside rugged terrain *sensu* mountains.

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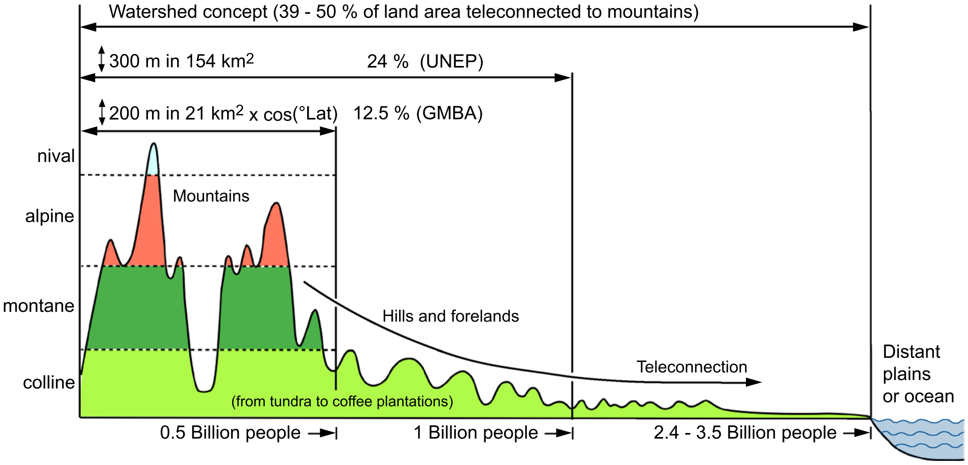

Fig. 1 Definitions of mountainous land by UNEP or GMBA based largely on ruggedness criteria (for details see the text). Note how the different definitions, and in particular the size of land area to which they are applied, affect the fraction of global mountainous terrain and the number of people considered living in the proximity or under some influence of mountains (for clarity the USGS definition that arrives at 30% land area is not shown here). The vertical amplitude (left) refers to a 3×3 grid of 30 arcsec, with the resulting binary ruggedness (yes or no) applied to different reference areas in the landscape (km^2)

Comparison of mountain definitions

Mountains have always been and remain difficult to define, not because of their ridges and tops, which are relatively easy to identify, but because it is difficult to define where exactly mountainous terrain grades into surrounding hills or flatland. What is regarded as a mountain by some people may appear to others as a hill (Smith and Mark 2003). Over the years, different definitions have been proposed to capture the spatial extent of mountainous areas (Meybeck et al. 2001; Sayre et al. 2018; Price et al. 2019). All have been extensively used for various applications, including calculations of food insecurity (Romeo et al. 2020) or of global biodiversity conservation indicators.

Currently, the approaches most commonly employed to define mountains are those by Kapos et al. (2000), Körner et al. (2011, 2017), and Karagulle et al. (2017) (Fig. 1). These approaches use combinations of geomorphometric parameters such as elevation, slope, ruggedness or relief, which are nowadays derived from digital elevation models (DEMs; in m or arc seconds), and attribute threshold values to decide which terrain is mountainous and which is not. Here, we briefly summarize the criteria applied by these definitions, explain why the resulting global areas of mountainous terrain differ, and discuss what this implies in practical terms.

To understand why all three definitions presented below account for relief (landform) or ruggedness (also roughness)—two terms that are typically used synonymously in the literature—it should be recalled that neither elevation as such nor a certain climate are useful for defining mountains. Elevation is not a useful criterion because high elevation areas, so-called tablelands, do not show a mountain topography. Climate is not one either, because mountains stretch across almost all climates. All definitions employ so-called Neighbour Analysis Windows (NAWs) of specific sizes, to which critical topographic parameters are assigned such as ruggedness or slope. In the different approaches, mountain terrain is defined by these parameters in combination with specific threshold values. All three definitions employ ruggedness as the maximum elevation range among 9 grid points separated by 30 arcsec (when combined with 'slope', slope is referred to as the steepest inclination amongst them). The parameter and threshold values, together with the resolution of the DEM and the size of the NAW, cause land to fall—or not—into the mountainous category. The below descriptions are simplifications and should provide non-GIS-expert users of global statistics or maps of mountainous terrain an idea of what is behind such definitions. We refer to the original texts for detail.

Mountain delineation by Kapos et al. (2000). This approach was developed for the United Nations Environmental Program (UNEP) through their World Conservation Monitoring Centre (WCMC) in an attempt to estimate the global area of mountain forests. Given this aim, this approach considers all land below 300 m elevation as too low to be included in mountainous terrain and it includes all land above 2500 m elevation irrespective of ruggedness. Using moving circular NAWs of a radius of 7 km (154 km^2), the land between 300 and 2500 m elevation is rated as mountainous in a 30″ DEM if the amplitude of elevation across a central grid of 3×3 cells either is > 300 m or if the slope across this grid window exceeds 2° between 1000 and 1500 m elevation, and 5° between 1500 and 2500 m elevation. By moving the large NAW cell by cell across the landscape and repeating this procedure, the results account for the topography at the resolution of the DEM and local results become smoothed over larger areas.

Mountain delineation by Körner et al. (2011). This delineation was developed by the Global Mountain Biodiversity Assessment (GMBA) as a reference for global biogeographic comparisons in mountains and for stratifying mountain terrain into climatic belts. This definition also uses a 3 × 3 grid of a 30″ DEM to calculate elevation ranges (over 1.8 × 1.8 = 3.4 km^2 × cos °Lat) and then applies a ruggedness threshold to delineate mountainous terrain. The ruggedness threshold representing mountainous terrain was set to 200 m across these 9 points. The result is then assigned to the coarser 2.5′ resolution grid (corresponding to 4.6 × 4.6 = 21.2 km^2 × cos °Lat) at which the climatic data were available in the WorldClim global climate database in 2011. By adopting the 2.5′ resolution, each 2.5′ window receives a unique ruggedness and climatic value.

Mountain delineation by Karagulle et al. (2017). This delineation proposed by the US Geological Survey (USGS) employs landform classes following a concept developed in the 1950s by Hammond (1954). Using the three basic landform attributes 'gentle slope' (a virtual mean inclination), local relief (i.e. ruggedness), and profile type, this approach arrives at 16 landform classes, of which four classes are considered to include mountains: high and low mountains, as well as scattered high and scattered low mountains (Sayre et al. 2018). Relief (ruggedness) is also first defined via a 3 × 3 cell grid (in a 30″ DEM) centred within a 6 km radius circle (113 km^2 moving NAW), and once relief (ruggedness) exceeds 300 m, the entire window is considered mountainous. The signal is then smoothed by moving the window in small steps across the landscape. A subdivision into 'low' and 'high' mountains is achieved by combining the slope (< or > 8%) and ruggedness (> or < 900 m) criteria. The subdivision into scattered high and low mountains is achieved by applying smaller test windows, all within the same NAW. The resulting four classes do not affect the overall mountainous area.

Based on the UNEP definition, regions, which include mountains, cover 24% of all land outside Antarctica (a value recently modified by Romeo et al. 2020), whereas they cover 12.5% based on the GMBA definition. The exclusion of land below 300 m and the inclusion of all tableland above 2500 m (irrespective of ruggedness) hardly contributes to the greater UNEP mountain area (Fig. 2). Differences are instead largely explained by the larger area (154 km^2 instead of 21 km^2) to which the ruggedness obtained from the central 3 × 3 grid points (30″ grid) is applied, which results in the inclusion of more hills and forelands in the UNEP definition. With the USGS approach, Sayre et al. (2018) arrive at a 30% global land area fraction outside Antarctica that includes mountain landforms. Similar to the UNEP approach, the larger area that includes mountain landforms results from the fact that relief exceeding the 300 m threshold is applied to larger NAWs. Thus, the three definitions mainly differ in the degree to which they include forelands and plains adjacent to mountains and they differ less in terms of the ruggedness criteria as such.

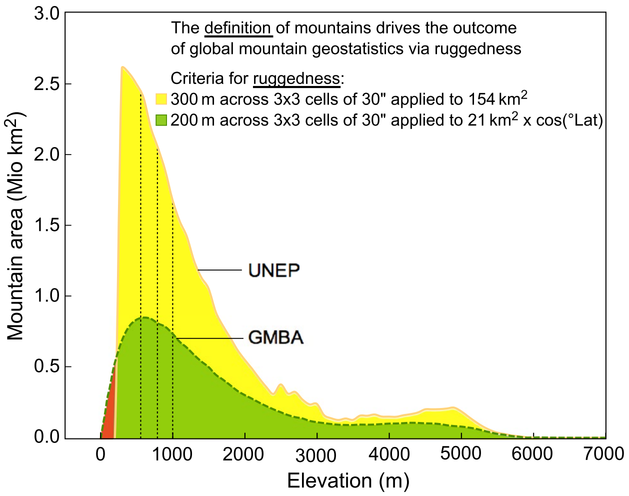

Fig. 2 Comparison of the two most popular mountain definitions (as depicted in Fig. 1). The dotted lines mark 600, 800 or 1000 m of elevation, illustrating that the differences between the two definitions largely emerge at low, commonly very warm life conditions. The red area (< 300 m elevation) is included by GMBA, but excluded by UNEP, which hardly affects the total mountainous area

Consequences of the different mountain definitions

The application of large NAWs increases the probability that large areas of flat or hilly land «skirts» around mountain ranges fall into the category of land considered mountainous. This, in turn, results in the inclusion of highly populated areas (including some mega-cities; Table 1). For instance, Bogota, Santiago de Chile, Salt Lake City, Ankara, Zurich, and Bern all fall into the category of 'mountain land' by the UNEP approach, but not by the GMBA approach. In the USGS approach, Geneva and even Hong Kong, Lima, and Barcelona and several other coastal mega-cities belong to 'mountain land'. On the other hand, the GMBA approach (as well as the UNEP and USGS ones) considers Kathmandu, La Paz, and Innsbruck as belonging to the mountainous land category, lining up with the evidence that many large cities are built on quite rugged terrain (Ehrlich et al. 2016). Hence, depending on the definition adopted, inhabitants of

Table 1 Urban population (in Millions) considered to be living in mountainous terrain by the GMBA approach only (second column), or by the UNEP and USGS approaches (n settlements per type; no difference between the last two definitions, hence, we show only one data column)

Population category in millions inhabitants	GMBA	UNEP or USGS
> 5	28	51
1–5	56	165
0.5–1	21	84
0.1–0.5	40	105
0–0.1	15	28
Total population captured by PPNE	161	432
Global total population in mountains	511	c. 1000–1500

The somewhat arbitrary position of the centroids of cities can influence such statistics. The data include the 7343 cities listed in the Populated Places layer of Natural Earth (PPNE; https://www.naturalearthdata.com/downloads/10m-cultural-vectors/10m-populated-places/) and accounts for 2.4 Billion people. Based on the GMBA definition, the biggest of these cities are Rio de Janeiro, Seoul, Chongqing, Guiyang, Busan, San Francisco, Cape Town, and Caracas. Based on the UNEP and USGS definition, they are: Lima, Bogota, Shenzhen, Hong Kong, Santiago, Belo Horizonte, Barcelona. These data illustrate that a large fraction of so-called mountain populations is statistically living in mega-cities by all definitions. Note, these statistics by PPNE include only a 30% sample of the global population

some of the richest cities on Earth (e.g. Zurich, Geneva) and of mega-cities statistically become ‘mountain people’ as if they were dwellers far up in the Himalayas or Andes. This is important, because mountain inhabitants are often considered vulnerable to food insecurity and other threats. All three approaches include intra-mountain valleys as ‘mountain land’, with such valleys often exhibiting a high degree of urbanization (Ehrlich et al. 2016). Here, we use human population data to illustrate the consequences of adopting the different definitions because no other (biological) global mountain inventories is available. Yet, these data make it clear that depending on the definition, areas that are at least twice as large as the actual mountainous terrain (in the widest sense) are treated as mountainous. Since even the less inclusive GMBA definition covers major urbanized areas and intra-mountain basins, the area to which mountain biota are attached (the montane, alpine, and nival belts) and to which human hardship of land use does apply covers clearly less than 10% of the land area outside Antarctica.

In addition to their ruggedness, the other common physical features that characterize all mountains are vertical gradients of temperature and atmospheric pressure (Körner 2007), which cause life conditions to be radically different between mountain regions and their (commonly lower elevation) forelands. Because of these large differences, the degree to which forelands are included or excluded from ‘mountain land’ affects all other attributes of areas considered to belong to the mountainous land category such as wild biota, human population, infrastructure etc. For example, on Kilimanjaro the mountain climate is very humid, but the immediate forelands, which are either included or excluded from the estimated regional mountain area depending on the definition, belong to dry savanna. Further, land above 1000 m can be glaciated in N-Scandinavia, whereas in Ethiopia and Colombia it is covered with coffee plantations. Hence, in Humboldt’s legacy (Körner and Spehn 2019), there is the need to go beyond topography and elevation when comparing life conditions in mountains and account for the actual climate, which depends on the definition of mountain land. Bioclimatic layers, such as those developed by GMBA[1] (Körner et al. 2011, 2017; Paulsen and Körner 2014), become a central tool in GIS applications, such as the GMBA Mountain Portal (http://www.mountainbiodiversity.org) and its link to organismic inventories such as Map of Life (Jetz et al. 2012). The UNEP and USGS mountain layers do not permit stratifying mountain terrain by climatic conditions (elevational climatic belts).

The application of the GMBA mountain definition and bioclimatic layer revealed that of the 0.5 Billion people who are living within the global mountain terrain or within < 4 km of its boundaries sensu GMBA, 248 Million (that is half) are actually living in a low elevation, frost-free climate at the edges of mountains (mostly tropical or subtropical), 108 Million in a warm temperate-subtropical setting, 133 Mio are living in montane elevations that are periodically cool, and only 19 Million people in periodically really cold places (Körner et al. 2017). Accordingly, most of the 1–1.5 Billion people who are considered to be living in mountains based on the more inclusive UNEP and USGS mountain land definitions, are actually living on land that hardly touches upon terrain that exhibits mountainous features. Hence, of the 0.5–1.5 Billion people living on land included in the mountainous category by the three definitions, not more than c. 250 Million are actually inhabiting land to which the hardship attributes of the mountain life apply, while downslope risks may reach far greater (mostly urban) populations.

In summary, the inclusion of hills and plains into the mountainous land category results in the addition of predominantly warm, flat, and typically highly populated terrain. Although, such an inclusion might in specific cases be desirable given the strong teleconnections between mountains and distant plains or catchments (Viviroli et al. 2020; Fig. 1), awareness, caution, and transparency are needed when selecting a mountain definition or using published mountain statistics, particularly in a biogeographic context. An advancement of this field of research is to be expected by a clear and quantitative definition of mountain boundaries,

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with the great benefit that mountain forelands can be defined as categories in their own right. Moreover, given that it is the climate that drives both wildlife and the wellbeing of humans in an around mountains, mountain geostatistics are best combined with the local climatic reality, which requires a small gridded definition that can account for elevational changes in climate over short distances.

Acknowledgements We thank Mark Snethlage (GMBA) for his advice

Author contributions CK and DP wrote the manuscript, JP provided the GMBA mountain statistics.

Funding Open Access funding provided by Universität Basel (Universitätsbibliothek Basel).

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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