

Article

Soil Transition and Characteristics Along a Periglacial–Agricultural Gradient in the Carihuairazo Volcano Area

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Abstract

Climate change and glacial retreat in the tropical Andes—as evidenced by environmental changes in the Carihuairazo volcano area and human-induced alterations to the páramo—reveal complex environmental dynamics that require an integrated understanding. This study evaluates edaphic variation along a periglacial–agricultural spatial gradient, relating soil properties to sustainable management strategies. Using a methodological approach that includes multi-criteria spatial delineation, altitude-stratified sampling, and multivariate modeling via HJ-Biplot, the physical, chemical, and biological properties were analyzed, with a focus on basal microbial respiration. The data show that periglacial soils exhibit geochemical–mineral control and high basal respiration, potentially influenced by moisture peaks, despite their low organic matter content. In contrast, lowland andisols exhibit biological–structural control conditioned by organic matter accumulation, reflecting distinct conditions associated with agricultural management and land use. It is concluded that understanding these spatial edaphic patterns and their vulnerability to human intervention is essential for designing sustainable management and conservation frameworks that mitigate the impact of climate change on high-mountain ecosystems.

Keywords: Ecuadorian Andes; andisols; basal respiration; microbial communities; high-mountain soils; principal component analysis



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1. Introduction

Global climate change represents the greatest environmental challenge to the conservation of the Earth's cryosphere. This phenomenon is manifested in the accelerated and widespread retreat of glaciers, with average rates of length reduction reaching 125 meters per year [1]. In the tropical Andes, this process has been particularly pronounced, driven by rising atmospheric temperatures resulting from anthropogenic emissions, which has led to a marked reduction in glacier area at high altitudes [2,3]. Although advances in satellite remote sensing have improved our understanding of these changes, macroclimatic projections still require greater spatial and temporal resolution to anticipate local variations in hydrological, thermal and geomorphological dynamics [4].

Beyond climate forcing, human activities are significantly accelerating the degradation of the Andean cryosphere. Practices such as recurrent burning of the páramo, overgrazing, deforestation and intensive land-use changes modify the surface albedo, alter glacial mass balances and compromise the regulatory capacity of high-mountain ecosystems [5–7]. These anthropogenic pressures act synergistically with global warming, exacerbating ice loss and altering biogeochemical processes in newly exposed proglacial environments [8].

In Ecuador, this trend is particularly evident on the Chimborazo (6263 m a.s.l.) and Carihuairazo (5120 m a.s.l.) volcanoes. The former has lost approximately 21 percent of its glacial area, with its ice fronts retreating by more than 180 meters [9]. Carihuairazo, situated within the Chimborazo Wildlife Reserve, experienced the complete loss of its remaining glacier in 2024, having shrunk from 0.333 km² in 1956, a terminal collapse comparable to that recorded on the Cotacachi volcano at the end of the last century [10,11]. Historical records on the melting dynamics of Ecuadorian glaciers remain limited and fragmentary [9].

The retreat of the Carihuairazo glacier has exposed young periglacial soils subjected to intense cryoturbation processes and freeze–thaw cycles. These soils modulate the carbon cycle, chemical weathering and the local hydrology through thermal fluctuations in the active layer [11,12]. In the early stages of succession, microbial respiration may remain high due to moisture pulses associated with melting, even with low initial carbon and nutrient contents [13,14].

These proglacial deposits are connected altitudinally with mature andisols in the lower-lying areas, characterized by their high carbon sequestration capacity and considerable natural fertility [15,16]. However, these agricultural soils are facing advanced degradation processes associated with intensive grazing, agricultural practices on steep slopes and deforestation of the páramo. Much of the previous research has addressed glacial mass balances or the fertility of lowland agricultural soils in isolation, with limited integrated approaches analyzing the edaphic chronosequence and biogeomorphological interactions along the altitudinal gradient using multivariate techniques [17–19].

The aim of this study is to assess the soil transition and characteristics along a periglacial and agricultural gradient on the Carihuairazo volcano. To this end, this study seeks to (i) delineate the periglacial zone using spatial multi-criteria analysis; (ii) characterize the physical, chemical and biological properties (including basal microbial respiration) of the soils through altitude-stratified sampling; and (iii) analyze the edaphic interrelationships and transition patterns using the HJ-Biplot model. Based on the scientific evidence and the patterns observed in Andean proglacial environments, it is considered that newly exposed periglacial soils are dominated by geochemical–mineral control and high basal respiration driven by moisture pulses, whilst agricultural soils exhibit biological–structural control conditioned by the accumulation of organic matter and a gradual edaphic transition vulnerable to human intervention [13,14,17].

2. Materials and Methods

2.1. Area of Study

The Chiquicahua River micro-basin is situated in the province of Tungurahua, in the canton of Ambato. From a hydrographic perspective, it forms part of the Ambato River sub-basin and the wider Pastaza River basin [20]. The micro-basin has a total area of 3515.31 ha, and its main watercourse, the Chiquicahua River, is 14 km long, situated in UTM zone 17S at coordinates 749,632 m E and 9,846,676 m N (Figure 1). The area spans an altitudinal gradient ranging from 3000 to 5116 m above sea level, with an average annual temperature ranging from 4 °C to 18 °C and an average annual rainfall of 597.7 mm. The characteristic flora of the ecosystem is dominated by species such as *Calamagrostis intermedia* (Poaceae) and *Baccharis caespitosa* (Asteraceae) [21]. Geographically, the micro-watershed is bounded to the north by the communities of Tamboloma, Yatzaputzán, Pucara Grande, Chibuleo San Francisco, Chibuleo San Pedro and Chibuleo San Luis; to the south by the Mocha and Blanco rivers; to the east by the Ashpacha micro-watershed and the Pataló stream; and to the west by the Yatzaputzán Grande stream [22], specifically in the parish of Pilahuín, covering the territories of the communities of Yatzaputzán and Pucara Grande, on the northern flank of the Carihuairazo volcano's zone of influence.

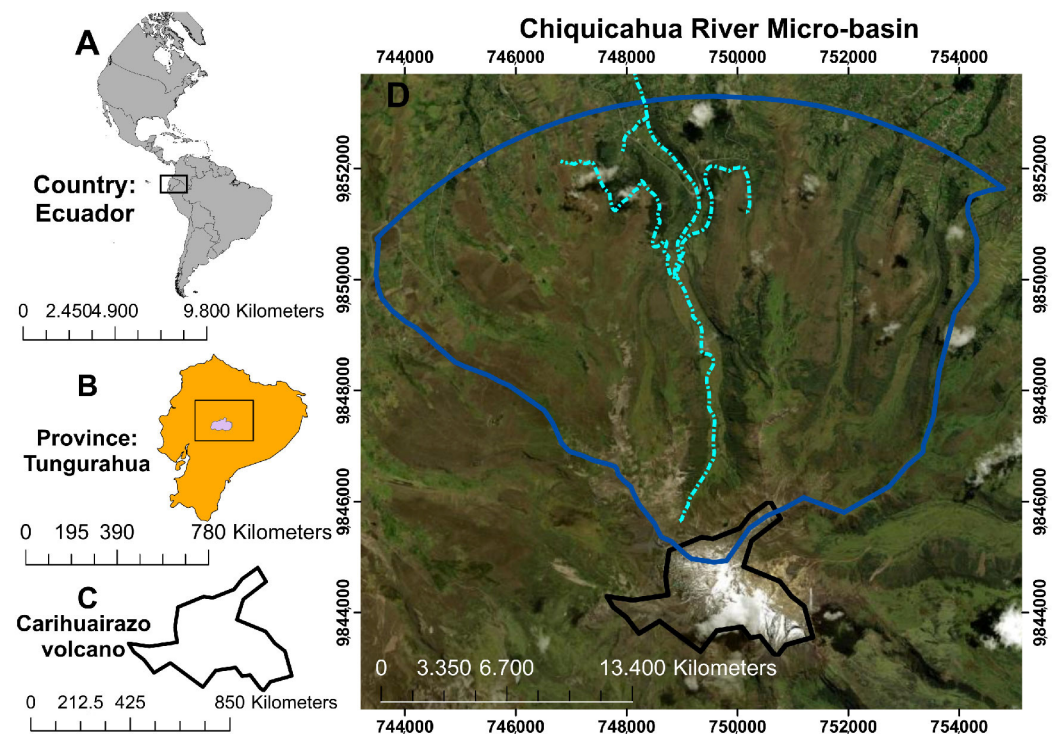


Figure 1. (A) Location of the study area relative to South America; (B) location relative to Ecuador; and (C) boundaries of the Minas de Chiquicahua River micro-watershed and location of the Carihuairazo volcano.

2.2. Methodology

A structured methodology comprising three main phases (P1: Delimitation, P2: Characterisation and P3: Principal component analysis) was applied to assess soil transition and evolution along the periglacial–agricultural gradient of the Carihuairazo volcano, as shown in Figure 2.

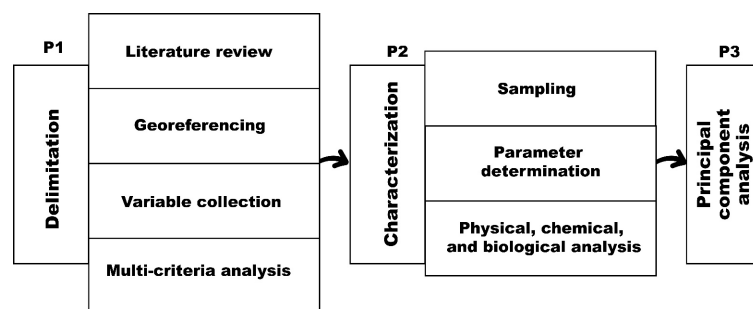


Figure 2. Research methodology organized into three main phases (P1, P2, and P3).

2.2.1. Delimiting the Periglacial Zone

A spatial multi-criteria analysis was performed using the weighted overlay tool with vector and raster layers that had been standardized in terms of both resolution and format [23].

For the climatic criterion, temperature and precipitation data from the BIO1 (annual mean temperature) and BIO12 (annual precipitation) layers were used, obtained from the WorldClim database [24]. For the vegetation cover criterion, the following were used: the Normalized Difference Vegetation Index (NDVI), which assesses the health, density, and vigor of vegetation, and the Normalized Difference Water Index (NDWI) for biomass water content or detection of water bodies, downloaded from Google Earth Engine, LANDSAT 8 satellite. These images correspond to atmospheric surface reflectance corrected by the USGS LaSRC algorithm, with a spatial resolution of 30 m. The NDVI was calculated using the near-infrared (SR_B5) and red (SR_B4) bands, while the NDWI (McFeeters version) was derived from the green (SR_B3) and near-infrared (SR_B5) bands. Both layers are in GeoTIFF format, with dimensionless values that theoretically range from -1 to $+1$ [25–27].

Finally, for the land-use criterion, data from Ecuador's land cover and land use layer was used, which was downloaded in compressed .shp format (*.rar). The layer contains geolocated information on biophysical features and socioeconomic activities, allowing for the identification of soil type, area, and length, as well as code information, descriptions of land cover types, and surface areas [21].

The homogenization and conversion from vector to raster format were performed using ArcGIS 10.8 software, with a UTM Zone 17 South projection and WGS84 datum [9].

The reclassified layers were assigned a weighting scheme that gives priority to climatic factors and substrate stability. The weightings of 40% for climatic variables (temperature and precipitation), 40% for combined vegetation cover and land use, and 10% for each of the NDVI and NDWI indices were established using expert judgement, guided by the relative importance attributed to these factors in the literature on periglacial and high-mountain geomorphology.

A weight of 40% was assigned to climatic variables (temperature and precipitation) since temperature and freeze–thaw cycles are the primary drivers of cryogenic processes and the dynamics of the active layer in the Andes [11,17]. Precipitation acts as a critical modulator of soil moisture, regulating mechanical processes such as gelifluxion and frost heave [28,29].

Vegetation cover and land use were assigned a combined weight of 40% due to their critical role in sediment stabilization and erosion control on proglacial slopes, functioning as a biogeomorphic regulator of surface processes [30,31].

Additionally, the NDVI and NDWI were each weighted at 10% as secondary indicators. NDVI acts as a proxy for biological colonization following glacial retreat [31], while NDWI identifies patterns of moisture and water runoff essential for periglacial processes [32,33]. This weighting scheme reflects a pragmatic yet reasoned approach grounded in the domi-

nant geomorphological controls identified in previous high-mountain studies [15,17,30], where the interaction between climate and vegetation is considered the main determinant of periglacial thresholds. This model is consistent with high-mountain mappings where the climate–vegetation interaction defines geomorphological thresholds [15].

Once the percentage weights were defined, the weighted overlay tool was applied using the formula $Final\ Raster = \sum_{i=1}^n (w_i \times R_i)$, where R_i is the value of each cell in the input raster and w_i is the weight or percentage of influence assigned to the raster defining the periglacial zone [34].

2.2.2. Demarcating the Adjacent Agricultural Area

A high-precision GNSS RTK station was used to delineate the agricultural area adjacent to the micro-watershed, followed by a real-time survey that retraced the boundaries of the cultivated plots. Subsequently, the cultivated areas within the micro-watershed, located between 3000 and 3840 m above sea level, were georeferenced. Once the field survey was obtained, the points and lines were digitized and connected to generate the polygon of the agricultural zone. This altitudinal band corresponds to the RC's buffer zone, where the boundary of agricultural activity acts as a transition between the areas of human use and the reserve's protected zones.

2.2.3. Assessment of the Physical, Chemical, and Biological Characteristics of the Soil

The periglacial zone covers an area of 113.31 hectares, and the agricultural zone covers 1860 hectares. Grid cells measuring 200m × 200m were created, resulting in a total of 21 cells for the periglacial zone and 399 cells for the agricultural zone (Figure 3). Stratified sampling was performed, for which the sample size was calculated for a finite population in each study area using the following formula from [35]: $n = \frac{N \cdot Z^2 \cdot p \cdot q}{(e^2 \cdot (N-1)) + (Z^2 \cdot p \cdot q)}$. In the Equation, N is the population size; Z is the value obtained using the confidence level 1.96; p is the expected proportion (0.5); q = 1 − p (if p = 0.5, then q = 0.5); and e is the sampling error, 0.06, when selecting a sample of 20 cells for the periglacial zone and 160 for the agricultural–livestock zone [36,37].

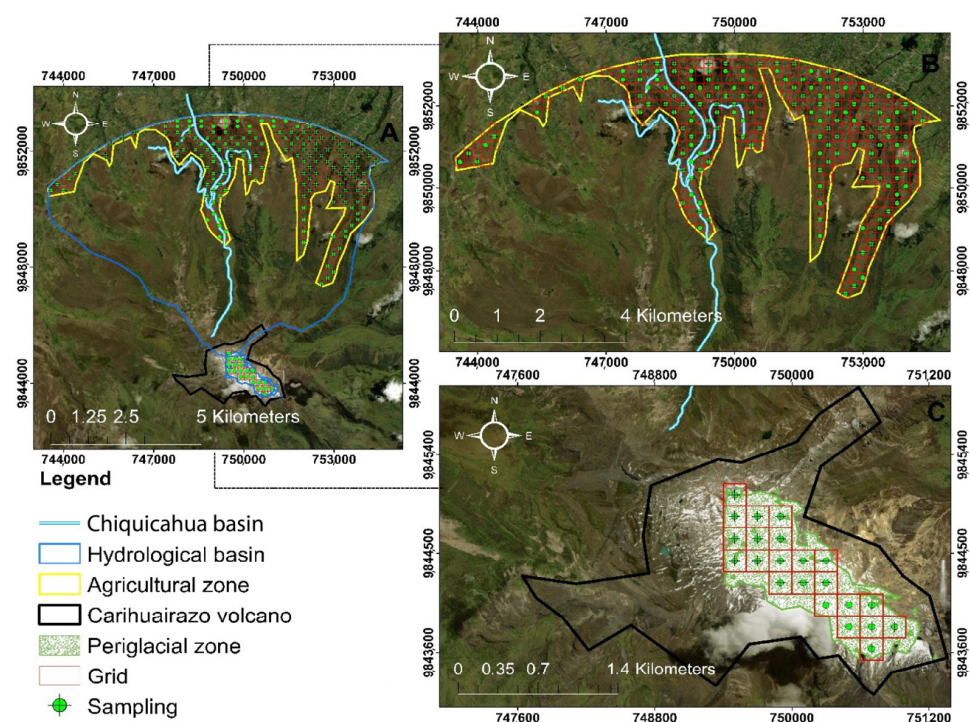


Figure 3. Map showing the sampling points.

To ensure the spatial representativeness of the soil sampling, a zigzag sampling method was used, with 5 subsamples per composite sample [38]. Excavations 30 cm deep were then carried out; the samples were stored in labelled Ziploc bags and transported in insulated containers to preserve their freshness, in accordance with the protocols established by the Agency for Phytosanitary and Zoosanitary Regulation and Control [39].

The physical, chemical and biological analyses were carried out in triplicate (laboratory replicates for quality control and analytical precision, rather than independent field replicates), in order to minimize error, at the soil laboratory of the Faculty of Natural Resources at ESPOCH. For the physical analysis, the guidelines for soil description [40] were followed. For texture, the Bouyoucos method was applied, which consists of weighing 100 g of soil, transferring it to plastic bottles, adding 50 mL of distilled water and 10 mL of dispersing agent; letting stand, adding 200 mL of water, shaking, and transferring to Bouyoucos cylinders; bringing the volume to 1.205 mL with a submerged hydrometer, shaking the suspension for 1 min, taking readings at 40 s and 2 h, and calculating the percentages of sand, silt, and clay [41–43].

The cylinder method was used to calculate the bulk density; the samples were dried at 105 °C for 24 h and then weighed [44,45]. Finally, the following formula was applied:

$$\text{Bd (Bulk density)} = \frac{\text{Pss (Dry weight)}}{\text{Vc Sample volume}} \left(\frac{\text{g}}{\text{cm}^3} \right)$$

The true density (Pp) was determined using the pycnometer method, as described by Blake and Hartge [46]. Using this value and the bulk density (Bd), the total porosity (f) of the soil was calculated using the physical equation proposed by Danielson and Sutherland [47]:

$$f = 1 - \frac{\text{Bd}}{\text{Pp}} \times 100$$

For the moisture analysis, the soil was weighed when moist and dry, and the following formula was applied:

$$\% \text{ Humidity} = \frac{\text{Moist weight} - \text{Dry weight}}{\text{Dry weight}} \times 100$$

For the chemical analysis, the pH was determined by dissolving 10 g of soil in 25 mL of distilled water, stirring the mixture for 30 min, and measuring the pH of the supernatant without stirring, using a pH meter [48,49].

To calculate electrical conductivity (EC), a semi-saturated soil paste was prepared with distilled water in a beaker. The mixture was stirred and allowed to stand for 30 min to stabilize the solution. Next, the conductivity meter electrode was inserted into the suspension to record the EC value. Subsequently, the salinity level was interpreted, and the total salt content was calculated using the corresponding formula [50,51]:

$$\text{Total dissolved solids (g/L)} = 0.64 \text{ (Empirical conversion factor)} \times \text{CEe (Electrical conductivity) dS/m}$$

To determine the percentage of organic matter, the combustion method was used. A clean, dry crucible was weighed. Then, 5 g of soil was added, and the crucible was placed in an oven at 105 °C for 24 h to remove moisture. It was allowed to cool and weighed again. Next, the crucible was placed in a muffle furnace at 450 °C for 30 min to oxidize the organic matter. Afterward, it was allowed to cool, and a final weighing was performed [52–54].

The formula was used to calculate the percentage of organic matter based on the loss on ignition [55].

$$\%MO = \frac{\text{Weight of the stove} - \text{Weight of the muffle}}{\text{Weight of the stove}} \times 100$$

For validation, the equipment was calibrated and verified in accordance with ISO/IEC 17025:2017. These validation criteria, which include linearity, precision and accuracy, were applied consistently to evaluate the laboratory analytical replicates of the soil samples in order to ensure the reliability of the data. The Kjeldahl digester–distiller was calibrated using certified ammonium sulfate (recovery 96–99%). The UV-Vis spectrophotometer was calibrated for wavelength and absorbance for the phosphorus method. The flame photometer was calibrated daily with potassium standards (0–10 mg/L). Once the performance of the equipment was verified, the complete methods were validated by evaluating linearity ($r^2 \geq 0.99$), precision ($RSD \leq 5\%$), accuracy (recovery 97–103%), LOD, LOQ, and measurement uncertainty (ISO GUM). All parameters met the acceptance criteria [56].

For the chemical characterization of available nutrients, extraction procedures specific to volcanic soils (andisols) were applied. Available phosphorus (P) was extracted using Olsen’s solution (0.5 M NaHCO_3 at pH 8.5), which is the standard and effective method for extracting available phosphorus from volcanic soils, as it minimizes phosphate fixation [57]. An aliquot of 0.5 mL of the extract was mixed with 9.5 mL of distilled water and 10 mL of reagent B, left to stand for 20 min, and the result was read on a colorimeter [58,59]. Exchangeable potassium (K) was extracted using ammonium acetate (1 M $\text{CH}_3\text{COONH}_4$ at pH 7.0) to determine the fraction available for uptake by plants [60]; the measurement was carried out using flame photometry with the addition of lanthanum oxide to suppress interferences [59]. Available/mineralizable nitrogen (N) was quantified using extraction procedures with potassium chloride (2 M KCl), and the extract was analyzed by mixing 1 mL of extract, 9 mL of basic phenol and 10 mL of bleach and allowing the mixture to react for 20 min before the colorimetric reading [58].

For the biological analysis, the methodology described in the USDA Manual of Laboratory Methods for Soil Analysis was used, with the necessary adjustments to determine basal respiration. Twenty grams of fresh soil were placed in a perforated plastic beaker inside a wide-mouthed glass jar containing 20 mL of NaOH (0.05 M); the jar was sealed airtight and incubated at 25 °C for 24 h to characterize current basal metabolic activity, including three blanks per sample [61,62]. The amount of CO_2 evolved was determined by titration. The following formula was used: $\text{mgCO}_2 = \left(C - S \times 2.2 \times \frac{100}{\text{SW} \times (1 - \text{MC})} \right)$, where C is the volume of HCl used in the blank (mL), S is the volume of HCl used in the sample (mL), 2.2 is a conversion factor (1 mL of 0.1 M HCl $\equiv$ 2.2 mg CO_2), SW is the initial soil weight (g), and MC is the moisture content (fraction). Measurements were taken after 24 h.

Mass-based values ($\text{mg CO}_2 \text{ g}^{-1} \text{ soil } 24 \text{ h}^{-1}$) were converted to area-based units ($\text{mg CO}_2 \text{ m}^{-2} \text{ h}^{-1}$) using the measured bulk density and the sampling depth (30 cm) according to the equation $\text{Rarea} = \frac{\text{Rmass} \times \text{BD} \times \text{D} \times 10}{t}$, where Rarea is the basal respiration ($\text{mg CO}_2 \text{ m}^{-2} \text{ h}^{-1}$), Rmass is the mass-based respiration ($\text{mg CO}_2 \text{ g}^{-1} \text{ soil}$), BD is the bulk density (g cm^{-3}), D is the sampling depth (cm), and t is the incubation time (h). This conversion allows standardized ecological comparisons at the landscape scale [63,64]. Laboratory incubations at 25 °C permit comparison of metabolic potential but do not represent absolute in situ CO_2 fluxes at the soil surface.

2.2.4. Univariate Analysis

To assess the differences in the physical, chemical and biological properties of the soil between the periglacial zone and the agricultural zone, compliance with the assump-

tions of normality was first verified using the Shapiro–Wilk test, and compliance with the assumption of homogeneity of variances was verified using Levene’s test. Where these assumptions were met, Student’s *t*-test for independent samples was applied; otherwise, the non-parametric Mann–Whitney U test was used, in accordance with the methodological recommendations for comparing two independent groups [65–67]. Differences were considered significant at a significance level of $p < 0.05$ and are represented in the tables using different letters (a, b).

2.2.5. Assessment of Soil Relationships and Patterns

To determine the relationships among the soils in each zone, a principal component analysis was conducted separately for the periglacial zone and the agricultural zone. Only continuous quantitative variables were included in the models; categorical descriptors (texture and structure) were excluded. The variables weighted for both analyses were as follows: moisture content (%), bulk density (g cm^{-3}), porosity (%), pH, electrical conductivity (dS m^{-1}), organic matter (%), total nitrogen (mg kg^{-1}), available phosphorus (mg kg^{-1}), exchangeable potassium ($\text{cmol}(+) \text{ kg}^{-1}$), and basal respiration ($\text{mg CO}_2 \text{ m}^{-2} \text{ h}^{-1}$). True density was measured but omitted from the HJ-Biplot due to its high collinearity with bulk density and porosity. The data were standardized prior to analysis to equalize the contribution of variables measured on different scales. The analyses were performed using MultBiplot 23.11.0 software; two-dimensional plots were generated in which the points represent the samples and the vectors represent the variables, allowing for the identification of contributions, correlations, and sample groupings, as well as the quantification of explained variance [68–70].

3. Results

3.1. Delimitation of the Periglacial Zone

On the Carihuairazo volcano, the periglacial zone covers an area of 113.31 hectares (Figure 4) and has an average annual temperature of 1.18°C (max. 3.43°C ; min. -1.56°C), with an average annual rainfall of 690.22 mm (max. 749 mm, min. 647 mm), which promotes frequent freeze–thaw cycles. The NDVI (average 0.08; min -0.12 ; max 0.38) and NDWI (average -0.06 ; min -0.35 ; max 0.12) indices indicate sparse or absent vegetation and areas that are predominantly dry or have very low water content.

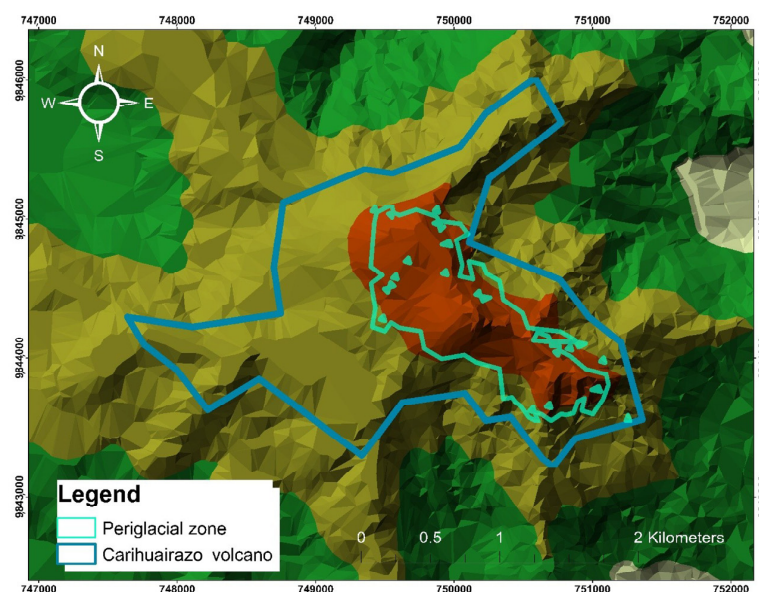


Figure 4. Periglacial zone and Carihuairazo volcano overview. The background colors represent the elevation gradient of the terrain derived from the digital elevation model.

3.2. Physical, Chemical and Biological Characteristics of Soils

3.2.1. Physical Characteristics

Table 1 presents the results of the analysis of soil texture, structure, moisture content and standard deviation (SD), bulk density, true density, and porosity.

Table 1. Physical properties of the soil in the two study areas. Different letters in the same column indicate statistically significant differences between zones ($p < 0.05$).

Zone	Texture	Structure	Moisture Content %	SD (Moisture)	Bulk Density g cm^{-3}	True Density g cm^{-3}	Soil Porosity (%)
Periglacial	Sandy loam Sand Loamy sand -Silty loam	Loose Subangular blocks	73.56 ± 2.24 a	2.24	1.53 ± 0.12 a	2.39 ± 0.11 a	35.66 ± 2.45 a
Agricultural	Sandy loam -Loamy sand	Loose	59.70 ± 1.81 b	1.81	1.58 ± 0.15 a	2.49 ± 0.14 b	36.03 ± 1.12 a

The physical analysis of the periglacial zone soil indicates a texture comprising sandy loam, sand, silty sandy loam and silty loam; the structure of these soils is loose, with sub-angular blocks. The average moisture content is 73.56% (SD 2.24), a high value indicating high water retention or conditions of habitual saturation where water may be present as ice or in liquid form. The soil's bulk density of 1.53 g cm^{-3} (SD 0.12) and its true density of 2.39 g cm^{-3} (SD 0.11) are reflected in a porosity of 35.66% (SD 2.45). These values indicate a more limited pore space compared with typical highly organic soils, influenced by the mineral nature and the compaction characteristic of these high-mountain environments.

In the agricultural area, the soil texture is mainly sandy loam and loamy sand, with a loose structure. The moisture content is 59.70% (SD 1.81), indicating a significant proportion of water relative to its dry weight, possibly due to recent irrigation, rainfall or good water-holding capacity. The bulk density is 1.58 g cm^{-3} (SD 0.15) and the true density of 2.49 g cm^{-3} (SD 0.14) is slightly higher due to a composition with denser minerals or a lower proportion of organic matter, and it corresponds to a porosity of 36.03% (SD 1.12). This similarity in porosity between the two areas shows that agricultural soils retain stable structural properties under current management practices, maintaining suitable conditions for aeration and root development.

3.2.2. Chemical Properties

The results of the analyses for pH, electrical conductivity (EC), total salts (TS), organic matter (OM), nitrogen, phosphorus, and potassium are presented in Table 2 for the periglacial zone and the agricultural zone.

Table 2. Soil chemical properties in periglacial and agricultural areas. Different letters in the same column indicate statistically significant differences between zones ($p < 0.05$).

Zone	pH	Total Salts (g/L)	Electrical Conductivity (dS/m)	Organic Matter (%)	Nitrogen (mg/kg)	Phosphorus (mg/kg)	Potassium (cmol(+)/kg)
Periglacial	6.09 ± 0.15 a	64.63 ± 2.12 a	0.12 ± 0.2 a	1.24 ± 0.11 a	13.69 ± 1.25 a	51.08 ± 1.30 a	0.05 ± 0.01 a
Agricultural	6.00 ± 0.12 b	50.60 ± 1.25 b	0.15 ± 0.02 b	5.17 ± 0.45 b	21.87 ± 2.10 b	70.83 ± 2.12 b	0.36 ± 0.04 b

In the periglacial zone, a pH of 6.09 indicates a slightly acidic to nearly neutral soil, meaning that the acidity is moderate and allows for good overall availability of most

essential plant nutrients; this value typically results from weathering processes in cold, humid environments influenced by organic matter. The total salts indicate a moderate concentration of salts in the soil (Table 2), reflecting an average salinity that does not cause osmotic stress to plants, possibly resulting from mineral inputs from parent rocks or limited evaporation under periglacial conditions and consistent with intense leaching and low mineral input under periglacial conditions. The low electrical conductivity value indicates that salinity is not a problem and that the soil has good water permeability, with no risk of salt toxicity, a common characteristic of soils with adequate drainage and low salt accumulation. The organic matter content of 1.24% indicates that the content of plant debris, microorganisms, and humic compounds is low, implying limited nutrient capacity, reduced biological activity, and a less stable structure—a value typical of periglacial environments with low plant biomass production and slow decomposition due to cold temperatures. The nitrogen content indicates the level of this nutrient, which is essential for plant growth (proteins, chlorophyll), is a moderate value reflecting supply via mineralization of organic matter or limited biological fixation (13.69). Phosphorus is an essential element for plant energy; the phosphorus level, at 51.08, is high, suggesting good availability (due to a favorable soil texture or pH), possibly of mineral origin or accumulated in the surface horizons. Finally, the potassium content, at 0.05 cmol(+)/kg (Table 2), indicates a very low concentration of this cation, which is vital for osmotic regulation and stress tolerance; this value reflects possible leaching or fixation in the clays.

In the agricultural areas, a pH of 6.00 indicates a slightly acidic soil (Table 2), which promotes the availability of phosphorus and micronutrients such as iron and is a common finding in soils cultivated with acidic fertilizers. This allows for good growth of most crops, but it requires monitoring to prevent deficiencies. A total salt content of 50.60 indicates a moderate amount of soluble cations, reflecting a non-limiting salinity and a good ionic balance for root uptake, resulting from agricultural management that includes drainage and avoids the excessive use of saline fertilizers. The electrical conductivity measures the total salinity based on dissolved ions; the low value (113.44) indicates the absence of salinity problems, allowing for normal water and nutrient uptake, typical of well-managed agricultural soils without salt accumulation.

The organic matter content of 5.17% indicates a high concentration of organic compounds (Table 2), which translates into excellent water and nutrient retention capacity, improved soil structure, increased microbial activity and the gradual release of nutrients through mineralization. The high figure could be due to the inclusion of plant residues or manure or the use of crop rotation in the agricultural areas. The nitrogen content, at 21.87, indicates a moderate-to-high level of this nutrient, resulting from the mineralization of the high organic matter content and, perhaps, the application of fertilizers, which promote good vegetative growth and high yields. The phosphorus figure, 70.83, reflects a high concentration of this element, which is essential for root development and energy production, and may be due to fertilization or a favorable pH that prevents excessive fixation. The potassium value of 0.36 indicates a moderate content (Table 2), sufficient for many physiological functions such as stomatal opening and stress resistance, and it is a value that reflects contributions from fertilizers or soil minerals in agricultural management.

3.2.3. Biological Characteristics

The analysis shows basal respiration in the periglacial zone and the agricultural zone, detailed in Table 3:

Table 3. Basal soil respiration rate in the two study areas. Different letters in the same column indicate statistically significant differences between zones ($p < 0.05$).

Zone	Basal Respiration mg CO ₂ m ⁻² h ⁻¹
Periglacial	22.38 ± 2.15 a
Agricultural	6.08 ± 0.74 b

In the periglacial zone, the basal respiration rate in the laboratory was 22.38 ± 2.15 mg CO₂ m⁻² h⁻¹ (Table 3). This value, obtained under standardized incubation conditions (25 °C, 24 h), reflects the potential heterotrophic microbial activity of the soil rather than a direct measurement of CO₂ emissions at the soil surface. It primarily indicates the respiration of microorganisms that mineralize native organic matter, with a possible minor contribution from roots, if present. This relatively high rate is due to a combination of factors, such as a high moisture content (73.56%) and a moderate-to-low organic matter content (1.24%), and is consistent with the activity of cold-adapted microbial communities that respond to moisture peaks and freeze–thaw cycles. These results suggest the existence of an active carbon cycle in this high-mountain environment, despite generally low plant productivity.

In the agricultural zone, the basal respiration rate in the laboratory was 6.08 ± 0.74 mg CO₂ m⁻² h⁻¹ under the same incubation conditions (25 °C, 24 h) (Table 3). This value reflects the potential heterotrophic microbial activity involved in the mineralization of soil organic matter in the absence of recent external inputs and indicates relatively low biological activity. This lower rate is consistent with the reduced availability of easily degradable substrates and with the possible effects of tillage or fertilization, which temporarily alter the microbial community, resulting in a less intense carbon cycle compared to undisturbed systems, although it remains functional for sustaining crops without the excessive loss of organic carbon.

3.2.4. Univariate Analysis of Physical, Chemical and Biological Properties

The results reveal marked differences in the physical and chemical properties of the soils between the periglacial and agricultural zones. The moisture content was significantly higher in the periglacial zone (73.56% vs. 59.70%, $p < 0.001$), whilst the bulk density showed a slight but significant difference, being higher in the agricultural zone. No differences were observed in the bulk density or the porosity ($p > 0.05$). With regard to the chemical properties, organic matter, nitrogen, phosphorus and potassium were substantially higher in the agricultural zone ($p < 0.001$) as a result of anthropogenic inputs from fertilization and greater biogeochemical activity. There were no significant differences in the pH between the two zones. The total salts and the electrical conductivity showed significant differences, with higher conductivity in the agricultural zone and higher total salts in the periglacial zone.

With regard to the biological activity, basal respiration in the laboratory was significantly higher in the periglacial zone (22.38 versus 6.08 mg CO₂ m⁻² h⁻¹, $p < 0.001$). This contrast with the lower organic matter content in that zone suggests a greater metabolic efficiency of the cold-adapted microbial communities under the incubation conditions used. Overall, the data indicate that the periglacial zone retains more natural and dynamic physical and biological characteristics, whilst the agricultural zone is characterized by greater chemical fertility induced by human management.

3.3. Soil Relationships and Patterns

3.3.1. Relationships and Patterns in the Periglacial Zone

The first two principal axes account for 58.85 percent of the total cumulative variance (Figure 5); Principal Axis 1, which accounts for 36.22 percent of the inertia, represents a pedogenetic gradient and a gradient in organic fertility within the periglacial zone. This component is defined primarily by the high contributions of pH, total nitrogen, organic matter and electrical conductivity. This axis illustrates the internal edaphic variations characteristic of the high-mountain periglacial environment, which is marked by bioclimatic constraints and limited edaphic development, differentiating local patches based on organic fertility and physicochemical properties.

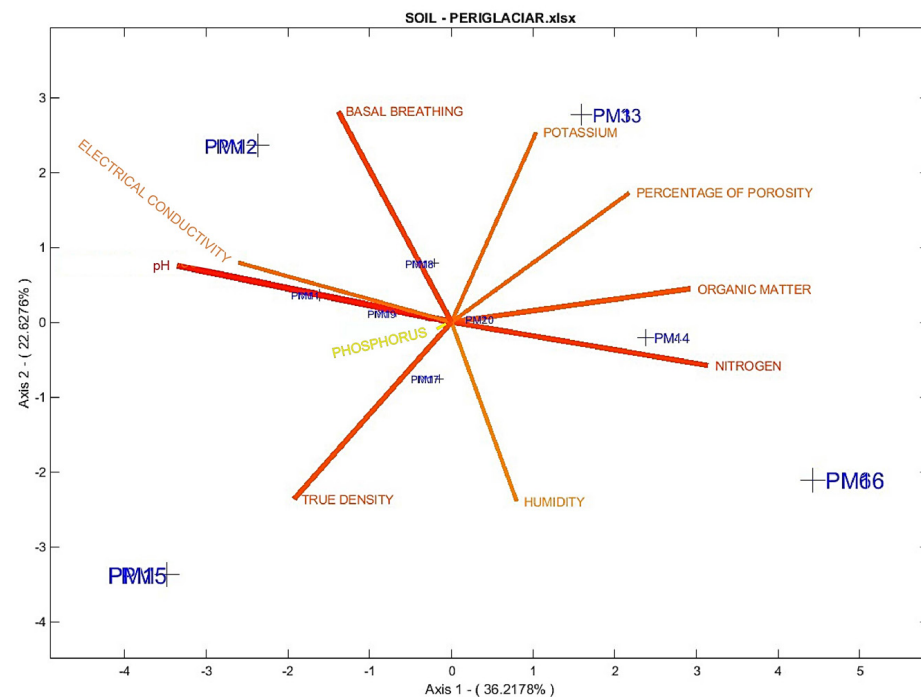


Figure 5. PCA of soil from the periglacial zone. The red arrows represent the soil variables assessed, and the blue dots indicate the sample plots plotted on the factorial plane.

Axis 2, for its part, explains 22.63 percent of the variance and forms a gradient of hydrophysical functionality and microbial activity (Figure 5). This axis is determined by basal respiration, exchangeable potassium, soil moisture and bulk density. The reported covariation indicates that the metabolic activity of the soil microbiota is strongly regulated by the water-holding capacity and the structural properties of the Andean volcanic matrix. Furthermore, potassium dynamics are related to processes of primary mineral alteration and local organic recycling.

The available phosphorus is concentrated almost exclusively on Axis 3; this statistical independence confirms that phosphorus responds to specific geochemical processes, primarily fixation in allophanes and amorphous complexes characteristic of volcanic soils.

Analysis of Relationships in the Periglacial Zone

There is an opposing relationship along Axis 1 between the bioorganic group (organic matter and nitrogen) and the alkalinity and salinity group (pH and electrical conductivity), reflecting a strong negative correlation: areas with the highest accumulation of organic matter and total nitrogen have a significantly more acidic pH and a lower concentration of dissolved salts, a pattern typical of edaphic maturation in Andean soils, where the accumulation of humus acidifies the matrix and displaces the soluble cations.

The sharp angle between basal respiration and potassium suggests that the soil biological activity promotes or is favored by the presence of this cation (associated with mineral weathering and biological cycling), whilst an inverse relationship with the soil moisture indicates that higher rates of microbial respiration occur under conditions of optimal drainage and lower water saturation.

3.3.2. Relationships and Patterns in the Agricultural Zone

The PCA explains 59.57 percent of the total cumulative variance across its first two factor axes (Figure 6); Axis 1 accounts for 35.09 percent of the inertia and represents a gradient of biological activity, organic matter content and the availability of major nutrients. This component is defined primarily by the high contributions of basal respiration, potassium, organic matter and, to a lesser extent, phosphorus. From an edaphological perspective, it reflects the close relationship between heterotrophic microbial metabolism and the nutrient reservoir, where the accumulation of biomass and organic matter stimulates mineralization and the retention and release of potassium and phosphorus, both of natural origin and derived from agricultural amendments.

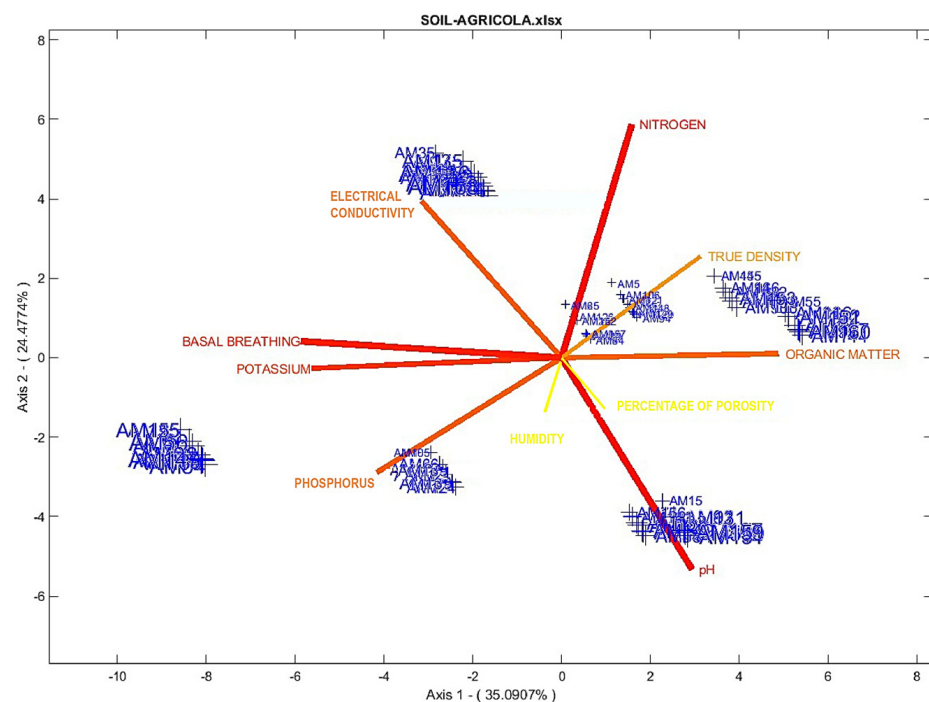


Figure 6. PCA of soil from agricultural areas. Red/colored arrows represent the evaluated soil variables, and blue points indicate the sample plots projected on the factorial plane.

Axis 2 explains a further 24.48 percent of the variance and represents a hydrochemical and exchange complex regulation gradient, dominated by total nitrogen, pH and electrical conductivity (Figure 6). In an agricultural context, nitrogen is decoupled from total organic matter and strongly covaries with pH and apparent salinity, highlighting the influence of synthetic nitrogen fertilizers or high-salinity organic amendments that directly alter the soil reaction and the ionic strength of the soil solution. Meanwhile, the physical properties show a clear separation from the 1–2 plane: soil moisture is projected almost exclusively onto Axis 3, whilst porosity makes only minor contributions, indicating relative structural homogeneity in agricultural soils and concentrating the system's critical variability in the metabolic–biological and chemical–fertilizer dimensions.

Analysis of Relationships in the Agricultural Area

A diametrical opposition is observed along Axis 2 between nitrogen and pH, demonstrating that a greater accumulation of nitrogen (associated with the application of nitrogen fertilizers or acidifying soil amendments) induces a drastic reduction in the soil reaction, promoting acidification in agricultural patches. In addition, a functional synergy is evident in the left-hand sub-plane between basal respiration and potassium (vectors that are almost collinear with a very acute angle), which demonstrates that microbial metabolic activity is closely linked to the availability of potassium in the soil solution, driven by accelerated biological cycling and the mineralization of biomass under agricultural management.

3.3.3. Analysis of the Transition Between Periglacial and Agricultural Soils

This study highlights a clear restructuring of the biogeochemical covariation mechanisms associated with the differences in land use along the altitudinal gradient. In the periglacial environment, the principal factor plane is determined by natural pedogenic divergence, where Axis 1 contrasts bioorganic accumulation (organic matter and nitrogen) against alkalinity and salinity (pH and electrical conductivity), reflecting the key edaphic variations linked to the accumulation of organic matter and the distribution of cations in these high-mountain soils. In this natural system, microbial activity (Axis 2) is associated with hydrophysical conditions and the properties of the volcanic parent material, whilst phosphorus remains statistically independent (Axis 3), possibly due to geochemical fixation mechanisms associated with mineral fractions such as allophanes.

In the agricultural context, although the explained variance on the main plane remains equivalent (59.57 percent), the factors determining soil differentiation differ markedly under human intervention. Axis 1 plays a predominantly metabolic role, in which basal respiration and potassium interact closely, probably in response to biological cycles and the application of soil amendments. A considerable functional shift occurs on Axis 2, where nitrogen relates differently to total organic matter reserves and contrasts with pH; this pattern suggests that agricultural management practices, such as fertilization or the use of soil conditioners, contribute to altering the chemical properties of the soil in cultivated plots, shifting the edaphic controls of purely natural pedogenic regimes towards patterns influenced by agricultural management.

4. Discussion

4.1. Spatial Variation and Comparative Edaphic Patterns Along the Gradient

The results reveal differences in soil properties and in the relationships between the periglacial zone and the agricultural zone along the gradient studied. In the periglacial zone, the first principal component of the principal component analysis (PCA) (36.22% of the variance) represents a gradient of edaphic and organic fertility, characterized by the contrast between the bioorganic block (organic matter and nitrogen) and the indicators of alkalinity/salinity (pH and electrical conductivity). This pattern is consistent with soils exposed to high-mountain conditions, where processes of mineral weathering and fixation in volcanic materials (allophanes) play a predominant role [71,72].

The relatively high basal respiration ($22.38 \text{ mg CO}_2 \text{ m}^{-2}\text{h}^{-1}$), despite the low organic matter content (1.24%), indicates intense microbial activity, possibly favored by the peaks in moisture and the physical processes associated with the high-mountain environment [17,73]. The second axis highlights the relationship between basal respiration, potassium and moisture, indicating that microbial activity is strongly influenced by the hydrophysical conditions of these soils.

In contrast, in the agricultural zone, the first component (35.09 percent) comprises basal respiration, organic matter, potassium and phosphorus, reflecting greater metabolic-

biological control. The second axis shows the dissociation of nitrogen from organic matter and its opposition to pH, suggesting a significant influence of agricultural management, particularly nitrogen fertilization [74,75]. These patterns illustrate a comparative spatial shift in edaphic mechanisms along the altitudinal and land-use gradients.

4.2. Biogeochemical Transition and Resilience of Andisols Along the Gradient

The results indicate a comparative shift from soils with higher metabolic activity and geochemical processes in the periglacial zone—as evidenced by a significantly higher basal respiration rate ($22.38 \text{ mg CO}_2 \text{ m}^{-2} \text{ h}^{-1}$)—towards systems with a higher content of accumulated organic matter and a strong anthropogenic influence in the agricultural zone ($6.08 \text{ mg CO}_2 \text{ m}^{-2} \text{ h}^{-1}$). In the latter, the higher organic matter content (5.17 percent, compared with 1.24 percent in the periglacial zone) appears to promote soil fertility and could contribute to greater soil resilience [72,75]. However, nitrogen decoupling and the trend towards acidification point to the possible effects of agricultural management [76,77].

Although the altitudinal gradient and the environmental context of Carihuairazo provide a natural framework for interpreting these differences, the comparison between the zones also reflects profound variations in vegetation, land-use history, hydrology and agricultural practices. Therefore, the observed differences should be interpreted as the result of multiple factors interacting spatially, rather than as a strict chronosequence driven by glacial retreat [17,78].

This transition has significant implications for the resilience of agricultural andisols in high-mountain areas. Maintaining an adequate organic matter content and carefully managing the pH and fertilization levels can help to preserve the structure and ecosystem functions [75,79]. However, greater care is required to prevent degradation processes such as acidification and compaction, particularly in the context of climate change.

Overall, the multivariate analysis shows that the transition from a periglacial to an agricultural environment not only reconfigures the individual soil properties but also profoundly restructures their functional interrelationships. There is a shift from the predominance of natural biogeochemical controls at higher altitudes towards dynamics strongly conditioned by human management. This structural vulnerability of tropical andisols to global change and anthropogenic pressure highlights the urgent need for management practices that harmonize agricultural productivity with the conservation of the Andean cryosphere.

5. Conclusions

This study reveals a marked contrast in soil properties and the mechanisms governing soil dynamics along altitudinal and land-use gradients in the Carihuairazo volcano area. A notable feature is the marked biological contrast: basal respiration rates are almost four times higher in the upper periglacial zone than in the lower agricultural zone; however, the latter has a significantly higher organic matter content. This demonstrates that the high-mountain periglacial soils maintain an active microbial metabolism, possibly influenced by specialized microbial communities that respond to the high moisture levels and the freeze–thaw cycles, positioning these environments as active sites for carbon dynamics rather than as biological deserts.

The underlying multivariate patterns reveal a fundamental difference in the environmental controls between the two zones. In the periglacial environment, the soil variation is primarily determined by the natural abiotic and geochemical gradients, in which the accumulation of organic matter and the weathering of minerals interact with minimal human interference. In contrast, in the agricultural zone, human intervention and land use substantially alter these processes. Nitrogen is decoupled from the total organic matter and

shows an inverse relationship with the soil pH, suggesting the influence of agricultural practices, fertilization and local management regimes on the chemical properties.

Therefore, the observed differences highlight a complex spatial transition determined by interrelated altitudinal, ecological and anthropogenic factors rather than a direct temporal succession. Understanding these distinct functional states is essential for the sustainable management, conservation and assessment of the climate vulnerability of high-mountain andisols following the rapid retreat of the cryosphere in the region.

Furthermore, these results validate the central hypothesis regarding the changes in soil control between the periglacial and agricultural areas; therefore, it is advisable to prioritize, as future lines of research, the long-term assessment of soil resilience and the metagenomic study of the microbial communities inhabiting these high-mountain environments.

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