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Ecosystem Disruption in Colombia's Páramo: Assessing Anthropogenic Change through a DPSIR Framework

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Abstract

The Páramo ecosystem is one of the most distinctive high-Andean ecosystems in the world, hosting extraordinary biodiversity and playing a critical role in the provision of ecosystem services. Notably, nearly half of the global extent of páramos lies within Colombia, making them essential not only for national sustainability but also for global climate regulation. These ecosystems sustain millions of people through water provision, regulate regional hydrology, and act as carbon sinks, while supporting exceptionally high levels of endemism. However, they are increasingly threatened by the dual forces of climate change and human activity, including agriculture, mining, and infrastructure development. Understanding the drivers of change and their cascading consequences is therefore essential for informed conservation and governance.

This study applies the Drivers-Pressures-State-Impact-Response (DPSIR) framework to examine the complex socio-ecological dynamics affecting Colombian páramos. The framework allows a structured assessment of how socio-economic and climatic drivers translate into pressures such as land-use conversion to mining and agriculture, and hydrological disruption, which in turn alter the ecological state of these fragile landscapes. Evidence shows that although 86% of Colombia's páramos still retain natural vegetation, their integrity is increasingly compromised by habitat fragmentation, soil degradation, and water imbalance. Projections under climate change scenarios further indicate upslope displacement of species and ecosystems, leading to habitat compression and heightened risks of biodiversity loss. By mid-century, up to half of the páramo extent in key areas such as Chingaza National Park could become climatically unsuitable, with severe implications for water security and carbon storage. The impacts of these changes extend beyond ecological integrity to human well-being, given that páramos supply about 70% of Colombia's freshwater and underpin hydroelectric generation, agriculture, and urban consumption. Loss of regulating services also raises the risk of conflicts over land and water use, particularly in vulnerable rural communities. Responses have emerged at multiple levels. Yet these measures are unevenly enforced and often clash with local livelihood strategies. This analysis highlights the urgent need for integrated, participatory governance that bridges ecological science with socio-cultural realities.

Keywords: Colombian páramo; DPSIR framework; ecosystem services; climate change; biodiversity conservation; land-use change; adaptive governance; socio-ecological system

1. Introduction

Perched atop the Andes mountains, the páramo ecosystem is one of the world's most extraordinary and fragile landscapes. Its ancient vegetation, over four million years old, has birthed an extraordinary array of life with high endemism, sustained by its unique combination of low temperatures, high precipitation, and specialised biota (>3,400 vascular plant species with ~60–90% endemism; and ~30 endemic genera out of 300) (Madriñán *et al.*, 2013; Vargas *et al.*, 2023). Páramos are considered a biodiversity hotspot, the most species-rich ecosystem in the world's tropical montane regions (Rangel & Orlando, 2018; Sklenář *et al.*, 2014), and the richest alpine vegetation type globally (Hofstede & Llambí, 2020)—within which Colombia hosts nearly ~51% of the world's páramos (Molina *et al.*, 2019; Sarmiento *et al.*, 2013), making it critical to global páramo conservation. Páramos supply 70% of Colombia's water (Burbano-Girón *et al.*, 2020), sustaining human livelihoods for over 8,000 years (Farley & Bremer, 2017). Comparative analyses with other ecosystems and biomes at a global scale further highlight the páramo's singular value, emphasising the urgency of conservation strategies that can strengthen its resilience to both anthropogenic pressures and climatic stressors (Sgrò *et al.,* 2010; Diazgranados *et al.*, 2021). Importantly, páramos provide key ecosystem services, *primarily* water provision, climate regulation via carbon sequestration, and biodiversity maintenance (Buytaert *et al.*, 2006; Buytaert *et al.,* 2011; Farley *et al.*, 2013; Suarez *et al.*, 2022; Vergara & De-Pellegrin, 2025). Given that socio-economic, political, and cultural drivers vary by country (Ostrom, 2011), and Colombia's páramos face distinct pressures, this analysis focuses specifically on the Colombian context.

This paper applies the Drivers-Pressures-State-Impact-Response (DPSIR) framework to critically assess how anthropogenic activities drive environmental change (Kyere-Boateng & Marek, 2021; Tscherning *et al.*, 2012) in Colombia's páramos, disrupting ecosystem services such as water regulation, carbon sequestration, and biodiversity maintenance.

Figure 1 illustrates the DPSIR framework applied to anthropogenic activities affecting the páramo's ecology and ecosystem services. Drivers (left panel), such as economic growth, population expansion, social changes, political systems, and climate change, drive land-use changes (central-left panel), represented by mining, agriculture, infrastructure development, and industry. These changes create Pressures (e.g., habitat degradation, pollution, resource extraction), which in turn alter the State of the environment by modifying key ecological conditions. The resulting Impacts (central-right panel) affect ecosystem services, including water provision and regulation, biodiversity, climate regulation and climate resilience. Responses (far right)—legal protection, participatory land-use planning, restoration and monitoring, and payment for ecosystem services (PES)—aim to curb pressures, stabilize state, and secure benefits.

2. Objectives

The purpose of this study is to unravel how Colombia's páramos are being reshaped by both direct anthropogenic pressures—such as agricultural expansion, mining, urbanisation, and land-use change—and the indirect effects of climate change. Using the DPSIR framework as a guiding framework, the research first seeks to identify the drivers of change, from economic expansion and shifting political agendas to global warming and demographic growth. It then examines how these forces translate into direct pressures, such as agricultural intensification, mining, and hydrological disruption, that steadily erode the páramo's ecological fabric.

Beyond cataloguing pressures, the study evaluates the current state of the ecosystem's resilience —reflected in the remarkable proportion of intact vegetation— as well as its vulnerabilities, including habitat fragmentation and declining capacity to regulate water and carbon. The analysis further explores the cascading impacts these transformations have on biodiversity, water security, carbon storage, and the livelihoods of communities who depend on these upland landscapes.

Finally, the research critically reviews responses to address these challenges, ranging from legal protections and participatory land-use planning to payment for ecosystem services schemes and ecological restoration. By integrating these strands, the study aims to propose governance strategies that not only tackle immediate threats but also build long-term resilience, bridging

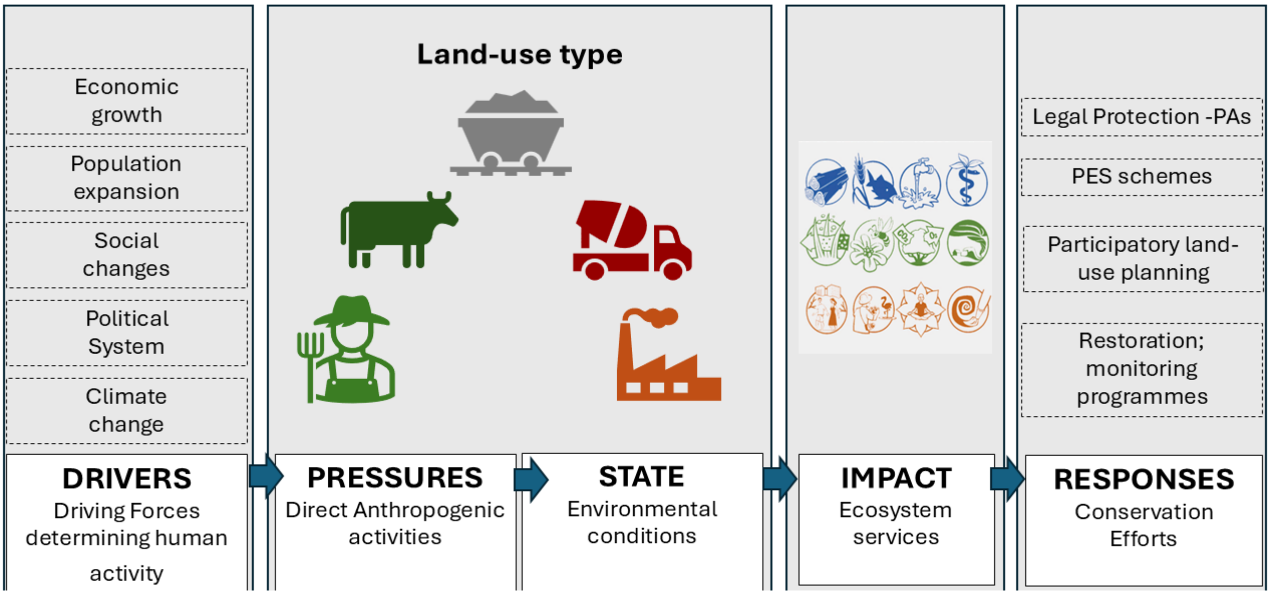

Figure 1*. DPSIR framework applied to land-use changes in Colombia's páramo ecosystem. This diagram illustrates the Drivers-Pressures-State-Impact-Responses (DPSIR) model in the context of anthropogenic activities affecting the páramo. Source: Author's own elaboration, adapted from Schirpke et al. 2023; Icons for ecosystem services by Jan Sasse designed for TEEB*

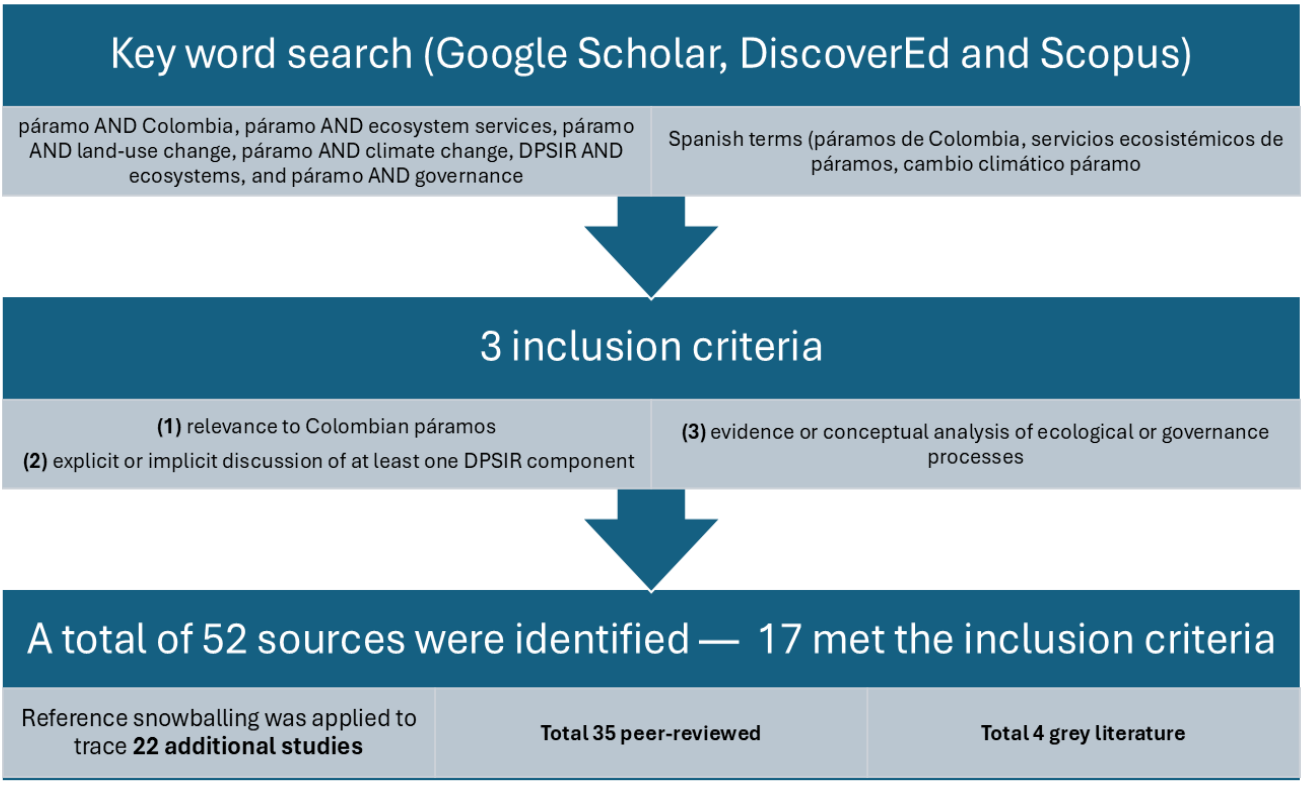

Figure 2*. Methodological workflow of the systematic literature review. The process included a keyword search in multiple databases (Google Scholar, DiscoverEd, and Scopus), application of three inclusion criteria, and final selection of sources. From 52 identified publications, 17 met the criteria. Reference snowballing identified 22 additional studies for analysis.*

ecological science with the socio-cultural realities of Colombia's high mountain landscapes.

It is important to clarify this study's scope and contribution. Whilst the DPSIR framework facilitates systematic review of existing responses, this analysis does not attempt to comprehensively evaluate whether current conservation strategies are sufficient or to identify detailed opportunities for enhancement across all initiatives. Given the substantial attention Colombian páramos have already received—including major programmes such as the GEF-funded 'Páramos for Life' project—such a comprehensive strategy assessment would constitute separate research. Instead, this study's contribution lies in applying the DPSIR framework to reveal the complex inter-relationships between drivers, pressures, ecosystem states, impacts, and responses at a national scale, providing an integrative diagnostic assessment that can inform prioritisation of future governance attention and research.

3. Materials and Methods

This study applies the Drivers-Pressures-State-Impact-Response (DPSIR) framework to analyse the socio-ecological dynamics of environmental change in Colombia's páramo ecosystems. DPSIR is a widely used conceptual tool (Folkens *et al.*, 2023; Kyere-Boateng & Marek, 2021; Maxim *et al.*, 2009) for linking human activities with ecological outcomes and policy responses (Tscherning *et al.*, 2012), providing a structured way to assess causal relationships between anthropogenic drivers, environmental pressures from human activities, ecosystem condition, resulting impacts, and societal responses (Folkens *et al.*, 2023). It becomes important to note that establishing causal relationships is not always a straightforward process, given that environmental impacts are usually caused by a variety of drivers and complex dynamics of synergies.

The methodology followed a systematic literature review —Illustrated in Figure 2— using the propositional inventory method (Folkens *et al.*, 2023). This approach systematically extracts and categorises information from the literature according to predefined criteria, ensuring transparency and reproducibility (Folkens *et al.*, 2023). The goal was to generalise patterns of socio-ecological change affecting the páramo through a synthesis of existing empirical and conceptual studies.

A keyword search was conducted across Google Scholar, DiscoverEd and Scopus, between September 2024 and September 2025. Search terms included: páramo AND Colombia, páramo AND ecosystem services, páramo AND land-use change, páramo AND climate change, DPSIR AND ecosystems, and páramo AND governance. Additional synonyms and Spanish terms (páramos de Colombia, servicios ecosistémicos de páramos, cambio climático páramos) were included to capture Latin American scholarship (see Figure 2). To avoid missing relevant material, grey literature (e.g. government reports, NGO assessments, and doctoral theses) was also reviewed, given its importance in Latin American environmental governance contexts.

All publications were screened against *three inclusion criteria*: **(1)** relevance to Colombian páramos; **(2)** explicit or implicit discussion of at least one DPSIR component; **(3)** evidence or conceptual analysis of ecological or governance processes (see Figure 2). Irrelevant studies, duplicates, or papers only peripherally mentioning páramos were excluded. A total of 52 sources were initially identified, of which 17 met the inclusion criteria. To broaden coverage, reference snowballing was applied (Jalali & Wohlin, 2012), whereby the bibliographies of these core publications were systematically reviewed to identify and include additional relevant studies not captured in the initial database search. This process yielded 22 further sources for analysis —for a total of 39 relevant scientific papers (35 peer-reviewed and 4 grey literature reports).

Each source was categorised according to DPSIR components (Folkens *et al.*, 2023; Kyere-Boateng & Marek; 2021; Maxim *et al.*, 2009). For example, drivers included economic growth, population expansion, climate change, and political agendas; pressures covered agriculture, mining, infrastructure development, and pollution; state captured hydrological, ecological, and land-cover conditions; impacts focused on ecosystem services disruption (e.g. water provision-regulation), biodiversity loss, and carbon balance; and responses encompassed legal frameworks, community initiatives, and market-based mechanisms such as payment for ecosystem services (Galvis *et al.*, 2018; Folkens *et al.*, 2023; Kyere-Boateng & Marek; 2021; Maxim *et al.*, 2009; Tscherning *et al.* 2012).

Climate change is categorised as a driver in this analysis, following established DPSIR applications at national and regional scales (Bruno *et al.*, 2020; Moss *et al.*, 2021) and is consistent with the IPBES global assessment, which ranks climate change as the third most significant driver of biodiversity change globally (IPBES, 2019). Whilst climate change is itself a consequence of global anthropogenic greenhouse gas emissions, at the scale of this study—focused on Colombia's páramo ecosystems—climate change functions as an external forcing factor that drives localised pressures (such as altered precipitation patterns, temperature increases, upslope displacement and glacial retreat) which in turn affect ecosystem state and generate impacts on biodiversity and ecosystem services. This framing is standard in national and regional DPSIR applications where the analytical boundary is drawn at the ecosystem or country level rather than globally.

Coding was performed manually and cross-checked against keyword occurrences to ensure consistency (see Table 1). In this context, coding refers to the systematic classification of textual information into analytical categories (i.e., DPSIR elements), allowing patterns and causal relationships across the literature to be identified, compared, and synthesised in a structured manner.

While the DPSIR framework structured the analysis, qualitative synthesis allowed for critical reflection on cross-scalar interactions (e.g., climate change amplifying socio-economic drivers), trade-offs (e.g., conservation vs. livelihoods), and governance tensions (e.g., conflicts over land rights) (Folkens *et al.*, 2023; Kyere-Boateng & Marek; 2021; Maxim *et al.*, 2009). This approach enabled not only a descriptive mapping of causal pathways but also an interpretative discussion of resilience and policy implications for safeguarding páramo ecosystems.

Table 1. *Example of coding method applied to selected sources within the DPSIR framework*

Reference	Drivers	Pressures	State	Impacts	Responses
Buytaert et al. (2011)	Climate change; population growth	Land conversion for agriculture and mining; water extraction	Altered hydrology	Declining water regulation; carbon loss	Restoration measures (suggested)
Burbano - Girón et al. (2020)	Policy change; socio-economic development	Agriculture; mining; infrastructure expansion	86% natural vegetation cover	Habitat fragmentation; biodiversity decline	Legal protection (Law 99/1993; Law 1930/2018)
Diazgranados et al. (2021)	Climate Change / Warming	Upslope species migration	Restricted elevational range	Risk to endemic species (*Espeletia*)	Monitoring recommendations

4. Results and Discussion

4.1 Drivers

Economic growth and population expansion in Colombia, driven by national and international market demands for diverse products—e.g. petroleum and coal exports, agricultural commodities (e.g. coffee, cut flowers, livestock, potatoes), manufactured goods, and services—have intensified land-use pressures on páramos alongside the accelerating impacts of climate change (Llambí *et al.*, 2020; Hofstede & Llambí, 2020). Climate change exacerbates socio-economic drivers by altering temperature and precipitation patterns, destabilising ecosystem function (Buytaert *et al.*, 2011; Cresso *et al.*, 2020; Diazgranados *et al.*, 2021; Hofstede & Llambí, 2020).

Warming in Colombian páramos has reached +0.7°C *warming-rate-per-decade* (Ruiz *et al.*, 2008), and 56% of Colombian páramos expect increased temperatures by 2050 (Ruiz *et al.*, 2008), exacerbating ecosystem service disruption (Buytaert *et al.*, 2011; Diazgranados *et al.*, 2021).

Beyond temperature shifts, climate change threatens páramos´ hydrological and carbon-storage functions: increased evapotranspiration, declining soil moisture, and altered precipitation regimes destabilise water regulation, affecting downstream water provision (Buytaert *et al.*, 2011). Warming also accelerates soil organic matter decomposition, potentially shifting the páramo from a carbon-sink to a net-carbon-source, reinforcing global climate feedback loops (Buytaert *et al.*, 2011). Climate change-driven rising temperatures are also expected to cause upslope displacement of páramos, whereby warming forces species and vegetation zones to migrate towards higher, cooler elevations (Buytaert *et al.*, 2011; Cresso *et al.*, 2020; Diazgranados *et al.*, 2021; Tovar *et al.*, 2013).

Projections indicate an upward-shift in the lower boundary (Figure 3) (Tovar *et al.*, 2013). However, unlike most biomes, paramos´ upper boundary (~5,000 m; green

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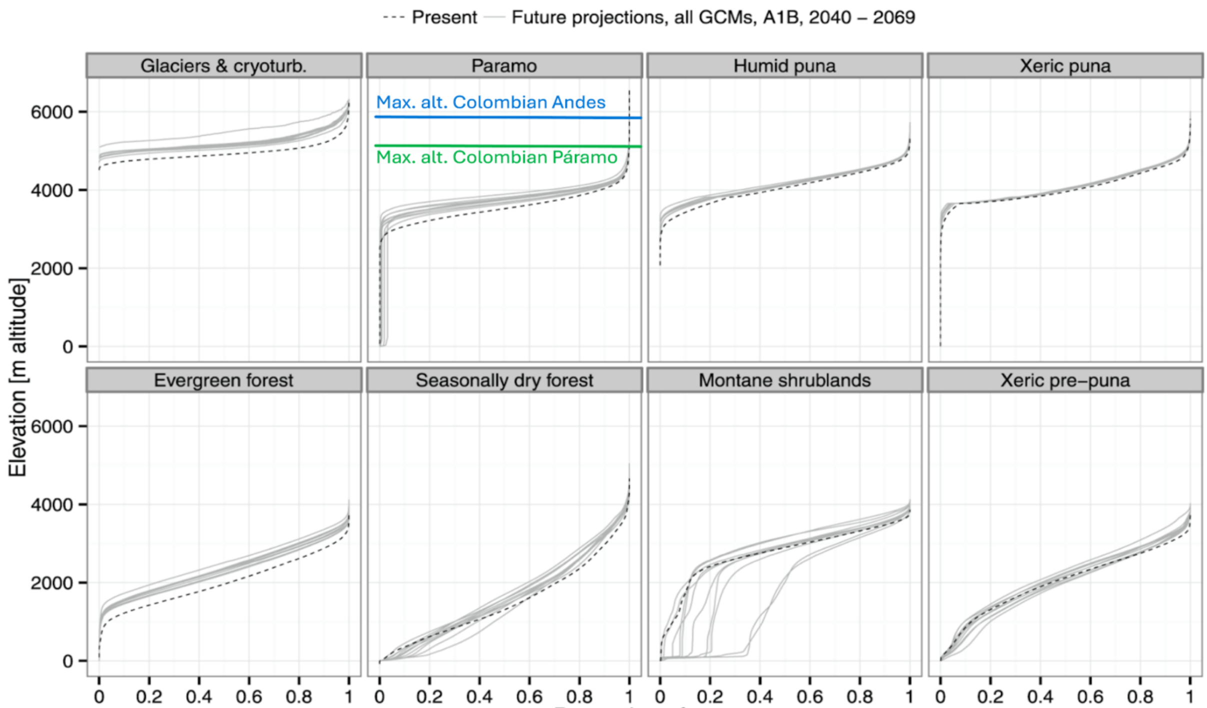

Figure 3. Elevational range shifts under mid-21st century climate projections (2040–2069). *Glaciers, páramo, humid puna, and evergreen montane forest display upslope displacement of their lower boundaries, as shown by future projections (grey lines) relative to current distributions (dotted line). Colombian Páramo's upper limit (~5,000 m; green) and the maximum altitude of the Colombian Andes (~5,800 m; blue) are indicated. X-values are scaled 0–1 for comparability across landscapes. Adapted from Tovar et al. (2013).*

line Figure 3) (Christmann & Oliveras, 2020) remains constrained by the Colombian Andean Mountain range (~5,800 m; blue line Figure 3), increasing the risk of *habitat compression* (Tovar *et al.*, 2013).

As an example, projections for Chingaza National Park—one of Colombia's most important páramos, supplying water to over 10 million people—indicate that by 2041–2060, climate change could render 39–52% of its páramo extent unsuitable during the dry season and 13–34% during the wet season (Cresso *et al.*, 2020). Figure 4 illustrates these projected shifts, comparing historical (1960–1990) and future (2041–2060) conditions under two Representative Concentration Pathways (RCPs), which depict greenhouse gas concentration trajectories: RCP 4.5 reflects a stabilisation pathway, while RCP 8.5 represents a high-emission scenario leading to stronger warming (Cresso *et al.*, 2020). Maps show dry (1, 3, 5) and wet (2, 4, 6) seasons, where green areas represent suitable conditions, dark grey indicates where temperature or precipitation thresholds are exceeded, and the red outline marks the current páramo extent (SIAC) (Cresso *et al.*, 2020).

These challenges are particularly acute for species with slow reproductive cycles —a common trait in this ecosystem— leaving them highly vulnerable to rapid climatic shifts (Diazgranados *et al.*, 2021). Climate change is accelerating upslope habitat migration in tropical mountain systems, yet keystone taxa such as *Espeletia*—already confined to the highest páramo zones—have not much higher ground to retreat to (Diazgranados *et al.*, 2021).

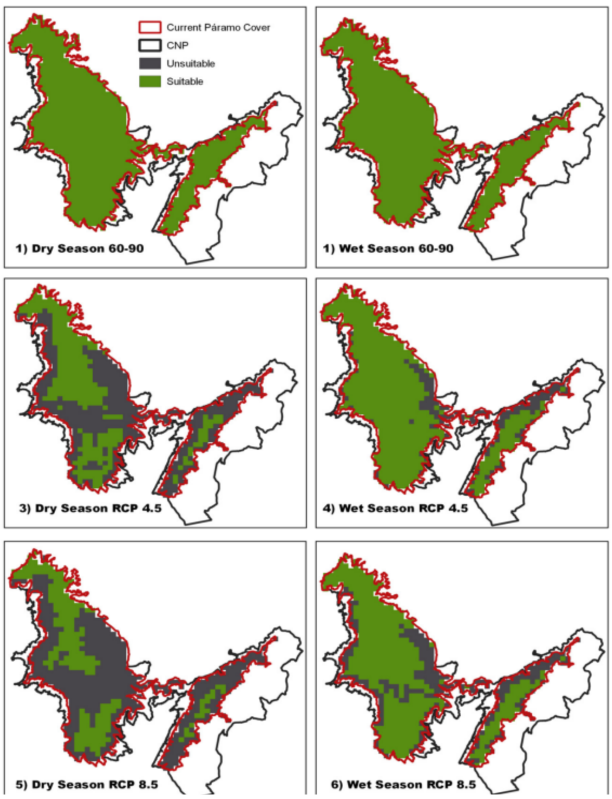

Figure 4. *Potential páramo extent in Chingaza National Park under historical (1960–1990) and future (2041–2060) climate conditions. Maps show dry (1, 3, 5) and wet (2, 4, 6) seasons under RCP 4.5 and RCP 8.5 scenarios. Green areas represent suitable conditions; dark grey indicates where temperature (T) or precipitation (P) thresholds are exceeded. The red outline marks the current páramo extent (SIAC). Adapted from Cresso et al. (2020).*

Table 2*. Summary of the DPSIR Framework Applied to Colombia's Páramo Ecosystem: This table synthesises the key socio-economic drivers, resultant pressures, changes in ecosystem state, their impacts on ecosystem services, and societal responses in Colombia's páramos. It provides a structured overview of how anthropogenic activities influence ecological integrity and ecosystem services provision, supporting the critical analysis in this study. Icons are visual aids for identifying framework categories.*

DPSIR Component	Description	Colombia's Páramo Case	Key References
Drivers	Socio-economic and environmental factors. Policy and governance.	Economic expansion Population growth. Social change Political systems Climate change.	→ *Buytaert et al., 2011* → *Cresso et al., 2020* → *Diazgranados et al., 2021* → *Hofstede & Llambí, 2020* → *Tovar et al., 2013*
Pressures	Direct human activities affecting the ecosystem	Land conversion for agriculture and mining Urban expansion Damming Pollution	→ *Burbano-Girón et al., 2020* → *Buytaert et al., 2011* → *Leroy & García, 2021* → *Vergara & De-Pellegrin, 2025*
State	Current ecological conditions resulting from anthropogenic pressures	Despite 86% *natural vegetation* cover, habitat loss is increasing Hydrological disruption threat	→ *Burbano-Girón et al., 2020* → *Buytaert et al., 2006, 2011* → *Christmann & Oliveras, 2020* → *Llambí et al., 2020*
Impact	Consequences on ecosystem function, structure and ecosystem services (ES)	Declining Water regulation & provision ESs Reduced Carbon sequestration ES Habitat fragmentation/ Connectivity loss Biodiversity loss	→ *Buytaert et al., 2011* → *Harden 2006* → *Farley & Bremen 2017* → *Suarez et al., 2022*
Responses	Legal, community, and policy measures addressing degradation	→ Protected Areas —Legal protection (Law 99/1993; Law 1930/2018) → Participatory land-use planning → PES schemes → Restoration and monitoring programmes	→ *Burbano-Girón et al., 2020* → *Farley & Bremen 2017* → *Leroy & Barrasa Garcia, 2021* → *Llambí et al., 2020* → *Suarez et al., 2022*

Paleoecological evidence (e.g. pollen records) supports the research done on upslope displacement of páramos, indicating that páramos expanded downslope during glacial periods but contracted and fragmented at higher elevations in warmer interglacial periods (Groot *et al.*, 2011; Hooghiemstra *et al.*, 2006; Madriñán *et al.*, 2013; Vuilleumier, 1987; White 2013). The current anthropogenic warming trend mirrors this pattern, but at an accelerated rate, limiting paramos' ability to adapt (Buytaert *et al.*, 2011; Diazgranados *et al.*, 2021; Cresso *et al.*, 2020; Groot *et al.*, 2011; White 2013).

Beyond climatic factors, socio-political processes shape páramo dynamics. Approximately 45-51% of Colombia's páramos fall under National Protection, while legal indigenous territories and community-led initiatives promote sustainable land-use (Llambí *et al.*, 2020). However, competing land claims, agrarian development policies, and post-conflict interventions—including land restitution and illicit crop management—create a complex governance landscape that varies spatially across Colombia's páramos. These governance challenges are particularly acute in regions affected by armed conflict and the subsequent peace process, where overlapping territorial claims and weak institutional capacity influence how anthropogenic pressures unfold (Burbano-Girón *et al.*, 2020; Llambí *et al.*, 2020; Vergara & De-Pellegrin, 2025). Additionally, a lack of an integrated monitoring system challenges the effective assessment of paramos' land-use changes (Llambí *et al.*, 2020).

4.2 Pressures

Colombia's páramos face escalating pressures from land conversion for agriculture and mining, hydrological modifications, and pollution (Buytaert *et al.*, 2011; Llambí *et al.*, 2020). The pursuit of economic growth and ensuring food security relies on agricultural expansion, particularly potato, blueberry, and livestock farming, which increases environmental pressures. Associated activities drive deforestation, soil degradation, and habitat fragmentation, thereby weakening ecosystem resilience (Buytaert *et al.*, 2006). Although significant areas of agricultural land were re-designated as reserves —especially between 1976 and 1982 (Burbano-Girón *et al.*, 2020)— agriculture and grazing remain dominant land uses. This creates persistent conflicts between national conservation policies and the livelihood needs of rural communities (Leroy & García, 2021.

Land-use restrictions aimed at páramos´ conservation often overlook local cultural ties to the landscape, exacerbating tensions (Leroy & García, 2021). Legal and illegal gold mining further degrades páramo soils and contaminates water sources with heavy metals (Buytaert *et al.*, 2011; Llambí *et al.*, 2020). Meanwhile, infrastructure development, including roads, urban expansion, dams and artificial reservoirs, disrupts ecosystem function and hydrological balance (Buytaert *et al.*, 2006, 2011; Burbano-Girón *et al.*, 2020).

Despite legal protections, >13–15% of páramos (449,500 ha) have been converted to pastures, crops, and exotic plantations (Burbano-Girón *et al.*, 2020; Llambí *et al.*, 2020). Additionally, numerous mining concessions for carbon and gold extraction, influenced by fluctuating governing parties, fuel social conflicts (Llambí *et al.*, 2020).

Anthropogenic drivers exert mounting pressures on Colombia's paramos, reducing ecosystem services and causing habitat loss (Table 2).

4.3 State

The intrinsic state of Colombia's páramo, shaped by high specialisation, has evolved over millions of years (Christmann & Oliveras, 2020; Madriñán *et al.*, 2013). While water regulation is widely recognised as a key ecosystem service (Buytaert *et al.*, 2006), biodiversity is often undervalued by local communities (Leroy & García, 2021). Moreover, habitat fragmentation from mining, urban expansion, and agriculture disrupts biodiversity networks, weakening ecosystem resilience (Table 2) (Llambí *et al.*, 2020). Hydrological alterations from extraction and mining contamination disrupt water retention and downstream flow regulation (Buytaert *et al.*, 2006).

As shown in Figure 5, most Colombian páramos retain *natural vegetation*, but significant areas are transformed by human activities (Burbano-Girón *et al.*, 2020). These changes undermine key ecosystem services, including water retention, provision, and carbon sequestration: páramo's sponge-like soils and peatlands regulate water flow and store carbon, helping mitigate climate change (Buytaert *et al.*, 2011; Cresso *et al.*, 2020; Diazgranados *et al.*, 2021). However, ongoing land-use changes threaten these functions, reducing resilience (Sgrò *et al.*, 2010).

In a comparative analysis, we see that 86% of Colombia's páramos retain *natural vegetation* at a national level, (Figure 5) (Burbano-Girón *et al.*, 2020), a proportion matched *only* by the least disturbed global biomes (i.e. Tundra, Boreal forests/taiga) (Figure 6). In contrast, montane grasslands and shrublands—where páramos are classified (Olson *et al.*, 2001; Tovar *et al.*, 2013) —have far less intact vegetation globally, highlighting páramos' relative ecological integrity. However, increasing anthropogenic pressures threaten this state (Williams *et al.*, 2020). Recognising their strategic importance, Colombia has legally protected páramos since *Law 99 of 1993*, later reinforced by *Law 1930 of 2018* (Burbano-Girón *et al.*, 2020).

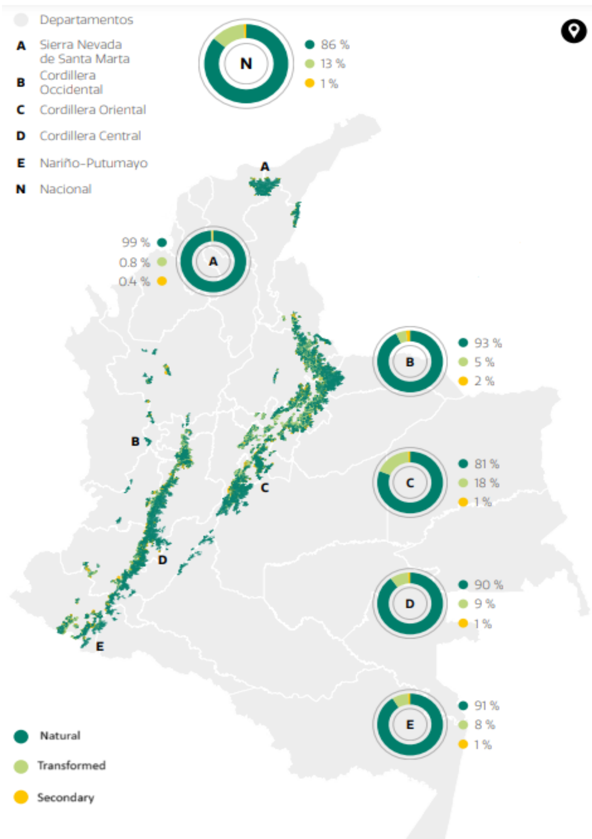

Figure 5. *Natural, secondary, and transformed land cover of Colombian páramos. The figure illustrates the current state of land cover, showing areas with natural vegetation (dark green), secondary vegetation (light green), and transformed areas due to human activities such as agriculture and infrastructure (yellow). The extent of transformation reflects the pressures exerted on the ecosystem and its capacity to maintain ecological functions. Figure sourced from Burbano-Girón et al. (2020).*

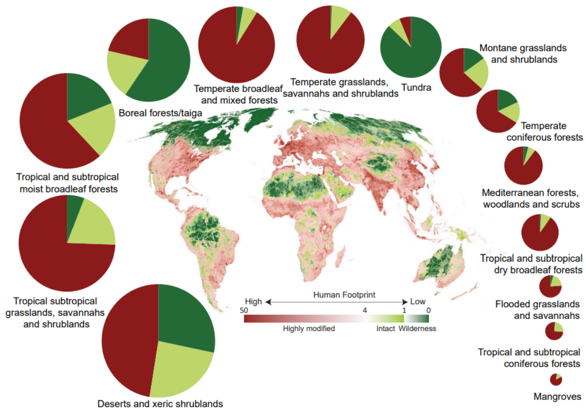

Figure 6. *Global Human Footprint Map (2013) showing levels of human modification across biomes. Pie charts indicate wilderness (dark green), intact (light green), and highly modified (red) areas. While tundra and boreal forests remain largely intact, montane grasslands and shrublands—where páramos are classified—show greater modification. Adapted from Williams et al. (2020).*

4.4 Impact

Grazing and burning of large extensions of Colombia's páramos began in the 1500s with European colonisation (Buytaert *et al.*, 2006; Harden, 2006), severely disrupting biodiversity, ecosystem service provision, and human well-being (Buytaert *et al.*, 2011; Burbano-Girón *et al.*, 2020). The loss of endemic species further weakens ecosystem resilience, making páramos increasingly vulnerable to change (Sgrò *et al.* 2010).

European-introduced livestock exert greater force-per-foot, compacting soils more than native camelids, reducing infiltration and moisture retention, with lasting hydrological impacts (Harden, 2006; White & Maldonado, 1991). Hydrological instability weakens water regulation services, disrupting biodiversity, agriculture, and water security for millions, with reduced availability potentially driving social conflicts, particularly in rural communities reliant on páramo-fed rivers (Buytaert *et al.*, 2011; Farley & Bremen 2017; Harden 2006).

Climate-induced shifts further jeopardise water regulation—*already* affecting drinking water and hydroelectric resources (Buytaert *et al.*, 2011; Diazgranados *et al.*, 2021)—, while accelerated soil decomposition risks reduced carbon sequestration capability (Cresso *et al.*, 2020; Diazgranados *et al.*, 2021) and shifting páramos from carbon-sinks to net-emitters - amplifying global warming (Buytaert *et al.*, 2011). Unlike above-ground biomass, soil carbon loss is largely irreversible, heightening páramos vulnerability (Buytaert *et al.*, 2011).

The cumulative effects of these impacts (Table 2) endanger ecosystem integrity, socio-economic stability and ecosystem services provision. As shown in Figure 7*,* 51% of Colombia's páramos benefit from legal protection, while Figure 5 indicates that only 13% are transformed, reflecting *high conservation value* (Burbano-Girón *et al.*, 2020). However, large, unprotected areas remain vulnerable, threatening ecosystem health (Buytaert *et al.*, 2011).

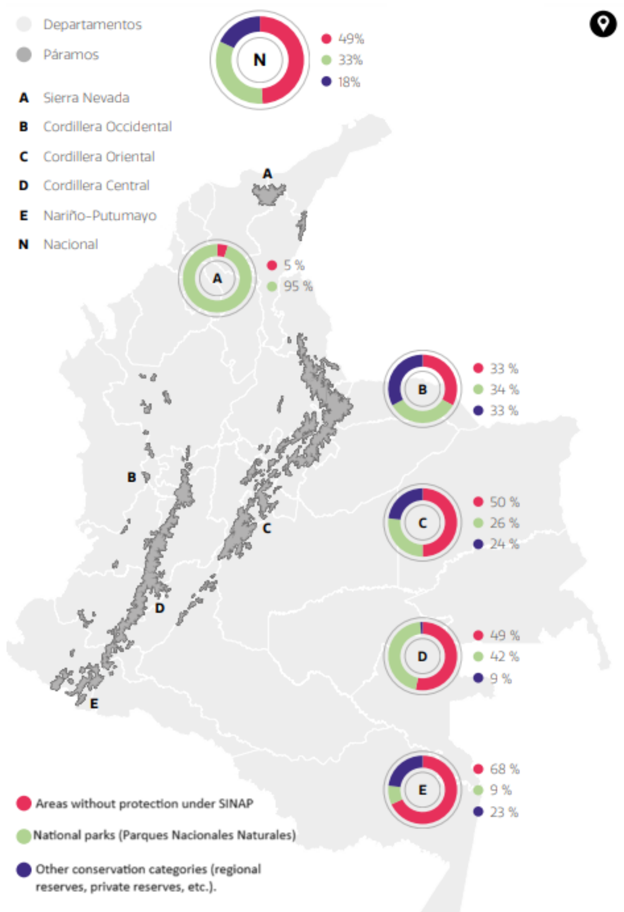

Figure 7. Proportion of conservation areas within Colombian páramos. *The figure illustrates the extent of protection under three categories: areas without formal conservation status (fuchsia/pink), national parks (green), and other conservation categories (i.e. regional reserves, private reserves, etc.). (purple). Variability in protection coverage is evident across different páramo complexes, with some regions benefiting from extensive conservation measures while others remain largely unprotected. Data sourced from Burbano-Girón et al., (2020).*

4.5 Responses

Colombia's páramos benefit from substantial national and international conservation attention and responses to the degradation of Colombia's páramo ecosystem have emerged across legal, institutional, and community levels. At the national scale, legal frameworks such as Law 99 of 1993 and Law 1930 of 2018 established páramos as strategic ecosystems, prohibiting extractive activities and mandating sustainable land-use alternatives (Burbano-Girón *et al.*, 2020). Notably, 51% of Colombia's páramos are currently under some form of legal protection (Figure 7) and 86% retain natural vegetation cover (Figure 5), reflecting a comparatively high degree of conservation (Burbano-Girón *et al.*, 2020). While these laws signal political recognition of páramos' value, their enforcement remains inconsistent, often clashing with agricultural practices and local livelihoods Beyond domestic legal frameworks, initiatives such as the GEF-funded 'Páramos for Life' project (implemented through Instituto Alexander von Humboldt), among others, demonstrate significant investment and institutional coordination. These efforts, alongside widespread environmental education programmes and public engagement, reflect the ecosystem's emblematic status within Colombia. The present DPSIR analysis, therefore, builds upon this existing foundation, providing a systematic framework for examining how conservation responses interact with the broader socio-ecological pressures affecting these landscapes

In order to ensure long-term ecological resilience, effective planning and decision-making for páramo management must also recognise and integrate the participation of local and Indigenous communities, whose leadership and cultural and socio-economic ties to the ecosystem are essential for reconciling conservation goals with livelihood needs (Burbano-Girón *et al.*, 2020).

Participatory land-use planning within Indigenous 'resguardos' (Indigenous reserves) and community-led sustainable agriculture projects illustrate adaptive governance models that balance conservation with socio-cultural needs (Llambí *et al.*, 2020; Leroy & Barrasa Garcia, 2021). Payment for ecosystem services (PES) schemes, including water funds, offer incentivise sustainable management, linking upstream conservation with downstream beneficiaries (Galvis *et al.*, 2018; Farley & Bremer, 2017). Similarly, restoration projects in degraded peatlands and grasslands provide opportunities to recover carbon storage and hydrological regulation functions (Suarez *et al.*, 2022).

At a broader scale, integrated monitoring strategies exist (Burbano-Girón *et al.*, 2020) and emphasise the need to track biodiversity, land-use dynamics, and ecosystem services collectively (Llambí *et al.*, 2020). Strengthening such monitoring would support adaptive management by aligning policy goals with ecological outcomes. Overall, these responses demonstrate that safeguarding páramos requires not only protective legislation but also mechanisms that integrate community knowledge, economic incentives, and long-term ecological monitoring into decision-making.

5. Conclusion — integration of evidence and critical analysis

Applying the DPSIR framework reveals that the erosion of Colombia's páramo resilience is the outcome of tightly coupled socio-economic, political and climatic drivers acting through direct anthropogenic pressures. Economic expansion, food-security goals and demographic change have translated into intensified land-use pressures (notably agriculture and grazing), mining, and infrastructure development; simultaneously, rising temperatures and altered precipitation regimes exacerbate hydrological disruption and biological stress (Buytaert *et al.*, 2011; Llambí *et al.*, 2020). Their combined impact is already producing detectable changes in state —from altered soil moisture and peatland condition to fragmentation of habitat networks— with cascading impacts on water provision, carbon storage and endemic biodiversity (Burbano-Girón *et al.*, 2020; Cresso *et al.*, 2020; Diazgranados *et al.*, 2021).

Comparative analyses further highlight the páramo's singular value among global ecosystems, emphasising the urgency of conservation strategies that can strengthen its resilience to both anthropogenic pressures and climatic stressors (Sgrò *et al.*, 2010; Diazgranados *et al.,* 2021). Although a relatively high proportion of páramo area remains under natural cover and some 51% lies within formal protection instruments (Burbano-Girón *et al.*, 2020), legal protection does not equate to effective conservation on the ground. Enforcement gaps, competing land claims, and livelihood dependencies mean that legal measures (e.g. Law 99/1993; Law 1930/2018) must be complemented by inclusive governance and locally appropriate management to avoid maladaptive outcomes.

On this basis, four interlinked policy and management priorities emerge.

1. **Strengthen cross-scale governance and co-management.** Legal protection should be paired with co-management arrangements that legally recognise and integrate Indigenous and local authorities, thereby aligning conservation goals with livelihood needs and customary land uses (Burbano-Girón *et al.*, 2020; Llambí *et al.*, 2020).
2. **Integrate climate adaptation into land-use planning.** Spatial planning must incorporate climate-driven vulnerability (upslope habitat compression, shifting hydrological regimes) to prioritise protection and restoration of climate refugia and key water-source catchments (Tovar *et al.*, 2013; Cresso *et al.*, 2020).
3. **Scale restoration and ecosystem-service mechanisms**. Restoration of degraded peatlands and expansion of payment-for-ecosystem-service schemes and water funds should be targeted where they yield the greatest co-benefits for carbon storage and downstream water security (Farley & Bremer, 2017; Suarez *et al.*, 2022).
4. **Improve enforcement and adaptive monitoring.** Strengthened enforcement of extractive restrictions must be supported by a national, integrated monitoring framework that tracks ecological and socio-economic indicators (e.g. vegetation cover, peat depth and carbon stocks, baseflow and water quality, species elevational ranges, and community well-being metrics) and triggers adaptive management responses (Llambí *et al.*, 2020).

Finally, the synthesis identifies *priority research needs* to reduce critical uncertainties and inform policy: **(a)** empirical quantification of páramo soil and peat carbon dynamics under warming and land-use change; **(b)** fine-scale hydrological modelling linking headwater condition to downstream water security; **(c)** spatially explicit vulnerability mapping that combines climatic, ecological and socio-economic layers; and **(d)** social-ecological studies on the effectiveness and equity outcomes of PES and co-management arrangements. Addressing these gaps will require interdisciplinary collaboration and long-term funding commitments.

In summary, safeguarding Colombia's páramos requires integrated, participatory strategies that combine legal protection, locally legitimate governance, targeted restoration, and a rigorous monitoring and research agenda. Aligning scientific evidence with socially responsive policy can strengthen the páramo's unique biodiversity, and therefore, its critical regulating services can be maintained in the face of accelerating anthropogenic and climatic pressures (Buytaert *et al.*, 2011; Williams *et al.*, 2020).

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Ethical statement

This study synthesises published literature on Colombian páramo ecosystems within a complex sociopolitical context involving land rights, livelihood dependencies, and conservation governance. All sources are cited according to best practice, and findings are presented to support informed, participatory approaches to páramo management that recognise local and Indigenous knowledge systems

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