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Authors: Camacho, Francisco, and Peyre, Gwendolyn

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Red List and Vulnerability Assessment of the Páramo Vascular Flora in the Nevados Natural National Park (Colombia)

Francisco Camacho[1] and Gwendolyn Peyre[1,*]

Abstract

Background and research aims. The Andean páramo is renowned for its unique biodiversity and sensitivity to environmental threats. However, vulnerability assessments remain scarce, which hinders our capacity to prioritize and apply efficient conservation measures. To this end, we established the Red List of the páramo vascular flora from the Nevados National Natural Park and proposed conservation strategies for its threatened species. **Methods**. We performed International Union for Conservation of Nature (IUCN) Red List assessments by evaluating Criterion B, including sub-criteria B1–Extent of Occurrence and B2–Area of Occupancy, and using a systematic geographic-ecological approach for conditions *a* (Location analysis) and *b* (Continuing decline). We then executed a Conservation Gap Analysis to prioritize species for in-*situ* and/or *ex-situ* conservation. **Results**. Summing our 233 evaluated species with previous assessments, we completed the Red List of 262 páramo species and encountered 3% Threatened (7 VU, one EN), 44% Not Threatened (65 LC, 50 NT), and 53% Data Deficient. We acknowledged *Lupinus ruizensis* as Endangered and *Aequatorium jamesonii, Carex jamesonii, Elaphoglossum cuspidatum, Miconia latifolia, Miconia alborosea, Pentacalia gelida,* and *Themistoclesia mucronata* as Vulnerable. **Conclusion**. The eight threatened species should be included as target species in the PNN Nevados management plan 2023–2028 and regarded as national conservation priorities. **Implications for Conservation**. We recommend *in-situ* conservation for Medium-Priority species *A. jamesonii*, *E. cuspidatum,* and *T. mucronata* with thorough monitoring, paired with sub-population transfers for High-Priority species *C. jamesonii.* For the endemic *L. ruizensis* and *P. gelida*, we suggest combined *in-situ/ex-situ* strategies taking advantage of national germoplasm collections, like the seed bank of the Bogotá Botanical Garden José Celestino Mutis.

Keywords

Colombia, land cover classification, species distribution model, vascular plants, International Union for Conservation of Nature - IUCN, Nevados National Natural Park - PNN Nevados, Andean páramo, Red List of Threatened Species

Introduction

The tropicalpine belt of the northern Andes belongs to the páramo biogeographical province (Luteyn et al., 1999). The Andean páramo is traditionally described as stretching from Venezuela to Peru, reaching the biogeographic barrier that is the Depression of Huancabamba in the south (approx. Lat. 5oS; Weigend, 2002), although similar biological and environmental features occasionally occur further south (e.g., López, 1998). It is renowned for its incredible biodiversity, as illustrated by its 3500 vascular plant species (Sklenář et al., 2005), and high endemism, estimated at 60% at the species level for plants (Luteyn & Balslev, 1992). Moreover, the páramo provides key ecosystem services to Andean people, in rural areas but also million inhabitants cities such as Quito and Bogotá, especially through water regulation and supply as well as carbon storage (Buytaert et al., 2006; Farley et al.,

[1]Department of Civil and Environmental Engineering, University of the Andes, Bogotá, Colombia

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Corresponding Author:
*Gwendolyn Peyre, Department of Civil and Environmental Engineering, University of the Andes, Cra. 1E # 19A-40, Bogotá 111711, Colombia.
Email: gf.peyre@uniandes.edu.co

2012). The páramo is currently facing multiple environmental threats, most of which are associated with unsustainable human practices related to agriculture, livestock, mining, and agroforestry (Hofstede et al., 2003; Rodríguez Eraso et al., 2013; Vásquez et al., 2015). Land-conversion from natural landscapes to land-use in the páramo goes back millennia, however, it has been significantly accelerating in the last centuries, first with the Spanish colonization and more recently with the main agrarian reforms of the XXth century (Anthelme & Peyre, 2019; F. O. Sarmiento & Frolich, 2002; White, 2013). Moreover, climate change is occurring at unprecedented speed in the northern Andes, as warming is expected to reach an additional 1–4°C by the end of the century, while precipitation is bound to increase by 5–20% over the region (IPCC, 2014; Pabón-Caicedo et al., 2020). As a result, important species local extinctions, migrations, and biotic community recomposition are expected in the near future, which will in turn influence the provision of ecosystem services and affect human wellbeing (Buytaert et al., 2011; Peyre et al., 2020; Tovar et al., 2013).

Considering the alarming speed and magnitude at which environmental threats are increasing, it is crucial to evaluate the páramo vulnerability to such threats and assess the efficiency of existing management and conservation strategies (both *ex-situ* and *in-situ*). Today, the main conservation measures put in place are protected areas, which currently include 40% of the total páramo extent (IUCN, 2009). Páramo protected areas are usually established to protect high mountain landscapes and ecosystem services, especially water-related ones, and some are furthermore integrated into the Ramsar network for their unique ecological features, for example, the Angel Ecological Reserve in Ecuador (Ramsar Sites Information Service, 2012). Protected areas are valuable *in-situ* conservation strategies that multiply management foci, including populations, species, functional units, ecosystem services, and ecosystems. However, additional initiatives are often needed to reverse threat status at the species and population levels, requiring, complementary *ex-situ* measures. To adequately assess what management strategies a species would benefit from, conservationists usually rely on specific evaluations such as the standardized Red list assessments of the IUCN (Cooke, 2008), followed by the design and establishment of a conservation plan fitted to the species' characteristics and ecological requirements. The IUCN evaluation methods, like the Red List of Threatened Species, represent valuable tools that are globally acknowledged and employed by scientists, environmental professionals, and policymakers; because of their use of easy-to-apply and rigorous criteria, data sharing, and robust information on data sources, justification, and uncertainties (Rodrigues et al., 2006; Vié et al., 2009). IUCN efforts to record páramo species vulnerability is quickly increasing, as illustrated by the Red Book of Endemic Plants of Ecuador (León-Yánez et al., 2012) and the Red Book of Endemic Plants of Peru (León et al., 2006). In Colombia, there are currently 18 volumes of Red catalogues (Moreno et al., 2019), and several assessments targeting high mountain and páramo species specifically (e.g., Díaz-Vasco et al., 2021). Nevertheless, substantial additional work is required to obtain a more complete overview of the threatened páramo biodiversity and boost integrative conservation strategies.

The Nevados National Natural Park, hereafter referred to as PNN Nevados, is one of the 44 National Natural Parks in Colombia (PNN, 2020a), and a key protected area for Andean landscapes as it covers an almost 3000 m elevation gradient, and hosts montane forests, páramos, and glacier ecosystems (PNN, 2017). The PNN Nevados is undoubtedly an important contributor to the Colombian páramo biodiversity and ecosystem services, providing water to many surrounding cities such as Manizales and Pereira (Sesquilé-Escobar, 2017). Despite the park's governance strict regulation policies regarding anthropogenic activities inside the protected area, current environmental threats toward páramo ecosystems include human-induced issues related to livestock and agriculture in punctual remote areas, such as invasive species and burning, on top of climate change and its related glacier retreat, and volcanic eruptions (PNN, 2017; Rabatel et al., 2018; Salamanca, Cleef, & Ragel-Ch, 2003; Sesquilé-Escobar, 2017). To efficiently employ its economic and human resources, the park focuses today on certain conservation and restauration strategies clearly established within its management plan 2017–2022. In particular, the plan mandates the active conservation and monitoring of target species present in Andean forests and páramos, such as the condor *Vultur gryphus* L. (Vulnerable), puma *Puma concolor* L. (Last Concern), and spectacled bear *Tremarctos ornatus* Cuvier (Vulnerable). The park also focuses on plant species, although in smaller amounts, as it includes the giant stemrosette *Espeletia hartwegiana* Sch.Bip. (Least Concern) and blue lupine *Lupinus alopecuroides* Desr. (Not Evaluated) (PNN, 2017). Because designing the next PNN Nevados management plan 2023–2028 is a priority, it is crucial to provide a prioritizing list of new target species based on clear vulnerability evaluations. However, we believe plant species lack representation in the park's conservation priorities to date, despite their crucial ecological importance regarding ecosystem functioning and services. Therefore, there is a need to provide sound and robust evaluations of the current threatened flora to support the park and encourage conservation professionals to lead activities in the PNN Nevados.

The main goal of our study was to establish the Red List of the páramo vascular flora in the PNN Nevados and propose conservation strategies for the species classified as threatened. Specifically, we first relied on the robust IUCN method to evaluate the full criterion B with a systematic approach to assess the *a* and *b* conditions. We then quantified conservation gaps for each threatened species and prioritized additional *in-situ* or *ex-situ* focus for each species given its ecological features and threat status.

Methods

Study Area

The PNN Nevados was founded in 1974 and it constitutes one of the first National Natural Parks of Colombia, in addition to being conveniently located at the crossroad of four departments: Caldas, Risaralda, Quindío, and Tolima (Figure 1; PNN, 2020a). The park covers 61.388 Ha and presents five mountain peaks, three of which are snow-capped, the Nevado del Ruiz, Nevado Santa Isabel, and the Nevado del Tolima. Because of its important altitudinal gradient between 2600 and 5321 m, the park shows important climatic variability in terms of temperature, that is, mean −4 to 13°C, and precipitation, that is, 1000–2500 mm/year. While diurnal seasonality can be abrupt in the park, especially at high elevation, yearly seasonality remains limited due to its proximity to the equator and takes the form of a bimodal regime including two humid periods (200–400 mm/month) and two dry periods (50–100 mm/month) (PNN, 2017; PNN, 2020a). In addition, the park hosts important ecosystem diversity, from Andean cloud forests, to mix grasslands with giant stem rosettes and shrublands in the páramo altitudinal belt, and high-elevation rocky deserts near glaciers (Rangel-Ch, 2000; Salamanca et al., 2003). Finally, soils are highly influenced by past and current volcanic activity, resulting in a dominance of Inceptisols, Andosols inforests and páramos respectively, and criic Entisols near glaciers (Thouret & Faivre, 1989).

Floristic Checklist And Data

We established the preliminary PNN Nevados floristic checklist for the páramo by consulting georeferenced vascular plant species occurrences and vegetation plot data from different biological databases. First, we extracted data from VegParamo—*the flora and vegetation database for the Andean Páramo* (www.vegparamo.com; Peyre et al., 2015), which we then complemented with additional geographically filtered information from the Humboldt Institute's Biodiversity Information System (SiB) (https://sibcolombia.net). Taxa identified at the supra-specific level and non-vascular plant names were removed and those determined at the infra-specific level were merged into their corresponding species. We checked taxonomy using The Plant List (www.theplantlist.org/) and Tropicos® (http://legacy.tropicos.org/Home.aspx). We then processed the final checklist through the IUCN Red List webpage (www.iucnredlist.org/), to look for evaluation and threat status, and compiled all available information. For species lacking threat status (either not evaluated or data deficient), we performed the IUCN Red List of Threatened Species assessment in four steps (criterion B: sub-criteria B1 and B2 and conditions *a* and *b*). To this end, we first retrieved additional information in form of species occurrence georeferenced records sampled after 1980 at a global scale, using VegParamo, the GBIF database (www.gbif.org/, Supplemental Table S1), and complemented national scale data by consulting the SiB database, the COL Herbarium at the National University of Bogotá (www.biovirtual.unal.edu.co/es/colecciones) and the JBB herbarium at the Bogotá Botanical Garden José Celestino Mutis (http://herbario.jbb.gov.co). Global-scale data was filtered using the South and Central America bioregionalization map from Morrone (2014), retaining only terrestrial occurrences and removing isolated outliers outside the occupied bioregions. Species were globally assessed except for species with presence points located outside the Americas, which were assessed at the continental scale (South America + North America). Duplicate records were checked through the source information and georeferentiation, and all records' geographic coordinates were converted to the decimal system in Datum WGS 84, including for the UTM 1 km resolution referenced VegPáramo plots whose centroid was used for coordinates. As a result from the data cleaning process (Supplemental Figure S1 resumes the complete procedure), we obtained a final dataset of 66.558 records (occurrences) for 233 vascular plant species.

International Union for Conservation of Nature evaluation-Criterion B

We performed a full criterion B assessment focusing on geographic ranges for all 233 páramo species (in addition, we conducted a preliminary evaluation of criterion A—Population size reduction, which was not directly used in this study but can be found as complementary information in Supplemental Table S2). Specifically, we evaluated sub-criterion B1—Extent of Occurrence (EOO), sub-criterion B2—Area of Occupancy (AOO), condition *a*—Location analysis, and condition *b*—Continuing decline (IUCN, 2017)

Sub-criteria B1—Extent of Occurrence and B2—Area of Occupancy

To calculate the EOO of each species, we mapped its occurrence points in ArcMap 10.7.1. and proceeded to define the smallest perimeter to encompasses the species' entire occupation area using function *Minimum bounding geometry* with a Convex Hull option. For AOO and to emulate the species' population size (Gaston & Fuller, 2009), we rasterized the datapoints into a grid with 4 km^2 pixels (IUCN, 2017) with function *Index entities grid*. All resulting pixels were then summed to obtain the final AOO estimate. We finally contrasted the EOO and AOO results against the categories and thresholds proposed by the IUCN Red List Criterion B method to classify each species according to its respective threat status. First, species not threatened by both

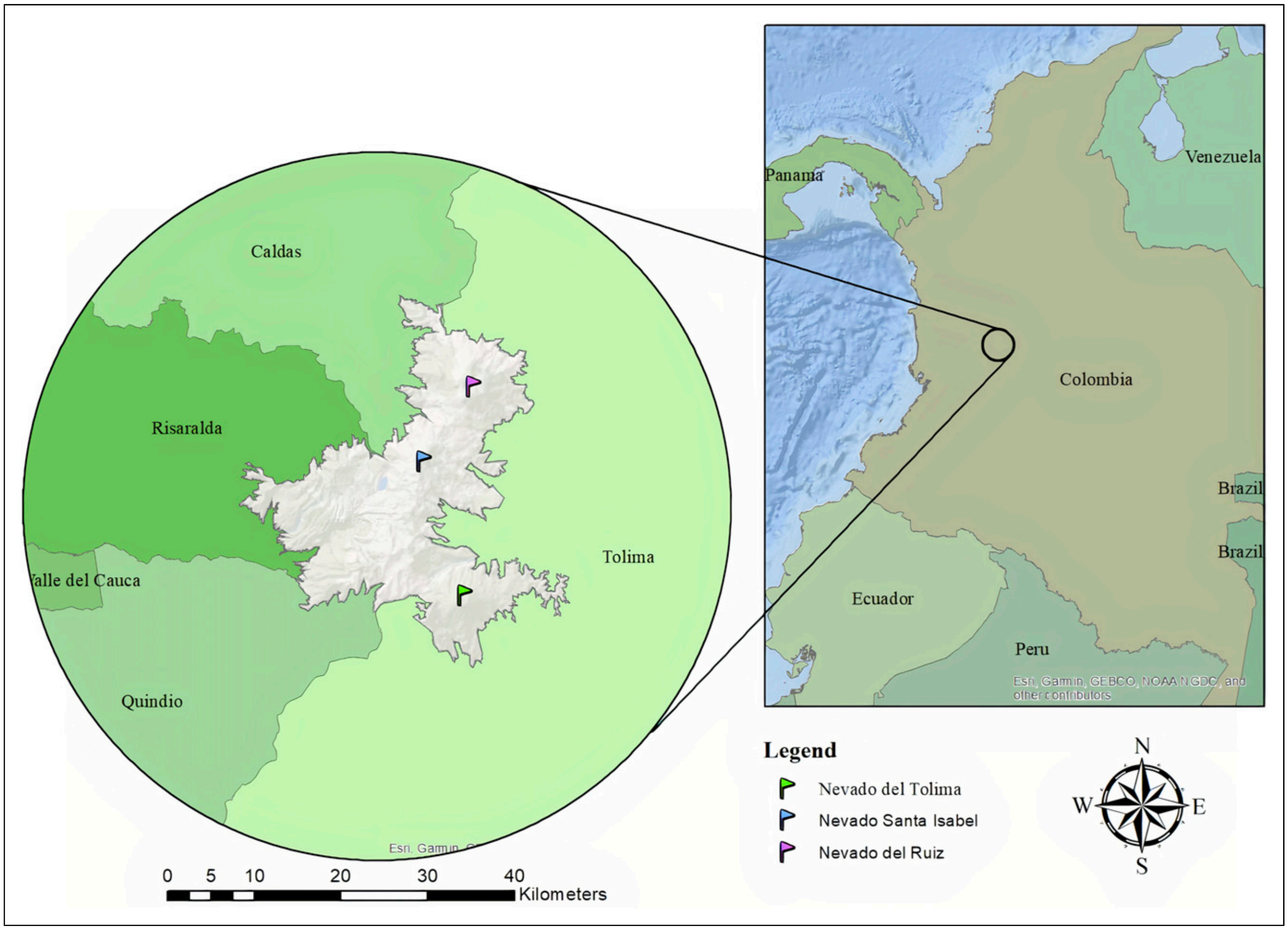

Figure 1. Geographic location of Nevados National Natural Park (PNN Nevados) in Colombia (4°48'00"N 75°22'00"W), a category II—National Park according to the IUCN Protected area classification, and its three snow-capped mountains.

EOO and AOO were directly classified as Least Concern (LC). Second, species threatened by AOO only and presenting less than 250 occurrences were classified as DD, or data deficient pending additional datapoints, because the AOO evaluation is highly dependent on sampling effort. We strategically established our minimum points at 250 because it corresponds to half the pixels needed to achieve the lowest AOO threshold to categorize a species as threatened (500 pixels of 4 km^2 = 2000 km^2). Species threatened by EOO only were included regardless of their datapoint amounts. Finally, species categorized as threatened by both EOO and AOO, but presenting less than 250 occurrences, were only accounted for by their EOO results. Therefore, all 68 species classified as threatened according to sub-criteria B1 and/or B2 were further evaluated with a complementary location analysis (condition *a*) and continuing decline study (condition *b*) at the regional scale (Andean páramo scale). Of this species pool, the ones that did not meet condition *a* or *b* were finally classified as LC, while species meeting one of the two conditions were classified as Near Threatened (NT), and finally those which met both were classified as either Vulnerable (VU), Endangered (EN), or Critically Endangered (CR) according to their results.

Condition A (Location Analysis). We applied a systematic analysis to evaluate Locations, that is, areas where native plant species might be at risk of important population decline and or extirpation (Rodrigues et al., 2006) in the Andean páramo (using the traditional delimitation Lat 5oS–11oN). We relied on the recently published páramo land-cover at 30 m resolution (Peyre et al., 2021) to produce a regional *Páramo Location Map* (PML), against which we compared the predicted current distribution of our species. To do so, we first reclassified into threat categories the 12 ecosystem classes used in the páramo land-cover: 1, crops; 2, desert; 3, forests; 4, glacier; 5, grasslands; 6, meadows; 7, rock; 8, rosette vegetation; 9, shrublands; 10, subnival vegetation; 11, urban areas; and 12, water. We adjusted these classes over a 0–1 range, assigning i) the maximum value, 1, to classes 1, 6, and 11 considered under intense human pressure; ii) the intermediate value, 0.5, to classes 5 and 8 where significant human influence occur, for example, areas undergoing periodic burning and/or grazing practices (Hofstede et al., 2003; Sarmiento et al., 2003); and iii) the lowest value, 0, to all other classes. The resulting adapted classification was aggregated by 30 m pixel mean values to a 1 km resolution to unify scales with all other spatial analyses. Every pixel with a value of 0.5 or above was considered a Location, and we applied a 5 km buffer to every location pixel to merge nearby Locations into a single one, resulting in a total of 63 potential Locations on the PML (pixels within the buffer were considered as belonging to the adjacent location) (Figure 2). Then, we mapped the species' current distribution obtained from a Species Distribution Model (*Realized SDM*, see condition *b* for details on the models used) onto the simplified classification, considering real locations those that coincided with areas potentially occupied by the species. We strategically chose to rely on SDM results instead of datapoints because undersampling and unprecise georeferencing are common limitations in the tropics, and we intended to overcome these issues and approach the species' realized current distribution with a modelling approach that combines the species' occurences, its niche bioclimatic requirements as well as dispersal range. Because we assumed that anthropogenic influence can transcend the previously defined locations and impact species in the direct proximity, we included the overlapping pixels comprised in the first 1 km adjacent pixel of a Location as part of said Location. Condition *a* was met when the species presented one to 10 locations according to the IUCN thresholds).

Condition B (Continuing Decline). To complete Criterion B evaluations, we assessed condition *b* regarding area or extent decline using SDMs. The approach used here followed Peyre et al. (2020), in which SDMs account for dispersal constraints and are run for current and future conditions under different climate change scenarios to be finally ensembled and averaged over the included scenarios. We built on Peyre (2022), a study that predicts changes in the distribution of high mountain plant species in the Andean páramo until 2070. Because our dataset included 27 species that were not represented in the species list from Peyre (2022), we followed the identical modeling protocol to produce comparable results.

To resume the procedure, we first calculated the dispersal distance of each species using the *dispeRsal* function parametrized with functional trait data on specific height, seed mass, and dispersal modes (Tamme et al., 2014). Height was averaged over four herbarium specimens to represent specific values (Danet et al., 2017), and the other traits were obtained at genus level due to data scarcity at the species level (Peyre et al., 2020). The trait data was compiled from information proceeding from diverse sources, including: COL Herbarium, JBB Herbarium, Field Museum, Kew Herbarium, and Millennium Seed Bank among others. The specific dispersal distance was then transformed into a dispersal factor by: (i) rescaling the dispersal distance onto a 0-1 scale (from worst to best dispersers), and (ii) calculating the dispersal range of the species in the study area by assessing the currently-accessible areas given the rescaled dispersal distance (*iForce* function, *iSDM* package, Hattab et al., 2017; Peyre et al., 2020). Second, we employed the seven bioclimatic variables used in Peyre (2022) obtained from the CHELSA project v. 1.1 (http://chelsa-climate.org; Karger et al., 2017) and cropped at the 3000 m isohypse for the páramo extent (Lat: 7o̲S–12o̲N; Long: 80o̲W–70o̲W): i) bio1 – mean annual temperature; ii) bio2-mean diurnal temperature range; iii) bio4-temperature seasonality; iv) bio12-total annual precipitation; v) bio15-precipitation seasonality; vi) bio17 -precipitation of the driest quarter; and vii) bio18 – precipitation of the warmest quarter. Each variable resulted from averaged annual values over the 1979–2013 period and we therefore considered that the average value could represent at the latest the year 2010. In addition, we used the variable set from Peyre (2022) predicted per decade until 2070, hence 6 decades of data, by the means of simple interpolated regressions. These data were available for five distinct General Circulation Models (GCMs): CNRM-CM5; FGOALS-g2; IPSL-CMA-LR; MPI-ESM-P; and MRI-CGCM3, according to two Representative Concentration Pathways (RCPs): CMIP5-RCP 4.5 and CMIP5-RCP 8.5, for a total of ten climate change scenarios. Third, we run SDMs (*Realized SDM*) for the current distribution of each species by fitting its presence (occurrences) and absence (from the VegParamo vegetation data) datapoints with the bioclimatic variables and the previously-calculated dispersal factor. Similarly, we run SDMs for current conditions without the dispersal factor (*Potential SDM*, fitting the presence-absence data with bioclimatic variables only) that we then projected onto future conditions per decade. All models were performed with a randomly selected 75–25% training-testing dataset and 100 run, 25 run with each of the following algorithms: i) Generalized Linear Model (GLM); ii) Random Forest (RF); iii) Multivariate Adaptive Regression Splines (MARS); and iv) Artificial Neural Network (ANN) (*biomod2* package; Thuiller et al., 2016). We assessed model performance using the true skill statistic (TSS) metric (Allouche et al., 2006; Peyre, Osorio, François, & Anthelme, 2021a) and retrieved all models with a TSS value of 0.6 or above for model ensembling into the final probabilistic predictions (Araújo & New, 2007; Marmion et al., 2009; Supplemental Table S3). Fourth, we binarized the final predictions, by using a threshold approach that maximizes the sum of the sensitivity and specificity metrics (*optimal.thresholds* function; *PresenceAbsence* package; Freeman & Moisen, 2008; Liu et al., 2005).

Last, we stacked the current and future binary predictions and performed a 10 years step-by-step distribution change for each species until 2070. To do so, we constrained the species' future distribution at the next step (decade) by its previously-computed dispersal distance and the presence of a biogeographical barrier set at the 3000 m isohypse and acting as weak filter for species dispersal between mountain ranges (*MigClim* package; Engler et al., 2012). Finally, we assessed the amount of area gained, lost, and maintained between 2010 and 2070, as well as the resulting potential yet unoccupied area per species and scenario and averaged results across GCM per RCP. All modeling analyses were carried out in R 3.5.0 (R Core Team, 2018). Therefore, we were able to track progressive changes in species distributions depending on available bioclimatic conditions and its capacity to

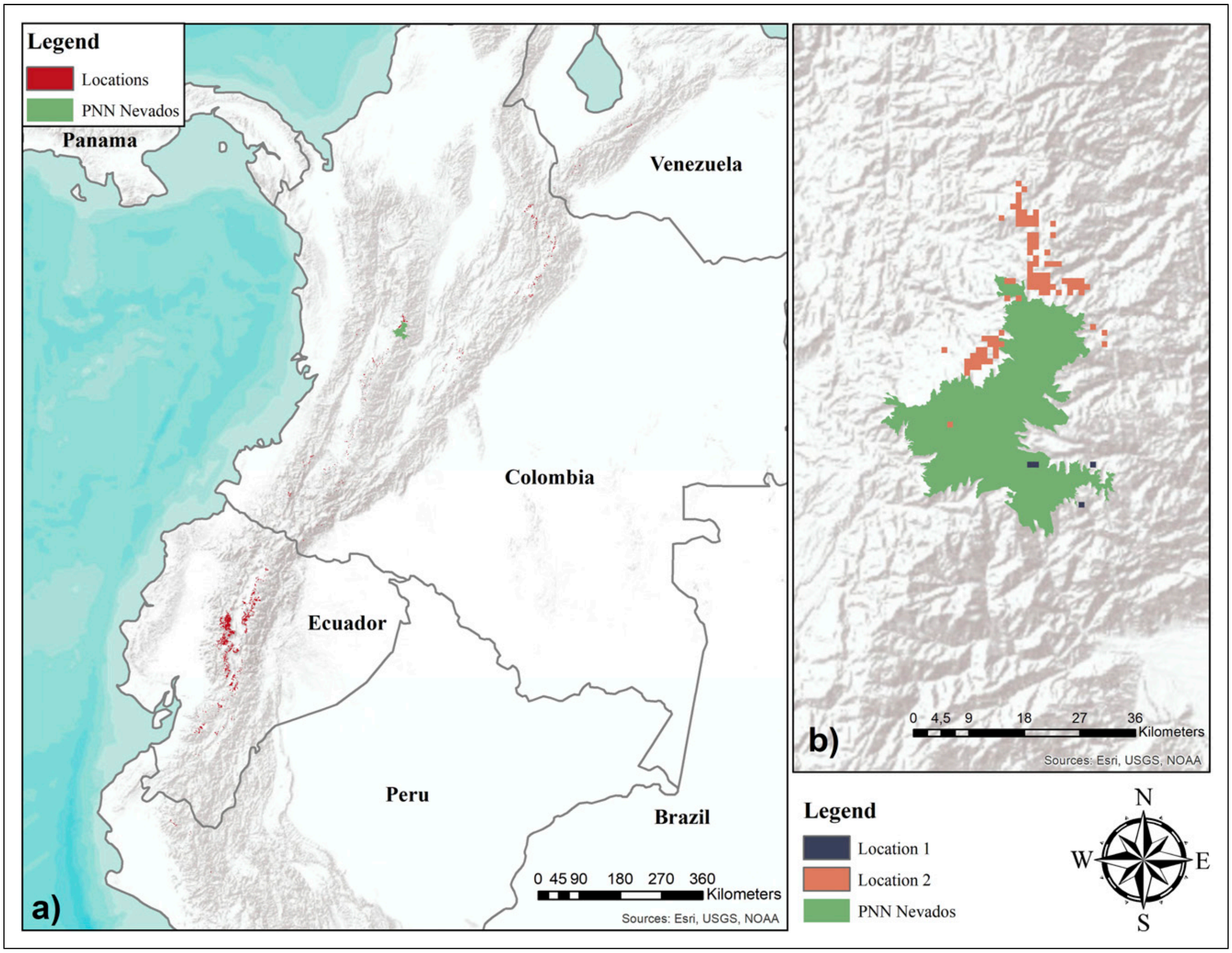

Figure 2. Distribution of the potential Locations for the evaluated species based on the simplified páramo land-cover (Peyre, 2022), at the (a) regional scale, or *Páramo Location Map* (PML); and (b) the scale of the Nevados National Natural Park (PNN Nevados).

disperse from the successive previous distribution (see an example Figure 3). Condition *b* was met when the area lost over them modeled time period was greater than the area gained.

Conservation Gap Analysis

For those species finally classified as threatened (VU, EN, or CR) after our full Criterion B evaluation as well as those previously evaluated, we performed a final analysis using an geographic-ecological approach to evaluate their conservation gaps and suggest prioritized initiatives depending on the species' threat status and its representation in conservation strategies. Towards this goal, we employed the Carver et al. (2021) method (package *GapAnalysis*), which relies on existing conservation practices targeting the species of interest and calculate nine metrics recommended by the Convention on Biological Diversity (CBD) and calculating conservation representativeness in both *ex-situ* and *in-situ* initiatives (CBD, 2020; Hoban et al., 2020; Khoury et al., 2019).

First, we compiled data on the conservation strategies involving our species by consulting the overlap between protected areas, as listed in the World Database of Protected Areas (WDPA) (IUCN, 2019), and the species' occurrence to assess *in-situ* representation. Then, we extensively searched for records of germoplasm collections and living organisms for *ex-situ* representation, using referent platforms for the Andean flora, including (but not restricted to) regional collections: Cotopaxi National Park Seed Bank, JBB Botanical Garden, Merida Botanical Garden, Parque de las Leyendas Botanical Garden, Research Institute Alexander von Humboldt and Santander Industrial University Tissue collection; as well as global ones: Gbif, Hortus Botanicus (the Netherlands), Kew Botanical Garden (UK), Royal Botanical Garden (Spain) and Svalbard Global Seed Vault. We made sure to delete duplicates by comparing the information label of each record. Because these are high-elevation plant species and their maintenance is challenging, we assumed for the simplicity of the study that there were no additional *ex-situ*

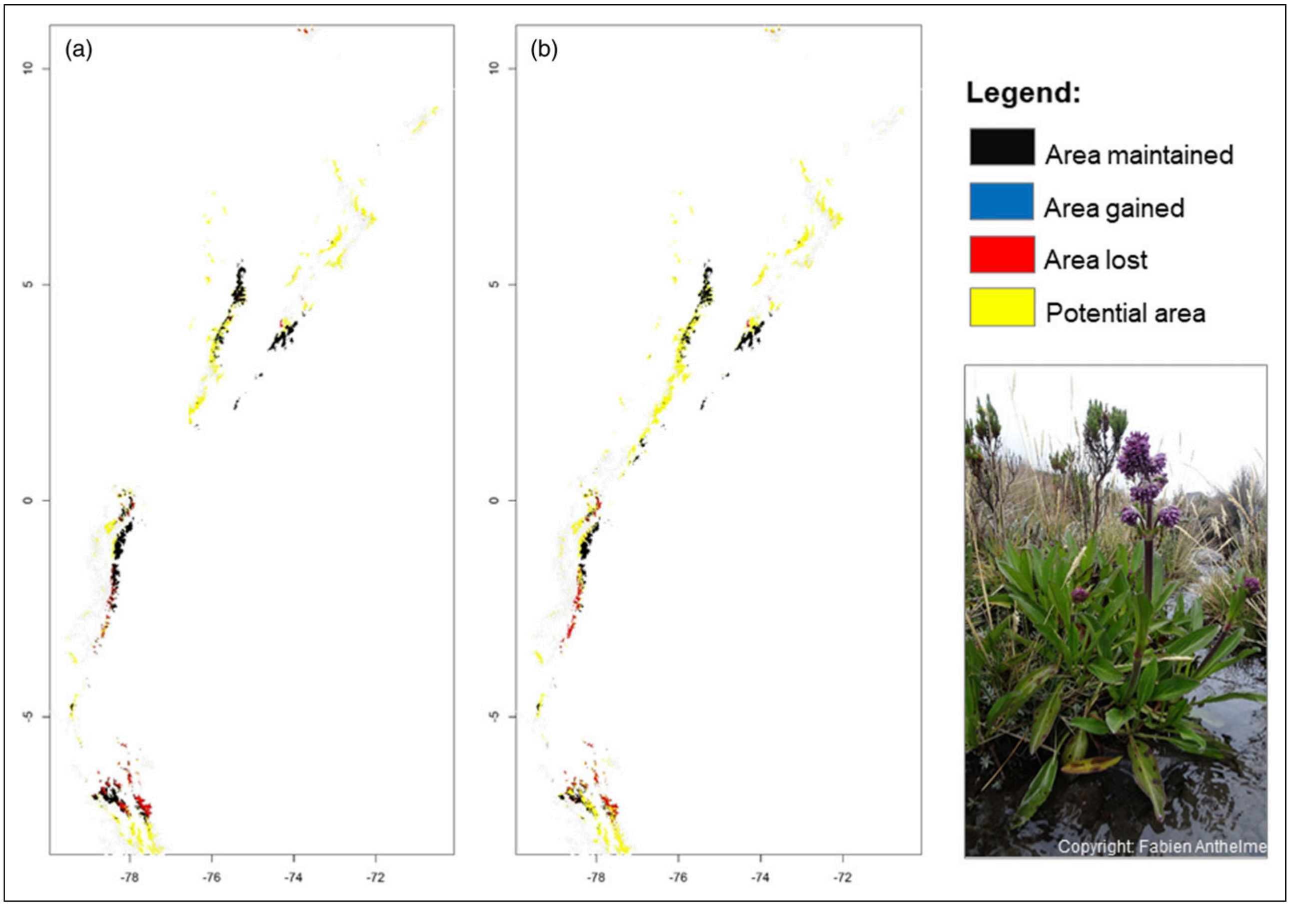

Figure 3. Distribution changes predicted by our models for *Valeriana pilosa* Ruiz & Pav. (VU) in the páramo region according to climate change scenarios CIMC5-RCP 4.5-FGOALS-g2 (a) and CIMC5-RCP 8.5- FGOALS-g2 (b) between 2010 and 2070. The potential area refers to the area where the species could potentially be present given its bioclimatic requirements, but is unoccupied due to dispersal limitation.

conservation practices, such as facilitated permanence in urban parks. Second, we calculated the following metrics for both *in-situ* and *ex-situ* conservation gaps: i) sampling score (SRS-ex and SRS-in), which corresponds to the proportion of occurrences protected by an *ex-situ* or *in-situ* strategy, respectively; ii) geographic score (GR-ex and GR-in), or the proportion of buffer area (points protected by an *ex-situ* or *in-situ* strategy) within the species' area of distribution (defined by the Realized SDM results for current conditions); and iii) ecological score (ERS-ex and ERS-in), as the proportion of ecoregions included and covered by the species' datapoints protected by an *ex-situ* or *in-situ* strategy. Finally, we averaged FCS-ex and FCS-in to obtain the mean final conservation score (FSC-mean). All three final conservation scores, FCS-in, FCS-ex and FSC-mean were finally classified according to the categories proposed by Carver et al. (2021): sufficiently conserved (SC) (FCS ≥75); low priority (LP) (50 ≤ FCS <75); medium priority (MP) (25 ≤ FCS <50); and high priority (HP) (FCS <25), to prioritize species for conservation and what practices.

Results

The final categorization of the 233 species led to the classification of the dataset into 59.6% of DD, 38% of not threatened species in the form of 16% LC and 22% NT, and around 2.4% of threatened species with 2% VU and 0.4% EN (Figure 4, Supplemental Table S4). 139 species fell into the DD category because they did not qualify on sub-criterion B1 but only on sub-criterion B2, however, their sampling effort was considered too low to show coherent results (<250 datapoints). The distinction between LC and NT species was made based on the number of conditions met, LC meeting none (38 species), while NT meeting only one of the two (50 species). In that regard, 14 species met condition *a* only, whereas 36 met condition *b* only. Of the remaining six species, five were classified as Vulnerable, and 1 as Endangered (Table 1).

When detailing each section of the IUCN Red List classification, we observed that 11 species resulted threatened by sub-criterion B1, including three threatened species, with the smallest EOO recorded at 492 km^2 for *Diplostephium*

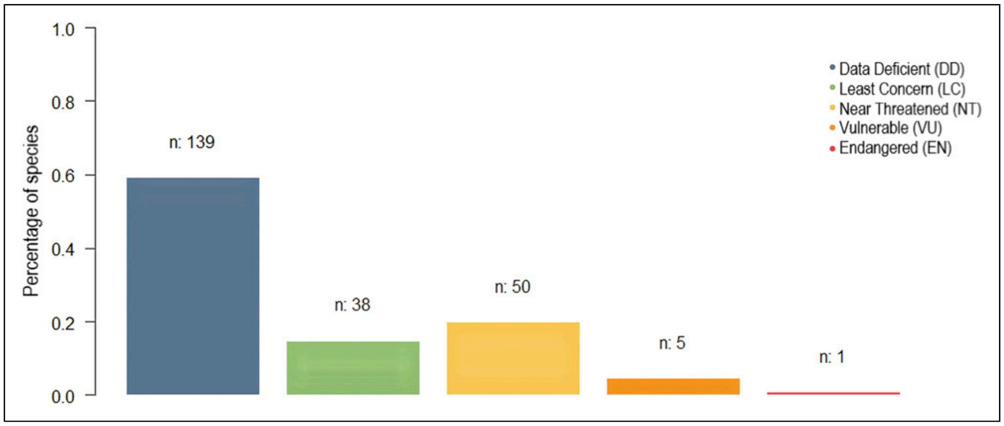

Figure 4. Distribution of the 233 evaluated species pool from the páramo flora of the Nevados National Natural Park (PNN Nevados) among the IUCN Red List categories, as a percentage (over 1) and values (*n* species).

Table 1. Summary evaluation of the six species classified as threatened according to our Red List Assessment, according to Criterion B including: i) Sub-criterion B1—extent of occurrence (EOO, expressed in km^2); ii) Sub-criterion B2—Area of occupation (AOO, calculated at a 4 km^2 resolution, expressed in km^2); iii) Condition *a*—Location analysis (expressed in number of locations derived from a land-cover classification); iv) Condition b—Continuing Decline (predicted distribution change of the species with climate change by 2070 according to five General Circulation Models and averaged for two Representative Concentration Pathways, one moderate [RCP 4.5] and one severe [RCP 8.5], expressed as percentage change in distribution between 2010 and 2070); and v) the final IUCN Red List classification. Detailed evaluations of the remaining species of the vascular páramo flora from the PNN Nevados can be found in Supplemental Table S4.

	Sub-criterion B1	Sub-criterion B2	Condition *a*	Condition *b*		
Species	EOO	AOO	Locations	Average Loss (RCP 4.5)	Average Loss (RCP 8.5)	Final Classification
Carex jamesonii	3211946	1016	8	−73.7%	−86.4%	VU (B2 ab (iii))
Elaphoglossum cuspidatum	3924522	912	3	−100.0%	−97.5%	VU (B2 ab (iii))
Lupinus ruizensis	2893	28	4	−14.4%	12.7%	EN (B1 ab (iii))
Miconia latifolia	2515323	576	2	−44.2%	−49.3%	VU (B2 ab (iii))
Miconia alborosea	9461	76	10	−47.9%	−6.6%	VU (B1 ab (iii))
Pentacalia gelida	5682	48	5	−30.7%	−11.4%	VU (B1 ab (iii))

violaceum Cuatrec. (NT). In contrast, a total of 57 species were classified as threatened by sub-criterion B2, including three threatened species, with the smallest AOO recorded at 12 km^2 for *Draba lindenii* (Hook.) Planch. Ex Sprague (DD). At the scale of the páramo land-cover, only 20 species out of 68 presented 10 or less locations, a requisite to meet condition *a*. Finally, for condition *b*, we deemed our model performance satisfactory and observed across scenarios, an average response that 41 species presented a net loss in distribution by 2070, while 27 species increased their distribution substantially over the same timespan (Supplemental Table S3 and Table S4). The most affected species predicted to potentially undergo regional extinction in the páramo by 2070 are i) *Diplostephium rosmarinifolium* (Benth.) Wedd (NT)*, Chusquea scandens* Kunth (NT), *Eriosorus flexuosus* (Kunth) Copel (NT), *Gaultheria buxifolia* Willd (NT) and *Elaphoglossum cuspidatum* (Willd.) T. Moore (VU) according to RCP 4.5 averaged scenarios; and ii) *Diplostephium rosmarinifolium*, *Chusquea scandens*, *Eriosorus flexuosus*, *Gaultheria buxifolia* and *Brachyotum strigosum* (L. f.) Triana (NT) according to RCP 8.5 averaged scenarios.

There were substantial differences between the representativity of *ex-situ* and *in-situ* practices for the eight concerned threatened species (Figure 5, Supplemental Table S5). FCS-ex results reached 4.9 on average and were spread over a wide amplitude of values between i) min: 0, meaning no records in the germoplasm inventories consulted, as observed for species *Lupinus ruizensis* C.P.Sm (EN)*, Miconia latifolia* (D.Don) Naudin (VU), *Pentacalia gelida* (Wedd.) Cuatrec (VU) and *Themistoclesia mucronata* (Benth.) Sleumer (VU); and ii) max: 12.1, as observed for *Elaphoglossum cuspidatum* (Willd.) T. Moore (VU). FCS-in results reflected better representation of our species of interest in protected areas than in ex-situ initiatives, with values averaging at 60.2 and ranging from i) min: 20.4 for *Carex jamesonii* Boott (VU); to ii) max: 82.4 for *P. gelida* (Wedd.) Cuatrec (VU). According to our FCS-mean results, we

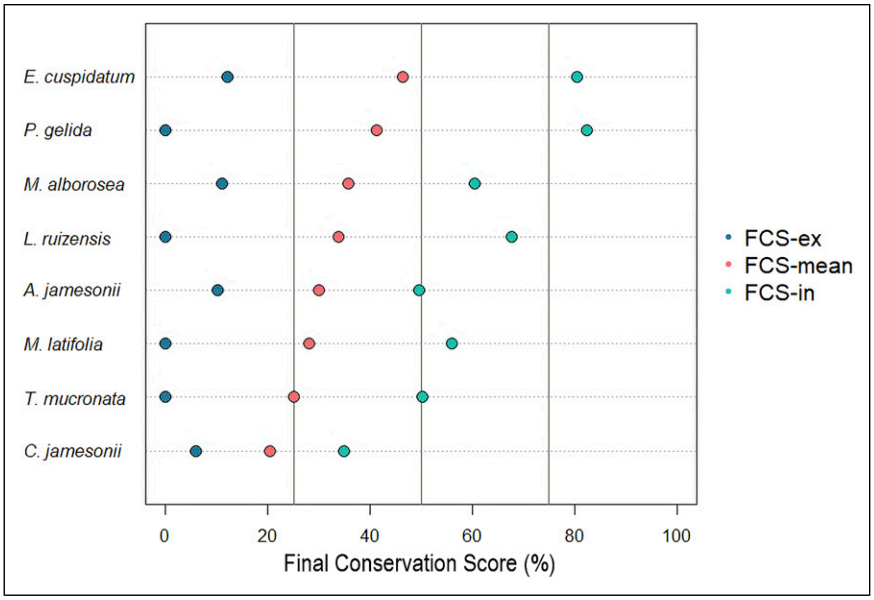

Figure 5. Final Conservation Scores of the eight threatened plant species from the Nevados National Natural Park, resulting from the Conservation gap analysis, for *ex-situ* (FCS-ex) and *in-situ* (FCS-in) strategies as well as their average score (FCS-mean). Vertical lines represent the thresholds of 25, 50 and 75% for the FCS-mean that define the conservation priorities as Sufficiently Conserved (SC) (FCS ≥ 75); Low Priority (LP) (50 ≤ FCS < 75); Medium Priority (MP) (25 ≤ FCS < 50); and High Priority (HP) (FCS < 25).

observed that the threatened species pool was categorized as Medium Priority for conservation on average (FCS-mean = 32.6, ranging between min: 20.4 and max: 46.3). Therefore, *Carex jamesonii* was classified as High Priority (FCS-mean < 25), and all other species fell into the Medium Priority category (25 ≤ FCS-mean < 50).

Discussion

Our study provides a preliminary checklist of the páramo vascular flora of the PNN Nevados and assesses its vulnerability by the means of a robust IUCN evaluation approach. We reported a total of 262 vascular plant species, which makes for 16% of the Andean flora in the Nevados mountain range, and almost 8% of the Colombian páramo vascular flora (Rangel-Ch, 2015). Red Lists provide a rapid overview of the overall vulnerability of a taxonomic group and therefore allow to prioritize conservation focus quickly (Rodrigues et al., 2006). In that regard, we established the Nevados páramo Red list by analyzing 233 plant species and accounting for recent works that had previously assessed 29 species. In total, our Red List included 139 species as Data Deficient (DD), 65 as Least Concern (LC), 50 as Near Threatened (NT), and finally, 8 as threatened, in the form of 7 species as Vulnerable (VU) and 1 as Endangered (EN).

Vulnerability Assessment Systematic Process

We employed a multi-criteria method relying on an array of data and techniques, to fully evaluate Criterion B, through its sub-criteria B1 and B2, conditions *a* and *b*. Of the 233 species evaluated, we were able to complete the assessment of 94 species, the most common limitation being sampling effort for the 139 remaining species. In fact, these species were considered as threatened according to sub-criterion B2-Area of Occupancy (AOO) only, but because they presented less than 250 datapoints and the AOO metric is highly dependent on how representative the sampling of a species' distribution is, we could not categorize these species as threatened with certainty and therefore classified them as DD at present. We are aware that as a result, the 139 species classified as DD can potentially qualify for an objective threat status, and we therefore encourage future research to focus on complementing field observations for these species and complete their evaluation. In priority, it would be important to focus on species with the smallest AOO and whose distribution might be severely fragmented and fall into Locations, as we suspect is the case for *Halenia campanulata* Cuatrec. (a small Gentianaceae usually found in open grasslands with an AOO of 12 km^2). From the remaining species pool, we classified 88 species as LC and NT, which when adding previous evaluations sums up to 115 non-threatened species, or 44% of the total PNN Nevados páramo flora.

We stress the importance to differentiate species that were classified as NT by meeting either condition *a* or condition *b*, as they could become threatened in the future by different means. We conducted the Location analysis in a systematic manner by taking advantage of the recent páramo land-cover (Peyre et al., 2021). The resulting 20 species threatened by condition *a* could therefore become threatened soon if their distribution is gradually overcome by Location areas. A clear advantage of our method is its objectivity to assess Locations throughout the páramo region based on robust land-use input, making it comparable between species' evaluations. However, potential drawbacks include i) leaving out other existing forms of threat for páramo species, even though they are usually deemed secondary at the regional level, such as mining (e.g., Hofstede et al., 2003); and ii) limiting our Location analysis to the strict páramo delimitation via the regional páramo land-cover, therefore ignoring threats in the vicinity of the páramo but that have not yet reached high elevations. We encourage future research to carefully monitor those species classified as NT by meeting condition *a* only, despite presenting positive tendencies in their predicted future distribution, since Locations can increase and expand over time. In fact, several endemic species from the Nevados mountain range fell into this category such as *Senecio isabelis* S.Díaz (1 Location), *Diplostephium violaceum* Cuatrec. (2 Locations) and *Draba pachythyrsa* Triana & Planch. (4 Locations), all threatened by EOO and with insufficient datapoints to be classified according to AOO while presenting relatively optimistic model results. Therefore, compiling additional data on the species' adaptative capacity and environmental threats would be important to ensure they are able to maintain or expand their distribution over time. Protected areas such as PNN Nevados are key in reversing the NT status of these species since they can reduce Locations within their jurisdiction with adapted planning of their management strategy.

Condition *b* was assessed based on species distribution models that account for the bioclimatic requirements and dispersal capacity of each species. The models therefore showed if a species tended to increase, stabilize or increase its distribution on the mid-term (2070), which we averaged over GCMs and RCPs for a more robust output. Including SDMs into IUCN Red List assessments has been largely debated over the predictive nature of SDMs and their consequent potential use and applicability into conservation strategies (e.g., Breiner et al., 2017; Syfert et al., 2014). Because SDMs cannot account for all factors driving a species' distribution, for example regarding their entire ecological network or multiple interactions with anthropogenic environmental pressures, assumptions need to be made, and the fit of the results to real conditions depends on the modeling strategy used. Nevertheless, we believe that in the context of condition *b*, our models prove very useful, especially because they account for dispersal capacity and predict species' future distributions over several climate change scenarios periodically constrained by step-by-step dispersal (Peyre et al., 2020). Therefore, even though SDMs usually offer a partial view of species' ecological niche, they are able to forecast the main trends in future distribution change to be expected, which makes them great systematic tools easy to combine with expert input in a Red List assessment context. This is especially true for species with few datapoints in relation to their geographic distribution, since their occurrences only partially represent their ecological niche and extent, such is the case of many tropical plant species. For example, in our dataset, species *Gunnera magellanica* Lam. (NT), *Ranunculus peruvianus* Pers. (LC), and *Rhynchospora aristata* Boeckeler (NT) presented broad EOOs over six million km^2 and relatively few datapoints (between 250–270), making their model results very useful to contrast with the Páramo Location Map. A total of 52 species were encountered meeting condition *b*, of which 39 did not meet condition *a*. In our opinion, it would be important to focus additional research and monitoring efforts on the species predicted as regionally extinct by 2070 due to climate change, even though they do not meet condition *a* at the scale of the páramo region. Therefore, we urge scientists and conservationists to evaluate further *Diplostephium rosmarinifolium* in priority, as well as *Chusquea scandens*, *Eriosorus flexuosus*, *Gaultheria buxifolia* and *Brachyotum strigosum,* to assess their adaptative capacity and be ready to propose *ex-situ* conservation strategies for these species.

Threatened Species In The PNN Nevados

Previous studies had identified *Aequatorium jamesonii* (S.F.Blake) C.Jeffrey and *Themistoclesia mucronata* (Benth.) Sleumer as Vulnerable species (Montúfar & Pitman, 2003; Salinas et al., 2019). To this list, we contributed six newly identified threatened species: *Carex jamesonii, Elaphoglossum cuspidatum, Miconia latifolia, Miconia alborosea, P. gelida* as Vulnerable, as well as *Lupinus ruizensis* as Endangered. In other words, the páramo threatened flora from the Nevados National Park at present includes one species from the Asteraceae family, one Cyperaceae, one Dryopteridaceae, one Ericaceae, one Fabaceae, two Melastomataceae, and one Onagraceae.

The two previously evaluated species as well as several of our new species, naming *M. latifolia, M. alborosea* and *E. cuspidatum*, are usually found at the ecotonal sub-páramo between the Andean cloud forest and the páramo, which takes the form of shrubby vegetation or dwarf forests (Peyre et al., 2018; Salamanca et al., 2003). The species from the list that transition into the mid-páramo altitudinal belt, mostly covered by mix grasslands with giant stemrosettes and shrubs, is *C. jamesonii* (Rangel-Ch, 2000; 2015; Salamanca et al., 2003). Throughout the Andean páramo, land-use generally progresses from lower to higher elevations, which results in decreasing human impact and the consequent land-degradation from the sub-páramo and mid-páramo to the super-páramo (Hofstede et al., 2003; Peyre et al., 2021; Rodríguez Eraso et al., 2013). In that regard, the PNN Nevados has passively contributed to protecting these species, by progressively banning land-use activities and strongly regulating tourism and other transitory enterprises within its jurisdiction for the past 50 years. At present, few vestigial testimonies of past land-use remain in certain low-elevation areas of the park, and they are experiencing either active restauration and/or passive secondary succession, which will result in soon-to-be quality habitats for our species of interest. However, there is an ongoing threat with the expansion of land-use in the park's transition zone and illegal practices in its remote areas, which have been captured by the páramo land-cover (Peyre et al., 2021) and can significant environmental pressure on these species if not regulated (species' occurrences in these areas should be transplanted whenever possible into equivalent healthy ecosystems within the park). At higher elevations, in the super-páramo altitudinal belt, we identified two threatened species, *L. ruizensis* and *P. gelida* (Peyre et al., 2018; Salamanca et al., 2003), both of which are endemic to the Nevados super-páramo (Bernal et al., 2016). Today, human activities remain scarce in the super-páramo due to its harsh environmental conditions (Luteyn et al., 1999; Rangel, 2015). However, this altitudinal belt is particularly sensitive to climate change and bound to suffer pronounced warming paired with strong species' ecological responses in the near future (Buytaert et al., 2011). In fact, super-páramo species usually have little dispersal capacity, and as a result, they are often unable to track climate change at its current speed and, need to count on their adaptative capacity to remain where they currently are, while they enter newly found competitive interactions with uprising mid-páramo species (Anthelme et al., 2014; Peyre et al., 2020). Furthermore, because the PNN Nevados is subject to volcanic eruptions, the last event being recorded in 2016 for the Ruiz Volcano, both species, and especially *L. ruizensis,* require urgent *ex-situ* conservation strategies.

Among our studied species, we revealed three threatened by EOO and AOO (although below the undersampling threshold), and meeting both *a* and *b* conditions:, *L. ruizensis, M. alborosea, P. gelida.* These species are threatened and either endemic to the Nevados range or restricted to a slightly larger area including the surrounding mountains (Bernal et al., 2016). In contrast, *C. jamesonii, E. cuspidatum* and *M. latifolia* were only threatened by AOO (above the undersampling threshold) and therefore indicate larger distributions that are usually fragmented and/or spread over human-disturbed areas with important habitat loss, as for the previously studied species *A. jamesonii* and *T. mucronata.* For four of our species, we could complement our assessment with sub-population trends in relative cover in vegetation samples over 10 years in the past two decades (Criterion A, sub-criterion A2, Supplemental Table S2). Despite data availability being limited, we encountered that *M. latifolia* showed no sign of cover decrease, while *C. jamesonii* increased and *E. cuspidatum* and *P. gelida* decreased. Although these complementary observations do not constitute robust Criterion A assessments alone, they do strengthen our interpretation and suggest that special attention should be paid to the super-páramo species *P. gelida* as well as *E. cuspidatum*, whose SDMs predicted almost regional extinction by 2070 (in part due to short spore dispersal).

Implications For Conservation

By the means of the IUCN Red List Assessment, we identified that eight páramo plant species should benefit from further study and conservation planning in priority. Our study's results and their derived additional evaluations will be made available through several open-access portals, including the global Red List and subsequently incorporated in national Red Lists (Garcia et al., 2006), so to contribute valuable data for future studies and plans. At this stage, we call to the protected areas presenting these species to acknowledge and account for them in their next management plans and adjust their conservation goals, for instance in the PNN Nevados 2023–2028 Management plan, at least until their threat status is reversed. Prior to decision making, it would be important to generate new information on their genetic, population, ecological and threat characteristics to complete the IUCN Red List evaluations. For Criterion A, additional occurrence data should be sampled over time, for example as a monitoring strategy based on permanent vegetation plots. For Criteria A and C, we suggest using fine population models and viability population analyses to assess the species trajectory in the near future without accounting for additional conservation measures, so to provide additional information on the species' threat status.

Our results from the Conservation Gap Analysis highlighted that seven out of the eight species classified as threatened fell into the Medium Priority category and *C. jamesonii* as High Priority. For those species with a Medium Priority and a Vulnerable status, *A. jamesonii*, *E. cuspidatum, M. latifolia, M. alborosea,* and *T. mucronata,* we recommend promoting *in-situ* conservation measures, for example managing local threats and aiding gene flow through spatial transfer of individuals between sub-populations and maintaining spatially connecting corridors between sub-paramo fragments and with cloud forests. Because protected areas play a fundamental role toward sustainability and conservation goals, but resources can sometimes be limited, there is a need to improve the efficiency of current strategies and design new innovative and observation-based programs (PNN, 2020a; Watson et al., 2014). For instance, improving these species' ecological and threat conditions toward a Near Threatened and later Least Concern status is realistically achievable in the PNN Nevados by, i) regulating threats related to human activities; ii) ensuring adequate restoration of the sub-páramo and highly degraded mid-páramo; and iii) monitoring these species within the park and at its transition zone through collaborative community programs. For *C. jamesonii*, a Vulnerable High-Priority species, we found that the pessimistic predictive model results contradicted the few data on sub-population trends available, and as result require additional information to propose a clear diagnostic. A main concern for this species is its lack of representation in any acknowledged conservation strategy at the moment. As a result, a potential initiative would be to transfer individuals from the disturbed transition zone of the PNN Nevados to healthy sub-páramo and low mid-páramo patches within the park in equivalent plant communities to ensure its survival *in-situ*. We propose that this initiative is copied in other protected areas, such as the Tatama National Natural Park, which has a record of excellent conservation status, and recently integrated the Green List Protected Area IUCN strategy for pilot model protected areas in South America (Paredes-Leguizamón, 2018).

For the species i) classified as Endangered, ii) strictly endemic to the Nevados range, and iii) distributed in the super-páramo (Sup) altitudinal belt and therefore likely to suffer drastic impacts from climate change, we recommend urgently pairing *in-situ* and *ex-situ* conservation strategies. In order of priority, we first promote *L. ruizensis* (EN, Endemic, FCS-mean Medium), followed by *P. gelida* (VU, Endemic, Sup, FCS-mean Medium). The next candidates for additional ex-situ focus should be the species predicted to undergo regional near-extinction in the páramo by 2070, particularly *E. cuspidatum* (VU), as well as the threatened species geographically restricted to the Nevados range and few additional mountain ranges *M. alborosea*. Conservationists should make sure that the minimum viable population levels are not crossed if removing complete individuals to take them to external conservation institutions, such as the Bogota Botanical Garden (JBB) or the Research Institute Alexander von Humboldt's collection (IAvH). However, since maintaining live individuals in controlled conditions outside of the páramo is challenged by the difficult replication of its very specific climatic and edaphic conditions, we recommend assigning resources to establish greenhouses within the park for local propagation as successfully carried out by the Chingaza Natural National Park (PNN, 2020b). Finally, because páramo plants present orthodox seeds able to endure long periods of environmental harshness, we advance the utility of conducting seed collecting field campaigns to increase national collections, such as the JBB and IAvH's and, and preserve genetic material at reduced costs and effort.

Declaration of conflicting interests

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Data Availability Statement

The distribution and population data used in this study is freely available from VegParamo (www.vegparamo.com, Peyre et al., 2015), SiB Colombia (wwwww.sibcolombia.net), the COL Herbarium (www.biovirtual.unal.edu.co/), the JBB herbarium (http://herbario.jbb.gov.co) and GBIF (www.gbif.org/, Supplemental Table S1). The bioclimatic data used to conduct the models can be freely retrieved from the CHELSA project v. 1.1 (http://chelsa-climate.org; Karger et al., 2017). The Land Cover map employed to obtain the Paramo Location Map is available from Peyre et al., 2021.

ORCID iD

Gwendolyn Peyre https://orcid.org/0000-0002-1977-7181

Supplemental Material

Supplemental material for this article is available online.

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