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On the Use of "Alpine" for High-Elevation Tropical Environments

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The study of mountain ecosystems has a long tradition. This can be traced from the extensive geological surveys of Horace de Saussure in the 1800s in the European Alps (Billing 2019) to the seminal research that Humboldt performed on his trip through the Andes (Linder et al 2019; Moret et al 2019). However, the geographical distribution of the research has remained biased toward the global North and, more specifically, to the mountain ranges of Europe and North America (Körner 2003). This bias means that the understanding of mountains has been mostly based on temperate ranges in which the lives and ecology of organisms are tied to the marked rhythms that seasons impose on temperature, precipitation, and irradiance (but see Llambí and Rada 2019).

The historical bias seems also to have percolated into the language that we use to describe mountain ecosystems. The adjective "alpine," for example, has become a standard term to describe the high-elevation ecosystems that occupy the higher reaches of mountains, above the climatic tree line. Similarly, "tropical alpine," is used to describe the ecosystems and vegetation that characterize the high-elevation landscape of the Northern Andes and other tropical mountains (Hedberg and Hedberg 1979; Smith and Cleef 1988; Christmann and Oliveras 2020). However, this generalized use of "alpine" could result in 2 unintended outcomes. On the one hand, it might restrict the usefulness of the word "alpine" as a descriptor of the particular ecosystem traits and environmental characteristics of the temperate mountains that inspired the original use of the term. On the other hand, while used to describe the outstanding diversity of high-elevation ecosystems in the world, "alpine" might become simply synonymous with "high mountain," thus failing to convey any meaningful idea of the diverse and unique environments that dominate the upper reaches of the mountains of the world.

Therefore, does the term "alpine" accurately encompass the heterogeneous nature of all high-elevation ecosystems across the world, or does its reference to the temperate, seasonal landscape entail an ambiguous generalization? In this commentary, we examine the use of "alpine" as an overarching term to broadly describe high-elevation ecosystems and their species, using as an example the *páramo* of the humid Northern Andes.

What is an "alpine" landscape?

The challenge with delineating a term such as "alpine" starts with the basic definition of a mountain. Traditionally, mountains have been defined as natural elevations that protrude above their surroundings and are usually characterized by steep or precipitous rocky terrain, sharp environmental gradients, and seasonal or permanent presence of snow and ice (Barsch and Caine 1984). Barsch and Caine further define 4 types of mountains: alp-type, Rocky Mountain-type, polar mountains, and desert mountains. These fail to include the heterogeneity of high-elevation environments in tropical mountains. For example, while the "alp" and "Rocky Mountain" types can be found in certain areas of the Cordillera Blanca and Huayhuash in Peru or in the Patagonian Andes, this categorization is utterly insufficient to describe the diversity of mountains in the broad high-elevation ranges with isolated peaks that are common in the equatorial mountains of the Northern Andes, Mesoamerica, and eastern Africa.

In general, "alpine" (from the Latin *alpes*, meaning high rugged mountain) has been used to describe high-mountain environments that lack trees and resemble a tundra ecosystem (Owens and Slaymaker 2004). However, besides these characteristics, cold temperatures, and open vegetation, the term "alpine" has been applied to ecosystems that are fundamentally different from anything that can be found in the European Alps or tundra. An emblematic example in the wet tropical Andes is the caulescent rosette (genus *Espeletia*) and tussock-grass-dominated *páramo* (Figure 1). This environment is considered "tropical alpine" in scientific literature, just like its dryer southern extension (*puna*) and its African equivalent on Mount Kenya and Mount Kilimanjaro (Hedberg and Hedberg 1981; Smith and Cleef 1988). However, although these environments fit the basic characteristics of an "alpine" life zone, we suggest that the indiscriminate use of this term for such a wide array of ecosystems can be misleading. To exemplify these differences, we take *páramo* ecosystems and highlight some of the features that separate them from other mountain environments that have also been termed "alpine," although they bear little similarity.

How are *páramo* ecosystems different from the traditional definition of "alpine"?

Rates of ecological and evolutionary processes

As a result of the tropical climate, lack of seasonality, and geological setting, *páramo* ecosystems exhibit relatively high rates of primary production and speciation, compared with temperate mountains. For example, the endemic genus *Espeletia* originated in what is now Venezuela and rapidly

FIGURE 1 Examples of the outstanding diversity of environments that could or have been described as "alpine" in the Andean *páramo* and in the Rocky Mountains of North America. (A) Frailejonal of *Espeletia pycnophylla* and *Calamagrostis* sp (4150 m). (B) Cushion-plant-dominated peatland (4400 m). (C) *Neurolepis*-dominated *páramo* grassland (4097 m). (D) Sparsely vegetated super-*páramo* with *Xenophyllum* sp and *Loricaria* sp (4340 m). (E) *Polylepis* sp forest above tree line (4130 m); (F) Dry *páramo* with *Chuquiraga jussieui* (4250 m). (G) Alpine tundra (3358 m). (H) Krumholtz trees in the alpine zone (3250 m). (A–F) *Páramo* vegetation types in Ecuador. (G and H) Vegetation types in Rocky Mountain National Park in the United States. (Photos by Esteban Suárez)

spread through Colombia and northern Ecuador, radiating into more than 120 species over the last 3 to 5 million years. This represents one of the fastest known cases of speciation (Monasterio and Sarmiento 1991; Rauscher 2002; Madriñán et al 2013; Cortés et al 2018).

Environmental heterogeneity

At least 2 main sources of environmental heterogeneity distinguish *páramo* ecosystems from temperate mountain ecosystems. On one hand, by extending roughly from 8°N to 6°S, *páramo* ecosystems experience diverse climatic regimes that originate from the influence of large-scale features such as the Amazon basin, the Pacific Ocean currents, and local rain shadow effects (Buytaert, Célleri, Willems, et al 2006; Célleri et al 2007). At the same time, *páramo* ecosystems have developed on an active and complex geological setting, which includes more than 40 active volcanoes, thousands of geological faults, and a recent history of glacial activity. Arising from this environmental heterogeneity, *páramo* ecosystems are remarkably diverse and include vegetation types as different as open grasslands, shrublands, high-elevation forests, desert-like ecosystems, and extensive peatlands (Figure 1).

Soil thickness and water regulation

As a result of the sloping and dynamic nature of mountain topography, high-elevation soils in temperate zones are typically shallow, poorly developed, and constantly rejuvenating (Egli and Poulenard 2016). In contrast, because of factors such as constant productivity, high humidity, low decomposition rates, and, in some regions, interactions with volcanic ashes that stabilize organic matter, *páramo* ecosystems tend to have very deep soils with high carbon storage capacity (Poulenard et al 2003). In the Ecuadorian *páramo*, for example, well-drained soils have average depths of 2.7 ± 0.1 m, and *páramo* peatlands can be as deep as 3.5 ± 0.5 m in cushion-plant-dominated peatlands and 9.4 ± 0.2 m for sedge-dominated peatlands (Hribljan et al 2017). These deep and carbon-rich soils are common in most *páramo* environments and set them apart from other mountain ecosystems. Emerging from these soil characteristics, *páramo* ecosystems also differ from "alpine" environments in their role in water supply for human societies. In general, the presence of large glaciers and snowfall allows mountain ecosystems to function as water towers (Messerli et al 2004; Buytaert et al 2017). In contrast, the crucial role of *páramo* ecosystems in water supply emerges from their vast reservoirs of soil organic matter, which effectively store and regulate water that is used by more than 100 million people (Buytaert, Célleri, De Bièvre, et al 2006).

Human dimensions

Like other mountain landscapes, the *páramo* has coexisted with human populations for many centuries, creating a unique socioecosystem with very particular management and land-use dynamics (Cortés-Duque and Sarmiento 2013; Monasterio and Molinillo 2013; López-Sandoval and Maldonado 2019; Joslin 2021). As a result, the term *páramo* has been used colloquially to describe several dimensions related to the human experience in the Northern Andes. For many Andean cultures, *páramo* can describe features such as a productive piece of land for food and cattle in the mountain, the high-elevation landscape that lies beyond human settlements, or even a specific weather pattern characterized by mist and low-intensity precipitation (eg "*está parameando*" meaning "it is drizzling"). Similarly, *páramo* areas have been traditionally used for rituals and ceremonies (Varela 2008). As a result of this close relationship, people that settled in the *páramo* named every hill, valley, and peak, giving the geography an additional value, and creating a specific Andean identity that revolves around countless stories and tales about the topography, climate, and biodiversity of the mountains.

A more specific terminology

In summary, we suggest that the term "tropical alpine" is the result of historical bias toward northern latitudes and thus is inadequate to properly describe the diversity of high-mountain environments throughout the world. As we have shown here, using the *páramo* as an example, most of the vegetation types in this bioregion are fundamentally different from the environments of temperate mountains. Pockets of *Polylepis* forests occurring at 4300 m, well above the closed tree line, the thick tussock grasslands dotted with giant rosettes of *Espeletia* or *Puya*, or the dense scrublands of *Loricaria* can be described as "alpine" only to the extent that they occur in high mountains, but their structure and function can hardly be equated to temperate alpine ecosystems. In this context, we suggest that a more specific terminology is needed in order to depict the contrasting vegetation types that characterize tropical and subtropical mountains.

Defining specific terms to distinguish the many ecosystem types that occur in the high mountains of the world might be challenging. At the same time, using "alpine" as an all-encompassing term sacrifices the ecological and biogeographical significance from which the term originated in the first place. From this perspective, we suggest that academic and management literature can address this ambiguity though a 2-pronged approach. First, when the term "alpine" is applied to ecosystems or species that fall outside of the traditional (temperate) meaning of the word, the context in which the term is used should be explained. Second, the use of the local terms and names that currently convey the historical, ecological, and socioeconomic particularities of the ecosystem and its species should be emphasized and promoted. For example, as discussed above, the term "*páramo*" brings together the ecological particularities of the Northern Andes, and the unique relationships between these ecosystems and the people that inhabit them, in ways that are impossible when an overarching term such as "alpine" is used.

Local names describing high-elevation environments might not always be available. Moreover, in some cases like the *páramo*, the term itself is also a relic from the Spanish conquest in the 1500s. But, despite its origin, the term is so inextricably rooted in the culture and recent history of the region that no other term can reflect the ecological, cultural, and socioeconomic dimensions attached to this environment. In cases like this, the use of general terms, such as "tropical alpine," not only hides that complexity, but also obscures its meaning and reduces its usefulness when analyzing management and conservation scenarios.

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