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Influence of soil texture, land cover, and photosynthetic activity on the flora composition of three altitudinal gradients of the Potrerillo wetland in the Chimborazo reserve

Eduardo Antonio Muñoz-Jácome[1], Javier Felix Yanqui-Ushiña[2], Elizabeth Mariela Abarca- Bonilla[3], Maritza Lucia Vaca-Cárdenas[4], Marcela Yolanda Brito-Mancero[5], Diego Francisco Cushquicullma-Colcha[6], Pedro Vicente Vaca-Cárdenas[7*]
[1,4,5]Faculty of Natural Resources, Escuela Superior Politécnica de Chimborazo, Panamericana Sur, km 1.5, Riobamba 060155, Ecuador; emunoz@espoch.edu.ec (E.A.M.J.) maritza.vaca@espoch.edu.ec (M.L.V.C.) mybrito@espoch.edu.ec (M.Y.B.M.).
[2]Andean Paramos, Research Center, Riobamba 060155, Ecuador; javier.yanqui@espoch.edu.ec (J.F.Y.U.)
[3]Faculty of Education, Humanities, and Technology, Universidad Nacional de Chimborazo, Av. Antonio José de Sucre Km 1 1/2 vía a Guano, Ecuador; elizabeth.abarca@unach.edu.ec (E.M.A.B.)
[6]Andean Páramos, Research Center, Riobamba 060155, Ecuador; diego.cushquiculma@espoch.edu.ec (D.F.C.C.).
[7]Doctoral Program in Natural Resources and Sustainable Management, Universidad de Córdoba, 14071 Cordoba, Spain; z42vacav@uco.es (P.V.V.C.).

Abstract: The Potrerillo wetland (Chimborazo Reserve, Ecuador, 4318 m a.s.l.) is a fragile ecosystem due to its importance for water regulation and carbon storage, threatened by glacial retreat and anthropogenic activities. This study analyzed the influence of soil texture, land cover, and photosynthetic activity on floristic composition at three altitudinal gradients (low: 4280–4306.6 m; middle: 4306.7–4333.2 m; high: 4333.3–4360 m). Using DJI M200 drones and multispectral sensors, an NDVI between 0.6 and 0.8 was determined, reflecting high photosynthetic activity. Fourteen species and nine families were inventoried, with Asteraceae being dominant (Calamagrostis intermedia, Distichia muscoides). Diversity ranged from moderate to low, with greater richness at the top of the gradient and interspecific competition at the middle and top levels. Statistical results identified two key components: Factor 1, which links soil texture and cover with lower diversity; and Factor 2, which establishes a positive correlation between photosynthetic assimilation and floristic richness. Redundancy analysis (RDA) integrated floristic and edaphic variables, confirming ecological gradients defined by the interaction between photosynthetic capacity and soil physical properties. The study demonstrates that floristic composition, ecosystem productivity, and plant diversity depend on edaphic and hydrological conditions and vegetation cover.

Keywords: *Floristic richness, Interspecific competition, Multivariate analysis, Photosynthetic activity, Species dominance.*

1. Introduction

High Andean wetlands, located above 3,800 meters above sea level in countries such as Colombia, Ecuador, Peru, Bolivia, Chile, and northeastern Argentina, are high mountain ecosystems with great ecological, hydrological, and socioeconomic importance. They act as essential habitats for a rich diversity of flora and fauna, contributing to the conservation of biodiversity in hostile mountain environments [1, 2]. In addition, they regulate water cycles by recharging aquifers, purifying water, and cycling nutrients, providing fundamental ecosystem services such as soil protection, carbon storage, and the production of high-quality pasture for wildlife and camelids [3, 4].

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* Correspondence: z42vacav@uco.es

These ecosystems face significant threats that compromise their functionality and biodiversity. The expansion of dominant species displaces native flora, reducing plant diversity, while glacial retreat, driven by climate change, alters hydrological regimes [5, 6]. Likewise, climate changes, such as variations in precipitation and extreme weather events, cause habitat degradation and biodiversity loss, affecting wetlands' ability to maintain their environmental services and landscape value [7, 8].

In the Andean region of Ecuador, specifically in the Chimborazo Reserve (RCH), which has been part of the National System of Protected Areas (SNAP) since 1987, covering 52,683.27 hectares, there are wetlands of varying sizes that occupy 5.36% of the protected area. One of the most important and difficult-to-access bogs is Potrerillo, located in the province of Tungurahua, at an altitude of 4,318 meters above sea level [9]. The extent of these ecosystems has decreased significantly, from 16,480.3 ha in 1991 to 6,456.34 ha in 2016, with projections of a reduction to 4,600 ha by 2032 due to anthropogenic factors and climate variability [10].

One of the main wetlands in the protected area is the Potrerillo wetland, located at the foot of the Carihuairazo volcano in the Yatzaputzan community, which is an ecosystem characterized by specialized biota adapted to extreme high-altitude conditions [11]. These systems exhibit significant vulnerability to climate change [12] despite their hydrological and ecological roles. Evidence indicates that greater vegetation cover in these wetlands correlates with higher sustainable water flows, highlighting their function as "water towers" for lower-altitude regions [13]. Additionally, they contribute to ecosystem services through carbon sequestration and nutrient cycling [14]. At the same time, they provide critical habitats for species such as amphibians and waterfowl [15]. The complexity of these wetlands extends to the specialized microbial communities that thrive under conditions of high radiation and low oxygen pressure, which are essential for maintaining the health and resilience of the ecosystem [11].

Furthermore, the floral composition of wetlands is determined by a complex interaction of climatic, anthropogenic, and other variables. These influence the composition, abundance, and survival of plant species, favoring communities adapted to flooding conditions or seasonally wet soils [16-20].

In this context, we analyzed the influence of texture, land cover, and photosynthetic activity on the floristic composition of three altitudinal gradients in the Potrerillo wetland within the Chimborazo Reserve, aiming to identify whether specific diversity patterns exist in each gradient.

2. Materials and Methods

2.1. Study Area

As shown in Figure 1, field surveys determined that the Potrerillo wetland covers an area of 87.67 hectares and is located in the province of Tungurahua, in the canton of Ambato, in the parish of Pilahuín, in the Andean community of Yatzaputzan on the slopes of the Carihuairazo volcano [21, 22]. The wetland is characterized by a maximum temperature of 8.0 °C in December and a minimum of -2.2 °C in August. Maximum precipitation is 90 millimeters per square meter (mm) in April, and minimum precipitation is 27 mm in August. Maximum solar radiation is 15.06 kWh/m^2 in September, and the minimum is 11.72 kWh/m^2 in February. The maximum wind speed is 5.5 m/s in July, and the minimum is 3.7 m/s in March.

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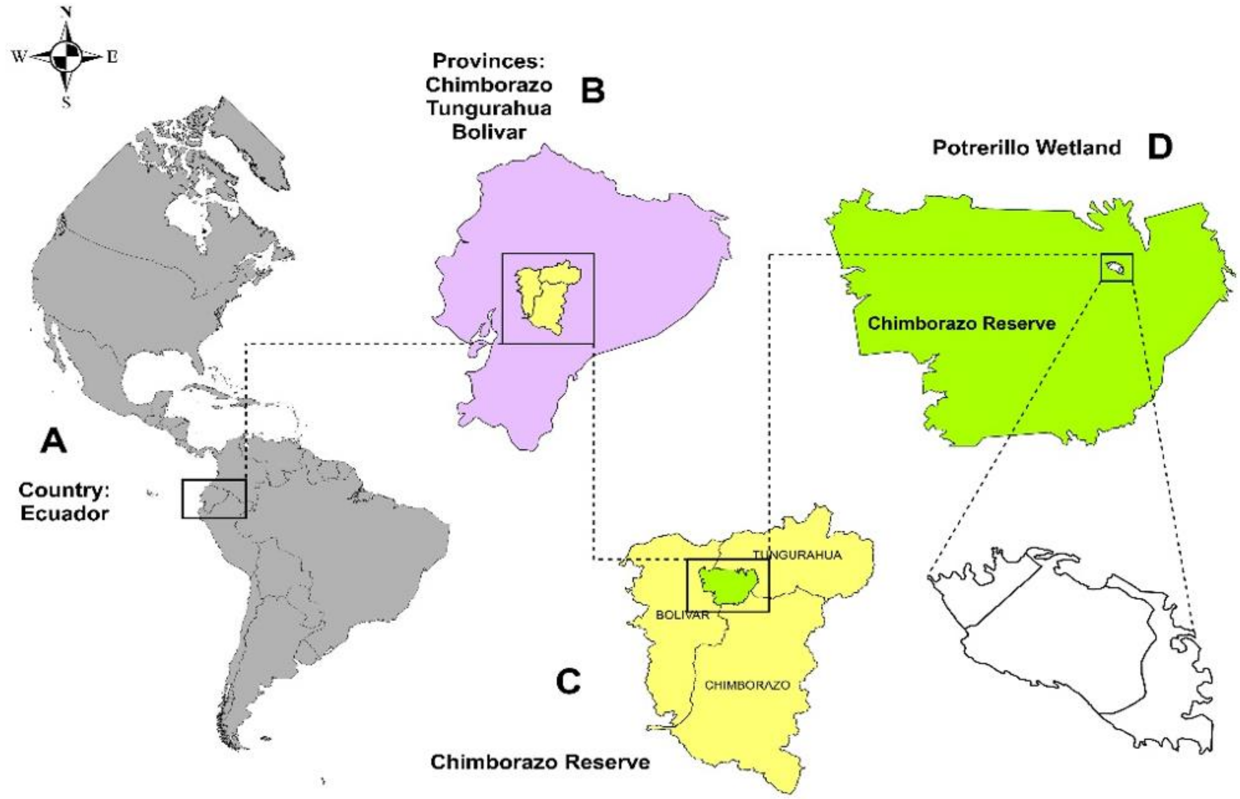

Figure 1.
(A) Location of the study area in relation to South America, located in Ecuador. (B) The territory of Ecuador (gray area: provinces of Chimborazo, Tungurahua, and Bolivar). (C) Protected area (green area: Chimborazo Wildlife Production Reserve). (D) The Chimborazo Wildlife Production Reserve (white area: where the Potrerillo wetland is located).

2.1.1. Methodology

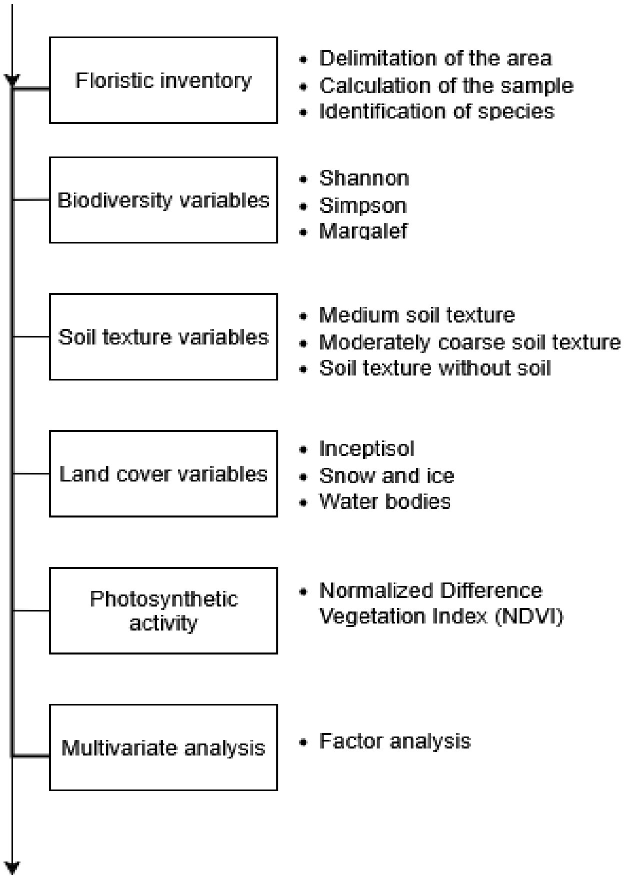

Figure 2.
Methodological process.

2.2. Research Methodology
2.2.1. Structure and Composition of Vegetation Cover
2.2.1.1. Floristic Inventory

Three altitudinal gradients were defined: low, medium, and high [23]. Altitude was considered because it influences water availability and vegetation variation [24].

The low gradient covered an area of 10.82 hectares at an altitude of 4,280 to 4,306.6 meters above sea level. The medium gradient covered 52.56 hectares at an altitude of 4,306.7 to 4,333.2 meters, while the high gradient covered 24.29 hectares at an altitude of 4,333.3 to 4,360 meters. To calculate the sample, 100 x 100-meter cells were created using the Create Fishnet and Spatial Join tools in QGIS version 3.40.1, recording 89 grids throughout the study area [25, 26].

A stratified proportional sampling was carried out, ensuring adequate representation [27]. The sample was calculated using the formula [28]: $\boldsymbol{n} = \frac{N*Z^2*p*(1-p)}{(N-1)*e^2+Z^2*p*(1-p)}$. Where: population size (N): 89.0, confidence level (Z): 1.96 (for a confidence level of 95%), expected proportion (p): 0.5 (maximum variability), margin of error (e): 0.20, the sample result is n: 20. Then, the proportionality constant $\mathbf{K} = \frac{19{,}07}{89} = 0{,}21$. And it is multiplied by the number of grids in each gradient [29]. The environmental conditions and topographical complexity inherent in high mountain ecosystems increase sample variability, justifying the application of a margin of error greater than 5% [30].

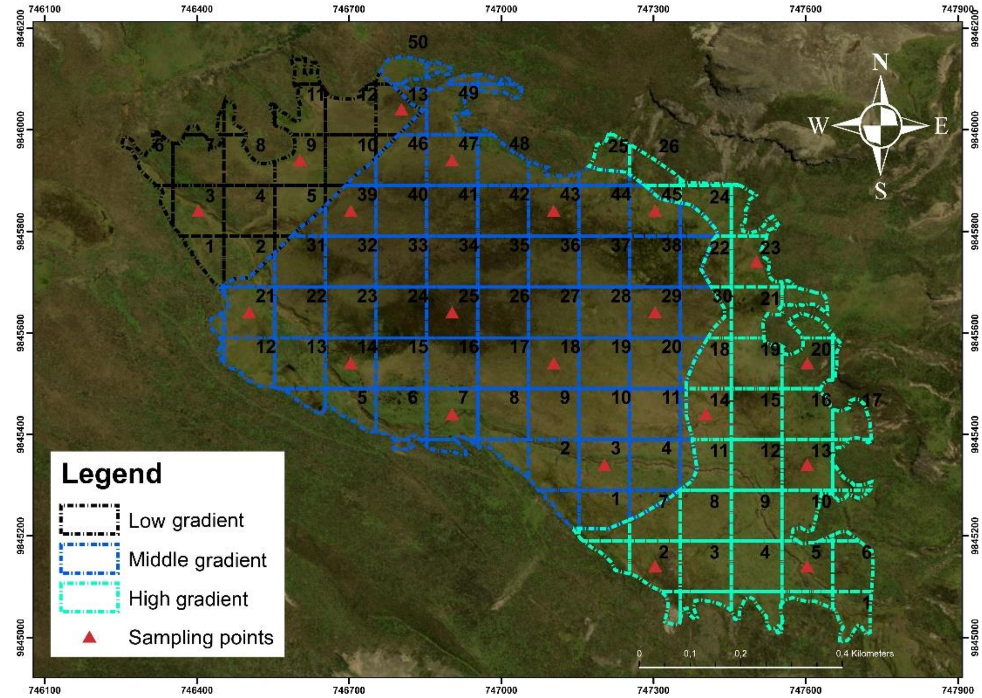

Figure 3.
The map shows low, medium, and high altitude gradients and sampling points.

Table 1.
Stratified sample distribution

Gradient	Sample size by gradient.
Low	3
Medium	11
High	6
Total	20

In Table 1, three sampling cells were identified for the low altitude gradient, 11 for the medium gradient, and six for the high gradient. For the floristic inventory, the transect methodology (Parker) was applied in high Andean wetlands, allowing for replicability and precision through straight lines of standard length and uniform width, enabling comparability in variable terrains [31]. Its integration with remote sensing improves reliability by capturing vegetation dynamics in challenging environments [32]. This involves walking a straight line of 100 steps in cardinal directions: north, south, east, and west. This technique assesses vegetation abundance and dominance, correlating habitat structure with biodiversity, and is valid for various taxa and abundance patterns [33]. During the plant species recording phase, this was only carried out in the selected grids. Finally, the species were identified in the Espoch herbarium [9].

2.2.2. Biodiversity Indices

The Shannon index was calculated using the formula: $SH = -\sum_{i=1}^{n}(\text{longnPi})$. Where: N: Number of species, Pi: Proportion of the total number of individuals.

The Simpson biodiversity index was calculated using the formula: IDS = $1 - \sum_{(\text{Pi})} 2$, where: Pi: Proportion of the total number of individuals, with an interpretation range of 0 to 1, where 0 represents

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high diversity and 1 represents low diversity [34]. Margalef's biodiversity index, using the formula: $\text{IDM} = \frac{S-1}{\ln N}$. Where: S = Number of species, N = Total number of individuals [35, 36].

2.3. Soil Texture and Land Cover Variables

Vector information in polygons was used, prepared in 2022 by the Ecuadorian Space Institute (IEE), the Ministry of Agriculture and Livestock (MAG) through the SIGTIERRAS program, and the areas of the State Natural Areas Heritage (PANE). For this analysis, the shapefiles were downloaded from the Geoportal of the Military Geographic Institute (IGM) in compressed .shp format (*.rar), with a 2D geographic coordinate system (WGS84 datum). The soil texture layer contains geolocated information on soil count, type, description, area, and length, while the land cover layer contains information on the code, description, and area of the cover. The layers were cut using the clip tool in the spatial analysis software.

2.4. Photosynthetic Activity

To evaluate photosynthetic activity, the normalized difference vegetation index (NDVI) was calculated using multispectral images captured by the DJI M200 industrial drone, which has a Sentera multispectral camera [37]. Flight planning was carried out using the Forecast and DJI Pilot applications, executing a total of six flights at a speed of 6 m/s and a duration of two hours per flight [38]. The flights were conducted at an altitude of 100 meters, capturing 633 images with a GSD pixel resolution of 4.31 cm/pixel and using 80 control points. The captures were made between 11:30 a.m. and 1:00 p.m., the optimal time for photosynthetic activity according to Essaadia et al. [39].

The calculation was performed using multispectral images obtained by a drone and processed with Pix4DmapperAg software. This index was determined using the equation NDVI = (NIR - RED) / (NIR + RED), which quantifies photosynthetic activity and plant biomass based on the absorption of the red band (RED) by chloroplasts and the near-infrared reflectance (NIR) generated by internal scattering in the leaf mesophyll [40-43].

The captured images were transferred from the multispectral camera to a computer and processed in Pix4DmapperAg, which recognizes the associated metadata (GPS coordinates, camera parameters) and the WGS 84 Zone 17 South geographic reference system. Radiometric calibration was applied during processing to obtain true reflectance values [44-46], ensuring spectral and geometric accuracy by incorporating ground control points (GCPs).

From the photogrammetric alignment, multispectral orthomosaics corresponding to the RED and NIR bands were generated, along with 3D models and dense point clouds [46]. Using the reflectance maps obtained, the NDVI was calculated within the software, derived directly from the spectral response of vegetation to the captured electromagnetic spectrum.

The resulting NDVI index enabled analysis and monitoring of vegetation's physiological conditions, coverage, and dynamics in the study area, providing accurate quantitative information on the vegetation's state [47].

2.5. Factor Analysis

To identify adjacent variables, reducing the dimensionality of the data and grouping them into principal factors, multivariate factorial analysis was used, for which a matrix was constructed in which the altitudinal gradients were placed in the rows and the variables, such as diversity indices, land cover, soil texture, NDVI index, were placed in the columns. The statistical software MULTBIPLOT 23.11.0 was used, which analyzed the different simultaneous variables using the equation: $X_i = \lambda_{i1}F_1 + \lambda_{i2}F_2 + \cdots + \lambda_{im}F_m + \epsilon_i$ Where: X_i: Is an observed variable. λ_{ij}: The factor loadings indicate the relationship between variable i and factor j. F_j: Are the latent factors that are not clearly observed. ϵ_i: Is the specific error associated with λ_i, which is not explained by the frequent factors. Where the variables X_i are correlated due to common factors (F_j). The common factors (F_j) are independent of each other. The specific errors ϵ_i are not correlated with each other or with the common factors [9].

2.6. Redundancy Analysis

A Redundancy Analysis (RDA) was performed using the vegan package in R, with Shannon, Simpson, and Margalef indices as response variables and environmental variables (water cover, litter, bare soil, vegetation cover, soil texture, rock, and NDVI) as explanatory variables.

Redundancy Analysis (RDA) is a robust multivariate statistical tool for evaluating relationships between community composition and environmental variables [48, 49]. In Andean páramo ecosystems, it allows the influence of gradients such as altitude, humidity, and temperature on the distribution of plant species to be quantified [50, 51]. By combining ordination and regression, RDA determines the proportion of floristic variance explained by abiotic factors, identifying the main drivers of plant diversity [52-54].

Based on a linear model of the main formula: $y_j = XB_J + e_J$ para j=1,…….,p. Where: y_j= column j of the response matrix Y(n*p). X: matrix of explanatory variables (n*m), usually centered. Bj: vector of coefficients. Matrix of adjusted values: $\hat{Y} = X(X^TX)^{-1}X^TY = XB$. Where: B = e is the matrix of regression coefficients. $\hat{Y} =$ covariance matrix.

Analyze the species matrix as a function of environmental variables [55-57]. Its application in ecological studies of páramo allows for a more accurate understanding of climatic interactions and provides key information for conservation strategies and sustainable management of these high Andean ecosystems [58-60].

3. Results

3.1. Floristic Composition

Nine families and 14 species were identified across the three gradients (Table 2). The family with the most species is Asteraceae, known for its floristic richness and traits that favor adaptation to various climatic conditions. It also excels in expanding within aquatic and terrestrial environments due to its morphological adaptations. These grasses are used in soil stabilization and carbon sequestration, contributing to climate change mitigation [61].

Table 2.
Families, species, and number of individuals.

Family	Scientific name	Low gradient (# individuals)	Middle gradient (# individuals)	Upper gradient (# individuals)
Poaceae	*Cinnagrostis intermedia* (J.Presl) P.M.Peterson, Soreng, Romasch. & Barberá	88	1341	675
Plantaginaceae	*Plantago rigida* Kunth	131	200	168
Bartramiaceae	*Breutelia tomentosa* (Sw. ex Brid.) Spruce	53	131	101
Lycopodiaceae	*Huperzia crassa* (Humb. & Bonpl. ex Willd.) Rothm	88	219	141
Juncaceae	*Distichia muscoides* Nees & Meyen	192	213	181
Caprifoliaceae	*Valeriana aretioides* Kunth	155	176	109
Asteraceae	*Xenophyllum humile* (Kunth) V.A.Funk	11	3	5
Poaceae	*Calamagrostis fibrovaginata* Laegaard	32	173	104
Apiaceae	*Eryngium humile* Cav	64	235	307
Asteraceae	*Loricaria thuyoides* (Lam.) Sch. Bip.	8	29	29
Asteráceae	*Baccharis caespitosa* (Ruiz & Pav.) Pers.	5	67	11
Asteráceae	*Gentiana sedifolia* Kunth	0	29	11
Asteráceae	*Lachimella orbiculata* (Ruíz & Pav)	0	5	5
Asteráceae	*Lasiocephalus ovatus* D.F.K.Schltdl.	0	0	11
Total		827	2821	1858

The three altitudinal gradients clearly differ in the number of species present: only 11 species are shared among the three gradients, with the middle gradient having two exclusive species (Gentiana sedifolia, Baccharis caespitosa) absent in the low gradient. The high gradient has one exclusive species (Lasiocephalus ovatus) not present in the middle and low gradients, showing marked segregation along the altitudinal gradient.

A total of 310 individuals were recorded in the low gradient, grouped into 9 families and 11 species. Noteworthy is the presence of the species D. muscoides with 72 individuals, V. aretioides with 58, and, in smaller numbers, B. caespitosa with 2. In the medium gradient, a total of 1,058 individuals were recorded, grouped into 9 families and 13 species. Noteworthy is the presence of the species C. intermedia with 503 individuals, E. humile with 88 individuals, and, in smaller numbers, the species X. humile with 1 individual. In the high gradient, a total of 697 individuals were recorded, grouped into 9 families and 14 species. Also noteworthy is the species C. intermedia with 253 plant individuals, E. humile with 115 plant individuals, and, in smaller numbers, X. humile and L. orbiculata with 2 individuals.

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3.2. Biodiversity Indices

Figure 4.
Biodiversity indices of low, medium, and high altitudinal gradients.

Regarding the Shannon index, the values range from 1.98 in the high gradient, 1.83 in the medium gradient, and 2.06 in the low gradient. These values indicate average diversity across all gradients. For the Simpson index, the values obtained were 0.81 in the high gradient, 0.74 in the medium gradient, and 0.85 in the low gradient, indicating low diversity in the high and low gradients and medium diversity in the medium gradient. This suggests dominance of one or a few species, especially in the high and low gradients. Finally, in the Margalef index, the values are between 1.99 in the high gradient, 1.72 in the medium gradient, and 1.74 in the low gradient, indicating low richness across all gradients.

3.3. Soil Texture Variables

Table 3.
Details of soil texture in the gradients.

Gradient	Medium soil texture	Moderately coarse soil texture	No soil texture
Low gradient	0.3	0	10.51
Middle gradient	38.21	11.56	2.75
High gradient	6.89	5.62	11.73

Medium texture dominates the wetland with 38.21 hectares (Table 3). This soil is characterized by a balance of sand, silt, and clay, contributing to water retention, nutrients, and aeration.

3.4. Land Cover Variables and Photosynthetic Activity

Table 4.
Land cover

Gradient	Inceptisol	Snow and ice	Bodies of water
Low gradient	9.06	0	1.76
Middle gradient	31.94	20.62	0
High gradient	0	24.29	0

Inceptisol soil predominates in the bofedal, covering 31.94 ha (Table 4). Additionally, 1.76 ha of water bodies, including streams, lagoons, and ponds, are present in the low-gradient area (Table 3), which are essential for maintaining ecosystem diversity.

3.5. Photosynthetic Activity

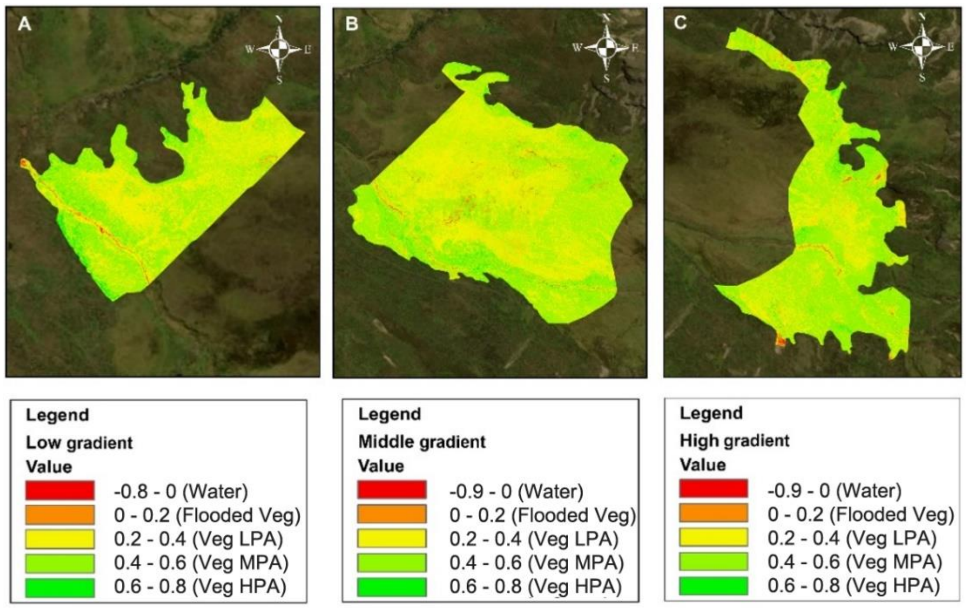

Figure 5.
Normalized Difference Vegetation Index (NDVI) (A) low altitudinal gradient. (B) medium altitudinal gradient. (C) high altitudinal gradient.

In the low gradient, high NDVI values (0.6–0.8) indicate greater photosynthetic activity and are located in the southwest of the bofedal, while low values (-0.8–0) are located in the south. On the medium gradient, high NDVI values (0.6–0.8) are found in the southeast of the bofedal, and low values (-0.9–0) are located in the west-southeast. Meanwhile, in the high gradient, high NDVI values (0.6–0.8) are located north-southeast of the bofedal, and low values (-0.9–0) indicate water and are located east-southeast (Figure 5). On the other hand, vegetation with high photosynthetic activity in the low gradient has an area of 0.5 ha, and water 0.17 ha. In the medium gradient, vegetation with higher photosynthetic activity covers an area of 1.13 ha, and water covers 0.07 ha. In the high gradient, vegetation with high photosynthetic activity covers an area of 0.61 ha, and water covers 0.05 ha (Figure 5).

3.6. Influence of Underlying Factors

Factor 1 explains 76.35% of the variance, demonstrating that this factor captures most of the information in the data. Factor 2 explains the remaining 23.65%, totaling 100% of the cumulative variance with the two main factors. Factor 3 does not provide additional information (eigenvalue = 0).

Table 5.
Factor loadings matrix.

		Inertia	
Axes	**Value**	**Expl Var**	**Cumulative**
Factor 1	8.399	76.356	76.356
Factor 2	2.601	23.644	100
Factor 3	0	0	100
Loadings		Factor	
Columns	Factor 1	Factor 2	Factor 3
Shannon Ind	-0.995	-0.101	0
Simpson Ind	-0.993	-0.119	0
Margalef Ind	-0.338	0.941	0
Water Cob	-0.474	-0.88	0
Litter Cob	0.993	0.122	0
Bare Soil Cob	0.993	0.119	0
Vegetative Cob	0.996	0.089	0
STex mean	0.996	-0.085	0
STex moderately thick	0.967	0.256	0
STex without soil	-0.931	0.365	0
NDVI	-0.572	0.82	0
Rows	Factor 1	Factor 2	Factor 3
Gradient 1 (low)	0.754	0.246	0
Gradient 2 (medium)	0.98	0.02	0
Gradient 3 (high)	0.205	0.795	0

Note. Table 5 shows the factor loadings matrix, which illustrates how the variables are linked to the factors. A concentration of high loadings can be seen in factors 1 and 2.

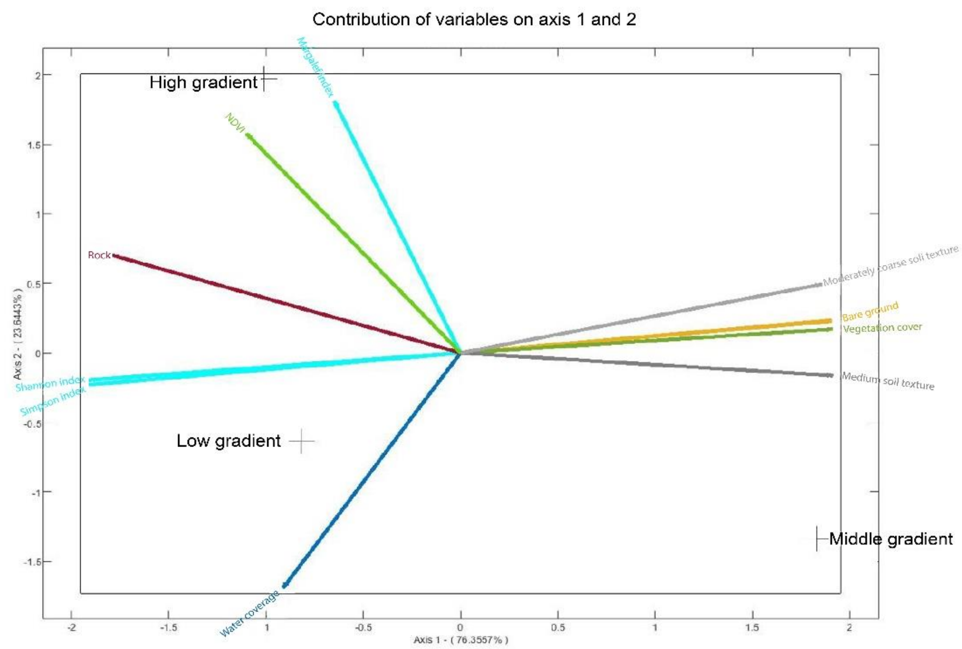

Figure 6.
Distribution of adjacent variables.

3.7. Gradient Analysis of Factors 1 and 2

The factorial analysis identified two main factors revealing data variability: factor 1, represented by "Vegetation cover and soil type," and factor 2, represented by "Richness and photosynthetic activity."

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"GRADIENT 1 (LOW)" has low loadings on both factors, indicating it receives information from all variables in factors 1 and 2. "GRADIENT 2 (MEDIUM)" contributes most to factor 1 with 0.98 units, while its value in factor 2 is very low at 0.02 units. "GRADIENT 3 (HIGH)" has a low contribution to factor 1 with 0.205 units, but a very high value for factor 2 at 0.795 units (Figure 6).

3.7.1. Factor 1 Variance (76.356%)

Variables with high and positive factor loadings include "litter (ha)," "bare ground cover (ha)," "vegetation cover (ha)," "medium soil texture," and "moderately coarse texture," indicating a strong association with vegetation cover and soil type. Variables with high and negative loadings are "Shannon Index" and "Simpson Index," suggesting an inverse relationship with vegetation diversity and dominance.

3.7.2. Factor 2 Variance (23.644%)

Variables with high positive factor loadings include the "Margalef Index" and "NDVI," indicating a link to richness and photosynthetic activity. Variables with high negative loadings are "Water coverage (ha)" and "Simpson Index," showing an inverse relationship with plant species dominance and water.

3.8. Influence of Underlying Factors

The RDA effectively integrates floristic data, including diversity indices, edaphic data, and photosynthetic activity data (NDVI), with results reflecting ecological patterns in the bofedal.

Table 6.
Load Matrix

Component	**RDA1**	**RDA2**
Eigenvalue	0.0279	0.0026
Proportion Explained	90-95%	5-10%
Site Scores		
Gradient (Low)	-0.965	-0.261
Gradient (Medium)	-1.298	0.123
Gradient (High)	0.333	0.139
Species Scores		
Shannon	0.601	-0.799
Simpson	0.681	-0.733
Margalef	0.992	0.131
Biplot Scores (Variables Explicativas)		
Cob water	-0.985	0.174
Cob vegetable	0.999	0.013
Rock	-0.519	0.855
NDVI	-0.366	0.931
VIF Scores		
Cob water	3.96	
Cob vegetable	5.69	
NDVI	2.89	

RDA1 explains between 90-95% of the variance in diversity indices, representing the main gradient of variation, while RDA2 accounts for 5-10%, capturing secondary variations. The low gradient, influenced by water coverage, has intermediate diversity, probably limited by waterlogged conditions. The medium gradient, with high vegetation coverage, could be dominated by competitive species, reducing diversity. The high gradient, soils with creeping vegetation and higher NDVI, suggests conditions that allow for greater species richness, possibly due to less competition and better resource availability. It should be noted that the small sample size (n=3) implies an overfitted model (100%

explained variance), which limits statistical inference. However, RDA remains valid as an exploratory analysis to identify patterns.

4. Discussion

The Potrerillo wetland is dominated by the Asteraceae family, whose efficient propagation and seed dispersal provide it with competitive advantages in open, high-light areas [62]. Its capacity for self-fertilization and tolerance to disturbances enables it to predominate in fragmented and humid environments [63-65].

D. muscoides is notable for its adaptation to poorly drained soils and positive water balance at high altitudes. It contributes to ecological processes like carbon storage and moisture retention, enhancing soil organic matter and creating microhabitats that stabilize plant communities, facilitating colonization in environments impacted by climate change. Its role is vital in these ecosystems [8, 66-69].

For its part, C. intermedia dominates in the middle and upper gradients, adapting to both anaerobic and aerobic conditions and using its robust root system to stabilize the soil, reduce erosion, and retain water and nutrients [70-72]; however, its dense biomass and coverage in nutrient-rich soils may limit the diversity of other plant species [73-75].

Soil texture and cover influence the floristic composition of wetlands. Fine-textured soils, such as clayey or organic-rich soils, retain more moisture and nutrients, favoring plant diversity [76, 77]. These properties influence microbial communities and plant growth [78]. Conversely, land cover, especially activities like grazing and trampling, alters soil properties, reducing biodiversity and impacting moisture and nutrient availability [79, 80].

Seasonal variations, such as droughts, amplify these effects, modifying moisture regimes and species distribution [81, 82]. Invasive species can also exploit nutrient-rich soils, displacing native flora [83]. Sustainable agricultural practices, such as organic amendments, can improve soil health and plant diversity, while monoculture reduces them [84, 85]. Urbanization alters hydrological regimes, affecting soil-vegetation interactions [86].

The morphology of wetlands, along with soil texture, creates microhabitats supporting unique plant communities [87, 88]. For ecological restoration, managing soil properties and land cover must be integrated to preserve wetland biodiversity and functionality [89].

The photosynthetic activity of vegetation cover influences flora composition; increased photosynthesis boosts plant biomass, promoting plant community diversity [90, 91]. Submerged vegetation alters sediment biochemistry, affecting nutrient availability such as phosphorus and influencing species dominance [92]. However, climatic factors such as temperature modify photosynthetic capacity, altering species composition due to differential responses among them [91]. Likewise, grazing and trampling reduce photosynthetic efficiency by affecting water availability and soil properties, leading to decreased biodiversity [93]. In addition, excessive nitrogen input from fertilizers can intensify photosynthesis in some species but also lead to eutrophication, which alters the structure of the plant community [94].

In the middle gradient of high Andean wetlands, high vegetation cover can favor the dominance of competitive species, reducing plant diversity through competitive exclusion. Nutritional enrichment, exacerbated by practices such as cutting and drainage, promotes fast-growing species and suppresses species richness [73, 95, 96]. The monopoly of resources by dominant species intensifies pressure on subordinate species, particularly in eutrophic soils [97]. Environmental variation and water connectivity influence community structure, but high cover limits available niches, resulting in low diversity [79]. Anthropogenic alterations, including water modifications and non-native invasions, increase dominance and decrease floristic diversity [79, 80, 96, 97].

In the high gradient of high Andean wetlands, rocky soils with high water retention and higher NDVI indicate favorable conditions for high species richness, mediated by lower interspecific competition and greater resource availability [81, 82]. Hydromorphism and peat accumulation generate microhabitats with abiotic variability, promoting the coexistence of hydrophilic plant species and associated fauna, including high avian diversity [83-85].

Inceptisols with high water retention capacity and organic matter sustain carbon cycles and facilitate niche partitioning, increasing floristic and faunistic biodiversity [86-88]. Dynamic interactions between biotic and abiotic factors, modulated by landscape variations, reinforce patterns of high species richness in these ecosystems [89, 90].

In the low gradient of high Andean wetlands, permanent water coverage creates waterlogged conditions that limit plant diversity to intermediate levels, mediated by water saturation and groundwater dynamics [91, 92]. Hydrological connectivity and water chemistry influence community structure, but fragmentation and low dispersal restrict species richness [93, 94].

Anthropogenic pressures, such as loss of surface area and degradation, exacerbate population fragmentation and reduce genetic diversity, compromising ecological integrity [73, 95]. Conservation is essential to mitigate these impacts and preserve characteristic intermediate diversity [96, 97].

5. Conclusions

In the Potrerillo wetland, the vegetation cover is dominated by the Asteraceae family, with species such as D. muscoides and C. intermedia, adapted to extreme altitude conditions and hydrological fluctuations. The low species richness in the high and low gradients indicates interspecific competition that limits floristic diversity. Biodiversity indices reflect medium to low diversity, influenced by environmental factors such as water availability and soil properties. Conversely, normalized difference vegetation index (NDVI) values, which range between 0.6 and 0.8, indicate high photosynthetic activity in areas with higher humidity, contributing significantly to the ecosystem's productivity and functionality.

The factor analysis of the Potrerillo wetland identified two main factors that explain 100% of the variance, highlighting positive and negative influences of the associated variables. Factor 1 (76.35% of the variance) is positively related to soil texture and cover (Inceptisols, medium texture, moderately coarse, and without soil), which promote water and nutrient retention, favoring the growth of plant species adapted to extreme climatic conditions. However, this factor shows a negative relationship with the Shannon and Simpson indices, indicating that high vegetation cover and soil properties are influenced by lower diversity and greater dominance of a few species, suggesting competition that could influence floristic richness.

Factor 2 (23.65% of the variance) shows a positive correlation between floristic richness and photosynthetic activity, reflecting greater richness and high photosynthetic activity (Margalef index and NDVI) in areas with adequate water availability, which contributes to wetland biomass productivity. Conversely, this factor exhibits a negative relationship with water coverage and the Simpson index, indicating that water bodies and species dominance reduce floristic richness and photosynthetic activity in certain sectors. The interaction of these factors demonstrates that edaphic and hydrological conditions are decisive in the structure and functionality of the bofedal, although the low diversity in high and low gradients highlights the ecosystem's vulnerability to disturbances that intensify the dominance of adapted species.

The RDA analysis integrated floristic, edaphic, and photosynthetic activity (NDVI) data, revealing clear ecological patterns along an altitudinal gradient in the bofedal. The main axis (RDA1) explains 90-95% of the variance in diversity indices, while RDA2 captures the remaining 5-10%, highlighting secondary variations. The middle gradient, characterized by high vegetation cover, contributes to competitive species that reduce specific diversity. The high gradient, with soils, creeping vegetation, and higher NDVI, promotes greater species richness due to less competition and better resource availability. The low gradient, influenced by water cover, shows intermediate diversity, limited by waterlogged conditions.

Soil texture and cover, along with the photosynthetic activity of vegetation, are key factors in the floristic composition of bofedales. Medium-textured soils, rich in organic matter, enhance moisture and nutrient retention, promoting greater plant diversity and supporting microhabitats that host unique plant communities.

The study of the Potrerillo wetland shows that floristic composition, ecosystem productivity, and plant diversity depend on soil, hydrological conditions, and vegetation cover, with species adapted to extreme environments dominating altitudinal gradients. However, low diversity at certain levels exposes ecological vulnerability to anthropogenic disturbances. These results highlight the importance of bofedales as key ecosystems for water and nutrient retention, water resource regulation, and biodiversity conservation. The information generated provides a scientific basis for proposing practical recommendations such as annual monitoring using remote sensors (NDVI) and soil moisture measurements, zoning of human use, and revegetation with native species in degraded areas for practical management.

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Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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