

Flora diversity and landscape patterns in high-Andean wetlands of the Chimborazo Wildlife Reserve, Ecuador

Diversidad florística y patrones paisajísticos en bofedales altoandinos de la reserva de producción de fauna Chimborazo-Ecuador

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Abstract: This study evaluated the floristic diversity of high-Andean bogs in the Chimborazo Wildlife Reserve (Ecuador) using biodiversity indices and remote sensing analysis (EVI and MNDWI). A total of 16 sampling sites distributed across three Andean provinces were analyzed, identifying 63 species grouped into 25 families. The most representative families were Asteraceae and Poaceae, with dominant species such as *Distichia muscoides* and *Plantago rigida*. Diversity indices (Margalef: 2.07–3.38; Shannon: 2.17–2.83) indicate moderate diversity typical of high-mountain ecosystems. Spatial analysis revealed that only 23% of the study area has vegetation cover, while the rest lacks biomass due to geological conditions. No significant correlation was found between spectral indices and floristic diversity. These results suggest that remote sensing indices, on their own, are insufficient to characterize the ecological complexity of Andean bofedales, highlighting the need to integrate additional environmental variables.

Keywords: floristic diversity, bofedal, vegetation cover, ecological importance, EVI, MNDWI.

Resumen: Este estudio evaluó la diversidad florística de bofedales altoandinos en la Reserva de Producción de Fauna Chimborazo (Ecuador) mediante el uso de índices de biodiversidad y análisis de teledetección (EVI y MNDWI). Se analizaron un total de 16 sitios de muestreo distribuidos en tres provincias andinas, identificándose 63 especies agrupadas en 25 familias. Las familias más representativas fueron Asteraceae y Poaceae, con especies dominantes como *Distichia muscoides* y *Plantago rigida*. Los índices de diversidad (Margalef: 2,07–3,38; Shannon: 2,17–2,83) indican una diversidad moderada típica de ecosistemas de alta montaña. El análisis espacial reveló que solo el 23% del área de estudio presenta cobertura vegetal, mientras que el resto carece de biomasa debido a condiciones geológicas. No se encontró una correlación significativa entre los índices espectrales y la diversidad florística. Estos resultados sugieren

que los índices de teledetección, por sí solos, son insuficientes para caracterizar la complejidad ecológica de los bofedales andinos, destacando la necesidad de integrar variables ambientales adicionales.

Palabras clave: diversidad florística, bofedal, cobertura vegetal, importancia ecológica, EVI, MNDWI.

Introduction

Biodiversity synergistically integrates life forms and their variability, as expressed in flora, fauna, and microorganisms, both between and within ecosystems (Pennington et al., 2010). It is the sum total of all biotic variation, from genes to ecosystems, and cannot be fully represented by a single indicator. Biodiversity promotes ecosystem functioning; communities with greater diversity are more resilient to environmental changes, which supports its conservation as a key strategy for sustainable ecosystem management. (Hong et al., 2022) Furthermore, biodiversity plays a key role in ecosystem services, acting as a regulator, as a final ecosystem service, and as an asset subject to valuation. (Mace et al., 2012) Effective biodiversity conservation is essential for human survival and the maintenance of ecosystem processes. (Rands et al., 2010) Furthermore, grasslands with more diverse plant communities exhibit greater drought resistance and more complete recovery, supporting the diversity-stability hypothesis. (Tilman & Downing, 1994)

The tropical Andes are home to some of the world's highest biodiversity hotspots; 6.7% of the world's endemic species are found in this mountain range, which extends from 3,000 to 3,500 meters above sea level in the subpáramo zone to 4,500 to 5,000 meters above sea level in the subnival or superpáramo zone (Myers et al., 2000). Part of this plant diversity found at high altitudes is due to the high variability of habitats and abiotic conditions, such as the climate and soils characteristic of mountainous areas (Mena, 2001). In the Andean region, the páramo constitutes a high-Andean ecosystem that extends along the Andes mountain range and is characterized by the presence of dominant plant communities adapted to extreme environmental conditions (Caranqui, Lozano, and Reyes, 2016).

Within this ecosystem, various types of vegetation cover are recognized, including páramo grasslands, sub-páramo evergreen grasslands and shrublands, evergreen shrublands, floodplain grasslands, ultra-humid grasslands, and upper high-mountain humid

grasslands (Zurita-Polo et al., 2020). Andean páramos are classified as a high-mountain neotropical ecosystem, essential for the collection, regulation, maintenance, and management of water resources in South America (De Groot et al., 2002). This is a result of a set of attributes such as low evapotranspiration, high humidity, high organic matter content, and the morphology of endemic plants (Córdova et al., 2015). In Ecuador, páramos cover approximately 1,250,000 ha, or about 6% of the national territory (Medina and Mena 2001). Relatively speaking, Ecuador has the highest proportion of páramos relative to its total land area; an altitude of 3,500 m is commonly used as the lower limit, but geological, climatic, and anthropogenic conditions cause this limit to vary greatly, and páramos are sometimes found as low as 2,800 m, especially in the south of the country (Coppus et al. 2001). The RPFCH is located in a geological zone of Quaternary origin, represented by a stratovolcano called Chimborazo; the geology of the area features primary and reworked pyroclastic deposits (cangahua); lahars, while the slopes near the crater feature domes composed of lava flows, andesite, and pyroclastics; this type of Pliocene-Quaternary formation results in eroded features (Egües et al., 2017). The most important environmental factors explaining the variability in the structure and composition of the plant community are temperature and altitude (Hofstede et al., 2018). The bioclimate of the area is classified as pluvial on a national scale; the climate, soils, and dominant vegetation (grasslands) of the area significantly affect water regulation and supply for densely populated inter-Andean valleys (Buytaert et al., 2006); (Célleri and Feyen, 2009; Mosquera et al., 2015).

Bofedales form in areas such as the Andean massifs located above 3,800 meters in elevation, where the plains store water from rainfall, glacial melt, and primarily surface seepage of groundwater (Carrasquel, 2012). On the one hand, they are considered high-altitude wetlands, where geomorphological and edaphic characteristics allow for the formation of marshes of varying, sometimes considerable, size, where a community of plants adapted to these conditions has established itself (Mena and Medina, 2013). Typical vegetation includes: *Isoetes*, *Lilaeopsis*, *Cortaderia*, *Chusquea*, *Neurolepis*, and various cushion-forming genera, *Oreobolus*, and the peat moss *Sphagnum magellanicum* (Pereyra and Moreno, 2013). Landscape ecology is an interdisciplinary field that aims to understand and improve the relationship between spatial patterns and ecological processes across a range of scales (Wu, 2007). Landscapes are spatially heterogeneous areas characterized by a mosaic of patches that differ in size, shape, content, and history; Landscape ecology is the science of studying and

improving the relationship between spatial patterns and ecological processes across a multitude of scales and organizational levels; furthermore, landscape ecology integrates biophysics and analyzes approaches with humanistic and holistic perspectives across the natural and social sciences (Wu, 2013).

The purpose of this research is to assess floristic diversity in the Bofedales of the RPFCH by characterizing diversity indices. This includes a multivariate statistical analysis to determine the relationship between spectral indices and floristic diversity variables. The aim is to analyze landscape ecology and spatial patterns using a Landsat 8 image through the geophysical methods EVI and MNDWI.

Methodology

Location of the Study Area

This descriptive-exploratory study was conducted in the Chimborazo Wildlife Reserve (RPFCH) at coordinates 1.4100° South latitude and -78.807525, located in the provinces of Chimborazo, Tungurahua, and Bolívar, where the Chimborazo Volcano stands at an elevation of 6,268 meters above sea level in the central Andes mountain range of Ecuador (Figure 1). For this study, a landscape analysis was conducted, taking into account land cover identification using EVI and NDWI remote sensing indices, as well as an analysis of alpha and beta diversity indices.

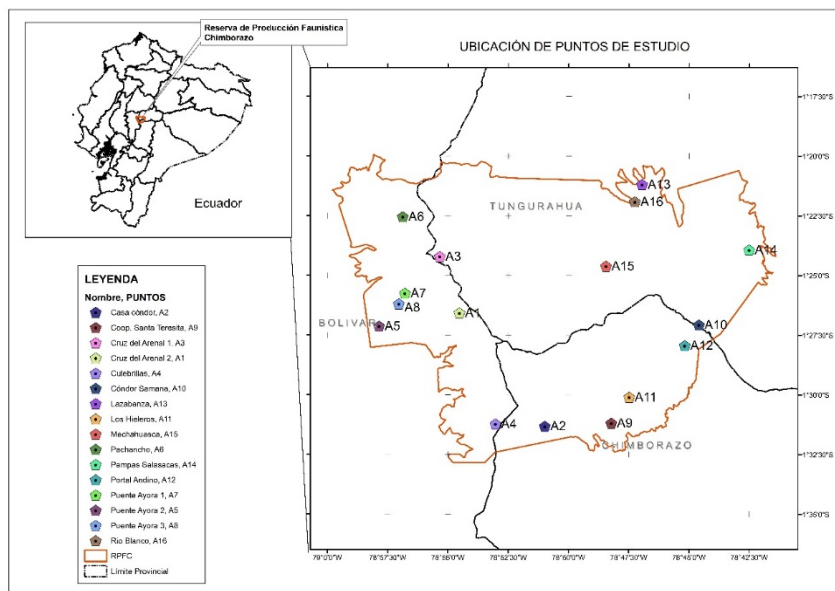


Figure 1. Location of sampling points: RPFC (Chimborazo Wildlife Production Reserve); A: Upper Bofedal, elevation above 4,100 m a.s.l.; B: Lower Bofedal, elevation below 4,100 m a.s.l.

To characterize the Bofedal, a Landsat 8 image from the OLI sensor dated November 20, 2016, was used, obtained from the USGS (<https://earthexplorer.usgs.gov/>) platform. The RPFCH study area (Figure 1) includes 16 sampling points for the assessment of floristic diversity.

Modified Normalized Difference Water Index

This index is widely used for real-time irrigation control, significantly improving agricultural activities. Two satellite images, Landsat 7 and 8 respectively, were obtained covering the entire study area, and the method proposed by (Xu, 2006) was applied, which employs a systematic approach analogous to that of McFeeters (1996) using the NDWI method. In this case, Equation 1 was applied after the preparation of maps and graphs, which provide information on the spatial distribution of water stress in vegetation.

$$1) \text{MNDWI}(\%) \text{ Landsat 8} = 100 \times \frac{(B3 - \text{MIR})}{(B3 + \text{MIR})}$$

Where: B3 = Band 3 and MIR = Band 6 for Landsat 8

The MNDWI index was calculated using the following equation:

$$\text{MNDWI} = (\text{Green} - \text{MIR}) / (\text{Green} + \text{MIR})$$

where Green corresponds to Band 3 and MIR to Band 6 of Landsat 8.

1 Table. *Classes for the NDWI*

Condition Coverage	Moisture NDWI
Very Wet	60–100
Wet	20–60
Dry	-20 to 20
Very dry	-20 to -60
Extremely Dry	-60 to -100

Enhanced Vegetation Index

the EVI (Liu and Huete, 1995) and EVI2 (Jiang et al., 2008) improve and optimize the vegetation signal compared to NDVI, thereby better detecting biomass (INTA, 2002) and enabling the detection of thresholds that define phenological stages (Zhang et al., 2003 and 2012). The EVI was used to determine the response to biomass present in the CRC, using Band 4 and Band 5 for Landsat 8. The Enhanced Vegetation Index was calculated using the following equation:

$$2) \text{ EVI}(\%) = 100 \times \left(\frac{(NIR - R)}{((NIR + C1) \times (R - C2) \times (B + L))} \right)$$

The Enhanced Vegetation Index (EVI) was calculated as follows:

$$\text{EVI} = 2.5 \times (\text{NIR} - \text{Red}) / (\text{NIR} + 6 \times \text{Red} - 7.5 \times \text{Blue} + 1)$$

where NIR corresponds to Band 5, Red to Band 4, and Blue to Band 2.

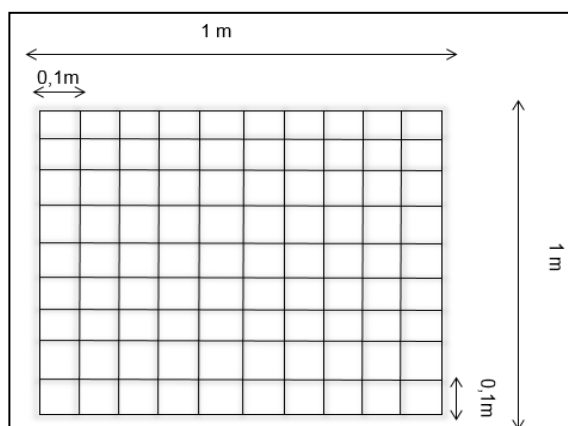
Table2 . Classes for the EVI

Condition Coverage	EVI
High Glacier	-40 to -25
Low Glacier	-25 to -15
Snow	-15 to 0
No Vegetation Cover	0 to 15
High Bofedal	15 to 25
Low Bofedal	25 to 40

Diversity Indices

The selection of areas for the flora inventory was carried out at each of the sampling points (Figure 1), using the GLORIA Project Fieldwork Manual (Pauli et al., 2015), adapted for Andean páramos by Eguiguren and Ojeda (2010). In each identified zone (3 per bofedal), a 1×1 m grid was established every 50 meters, divided into 0.10×0.10 m cells, resulting in 100 cells of 0.1×0.1 m. Within the plots, information regarding the number of species and individuals was recorded; this was used to calculate biodiversity indices and determine diversity by family and genus.

Figure 2. Dimensions of the sampling grid



To identify plant species, it was necessary to consult books on páramo flora such as: Flora and Fauna of the Páramos of Ecuador: A Brief Guide to Life at High Altitude (Anhalzer & Lozano, 2015, pp. 8–234); and Guide to the Plants of the El Ángel Ecological Reserve. (Chimbolema, et al., 2010, pp. 44–127)

Biodiversity indices—Pielou, Simpson, Shannon-Wiener, Margalef, and Bray-Curtis similarity—were subsequently calculated using Primer 5.0 software. Calculations for dominance, frequency, density, and species importance value index by family and order were performed using Excel. Past 2.17 software was used to calculate the species rarification curve.

Table 3. Margalef Index

Representation	Value
There is only one species	0
Equal number of individuals across all species	1
Low biodiversity	1.1–2.4
Normal or average biodiversity	2.5–3.5
High biodiversity	Greater than 4

To identify the species contributing to the vegetation composition and structure of the bofedales, the species importance value index was calculated by summing the relative frequency (Fr), relative density or abundance (Ar), and relative dominance (Dr) (Moreno, 2001, p. 37).

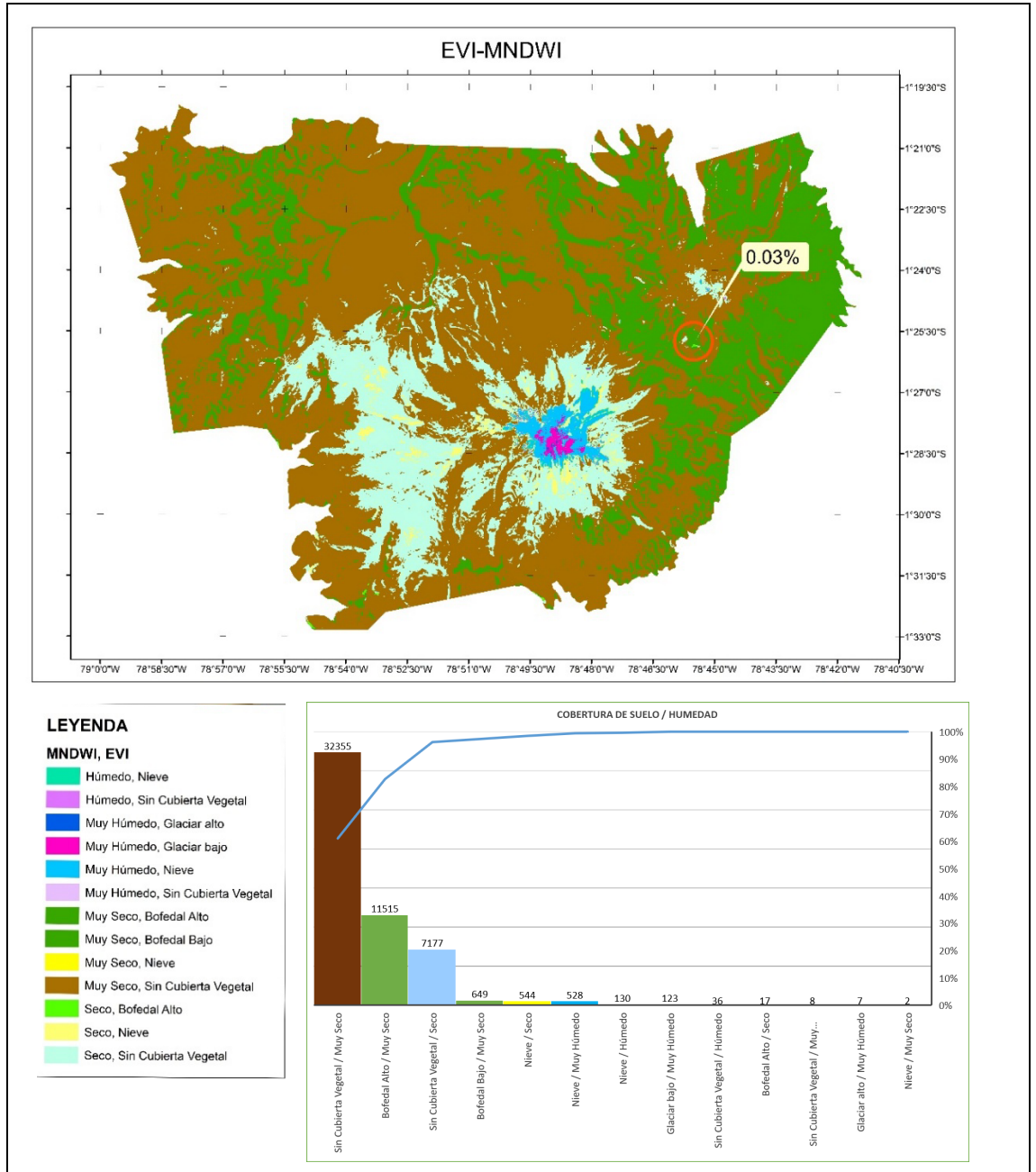
The sum of the three relative measures calculated for each species constitutes the IVI (Importance Value Index), which can range from 0 to 300%. Dividing this value by 3 yields a figure ranging from 0 to 100%. This value provides an overall estimate of the importance of each plant species to the bofedal ecosystem (Moreno, 2001, p. 38).

Results

Landscape Characterization

For this study, six classes of land cover were identified using the reflectance values extracted by the EVI (Table 2). The biomass present in the study area as of November 20, 2016, is empirically classified into High and Low Bofedals, with the High Bofedal being the most prevalent, covering 21.7% of the reserve's area, while only 1.22% consists of biomass classified as Low Bofedals (Figure 3). The largest area observed in the Reserve lacks biomass due to its geological characteristics derived from the Cotopaxi volcanoes; this area accounts for 74.54% of the Reserve's total area.

Figure 3. Characterization of Bofedal in the Chimborazo Wildlife Reserve using EVI and MNDWI



The moisture saturation level in the soil cover identified by MNDWI was classified into five moisture conditions (Table 1), where the “extremely dry” condition is absent; however, the range from “Dry” to “Very Dry” is predominant, covering 98% of the area comprising the RPFCH (Figure 3). The Chimborazo Wildlife Reserve exhibits significant humid characteristics; from the summit of the Chimborazo stratovolcano, 2.51% of glacier and snow cover is observed, extending down to the lower slopes of Chimborazo, followed by a dry area without vegetation cover representing 14%, regarding the bogs where plant organic matter is identified, 23% of the studied area is distributed across “dry” and “very dry” zones; of this latter percentage, only 0.03% (Figure 3) exhibits waterlogging characteristics and is located in the northeast of Chimborazo.

Floristic Diversity

The greatest floral diversity by family in the bofedales is found in Asteraceae (18.12%) and Poaceae (15.94%), followed by the Plantaginaceae family (14.48%), while the families with the fewest species are: Violaceae (0.01%), Ranunculaceae (0.07%), and Ericaceae (0.04%).

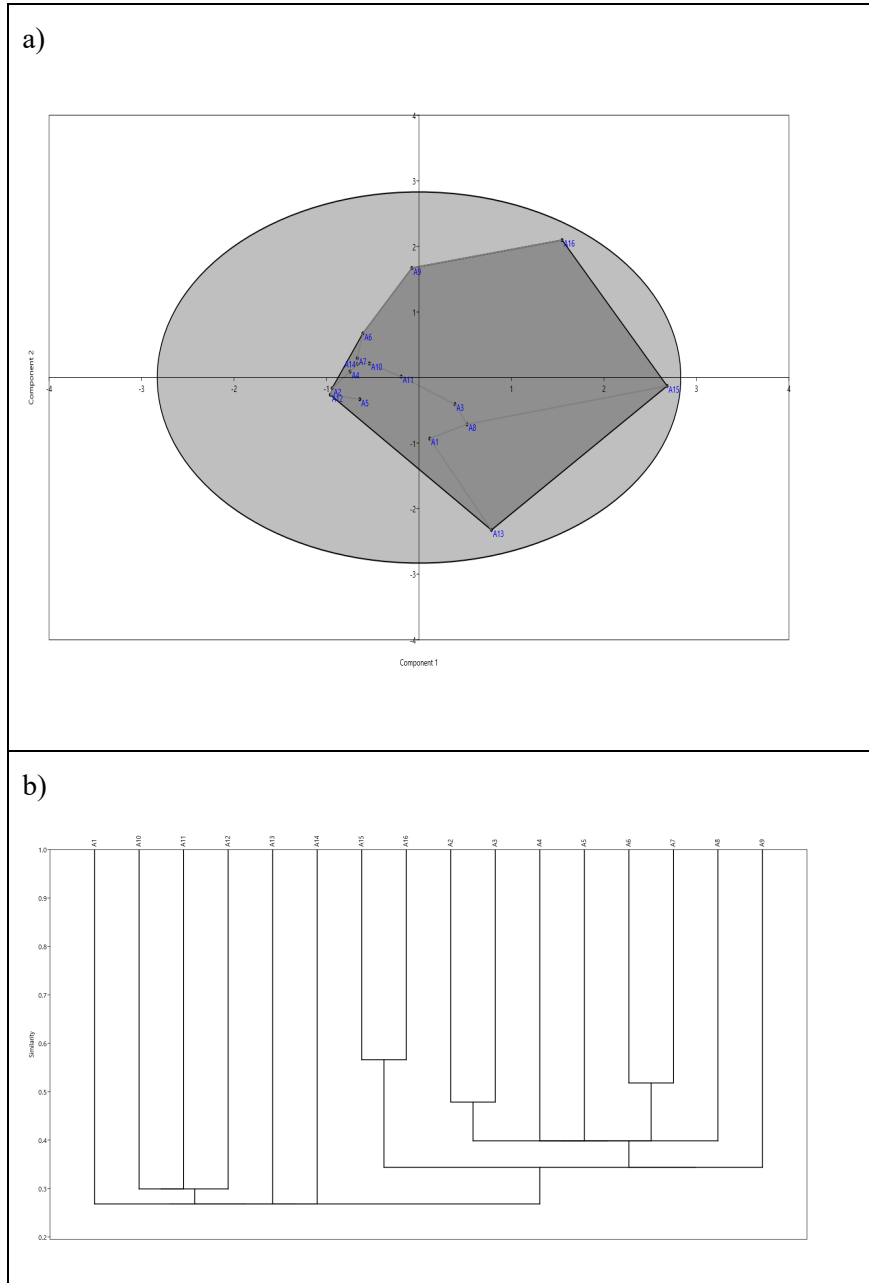
The orders with the highest number of species are: Asterales (18.12%) and Poales (15.94%); another dominant order is Plantaginales (14.48%), followed by Cyperales (9.91%) and Juncales (9.44%). The remaining orders each account for less than 8% of the species in the bogs.

The families with the highest number of species in the entire inventory are: Asteraceae with 12 species (19.0%); while the Poaceae family has 9 species (14.3%), followed by Apiaceae with 5 species (7.9%) and finally Rosaceae with 4 species (6.3%); these being the most dominant families.

The most dominant species are primarily herbaceous plants, notably species such as Yana tumbuzo (*Distichia muscoides*) and almohadilla (*Plantago rigid*), which are characteristic of the bofedales and make up the majority of the vegetation cover in this ecosystem.

Figure 4. Principal Component Analysis (a) and Bray-Curtis similarity index (b): A1: Cruz del Arenal 2; A2: Casa C3ndor; A3: Cruz del Arenal 1; A4: Culebrillas; A5: Puente Ayora 2; A6: Pachancho; A7: Puente Ayora 1;

A8: Puente Ayora 3; A9: Coop Santa Teresita; A10: Cóndor Samana; A11: Los Hieleros; A12: Portal Andino; A13: Lazabanza; A14: Pampas Salasacas; A15: Mechahuasca; A16: Rio Blanco



Using the Bray-Curtis similarity index with a stratified constant, the results are associated with the principal component characteristics observed in (Figure 4,a), thus showing a 58% similarity between the flora of the Mechahuasca and Rio Blanco wetlands; a 55% similarity is evident between the Pachancho and Puente Ayora 1 wetlands, followed by the Casa Cóndor and Cruz del Arenal 1 wetlands with 50%. On the other hand, the wetlands with the lowest similarity between them are Cruz del Arenal 2 and Culebrillas, as they share only about 27% of their vegetation. The other wetlands have a similarity ranging from 30% to 50%, which contrasts with the principal component analysis (Figure 4,a), which showed 15 interactions among the studied areas; thus, principal components 1 and 2 explain 58% of the data distribution, indicating significant intertwined groupings among the areas already detailed in the similarity indices.

Regarding Margalef's diversity indices (Figure 5,a) for the total number of specimens recorded in the inventory, values ranging from 2.0704 to 3.3827 individuals per species were obtained; which means that this ecosystem has average diversity, within normal parameters, considering that values greater than 4 indicate high diversity, and values less than 2 indicate low diversity. It should be noted that although each site has specific characteristics, none exhibits significantly different diversity levels across the study area. However, the bofedales that come closest to a low diversity value (less than 2.5) are Puente Ayora 1 with 2.0704 and Pampas Salasacas with 2.2024, suggesting that a certain species dominates in those areas; however, this is not significant, so they are still considered to have a normal level of diversity. Meanwhile, the wetland with the highest index among the sites is Los Hieleros, with a value of 3.3824; however, this value does not show a significant difference, suggesting that this area has similarly average diversity, which is considered normal for this type of ecosystem.

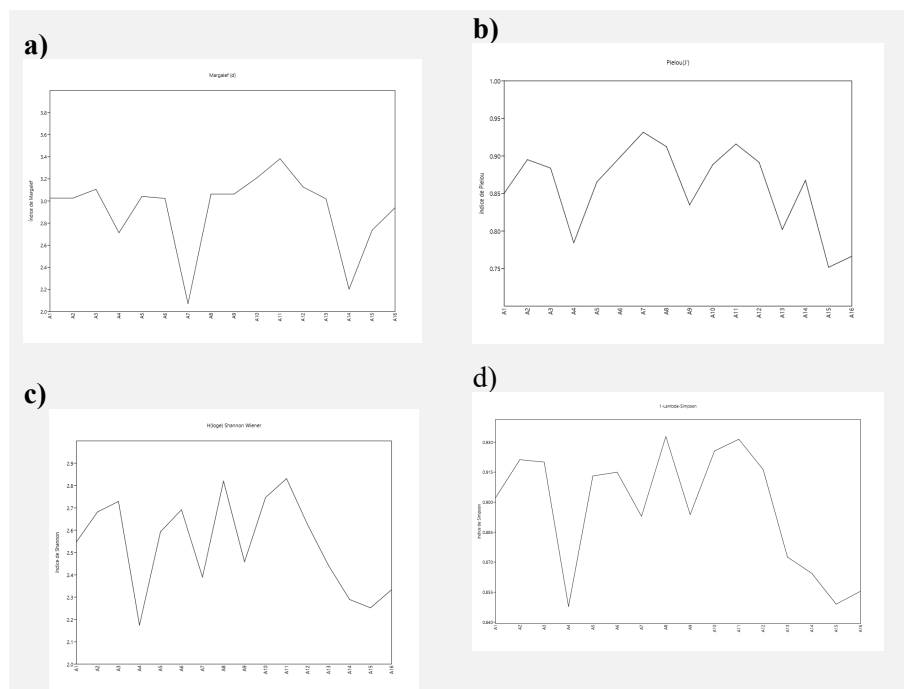
The results for the study areas regarding the Pielou Index of Equity (Figure 5b) range from 0.75181 to 0.93158, suggesting that the abundance of families in the sampling area is equitable; therefore, there is a certain degree of dominance by one group, but it is not representative, since Pielou states that values close to 1 indicate equity in the abundance of individuals per family, whereas values close to 0 indicate a clear dominance of a group or family. The lowest values correspond to the wetlands: Mechahuasca with 0.75181, and Río Blanco with 0.76643; however, they still adhere to the same principle of equity, since indices below 0.5 would be considered low equity. The wetlands closest to a value of 1, which represents greater equity, are: Puente Ayora 1 with 0.93158 and Puente Ayora 3 with 0.91245, meaning that in these wetlands there is greater equity and therefore less dominance by any single species.

From the total number of recorded individuals, it is found that the values for the **Shannon-Wiener Evenness Index** (Figure 5, c) range from 2.1746 to 2.8311, which shows no significant differences between sites, indicating that there is adequate evenness in the flora composition, as the environmental

factors of this ecosystem favor the existence of extensive vegetation cover characterized mainly by cushion-type species and herbaceous vegetation.

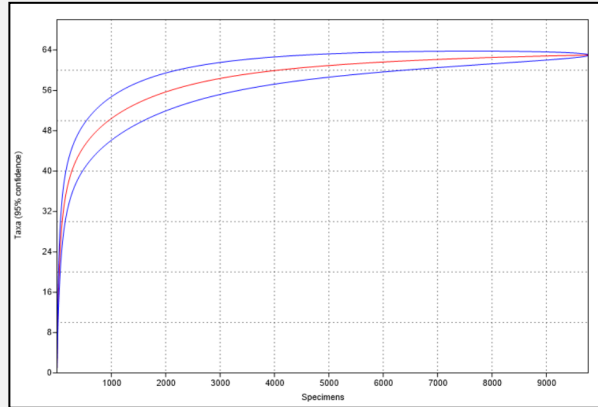
For the **Simpson Dominance Index** (Figure 5, d), the results indicate that in the bofedales, between 0.84899 and 0.93289 of the flora species dominate the vegetation composition of these sites, such as the cushion plant (*Plantago rigida*) in first place, meaning that this species dominates in this ecosystem, followed by species such as Yana tumbuzo (*Distichia muscoides*); at lower percentages, we find species such as conejo quiwa (*Gunnera magellanica*) and *Festuca sp.* It is important to note that the dominant species are primarily cushion-type plants, which are part of the typical vegetation of a bofedal according to (Mena and Medina, 2014). There is a 0.84% to 0.93% probability that two randomly selected specimens from a sample will be of the same species. All the bofedales studied share this characteristic, as there are no significant differences between areas.

Figure5 . Diversity indices¹



¹ a) Margaref index; b) Pielou index; c) Shannon index; d) Simpson index; e) Bray-Curtis dendrogram; f) Flora species rarity curve / X-axis: A1: Cruz del Arenal 2; A2: Casa Cóndor; A3: Cruz del Arenal 1; A4: Culebrillas; A5: Puente Ayora 2; A6: Pachancho; A7: Puente Ayora 1; A8: Ayora Bridge 3; A9: Santa Teresita Cooperative; A10: Cóndor Samana; A11: Los Hieleros; A12: Portal Andino; A13: Lazabanza; A14: Pampas Salasacas; A15: Mechahuasca; A16: Rio Blanco.

e)

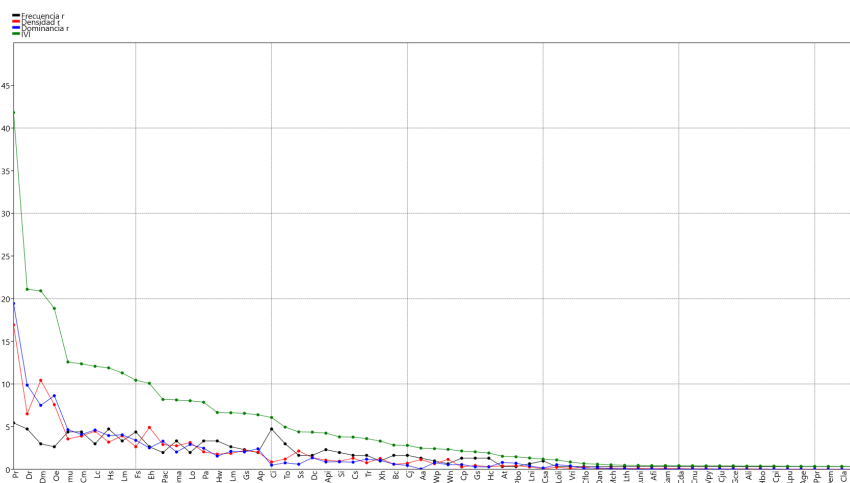


In the **flora species rarity curve** (Figure 5, e), the number of species recorded in an area increases as fieldwork progresses, up to a maximum point where it is believed that all necessary species have already been recorded (asymptote). Based on this approach, the graph shows an asymptote starting at 9,787 recorded individuals, indicating that an adequate sampling effort was made.

Importance Value Index

The following describes the relative frequency, relative density, relative dominance, and importance value index obtained for each species using the formulas proposed by Curtis and McIntosh (1951).

Figure 6 Importance Value Index by SP².



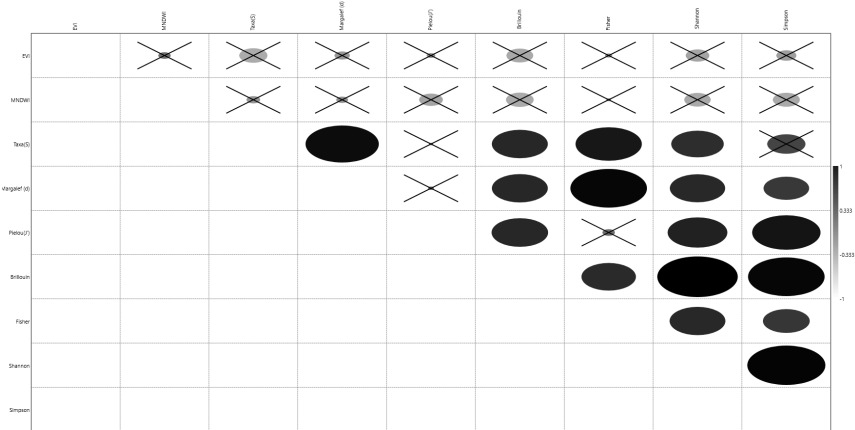
In the 16 study areas of the RPFC, of the 63 species inventoried (Figure 6), 30 species have the highest ecological importance value, accounting for 93.35% of the total Importance Value Index. In this context, the nine most representative species that contribute to the vegetation composition and structure of the bofedales are *Plantago rigida* (41.81%), *Deyeuxia rigescens* (21.1%), *Distichia muscoides* (20.92%), *O. ecuadorensis* (18.86%) *G. multipartitum* (12.58%), *C. mexicana* (12.36%), *L. conoidea* (12.08%), *Hypochaeris sessiflora* (11.89%), and *Lysipomia montioides* (11.3%).

The result of each importance value index derives from the presence or occurrence of these species in most of the study areas. This parameter is primarily determined by the number and size of individuals within the plots. The second factor helps to identify the degree of uniformity in the distribution of individuals of each species. That is, species with higher values exhibit a regular pattern, while those with lower values are characterized by an aggregated, irregular, and dispersed pattern.

Regarding the relationship between the landscape identified by two geophysical characteristics—EVI and MNDWI—there are no clearly determinative correlations (Figure 7) with the diversity indices.

² *Aa*: Aciachne acicularis; *Ali*: Aetheolaena lingulata; *Api*: Alchemilla pinnata; *Afi*: Arcytophyllum filiforme; *Age*: Astragalus geminiflorus; *Ap*: Azorella pedunculata; *At*: Azorella tridentata; *Bc*: Baccharis caespitosa; *Ci*: Calamagrostis intermedia; *Csa*: Caltha sagittata; *Cpi*: Carex pichinchensis; *Cda*: Cerasium danguyi; *Cflo*: Cerastium danguyi; *Cflo*: Cerastium floccosum; *Cl*: Cerastium latifolium; *Cj*: Chuquiraga jussieu; *Cnu*: Clinopodium nubigenum; *Cju*: Cortaderia jubata; *Cm*: Cotula mexicana; *Cs*: Culcitium sp; *Dr*: Deyeuxia rigescens; *Dem*: *Disterigma empetrifolium*; *Dm*: *Distichia muscoides*; *Dc*: *Draba confertifolia*; *Eam*: *Ephedra americana*; *Eh*: *Eryngium humile*; *Fs*: *Festuca* sp; *Gs*: *Gentiana sedifolia*; *Gmu*: *Geranium multipartitum*; *Gs*: *Geranium sessiliflorum*; *Gma*: *Gunnera magellanica*; *Hw*: *Halenia weddelliana*; *Hc*: *Huperzia crassa*; *Hbo*: *Hydrocotyle bonariensis*; *Hs*: *Hypochaeris sessiliflora*; *Lni*: *Lachemilla nivalis*; *Luni*: *Lachemilla uniflora*; *Lo*: *Lachimella orbiculata*; *Loli*: *Lobelia oligophylla*; *Lm*: *Lolium multiflorum*; *Lth*: *Loricaria lhuoides*; *Lc*: *Lucilia conoidea*; *Lpu*: *Lupinus pubescens*; *Lm*: *Lysipomia montioides*; *Mch*: *Miconia chionophila*; *Oe*: *Oreobolus ecuadorensis*; *Oan*: *Oreomyrrhis andicola*; *Pbo*: *Paspalum bonplandianum*; *Ppr*: *Pernettya protrata*; *Pac*: *Phylloscirpus acaulis*; *Pr*: *Plantago rigida*; *Pa*: *Poa annua* L.; *Ss*: *Sphagnum* sp.; *Si*: *Stipa ichu*; *To*: *Taraxacum officinale*; *Tr*: *Trifolium repens* L.; *Vri*: *Valeriana rigida*; *Vgl*: *Viola glandularis*; *Vpy*: *Viola pygmaea*; *Wn*: *Werneria nubigena* Kth; *Wp*: *Werneria pygmaea*; *Xh*: *Xenophyllum humile*.

Figure 7. Correlation of variables (EVI, MNDWI-DIVERSITY)



Vegetation indices are widely used for identifying spatial patterns and monitoring vegetation cover, as they are based on arithmetic combinations of spectral bands that allow for the differentiation of land cover types. However, their application in high-Andean ecosystems has limitations associated with topographic complexity and atmospheric conditions. In the case of the RPFCH, the presence of the Chimborazo stratovolcano introduces variations in solar incidence angles and reflectance, generating noise in the spectral signal.

In this context, the use of the EVI index improved vegetation detection compared to the NDVI by reducing the effects of saturation and atmospheric distortions, as has been reported in remote sensing studies of high-mountain ecosystems. However, the MNDWI index showed high moisture values in higher-altitude areas, particularly in areas with snow cover on the date the image was acquired (November 20, 2016), which introduces a bias in the interpretation of surface moisture compared to lower-altitude areas where saturated bogs and grasslands predominate.

These conditions lead to an overestimation of moisture in snow-covered areas and hinder the accurate identification of bofedales, whose water dynamics are determined by local processes such as waterlogging and the soil's high water-holding capacity. Furthermore, the 30-meter spatial resolution of the Landsat 8 images limits the detection of the structural heterogeneity of these ecosystems, which are characterized by small-scale spatial patterns.

The results obtained show that the floristic diversity of the RPFCH bogs responds to ecological patterns associated with altitudinal gradients and environmental conditions typical of páramo ecosystems. In this regard, recent studies in páramos in the province of Chimborazo have reported similar diversity values, as well as a clear influence of altitude on species composition

and dominance, highlighting the vegetation's adaptation to extreme conditions of temperature, radiation, and nutrient availability.

In particular, research conducted in the Ichubamba Yasepan páramo shows that floristic diversity varies across altitudinal strata, with average diversity according to the Shannon and Simpson indices, which aligns with the values obtained in the present study. Likewise, it has been shown that certain species exhibit greater dominance depending on altitude, reflecting processes of ecological adaptation and environmental differentiation in these ecosystems (Ati Cutiupala et al., 2023).

These results reinforce the idea that the floristic structure and composition of high-Andean bogs are strongly determined by environmental and altitudinal factors, which limits the ability of spectral indices to capture such complexity when complementary variables are not considered.

In line with studies conducted in high-Andean ecosystems (Carrasco Baquero et al., 2023; Zurita-Polo et al., 2020), these results demonstrate that spectral indices alone are insufficient to characterize the ecological complexity of Andean bofedales, necessitating the integration of environmental variables such as temperature, precipitation, topography, and soil physicochemical properties. This multivariate approach would improve the accuracy of the spatial characterization of floristic diversity in high-mountain ecosystems. Biodiversity indices, based on the Margalef index, indicate that all the bofedales (16) have average diversity; the same is true for the Shannon evenness index. Therefore, it is noted that none of the studied bofedales possess high diversity, but they fall within the normal range for this type of ecosystem. However, Fiallos et al. (2015) conclude that the existing biodiversity in páramos in general, taking into account the Margalef, Simpson, and Shannon indices, is variable in their study, with páramo ecosystems considered to have low biodiversity compared to other types of ecosystems. This may be because the biological diversity of the páramo has proven to be highly sensitive to ecological changes. On the other hand, Caranqui, Lozano, and Reyes (2016) mention that in the páramo ecosystem of the RPFCH, most of the areas studied according to the Simpson diversity index have mostly medium to low values ranging from 0.17 to 0.79. The low values obtained are presumed to be due to the high dominance of *Calamagrostis intermedia* found in most plots. Currently, adverse effects are being experienced in grass plant communities due to climate change. In a grass community, diversity is affected by changes in temperature during the day and night. (Monasterio, 2013), so it can be stated that diversity varies given the elevation of the study areas and the adverse climatic conditions.

The floristic composition of the RPFCH wetlands is dominated primarily by herbaceous species, notably characteristic species such as *Distichia muscoides* (yana tumbuzo) and *Plantago rigida* (almohadilla), which play a fundamental

role in the structure and functioning of these ecosystems. Similar results have been reported in studies conducted within the same reserve, such as that by Zurita-Polo et al. (2020), who identified the dominance of *Werneria pygmaea* in floodplain grassland ecosystems, demonstrating the floristic variability associated with microenvironmental conditions.

Complementarily, Baquero (2023) reported a high abundance of species such as *Lachemilla orbiculata*, *Agrostis breviculmis*, *Plantago rigida*, *Eryngium humile*, and *Hypochaeris sessiliflora*, which coincides with the dominance patterns observed in this study. Likewise, according to Bustamante (2011), in páramos above 4,000 m a.s.l., cushion-forming species such as *Azorella multifida*, *Distichia muscoides*, *Plantago rigida*, and *Xenophyllum humile* predominate, confirming that the analyzed bofedales exhibit floristic characteristics typical of high-Andean ecosystems.

Taken together, these results demonstrate that the floristic structure of the RPFCH bogs corresponds to well-established ecological patterns in high-mountain environments, where the dominance of species adapted to extreme conditions constitutes a distinctive feature of these systems.

Conclusions

The results obtained show that the floristic diversity of the RPFCH bofedales remains within average ranges, which is consistent with reports from high-Andean páramo ecosystems (), where extreme environmental conditions limit species richness and favor the dominance of specialized life forms. In this context, the high representation of cushion plants such as *Plantago rigida* and *Distichia muscoides* aligns with patterns described in recent studies of high-Andean vegetation, where these species play a key role in the structural stability of the ecosystem.

The absence of a significant correlation between spectral indices (EVI and MNDWI) and floristic diversity suggests that indicators derived from remote sensing do not adequately capture the ecological heterogeneity of the bofedales. Recent studies have indicated that, in high-mountain ecosystems, factors such as microtopography, edaphic variability, and microclimatic conditions have a decisive influence on vegetation distribution, limiting the ability of medium-resolution spectral indices to reflect biodiversity patterns.

Additionally, the spatial resolution of Landsat images (30 m) can lead to an overgeneralization of vegetation cover, especially in fragmented ecosystems such as bofedales, where vegetation structure is distributed in small-scale patches. In this regard, recent research recommends the

integration of complementary environmental variables, such as temperature, soil moisture, and topography, as well as the use of images with higher spatial resolution, to improve the interpretation of the relationship between landscape and biodiversity.

Taken together, these results highlight the need to adopt multiscale and multidimensional approaches for the study of high-Andean ecosystems, as the ecological complexity of the bofedales cannot be explained solely through spectral indices.

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