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Effects of the paramization phenomenon on the ecosystem resilience of the Andean páramo in a climate change context

Efectos de la paramización sobre la resiliencia ecosistémica del páramo andino en un contexto de cambio climático

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Abstract

The article synthesizes current knowledge on Andean páramo ecosystems, highlighting their ecological importance and their strategic role in providing essential ecosystem services such as water regulation, carbon sequestration, and the maintenance of high biodiversity. These high-mountain systems are fundamental to human well-being due to their capacity to store and regulate water that supplies millions of people. In this context, the process of "paramization" is analyzed as a transformation of high Andean forests into páramo conditions, driven by human activities such as agricultural expansion, grazing, potato cultivation, and burning, along with rising temperatures. This process leads to land-use changes, biodiversity loss, and alterations in key ecological processes such as vegetation regeneration, carbon retention, and hydrological dynamics. It was found that the ecological resilience of these ecosystems is being weakened by local pressures and climate change, increasing their vulnerability and reducing their adaptive capacity. Spatial analysis reveals fragmentation and variability in protection levels, while knowledge gaps persist, underscoring the need to strengthen conservation, restoration, and sustainable management strategies in the face of growing environmental threats.

Keywords: Andean páramos, climate change, ecosystem services, ecological resilience, paramization

Resumen

El artículo sintetiza el conocimiento actual sobre los ecosistemas de páramo andino, resaltando su importancia ecológica y su papel estratégico en la provisión de servicios ecosistémicos esenciales como la regulación hídrica, captura de carbono y mantenimiento de alta biodiversidad. Estos sistemas de alta montaña son fundamentales para el bienestar humano debido a su capacidad de almacenar y regular el agua que abastece a millones de personas. En este contexto, se analiza el proceso de paramización como una transformación de los bosques altoandinos hacia condiciones de páramo impulsada por actividades humanas como: la expansión agropecuaria, el pastoreo, el cultivo de papa y las quemas; junto con el aumento de la temperatura, lo que genera cambios en el uso del suelo, pérdida de biodiversidad y alteraciones en procesos ecológicos clave

Author's note: Paramization is an ecological degradation process whereby formerly high-Andean forest areas are transformed into páramo-like conditions due to human pressures and rising temperatures, leading to biodiversity loss and deterioration of essential ecosystem functions.

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como la regeneración vegetal, la retención de carbono y dinámica hidrológica. Se evidenció que la resiliencia ecológica de estos ecosistemas se encuentra debilitada por presiones locales y el cambio climático, incrementando su vulnerabilidad y reduciendo su capacidad de adaptación. El análisis espacial revela fragmentación y variabilidad en niveles de protección mientras persisten vacíos de conocimiento, resaltando la necesidad de fortalecer las estrategias de conservación, restauración y gestión sostenible frente a crecientes amenazas ambientales.

Palabras clave: cambio climático, paramización, páramos andinos, resiliencia ecológica, servicios ecosistémicos

1. Introduction

The Andes constitute one of the largest and most complex mountain systems in the world, characterized by an extraordinary diversity of vegetation formations and the presence of multiple altitudinal belts resulting from their extensive elevational gradient. Their configuration is shaped by ongoing geological processes, including tectonic activity and volcanism, which continue to influence the landscape.

In the northern Andes, the interaction of altitudinal, climatic, and ecological factors has favored the development of high-mountain ecosystems, among which the páramo is particularly prominent. The páramo is generally recognized as a humid tropical ecosystem occurring in regions of South America, Africa, and Oceania. It is characterized by open vegetation and occupies the altitudinal zone between the upper limit of continuous forest and the permanent snowline (Hofstede, 2020).

Within this context, the present study was conducted using a systematic literature review approach, complemented by documentary and geospatial analyses. The aim was to characterize Andean páramo ecosystems and examine the dynamics of their transformation.

Páramo ecosystems possess distinctive environmental characteristics resulting from the interaction of climatic, edaphic, and altitudinal factors that create unique ecological conditions across the American tropics. Their distribution is concentrated primarily along the Andean mountain range, encompassing Colombia, Ecuador, Venezuela, and northern Peru, with additional occurrences in Central America, particularly in Costa Rica.

Although ecological formations such as the Sierra Nevada de Santa Marta and certain Central American mountain systems share similar environmental features, they do not strictly belong to the Andean region. Owing to their marked ecological heterogeneity, páramos exhibit considerable variation in plant composition, structure, and ecosystem functioning across the biome. As a result, they constitute complex socioecological systems characterized by distinct ecological dynamics within each geographical region (Llambí & Cuesta, 2014).

Due to their high biological diversity and ecological complexity, páramo ecosystems provide essential ecosystem services that support human well-being and sustain biodiversity. Among the most important are water-related services, including the capture of atmospheric moisture, water storage, and hydrological regulation. These functions play a crucial role in maintaining watershed recharge areas and ensuring the conservation and availability of water resources (International Union for Conservation of Nature [IUCN], 2010).

Another key ecosystem function of páramos is climate regulation through the capture and storage of atmospheric carbon dioxide, acting as significant carbon sinks in both soils and vegetation (Quintero-Vallejo et al., 2018). Their high degree of endemism and ecological uniqueness, reflected in distinctive vegetation and fauna assemblages, climatic conditions, altitudinal gradients, and landscape diversity, distinguishes them from other mountain ecosystems. These characteristics make páramos particularly important for ecological research and biodiversity conservation initiatives, especially because of their critical role in hydrological regulation and water resource conservation (Corporación Autónoma Regional de Cundinamarca [CAR], 2018).

Among the principal threats to biodiversity in páramo ecosystems are anthropogenic activities, including potato cultivation, intensive grazing, and agricultural burning. Furthermore, the progressive loss of Andean forests, landscape fragmentation, and the ongoing transformation of páramo landscapes contribute substantially to the degradation of these ecosystems. Climate change represents an additional threat by modifying altitudinal distribution patterns, increasing global temperatures, and accelerating glacier retreat. These processes directly affect water availability, vegetation dynamics, and the composition and distribution of flora and fauna communities.

The resilience of páramo ecosystems to environmental degradation is progressively declining. Rising temperatures accelerate the mineralization of organic matter and disrupt biogeochemical cycles, thereby compromising the capacity of high-Andean soils to function as effective carbon sinks. This destabilization not only reduces carbon storage potential but also diminishes the ability of these ecosystems to withstand and recover from ongoing climatic disturbances (Llambí & Cuesta, 2014).

Paramization, in contrast, refers to a transformation process whereby areas formerly occupied by Andean forests or other montane ecosystems acquire characteristics typical of páramo environments because of the combined effects of anthropogenic pressures and rising temperatures. Although this phenomenon may be perceived as an expansion of páramo ecosystems, it reflects a process of ecological degradation characterized by biodiversity loss, habitat fragmentation, and the deterioration of essential ecosystem functions. Consequently, it indicates a decline in ecosystem resilience and a reduced capacity to provide critical ecosystem services.

2. Materials and Methods

This study employed a systematic literature review approach, complemented by documentary and geospatial analyses, to characterize Andean páramo ecosystems and examine their transformation dynamics. A structured search strategy was conducted using the indexed databases Web of Science [WoS] and Scopus. Search queries were developed from keywords associated with páramo ecosystems and their ecological characteristics. The selection of studies was carried out according to predefined inclusion and exclusion criteria, considering document type, thematic relevance, spatial scale of analysis, and data availability.

This process was structured according to the identification, screening, eligibility, and inclusion phases, ensuring the transparency and reproducibility of the review in accordance with the guidelines established by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol. Descriptors were applied to titles, keywords, and abstracts to identify relevant scientific articles and book chapters. The following search terms were used in WoS: (Andean Páramo) OR (Páramo* Colombia) OR (Páramo* Venezuela) OR (Páramo* Perú) OR (Páramo* Ecuador) OR (Paramero) OR (Páramo ecosystem services). In Scopus, the search equation was: (“Andean Páramo”) OR (“Colombia Páramo”) OR (“Venezuela Páramo*”) OR (“Perú Páramo*”) OR (“Ecuador Páramo*”) OR (“Paramero*”) OR (“Páramo ecosystem services*”).

The application of the search descriptors resulted in the identification of 192 records in WoS and 98 records in Scopus. Following the screening and eligibility assessment stages, 117 records were excluded due to lack of thematic relevance, 38 were removed as duplicates, and 20 did not meet the predefined inclusion criteria. Consequently, a total of 25 studies were selected for systematic review and analysis (Figure 1).

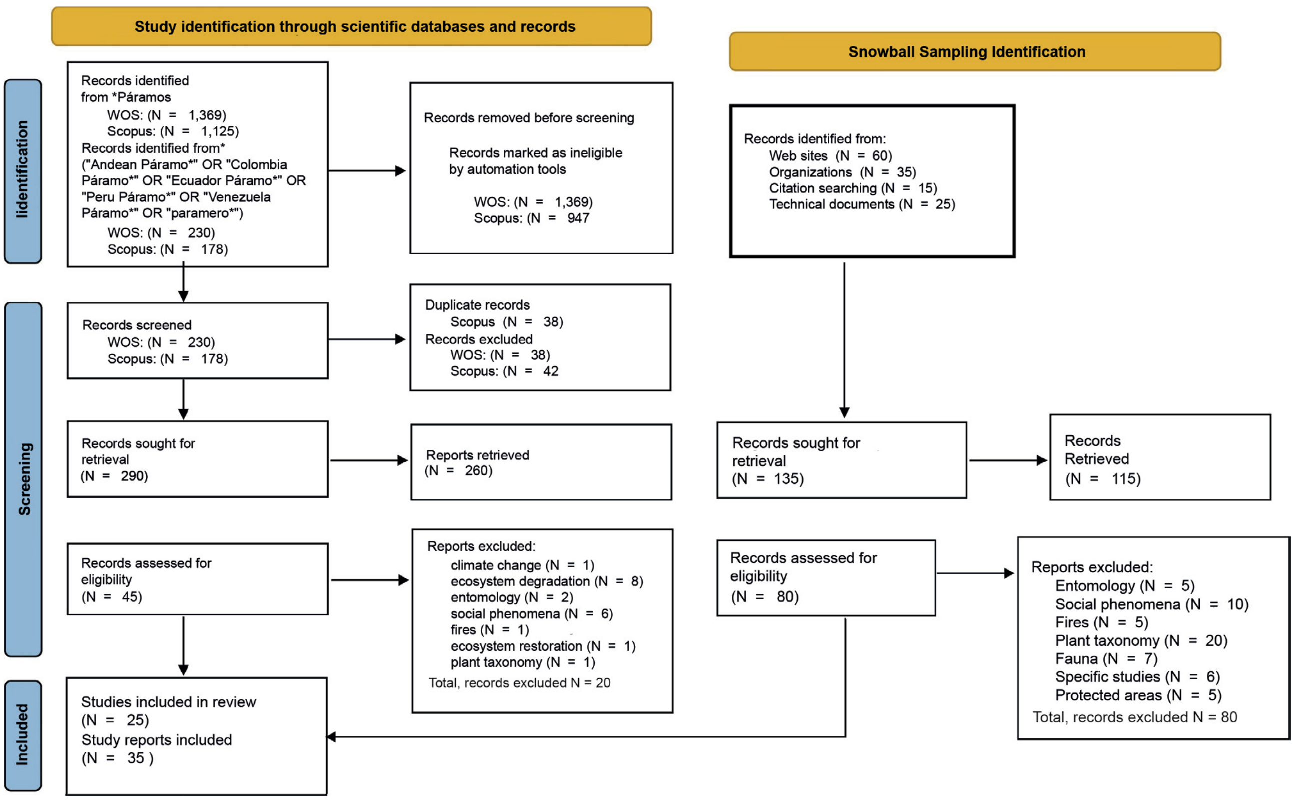

Figure 1. Application of the PRISMA Protocol.

However, this phase revealed a predominance of studies conducted at local and regional scales, often characterized by highly specialized approaches that limited a comprehensive biogeographical understanding of the Andean páramo. To address this limitation, a complementary strategy based on the snowball sampling technique was implemented (Figure 2), with the aim of broadening the documentary corpus through the inclusion of grey literature, such as technical reports, regulatory documents, and institutional publications.

This phase involved the use of Boolean operators in both academic databases and general search engines, with priority given to Spanish-language sources because of their regional relevance. In addition, backward and forward citation tracking of the previously selected studies was conducted as part of the snowball sampling approach to identify additional relevant sources. For this purpose, the following descriptors were used: ("Páramos") OR ("Páramos AND Andinos") OR ("Páramos AND Andes") OR ("Páramos AND Venezuela") OR ("Páramos AND Perú") OR ("Jalca AND Perú") OR ("Páramos AND Ecuador") OR ("Páramos AND Tropicales") OR ("Paramero*").

Boolean operators were employed to optimize search performance and facilitate the combination of keywords across bibliographic databases and Google search engines. Furthermore, the snowball sampling technique was applied through the systematic examination of references and quotes in the selected documents, thereby expanding the documentary corpus and enabling the incorporation of relevant grey literature (Table 1).

The search strategy, which incorporated both scientific and grey literature, resulted in a database of approximately 60 studies relevant to the characterization of Andean páramo ecosystems. These records were subsequently organized and classified using thematic descriptors to identify the most relevant approaches for inclusion in the analysis. Thereafter, the snowball sampling technique was applied to identify and incorporate additional secondary sources, thereby broadening the documentary corpus and contributing to a more comprehensive and transdisciplinary understanding of the subject.

The collected information was organized to enable a conceptual analysis of the selected studies under homogeneous analytical criteria, such as country, drivers of change, ecosystem services, and ecological attributes such as resilience, vegetation regeneration, carbon sequestration, and hydrological regulation. This approach facilitated the identification of variables analysis, as well as the detection of thematic and geographical knowledge gaps. Furthermore, it enabled the integration of a systematic literature review with a multi-country cartographic analysis, providing a comprehensive framework for examining paramization as both an ecological and socio-environmental phenomenon.

In addition, a cartographic component was developed through the collection and analysis of geospatial data in Shapefile format [GIS], obtained from open-access repositories, environmental agencies, and official geospatial platforms. Advanced search operators, including the *filetype:* command, were em-

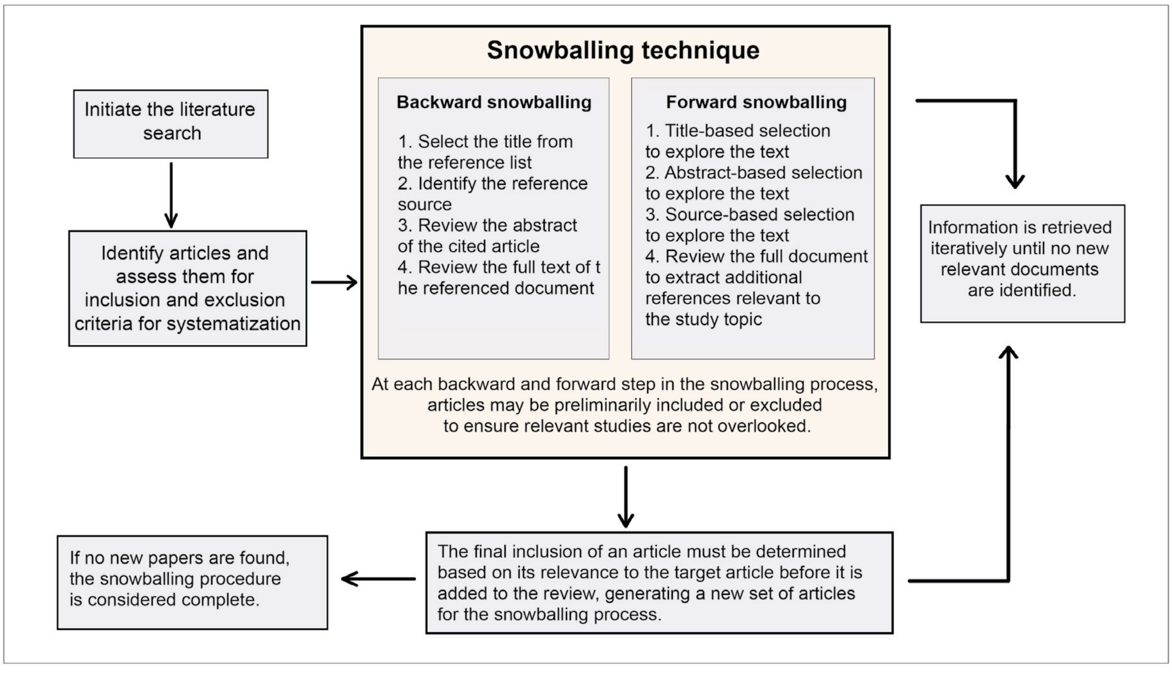

Figure 2. The Snowball methodology applied to information retrieval.
Source**:** Author's illustration based on Wohlin (2014).

Table 1. Boolean operators and commands used in the search for gray literature.

Bolean Operator	Symbol	Action	Application	Search	Description
AND / Y	“+” “&”	Choice	("Páramos*" OR “Páramos Andinos” OR “Páramos AND Andes” OR “Páramos AND Venezuela” OR “Páramos AND Peru” OR “Jalca AND Peru” OR “Páramos AND Ecuador” OR “Páramos AND Tropical” OR “Paramero*")	All terms used	Narrows and refines the search.
OR / O	”|“ó”	Union		Any of the terms	Broadens the search.
" "	" "	Limit		Exact words	Used to search for an exact phrase (regardless of word order).
*	(" "*)	Literal		Wildcard	Substitutes a word. It is commonly used in combination with the exact phrase operator.
( )	( )	Group		Limits the scope of the search.	Terms linked by logical operators to refine the search.
Filetype search operator:	Filetype:		*páramos.shp*	*Filetype:.shp*	Restricts searches to pages containing files relevant to cartographic information.

ployed to identify relevant geographic datasets, which were subsequently cross-validated with information from the UICN Protected Planet database. Following data integration, standardization, and refinement, a cartographic database was constructed, identifying 133 biogeographical units corresponding to páramo ecosystems across the Andean mountain range in Venezuela, Colombia, Ecuador, and Peru. Finally, a geospatial overlay analysis was performed to evaluate the extent of delimitation, identification, and coverage of these ecosystems within protected areas. The ecological variables assessed were integrated in the systematic review.

3. Results

3.1. Conceptual analysis

The term “*páramo”* is derived from the Latin word *paramus*, traditionally associated with cold, sparsely vegetated landscapes. Its application in the tropical Andes, however, emerged through a historical reinterpretation during the Spanish colonial period, when the term was used to describe the high-elevation Andean environments due to their perceived similarity to the cold uplands of the Iberian Peninsula (Llambí & Cuesta, 2014). The adoption of this terminology has not been uniformed throughout the Andes. In the central Andes of Peru and Bolivia, the term *puna* is commonly used, whereas in northern Peru the term *jalca*, derived from the Quechua word *sallqa*. The term “páramo” refers to the ecosystem found in wild high-mountain areas generally located between 3,500 and 4,000 m a.s.l. (Instituto Humboldt, 2012).

The coexistence of terms such as *páramo*, *jalca*, and *puna* has generated considerable conceptual ambiguity, as ecological and cultural classifications often overlap, complicating the delimitation and characterization of these ecosystems. In Peru, for instance, there is no clear consensus regarding whether *jalca* and *puna* should be considered equivalent to the páramo or recognized as distinct ecological units. Some authors adopt an integrative perspective, grouping these ecosystems under the broader category of Andean páramo based on shared ecological and functional characteristics. Nevertheless, the páramos of northern Peru exhibit distinctive features, including a drier climate, lower water availability, and a reduced capacity for water storage.

Páramo ecosystems exhibit remarkable environmental heterogeneity resulting from the interaction of multiple factors, including geology, topography, soil development, and rainfall, moisture, and slope gradients (Llambí & Cuesta, 2014). Based on variations in annual rainfall, several páramo types can be distinguished, reflecting the considerable ecological complexity of these high-mountain environments. Marked floristic differences are evident along the latitudinal gradient of the Andes. For instance, *frailejones* (*Espeletia* spp.) are characteristic components of páramo vegetation from Venezuela to northern Ecuador, but their presence gradually declines and eventually disappears toward the southern Andes. In Peru, páramo ecosystems lack *frailejones* and are predominantly composed of grassland formations (*pajonales*), closely associated with the *jalca* ecological region in the northern part of the country. These patterns illustrate the substantial biogeographical variation that exists within the Andean páramo system.

At a regional scale, variations in páramo ecosystems are mainly related to altitudinal gradients (CAR, 2018). Within this framework, there is a general consensus in the delimitation of three ecological units: the subpáramo, located approximately between 3,200 and 3,600 m a.s.l., which constitutes a transition zone between the montane forest and the páramo; the páramo proper, which extends between 3,600 and 4,100 m a.s.l. and is characterized by the dominance of grasslands and rosette formations; and the super páramo, located above 4,100 m a.s.l. up to the lower limit of the perpetual snow, where extreme environmental conditions determine a scarce and discontinuous vegetation cover (Cuatrecasas, 1958; Llambí & Cuesta, 2014).

According to IUCN (2010), the páramo is defined as the high-Andean ecosystem situated above the upper forest limit. It is characterized by a pronounced altitudinal gradient along which vegetation transitions from shrublands and open woodlands to increasingly simplified plant communities in terms of structure, and vegetation cover. The lower páramo is dominated by shrub formations, often accompanied by scattered trees whose height and density decrease with elevation. The middle or typical páramo is characterized by the predominance of perennial grasses, together with emblematic species such as *frailejones* (*Espeletia* spp.). In contrast, the super-páramo supports sparse vegetation composed mainly of grasslands and low-growing shrubs, interspersed with extensive areas of exposed soil and rocky substrates.

The altitudinal gradient in the páramos favors a high turnover of plant species, generating significant spatial heterogeneity and regional biodiversity. This dynamic reflects the remarkable capacity of plant communities to adapt to extreme conditions and is a key characteristic of the functioning of these ecosystems.

The high biodiversity characteristic of tropical environments is further enhanced by the diversity generated through local altitudinal gradients, together promoting pronounced beta diversity within these ecosystems. This pattern is particularly evident in isolated mountain systems, where high levels of endemism occur at both local and regional scales (World Wildlife Fund [WWF], 2016). In this context, the Andean páramo stands out for its remarkable floristic richness, which not only defines the physiognomy of the landscape but also shapes its ecological characteristics. These distinctive features are closely associated with the bioclimatic belts that structure the ecological and landscape transitions characteristic of this biome.

Consequently, páramo plant communities exhibit a range of structural adaptations, including reduced stem size and smaller leaf structures, in contrast to high-Andean forests, which are characterized by dense stands of taller trees and palms with well-developed canopies. From a physiognomic perspective, the páramo is distinguished by predominantly open vegetation composed mainly of shrub and herbaceous growth forms (CAR, 2018).

Andean páramos play a crucial role in the functioning of natural systems and in supporting human well-being through the provision of a wide range of ecosystem services. Among these, soil formation and nutrient cycling are particularly important, as they underpin food production and the use of medicinal plants. Likewise, these ecosystems possess significant cultural value, serving as territories of historical, spiritual, and cultural importance for many local communities, particularly Indigenous peoples. In addition, páramos provide recreational and aesthetic services associated with their unique landscapes and outstanding scenic beauty (Instituto Humboldt, 2012).

These ecosystems exhibit high levels of endemism and considerable ecological richness, reflected in the diversity of soil and vegetation types adapted to local environmental conditions. This heterogeneity confers unique characteristics upon each páramo ecosystem, highlighting the importance of considering their specific ecological attributes when designing management and conservation strategies.

Páramos are highly vulnerable ecosystems owing to both their intrinsic ecological characteristics and the pressures exerted by external drivers, including climate change and anthropogenic activities such as intensive agriculture, overgrazing, and the use of fire. These factors act as major drivers of ecosystem transformation. One of the most distinctive intrinsic features of páramos is their evolutionary development under conditions of geographic isolation, resulting in ecological systems that function as biogeographical islands. This isolation has promoted high levels of ecological specialization and endemism; however, it has also increased their susceptibility to external disturbances.

In this context, rising temperatures directly affect key ecological processes, altering the functional balance of these ecosystems and influencing the dynamics of human activities that depend on them. High-Andean ecosystems are considered more sensitive to global warming than tropical rainforests, as warming increases the rate of organic matter decomposition.

Climate change is generating significant impacts on communities located in areas surrounding páramo ecosystems, particularly in relation to food security. These effects are reflected in reduced availability and quality of agricultural products, increased incidence of pests, and decreased access to water resources during the dry season. An illustrative example is provided by the Rabanal Páramo in Colombia, where local communities perceive climate change as an inevitable process that is transforming both their productive practices and living conditions (Corbelle & Guzmán, 2020).

Historically, páramo ecosystems have been recurrently exposed to fire, reflecting their high flammability and the persistent influence of seasonal biomass burning, largely driven by anthropogenic activities. Vegetation components such as *frailejones* (*Espeletia* spp.) are particularly vulnerable to fire due to the accumulation of necromass with high combustibility, which facilitates ignition and fire spread. Similarly, *pajonal* grasslands contribute to fire propagation because of their structural characteristics. This situation is further intensified by environmental factors such as persistent winds and high solar radiation. This not only affects carbon regulation but also increases their vulnerability to wildfires, given how easily this material can catch fire; thereby compromising essential ecosystem functions, particularly their role as carbon sinks.

Some fires originate from burning practices associated with land clearing for agricultural and livestock production. When these fires escape control, they frequently spread into conservation areas. Therefore, post-fire ecological succession is reflected in changes in the relative abundance of plant growth forms, often leading to the dominance of upright shrub species, altering the structure and functioning of the ecosystem.

Although there are some specific studies on fires in particular ecosystems, there remains a significant lack of information regarding the páramos; consequently, this limitation makes it difficult to understand their deterioration processes over time, as well as their recovery capacity and the implications that these events have on the conservation of biodiversity and the maintenance of the ecosystem services that these systems provide.

The long-term implications of these changes for biodiversity conservation and ecosystem functioning require rigorous assessment grounded in scientific evidence (Zomer & Ramsay, 2020). Owing to the inherent fragility of mountain ecosystems, their capacity to recover from natural disturbances is often limited. Consequently, strengthening prevention and adaptation strategies, together with the promotion of a risk management culture, is essential. Such efforts should be supported by robust information systems and monitoring technologies capable of providing continuous assessments of environmental change (Organización de las Naciones Unidad para para la Alimentación [FAO], 2014).

The ecological resilience of páramo ecosystems is key to understanding how they respond to human and climatic disturbances. However, this capacity to maintain ecosystem structure and functioning is increasingly constrained by the disruption of key ecological processes, particularly vegetation regeneration and hydrological regulation. Factors such as vegetation cover loss and landscape fragmentation weaken these resilience mechanisms, compromising the stability and long-term provision of essential ecosystem services (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services [IPBES], 2019).

In páramo ecosystems, ecological resilience is defined, according to Zaccarelli et al. (2008), as the capacity of an ecosystem to absorb natural and anthropogenic disturbances and reorganize while maintaining its essential structure, functions, and ecological processes. This capacity does not necessarily imply a return to pre-disturbance conditions; rather, it involves the preservation of the ecosystem's functional identity, including key processes such as hydrological regulation, natural succession, and carbon storage, which are critical to maintaining long-term ecosystem stability.

Resilience in páramo ecosystems is closely associated with biological diversity, spatial heterogeneity, and the interactions among ecological components operating across multiple spatial and temporal scales. These attributes enhance the capacity of the ecosystem to self-regulate and adapt to environmental change, thereby contributing to its long-term stability. According to Zaccarelli et al. (2008), processes such as landscape simplification, habitat fragmentation, and alterations in natural disturbance regimes —associated with processes such as paramization in the context of climate change— can significantly reduce ecosystem resilience.

In this context, changes in climatic conditions and land use can drive páramo ecosystems toward less functional ecological states. Understanding resilience in these ecosystems requires consideration not only of immediate disturbances but also of the long-term processes that influence ecosystem stability Such an approach is essential for understanding both the historical and contemporary dynamics of páramo ecosystems, particularly in the face of increasing environmental pressures.

The introduction of exotic species and the occurrence of biological invasions in páramo ecosystems are closely associated with the accumulation of anthropogenic disturbances, including recurrent burning, livestock expansion, agricultural activities, and road construction. These disturbances modify habitat conditions, increase landscape openness, and facilitate the establishment of non-native species. By creating ecological opportunities and reducing biotic resistance, disturbed environments become more susceptible to colonization by invasive species, which are often characterized by high ecological plasticity, rapid growth rates, and efficient dispersal mechanisms. As a result, biological invasions can compromise the ecological integrity of páramo ecosystems by displacing native species, altering vegetation structure and composition, and disrupting key ecosystem processes. These impacts represent a significant threat to biodiversity conservation, as they reduce ecosystem resilience and limit the capacity of páramos to recover from subsequent disturbances.

Gorse (*Ulex europaeus*), included among the world's 100 worst invasive alien species by the International Union for Conservation of Nature [IUCN*, is also considered one of the most problematic invasive plants in Colombia. Originally introduced for use as a living fence, this species has demonstrated a remarkable capacity for adaptation and expansion across a wide range of ecosystems, including páramo environments. Its rapid growth, high seed production, and tolerance to adverse environmental conditions enable it to colonize disturbed areas efficiently, displacing native vegetation and altering ecosystem structure and composition. Consequently, the spread of *U. europaeus* represents a significant threat to biodiversity and ecosystem functioning in páramo landscapes, hindering restoration and conservation efforts (Instituto de Investigación de Recursos Biológicos Alexander von Humboldt y Ministerio de Ambiente y Desarrollo Sostenible, 2011).

This species forms dense, monospecific, and highly thorny stands that inhibit the germination and establishment of native plant species, reduce water infiltration into the soil, and create physical barriers that restrict wildlife movement. In addition, *Ulex europaeus* exhibits a remarkable capacity for regeneration through both seed production and vegetative resprouting following disturbances such as vegetation clearing and fire, resulting in the development of a persistent and abundant soil seed bank. The establishment of this invasive species can alter nutrient cycling processes in naturally nutrient-poor environments, creating conditions that favor its persistence while disadvantaging native species that are not adapted to such changes. Furthermore, its high pyrogenic potential increases fire risk during dry periods, reinforcing its capacity for expansion and exacerbating its impacts on the ecological dynamics of páramo ecosystems (Vargas, 2013).

Under climate warming sceneries, shrub species are projected to expand into páramos ecosystems, progressively occupying higher elevations that were previously unsuitable. Evidence of the upward colonization of invasive shrub species is already being observed in several high-Andean environments. A representative example is gorse, which has been recorded at elevations of up to 3,500 m a.s.l., demonstrating its considerable capacity for adaptation and expansion within these ecosystems (Vargas, 2013).

Various anthropogenic pressures are contributing to the alteration of natural conditions in páramos ecosystems, particularly through processes of paramization associated with land-use change in mountainous regions. Activities such as agricultural expansion, intensive grazing, potato cultivation, and the use of fire for land preparation directly affect the physical and chemical properties of soils. These disturbances can reduce water retention capacity and degrade water quality, thereby compromising groundwater recharge. In addition, activities such as mining, soil tillage, fertilizer application, and the replacement of native grasslands with forage species further intensify alterations to the hydrological balance. Collectively, these pressures diminish the ecological integrity and functionality of páramos ecosystems, significantly impairing their capacity to provide and regulate water resources (FAO, 2014).

The structure and functioning of Andean páramos ecosystems are strongly influenced by altitudinal gradients, which determine vegetation distribution, floristic composition, and the dominant ecological formations. In this context, altitudinal zonation allows the identification of distinct ecological belts that reflect transitions from high-Andean forests to the super-páramo. Each of these ecological units exhibits particular characteristics in terms of dominant species, vegetation cover, and bioclimatic conditions, revealing high levels of floristic turnover and pronounced spatial heterogeneity.

The altitudinal zonation of Andean páramo ecosystems reveals a gradual variation in floristic composition and vegetation structure with increasing elevation. At the high-Andean belt (3,000–3,200 m a.s.l.), relatively dense forests and tall shrublands predominate, characterized by genera such as *Weinmannia*, *Clethra*, and *Escallonia*, which indicate the transition toward colder environmental conditions. At higher elevations, within the sub-páramo zone (3,200–3,600 m a.s.l.), vegetation height and density progressively decrease, giving way to shrublands and scattered woody vegetation, where species of *Vaccinium*, *Gaultheria*, and *Hypericum* stand out.

Similarly, within the páramo proper (3,600–4,100 m a.s.l.), increasingly harsh climatic conditions favor the development of tussock grasslands and *frailejón*-dominated communities, characterized by genera such as *Calamagrostis* and *Espeletia*, which are highly adapted to intense solar radiation and low temperatures. At the highest elevations, in the super-páramo zone (above 4,100 m a.s.l.), vegetation becomes increasingly sparse and discontinuous because of extreme environmental conditions, where species of. *Draba* and *Senecio* are predominant. Overall, this altitudinal zonation reflects not only a progressive reduction in vegetation structural complexity but also an increase in the ecological specialization of species in response to increasingly restrictive climatic conditions (Table 2).

Payment for Ecosystem Services [PES] programs have emerged as an important strategy for promoting ecosystem conservation while simultaneously contributing to poverty alleviation and rural development. These schemes provide financial or in-kind incentives to those who maintain or enhance the provision of ecosystem services, thereby fostering a more equitable distribution of environmental costs and benefits among stakeholders. In this context, PES initiatives have facilitated collaborative agreements among farmers, ethnic communities, social organizations, and government institutions, encouraging the protection of strategic natural resources, particularly water resources. Furthermore, these mechanisms promote environmental awareness and community participation, thereby strengthening local governance and collective commitment to conservation efforts (Wunder et al., 2007).

Although páramo ecosystems have become a benchmark for the provision of key ecosystem services, including water regulation, carbon sequestration, biodiversity conservation, and the enhancement of rural livelihoods, their incorporation into environmental management schemes is not without challenges. Many PES programs have been developed based on still limited knowledge regarding the relationships between land-use practices and the effective delivery of ecosystem services. Therefore, integrating local knowledge with ecological scientific evidence is essential for developing more comprehensive analytical frameworks capable of effectively guiding environmental policy and management decisions. Furthermore, there is broad recognition that the knowledge, perceptions, and values of local communities constitute a fundamental component of successful conservation strategies, as they influence both the implementation and long-term sustainability of ecosystem management initiatives (Farley & Bremer, 2017).

3.2. Mapping Results

The map, developed using official information from the four Andean countries, identified 133 biogeographical units with distinct ecological and functional characteristics within páramo ecosystems, providing an updated cartographic contribution to the regional analysis of this biome. Its spatial distribution reveals the fragmented nature of these ecosystems along the mountain range, as well as their close relationship with altitudinal gradients. This exercise integrated diverse sources of geospatial information, offering a regional perspective on the delimitation, status, legislation, protection designations, and territorial organi-

Table 2. Altitudinal zoning and floristic composition of Andean páramo ecosystems.

Belt	Altitudinal Range (m a.s.l.)	Dominant Genera and Species	Vegetation Formations	Altitudinal Criteria	Bioclimatic Belts
High-Andean	3,000–3,200	*Hesperomeles* (Rosaceae), *Weinmannia* (Cunoniaceae), *Clethra* (Clethraceae), *Escallonia* (Escalloniaceae), *Drimys granadensis* (Winteraceae), *Gynoxys* (Asteraceae), *Vallea stipularis* (Elaeocarpaceae)	Tall forests and open shrublands	Transition between the High-Andean Forest and the Sub-páramo	High-Andean Belt
Sub-páramo (Lower Páramo))	3,200–3,600	*Pernettya*, *Vaccinium*, *Bejaria* and *Gaultheria* (Ericaceae), *Gynoxys*, *Pentacalia* and *Diplostephium* (Asteraceae), *Hypericum* (Clusiaceae)	Shrublands and scattered trees	Transition between the High-Andean Forest and the Páramo	High-Andean Belt
Páramo	3,600–4,100	Calamagrostis (Poaceae), Espeletia (Asteraceae), Chusquea tessellata (Poaceae)	Tussock grasslands and *frailejón* rosette communities	Typical Páramo	High-Andean Belt
Super-páramo (High-Andean Páramo)	4,100 – permanent snowline	*Draba* (Brassicaceae), *Senecio canescens* and S. isabelis (Asteraceae), *Loricaria* (Asteraceae), *Azorella* (Apiaceae), *Aciachne* (Poaceae)	Grasslands, low shrublands, and discontinuous cushion vegetation	Sparse vegetation due to low temperatures	Periglacial Belt

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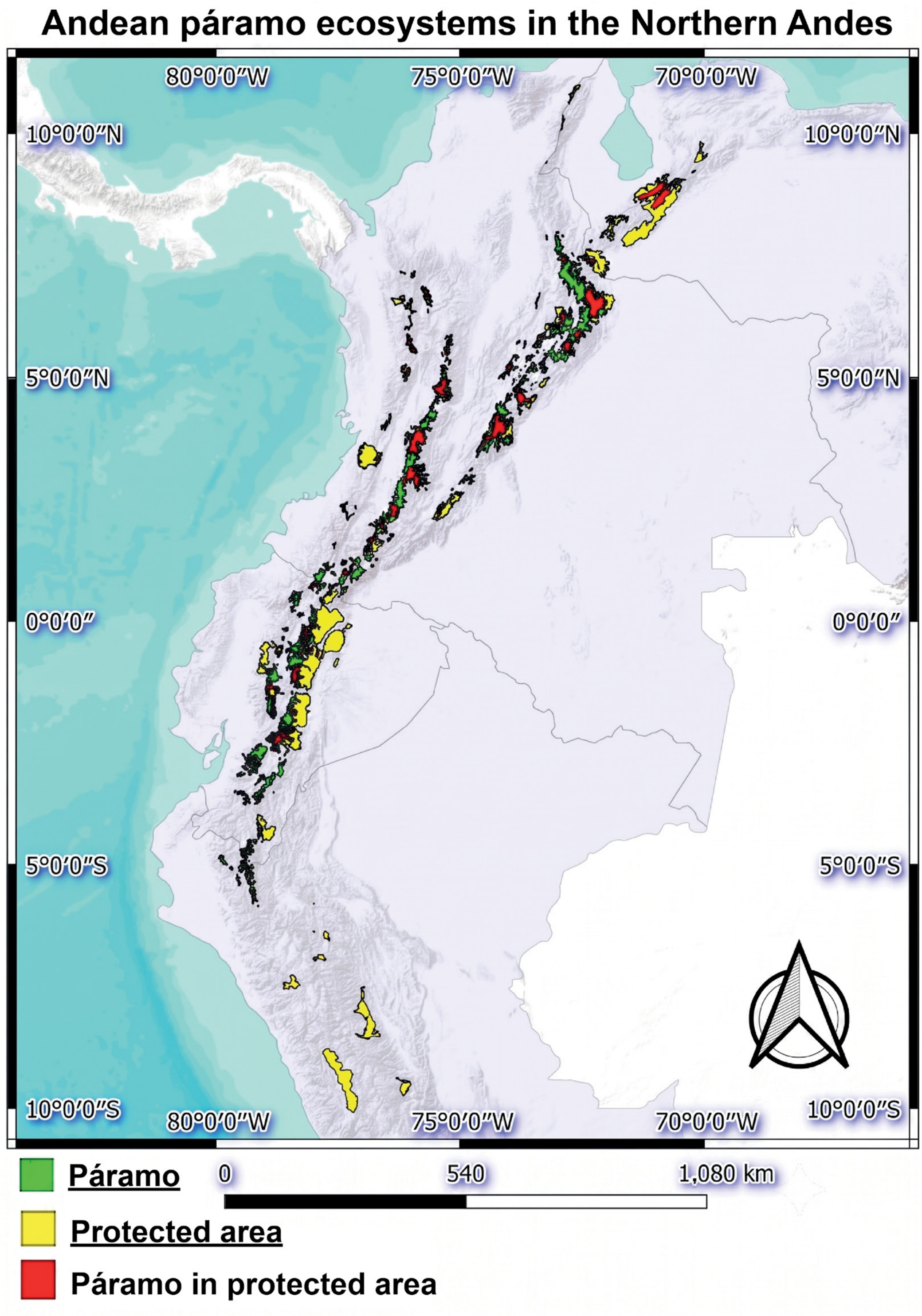
zation of the Andean páramos.

The results indicate that a substantial proportion of these ecosystems is encompassed within protected areas, primarily under National Park designations, although the extent of protection varies among countries, reflecting differences in conservation policies and management approaches. In this context, the cartographic database developed constitutes a valuable tool for territorial and environmental analysis, as it enables the assessment of the spatial relationship between páramo ecosystems and existing protected-area networks, as well as the identification of areas potentially vulnerable to transformation processes such as paramization and land-use change. Consequently, this information provides an important basis for environmental planning and the development of conservation strategies under scenarios of increasing anthropogenic pressure and climate change (Figure 3).

Figure 3. Map of Andean Páramo Ecosystems.



4. Discussion

Ecological resilience in páramo ecosystems can be understood as the intrinsic capacity of these high-mountain landscapes to maintain their structural and functional integrity in the face of external disturbances, whether natural or anthropogenic in origin. This attribute is particularly critical under current scenarios of accelerated climate change, where rising temperatures, together with human activities such as burning, intensive grazing, mining, and land-use change, exert increasing pressures on these fragile ecosystems.

In this context, ecological resilience encompasses not only the capacity of ecosystems to resist degradation but also their ability to recover following disturbance events, thereby ensuring the continuity of key ecological processes. From this perspective, processes such as paramization emerge as manifestations of ecosystem transformation associated with anthropogenic intervention, reducing ecological resilience and compromising the provision of critical ecosystem services in Andean páramo ecosystems (Zaccarelli et al., 2008).

Within the context of paramization, climate change has emerged as a major driver of ecosystem change through shifts in vegetation altitudinal ranges and the accelerated retreat of Andean glaciers. These processes reflect a sustained alteration of the environmental conditions that underpin the ecological balance and functioning of these high-mountain ecosystems. At the same time, agricultural activities, particularly potato cultivation and livestock grazing, together with the reduction of Andean forests, contribute to landscape fragmentation and the reconfiguration of natural land cover, thereby increasing ecosystem vulnerability. The findings indicate that the interaction between anthropogenic pressures, particularly vegetation cover loss and rising temperatures, alters hydrological, biological, and soil processes, affecting water availability, vegetation structure, and soil stability. In this context, paramization can be understood as a process of ecosystem degradation that reduces ecological resilience and constrains the capacity of páramo ecosystems to provide essential ecosystem services.

Furthermore, it is observed that the capacity for plant regeneration is a key indicator of the ecological state, since anthropogenic disturbances decrease this dynamic, affecting essential functions such as carbon capture and water regulation, which are fundamental for the stability of the Andean páramos.

Based on an analysis of the Protected Planet database, protected areas containing páramo ecosystems were identified. The spatial overlay of these areas with the existing ecosystem map allowed for a more precise delimitation of the distribution of páramos within protected areas, generating an integrated cartographic representation of their coverage in these zones.

In terms of conservation status, and according to the protected area categories established by the IUCN, Andean páramo ecosystems included within Category II (National Parks) are concentrated primarily in countries such as Colombia, Peru, and Venezuela. These areas are designed to conserve large-scale ecological processes, maintain ecosystem functionality and biodiversity, and support compatible activities such as scientific research and regulated ecotourism. From this perspective, the protection of páramo ecosystems under Category II designations is particularly strategic, given their high levels of endemism, unique ecological characteristics, and the essential ecosystem services they provide.

According to the IUCN report on the Protected Planet website, the largest proportion of Andean páramos are classified as Category II National Natural Parks, representing 95% in Venezuela, 74% in Ecuador, 66% in Colombia, and 46% in Peru. To protect specific natural features and outstanding biodiversity attributes, as well as the habitats associated with these ecosystems, approximately 3% of Venezuela's páramos are classified as Category III (Natural Monument or natural feature).

In Colombia, it is estimated that approximately 1% of páramo ecosystems are designated as Flora and Fauna Sanctuaries, corresponding to IUCN Category IV. This category focuses on active management for the conservation and restoration of specific habitats and species through conservation management actions tailored to their protected status. Meanwhile, in Venezuela, some páramos are classified under Category V, defined as protected terrestrial or marine landscapes, where the historical interaction between human communities and nature is recognized as a key element for their conservation.

Similarly, in Colombia, Peru, and Venezuela, areas have been identified under Category VI, focused on the sustainable use of natural resources, allowing human presence under management schemes that guarantee long-term conservation. In these countries, these areas adopt different names depending on their regulatory framework, In Colombia, they include designations such as Regional Integrated Management Districts, Civil Society Natural Reserves, and National Protective Forest Reserves. In Peru, conservation areas and hunting reserves; and in Venezuela, Protective Zones. These categories reflect management approaches that seek to reconcile the conservation of the páramos with the sustainable use of their natural resources.

Despite the regulatory advances implemented by Andean countries to protect these ecosystems, significant gaps remain in the knowledge of sensitive areas, as well as in the development of detailed inventories of biodiversity and invasive species or pests. In many cases, páramos are included within larger conservation units, without a specific delimitation that recognizes them as areas of priority biogeographical interest. While initiatives and projects aimed at their study and conservation have been developed, largely driven by international organizations, limitations in the available information still prevent a comprehensive understanding of their resources, potential, and vulnerabilities to the pressures of global change.

The regulatory frameworks and administrative measures implemented across different countries constitute a fundamental pillar for the governance and management of páramo ecosystems. A common feature is that a substantial proportion of these territories is under state protection, while to a lesser extent their management is shared with civil society initiatives and private landholders.

On the other hand, ethnic communities have their own governance systems that strengthen their autonomy in decision-making regarding these territories. Through these mechanisms, they are able to regulate land use with a conservation-oriented approach, as well as establish restrictions on extractive activities such as mining, in alignment with the protection and sustainability of páramo ecosystems.

5. Conclusions

Although Andean páramo ecosystems share a relative functional and environmental homogeneity, their broad geographic distribution and evolutionary history give rise to marked local differences. These variations are reflected in soil diversity, species composition, and vegetation cover, contributing to high levels of beta diversity at the regional scale.

The benefits these ecosystems provide to human societies are closely linked to their biodiversity and the ecological functions they perform. These include carbon storage in soils, their key role in regulating the hydrological cycle, climate moderation, pollination, and the generation of organic matter that sustains productivity in the Andean region. The páramos (high-altitude Andean grasslands) possess significant cultural value, serving as spaces of identity and ancestral exchange, as well as landscapes of great scenic beauty. Taken together, these characteristics position them as strategic biomes for the ecological and socio-environmental balance of the Andes.

Andean páramo ecosystems exhibit an increasingly compromised ecological resilience in the face of intensifying climate change and anthropogenic pressures, which affect their regenerative capacity. Furthermore, their high vulnerability, linked to geographic isolation and recurrent disturbances, limits their adaptive margins and places essential ecosystem services at risk, given the regenerative capacity of these ecosystems to maintain their stability and ecological functioning.

Although a substantial body of knowledge exists regarding páramo biodiversity, significant gaps remain in key ecological components such as invertebrate fauna, soil microbiota, trophic networks, and interspecific interactions. These limitations hinder a comprehensive understanding of ecosystem functioning. Therefore, further research in these areas is essential to more accurately assess ecosystem resilience under pressures such as climate change and land-use transformation, and to inform the design of effective management and conservation strategies aimed at preventing irreversible impacts.

On the other hand, the sociocultural dimension of the páramo and the communities that have historically inhabited its areas of influence requires continuous strengthening; although projects aimed at promoting participatory management have been promoted, it is necessary to delve deeper into studies that integrate social, economic and demographic variables, as well as the analysis of productive activities, land tenure and ecosystem services from an integral approach is especially relevant in the areas surrounding the páramo, particularly at the base of the mountain, where greater anthropogenic pressures and transformations of the territory are concentrated.

In the context of climate change, paramization can be understood as a manifestation of ecosystem transformation in Andean páramo environments, associated with alterations in altitudinal gradients, glacier retreat, and changes in thermal conditions. Evidence such as shifts in vegetation boundaries and the reduction of ice masses reflects structural changes that affect key processes, including hydrological regulation, vegetation dynamics, and carbon storage.

This scenario, intensified by interaction with human pressures, does not imply a functional expansion of the ecosystem, but rather a progressive deterioration of its ecological conditions, which reduces resilience and compromises the stability of ecosystem services. Consequently, paramization is a critical indicator of the state of degradation of these systems, underscoring the need to strengthen conservation, restoration, and sustainable management strategies in the Andean páramos.

The results of this study show that Andean páramo ecosystems exhibit high vulnerability to the interaction of anthropogenic and climatic drivers, which directly affect their structure and functioning. The systematic review identified land-use change, grazing, agriculture, and climate change as the main drivers of transformation, significantly affecting hydrological regulation, carbon sequestration, and vegetation dynamics.

Paramization is manifested as a process of ecosystem degradation associated with landscape fragmentation, biodiversity loss, and the alteration of the system's biophysical conditions. These changes are reflected in a decline in ecological resilience and in the capacity of the ecosystem to provide essential ecosystem services.

The evidence analyzed suggests that paramization does not represent a natural expansion of páramo ecosystems, but rather a process of functional degradation associated with anthropogenic disturbances. In contrast to the altitudinal transitions characteristic of high-Andean vegetation dynamics—defined by continuous and relatively stable ecological gradients—paramization results from the abrupt replacement of vegetation cover, primarily driven by deforestation, overgrazing, and recurrent fire use. This process leads to structural simplification of the ecosystem, a significant reduction in biological diversity, and the alteration of key ecosystem functions such as hydrological regulation and carbon storage. Consequently, paramization disrupts natural vegetation succession processes, reducing system resilience to environmental disturbances and compromising both ecological stability and the capacity to provide essential ecosystem services.

Systematizing the evidence allowed us to identify gaps in literature, particularly the limited integration of key ecological variables and the scarcity of comparative studies at a regional scale. These findings provide a basis for future research aimed at comprehensively understanding the ecological dynamics of the Andean páramos.

As part of the spatial analysis of páramo ecosystems, a cartographic dataset was developed through the integration of official information from the four Andean countries that share this biome. This exercise enabled the delineation of 133 biogeographic units, providing an updated contribution that enhances the accuracy and availability of regional-scale information.

The resulting cartography facilitates an improved understanding of the distribution and spatial heterogeneity of these ecosystems, while also highlighting their importance within conservation frameworks across the Andean mountain range. In this context, a substantial proportion of páramo areas was found to fall under IUCN Category II protection (National Parks). However, this coverage varies among countries, reflecting differences in management approaches, conservation priorities, and environmental governance, although the inclusion of these ecosystems within formal protected area systems generally predominates.

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Contributor roles

- Angela María Zapata Guzmán: conceptualization, investigation, methodology, resources, writing—original draft.

Data availability

Data will be made available on request.

Use of Artificial Intelligence

The authors declare that no artificial intelligence has been used in the preparation of the manuscript.

Ethical Implications

The authors declare that there are no ethical implications.

Conflict of Interest

The authors declare that they have no affiliation with any organization with a direct or indirect financial interest that could have appeared to influence the work reported.

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