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Multidimensional soil-property configurations across reference forest, pasture, and restored patches: a case study from a tropical Andean cloud-forest landscape

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Case Report

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Multidimensional soil-property configurations across reference forest, pasture, and restored patches: a case study from a tropical Andean cloud-forest landscape

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Abstract

Tropical forest restoration is commonly monitored through aboveground vegetation, whereas integrated characterization of soil condition across physical, chemical, and biological dimensions remains less common. We conducted a cross-sectional case study seven years after restoration initiation in a tropical Andean cloud-forest landscape in Colombia. Four existing landscape patches—a local reference forest, an actively grazed pasture, an actively restored patch established through native-tree planting, and a passively restored patch following cattle exclusion—were characterized using topographic context, woody vegetation structure, ground-surface composition, and soil properties. Each patch was represented by one 500 m² plot, and contrasts were interpreted descriptively. No common ordering of the four plots emerged across the measured soil properties. The active-restoration plot had greater woody-individual density and basal area than the passive-restoration plot and showed the lowest bulk density and highest total porosity and macroporosity. The passive-restoration plot had the highest observed aggregate stability and soil-borne arbuscular mycorrhizal fungal spore abundance, whereas the pasture had the highest exchangeable Ca and Mg. Among the restored plots, differences in woody structure were therefore not mirrored consistently across the broader set of soil properties, and resemblance to the local reference forest was property-specific rather than uniform. Together, these findings indicate that contemporary soil condition in this case was multidimensional and property-specific, with vegetation structure and individual soil dimensions differentiating the sampled landscape contexts in different ways rather than along a single axis of similarity to the reference condition.

Keywords: *ecological restoration; tropical montane forest; soil condition; soil indicators; active restoration; passive restoration; reference forest; Colombian Andes.*

1. Introduction

Tropical Andean cloud forests are among the most biologically distinctive ecosystems in the Neotropics, supporting high concentrations of species and endemism within naturally restricted and increasingly fragmented mountain landscapes [1,2]. Their vegetation and soils jointly contribute to carbon storage, hydrological regulation, nutrient cycling, erosion control,

and other ecosystem processes that are particularly important in steep Andean terrain [2–4]. Agricultural conversion, particularly the replacement of forest by pasture, alters vegetation structure, litter and root inputs, soil-surface protection, and physical, chemical, and biological soil properties [4]. Because these properties are shaped by different controls and differ in their sensitivity to land use and vegetation change, patterns of aboveground vegetation development need not be mirrored by corresponding patterns in soil condition during forest restoration [5].

This distinction is important for restoration assessment because soil indicators remain less consistently incorporated into tropical restoration monitoring than aboveground vegetation, despite the roles of soil properties in ecosystem processes [5,6]. Physical, chemical, and biological soil attributes may also differ in their degree of resemblance to reference ecosystems [7]. In a global review, chemical indicators were reported in 76% of forest-restoration studies, whereas potentially integrative indicators such as aggregate stability, oxidizable carbon, soil respiration, and enzyme activity were less frequently used [6]. Multidimensional assessment can therefore describe soil condition through complementary, property-specific patterns rather than assuming that different soil attributes provide equivalent information.

This evidence gap is particularly relevant in tropical Andean landscapes. A systematic review identified 34 studies reporting soil indicators during forest restoration and found biological indicators to be the least frequently represented soil dimension [8]. A subsequent meta-analysis of Colombian moist-forest restoration revealed a marked imbalance between evidence for vegetation structure and soil nutrients. The synthesis included 52 vegetation-structure cases from 11 articles, of which 26 were located in the Andean region, but only 13 soil-nutrient cases from three articles; among these soil-nutrient cases, only one was Andean, whereas the remaining 12 were from the Amazon region [9]. Integrated assessments combining physical, chemical, and biological/organic soil attributes with vegetation and ground-surface conditions can therefore contribute to the still limited evidence base for interpreting soil condition in Andean restoration landscapes.

Interpretation of soil-property patterns also benefits from considering the ecological setting in which they occur. Restoration patches can differ in woody vegetation structure and ground-surface conditions, including litter accumulation and herbaceous dominance, with implications for organic inputs and the soil-surface environment [4,10]. Topography can additionally influence water and material redistribution and contribute to spatial variation in soil properties, particularly in steep tropical montane landscapes [11]. Active and passive restoration are also better understood as positions along a continuum of intervention than as discrete ecological states [12]. Sites undergoing these restoration pathways occur within particular combinations of land-use history, vegetation structure, ground-surface composition, and environmental setting. Considering soil-property configurations together with these attributes therefore helps place observed contrasts among landscape patches within their ecological context rather than interpreting them solely in relation to restoration labels.

Here, we conducted a cross-sectional assessment seven years after restoration initiation in a tropical Andean cloud-forest landscape within the Orquídeas de Jardín Reserve, Colombia. We characterized four existing landscape patches: a local reference forest, a cattle pasture, an actively restored patch established through native-tree planting, and a passively restored

patch undergoing natural regeneration following cattle exclusion. The assessment integrated topographic context, woody vegetation structure, ground-surface composition, and a broad suite of physical, chemical, and biological/organic soil properties. Each patch was represented by one 500 m² study plot, which constituted the highest-level sampled unit; interpretation was therefore restricted to these four corresponding landscape patches and focused on their contemporary, property-specific configurations. Specifically, we aimed to: (1) characterize the topographic setting, woody vegetation structure, and ground-surface conditions of each patch; (2) describe their multidimensional soil-property configurations; and (3) interpret property-specific patterns of resemblance and contrast of each restored plot relative to the pasture and local reference-forest plots across soil dimensions. By integrating complementary soil properties with vegetation and surface context, this case study provides a site-specific basis for interpreting contemporary soil condition in an underrepresented tropical Andean restoration landscape.

2. Materials and Methods

2.1. Study Site

The study was conducted in the Reserva Orquídeas de la Sociedad Colombiana de Orquideología, a private protected area registered as a Reserva Natural de la Sociedad Civil (RNSC 005-17) in the Quebrada Bonita rural district of Jardín municipality, southwestern Antioquia, Colombia (5°34′10″ N, 75°45′32″ W; Fig. 1). The reserve encompasses 173.64 ha and lies on the eastern slope of the Western Cordillera of the Colombian Andes. According to its official ecological characterization, the reserve includes bosque muy húmedo Montano Bajo (bmh-MB) and bosque muy húmedo Montano (bmh-M) life zones and occurs within a floristic transition between Andean and Chocó biogeographic elements [13].

The reserve occupies rugged mountainous terrain with pronounced local topographic heterogeneity. The four study plots were located at elevations between 2515 and 2649 m a.s.l., with subplot-scale slopes ranging from 7% to 62%. Long-term climatic context was derived from WorldClim climate normals representing the 1970–2000 period at approximately 1-km spatial resolution [14]. Values extracted for the study area indicated approximately 3300 mm of annual precipitation and a mean annual temperature of approximately 16 °C.

The reserve lies within the Cuchilla Jardín–Támesis regional conservation landscape. Regional geological information describes volcanosedimentary materials associated with the Combia Formation and widespread volcanic-ash mantles in this sector of the Western Cordillera [13,15]. These sources were used to characterize the regional geological setting only; parent material was not independently determined for the individual study plots. No plot-level soil classification was assigned because diagnostic horizons and other properties required for pedological classification were not characterized.

The reserve comprises a heterogeneous mosaic of montane forest, secondary and regenerating vegetation, open grass-dominated areas, and patches undergoing ecological restoration [13]. This landscape mosaic provided the ecological context for the four study patches evaluated here: local reference forest (RF), pasture (PA), active restoration (AR), and passive restoration (PR).

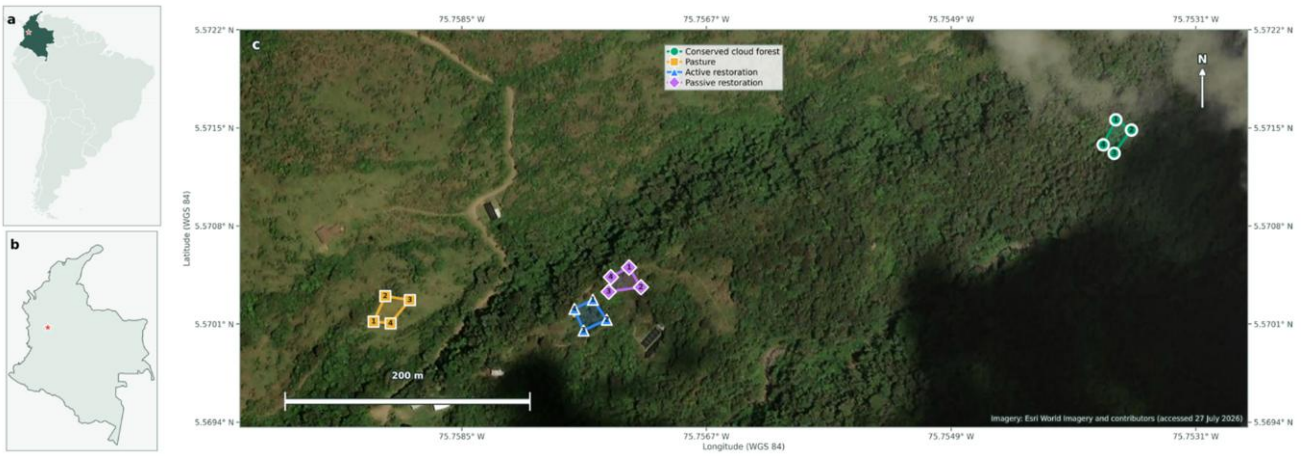

Fig. 1 Geographic setting and spatial arrangement of the study plots in the Reserva Orquídeas de la Sociedad Colombiana de Orquideología, Jardín, Colombia. (a) Location of Colombia within South America; (b) location of the study area in the Colombian Andes; and (c) satellite image showing the four 500 m² study plots: local reference forest (RF), pasture (PA), active restoration (AR), and passive restoration (PR). Four 1 × 1 m subplots were positioned at the vertices of each plot for topographic and ground-surface characterization. Numbered subplots represent within-plot spatial subsamples and not independent replicates of the corresponding landscape patch

2.2. Land-Use History, Restoration Pathways, and Study Design

Before its designation for conservation, portions of the property had a long history of cattle grazing. Following acquisition of the property by the Sociedad Colombiana de Orquideología, management priorities shifted toward biodiversity conservation and ecological restoration, and cattle were excluded from selected former grazing areas. The pasture patch included in the present study remained actively grazed at the time of soil sampling and represented the contemporary grass-dominated grazing context within the study landscape. Land-use and restoration histories were reconstructed from reserve management records and information provided by personnel involved in site management.

Two contrasting restoration pathways were initiated in former grazing areas approximately seven years before soil sampling. In the active-restoration patch, native tree seedlings were planted. During the first year after establishment, organic compost was applied locally around planted individuals and competing herbaceous vegetation was controlled around the seedlings. No further compost application or systematic control of herbaceous vegetation around planted individuals was conducted after this initial establishment period. Subsequent vegetation development reflected both growth of planted individuals and natural recruitment, with current management limited to occasional vegetation clearance along access paths. In the passive-restoration patch, cattle were excluded, and natural regeneration proceeded without tree planting, compost application, or systematic control of herbaceous vegetation. At the time of soil sampling, approximately seven years had elapsed since restoration was initiated in both patches.

The study included four pre-existing landscape patches, a local reference forest, an actively grazed pasture, an actively restored patch, and a passively restored patch. The local reference forest was the most structurally developed forest patch available within the reserve and was used as a local ecological benchmark rather than as an undisturbed old-growth endpoint. The pasture represented a contemporary grass-dominated, cattle-grazed patch, whereas the two restored patches represented contrasting intervention histories following cattle exclusion. The active- and passive-restoration patches were the only areas within the reserve representing these respective restoration pathways at the time of the study and were therefore not selected from a larger set of candidate restoration patches.

The study followed a comparative observational design. One 500 m² study plot (20 × 25 m) was established within each of the four landscape patches. Plot placement within each patch was purposive rather than probabilistic and was intended to characterize prevailing local vegetation and ground-surface conditions while avoiding patch boundaries, access trails, drainage channels, and localized recent disturbances unrelated to the land-cover context of interest. The four plots were therefore treated as site-specific ecological units and not as statistically representative replicates of broader land-cover or restoration categories.

Within each 500 m² plot, four 1 × 1 m subplots located at the plot vertices were used to characterize local topography and ground-surface conditions. These subplots were nested spatial subsamples of the corresponding study plot and were not treated as independent replicates of landscape patch or restoration pathway.

Land-use history, contemporary vegetation cover, and local topographic setting were spatially associated within the study landscape rather than independently distributed. Their individual contributions to observed soil-property differences could therefore not be disentangled. Accordingly, interpretation was restricted to descriptive contrasts among the four existing landscape patches, and no causal effects of active or passive restoration were estimated.

2.3. Vegetation Structure and Ground-Surface Characterization

2.3.1. Woody Vegetation Census and Structural Metrics

Woody vegetation was censused throughout each 500 m² study plot. All woody individuals with at least one stem having a circumference at breast height (CBH) ≥ 10.0 cm were included. Circumference was measured at 1.30 m above the ground on the upslope side of the stem and converted to diameter at breast height (DBH) as $DBH=CBH/\pi$, corresponding to a stem-level inclusion threshold of DBH ≥ 3.18 cm. When a deformity, buttress, or other stem irregularity occurred at 1.30 m, circumference was measured immediately above the irregularity at the nearest point where stem form was regular. For individuals branching below breast height, each branch was treated as a separate stem of the same individual; branching above breast height was measured as a single stem at 1.30 m. This relatively low threshold excluded seedlings and very small recruits while retaining established woody individuals within the small-diameter classes occurring in the restored plots.

For multistemmed individuals, each individual was counted once for individual-density calculations. The inclusion threshold was applied separately to each stem: all stems with CBH ≥ 10.0 cm were measured and retained for stem-level structural calculations and basal-area estimation, whereas smaller stems were excluded from these calculations. An individual

entered the census when at least one stem met the threshold. An equivalent individual diameter was calculated as

$$D_{eq,i} = \sqrt{\sum_{k=1}^{m_i} DBH_{ik}^2} \quad (1)$$

where D_eq,i is the equivalent diameter of individual i (cm), DBH_ik is the diameter at breast height of qualifying stem k belonging to individual i (cm), and m_i is the number of qualifying measured stems belonging to that individual. This formulation gives the diameter of a single circular stem with the same basal area as the combined qualifying stems of a multistemmed individual.

Individual basal area was calculated as

$$BA_i = \sum_{k=1}^{m_i} \left[\frac{\pi}{4} \left(\frac{DBH_{ik}}{100} \right)^2 \right] \quad (2)$$

where BA_i is the basal area of individual i (m^2) and DBH is expressed in centimeters. We obtained plot-level basal area by summing individual basal areas and standardizing to $m^2\ ha^{-1}$ using an area-expansion factor of 20, corresponding to the 0.05-ha plot area. Woody-individual density was standardized similarly to individuals ha^{-1}.

Plot-level structural descriptors included the number of censused woody individuals, number of qualifying measured stems, operational taxon richness, woody-individual density, mean stem DBH, mean equivalent individual DBH, maximum stem DBH, and basal area standardized to $m^2\ ha^{-1}$. Mean and maximum stem DBH were calculated from qualifying measured stems, whereas mean equivalent individual DBH was calculated across censused individuals. Operational taxon richness was defined as the number of distinct taxonomic units recorded within each plot using the finest reliable identification available. Individuals confidently identified to species were grouped by species; records resolved only to genus were retained as genus-level operational taxa when they could not be assigned reliably to species; and unresolved but morphologically distinct records were retained as separate morphotypes. Because not all census records were necessarily resolved to species level, this metric is referred to as operational taxon richness rather than species richness. Individual-level census records, stem measurements, quality-control fields, and associated taxonomic information are provided in Dataset S1 (ESM 3), and taxon-level structural summaries are presented in Supplementary Table S1 (ESM 1).

2.3.2. Ground-Surface Characterization

Ground-surface conditions were characterized in four 1 × 1 m subplots located at the vertices of each 500 m^2 study plot. At the center of each subplot, litter-layer depth was measured vertically using a graduated ruler. Local slope was measured across a 1 m horizontal run using a bubble level and graduated ruler. The level was used to establish the horizontal reference distance, and the corresponding vertical rise was measured and expressed as a percentage of the horizontal run. Elevation was recorded independently at each subplot using

a handheld GPS receiver. Because the vertical accuracy of handheld GPS measurements is limited over short distances, elevation measurements were used to characterize the general altitudinal context of each plot rather than fine-scale elevation differences among subplots (Supplementary Table S2 (ESM 1)).

One nadir photograph of each 1 × 1 m subplot was taken from approximately 1.30 m above the ground. For image analysis, the area corresponding to the field-delimited 1 × 1 m quadrat was isolated from each photograph and analyzed in ImageJ [16]. A 10 × 10 grid was superimposed on the quadrat area, dividing it into 100 equal sampling cells. We manually assigned each cell to one mutually exclusive ground-surface category—litter; grasses and other herbaceous vegetation (excluding ferns); ferns; mosses; woody debris; bare soil; and rocks— based on the category occupying the largest visible proportion of the cell. Estimated proportional cover for each category was calculated as the number of cells assigned to that category divided by 100 and expressed as a percentage. Because each cell received a single classification, category percentages summed to 100% for each subplot. Thus, cover values represent grid-based estimates of dominant ground-surface composition rather than pixel-level image classifications. Each photograph represented one subplot-level observation. The four subplots within each 500 m² plot were treated as nested spatial subsamples used to describe within-plot variation and were not considered independent replicates of the corresponding landscape patch. Complete subplot-level topographic and ground-surface observations are provided in Supplementary Table S2 (ESM 1).

2.4. Soil Sampling

We conducted soil sampling on 26 April 2025. Within each 500 m² study plot, ten sampling points were distributed across the plot following a zigzag traverse to provide spatial coverage of the plot. After removal of the surface litter layer, soil was collected from 0–20 cm depth using a soil auger. Approximately equal amounts of soil from the ten sampling points were combined and homogenized to produce one composite sample for each study plot. Approximately 0.5 kg of homogenized soil from each composite sample was retained for laboratory characterization. The ten sampling points therefore constituted within-plot spatial subsampling used to construct the composite sample and were not treated as independent soil replicates.

Composite samples were placed in labeled resealable plastic bags and transported to the laboratory on the day following field collection. Upon arrival, soil was subdivided according to the preparation requirements of the individual analyses. Subsamples intended for analyses requiring processed soil were air-dried and sieved according to the corresponding laboratory protocols, whereas subsamples required to remain field-moist for specific biological or biochemical analyses were stored under refrigeration at approximately 4 °C until processing. Property-specific preparation, storage, extraction, and analytical procedures are reported in Supplementary Table S3 (ESM 1).

Separately from the composite sampling scheme, four intact soil cores were collected within each plot for bulk-density determination. The four cores were spatially distributed across the plot to represent different within-plot locations. After removal of the surface litter layer, cylindrical metal cores with an internal diameter of 10.16 cm, an effective height of 11.64 cm, and an internal volume of approximately 944 cm³ were inserted vertically from the soil surface to their full effective depth, thereby sampling approximately the upper 0–11.6 cm of soil. The

intact-core samples were therefore distinct in both sampling procedure and sampled depth from the 0–20 cm composite samples collected with the auger. The four cores constituted within-plot spatial subsamples and were not treated as independent replicates of the corresponding landscape patch. Bulk-density determination and calculation procedures are detailed in Supplementary Table S3 (ESM 1). Representative field procedures for ground-surface characterization and soil sampling are illustrated in Supplementary Fig. S1 (ESM 2).

2.5. Multidimensional Soil Characterization

Contemporary soil conditions were characterized using a complementary set of physical, chemical, and biological/organic properties. Physical characterization included particle-size distribution, bulk density, particle density, aggregate size, aggregate stability, field capacity, total porosity, microporosity, and macroporosity. Chemical characterization included pH, electrical conductivity, exchangeable Al, Ca, Mg, K, and Na, effective cation exchange capacity (ECEC), Bray-extractable P, soluble P, S, nitrate, and B. Biological and organic characterization included total organic matter, active carbon, microbial respiration, potentially mineralizable N, and soil-borne arbuscular mycorrhizal fungal (AMF) spore abundance.

Laboratory analyses were conducted at Biofertilizar, Medellín, Colombia. Except for bulk density, which was determined from the intact soil cores described in Section 2.4, soil properties were determined from subsamples derived from the corresponding plot-level composite sample unless otherwise specified in Supplementary Table S3 (ESM 1). Sample preparation depended on the requirements of each analytical procedure. Analyses requiring processed soil used air-dried and sieved material as specified by the corresponding method, whereas analyses requiring field-moist soil used refrigerated subsamples that had not been air-dried.

For each soil property, Supplementary Table S3 (ESM 1) reports the sample source and preparation, analytical method, extraction or measurement procedure, operational definition, calculation where applicable, and reporting unit. Properties derived mathematically from other measurements are explicitly identified as calculated variables rather than analytically independent measurements.

2.6. Data Analysis and Visualization

Data analysis was designed to characterize the four existing landscape patches and their multidimensional soil-property configurations rather than to estimate causal effects attributable to land cover or restoration pathway. Each landscape patch was represented by a single 500 m² study plot; thus, the study plot was the highest-level sampled unit and the unit of ecological interpretation. Because neither land-cover category nor restoration pathway was independently replicated, analyses were descriptive and no inferential tests of differences among landscape patches were performed. Individual woody plants, stems, 1 × 1 m subplots, intact soil cores, and laboratory determinations were treated according to their respective nested or analytical levels and not as independent replicates of landscape category or restoration pathway.

Woody-vegetation data were summarized separately for each plot using the number of censused individuals and qualifying measured stems, operational taxon richness, woody-individual density, mean stem diameter at breast height (DBH), mean equivalent individual DBH, maximum stem DBH, and basal area standardized to $m^2\ ha^{-1}$. Because woody

vegetation was censused throughout each 500 m² plot, individual plants and stems represented census observations describing vegetation structure within the corresponding plot.

Topographic and ground-surface data were summarized from the four 1 × 1 m subplots nested within each plot. Local slope and litter depth were described using subplot-level observations and plot-level means, standard deviations, and ranges. Mean elevation from the four GPS observations was used as a descriptor of the general altitudinal context of each plot and was not used to infer fine-scale elevation variation. Ground-surface composition was summarized as proportional cover within each subplot and as mean proportional cover across the four subplots within each plot. Measures of dispersion for slope, litter depth, and ground-surface observations were used only to describe within-plot spatial variation.

Most physical, chemical, and biological/organic soil properties were represented by one analytical value obtained from the plot-level composite soil sample described in Section 2.4. Bulk density was determined from four intact soil cores collected within each plot and summarized to a single plot-level value according to the procedure specified in Supplementary Table S3 (ESM 1). Original measured values and units were retained for ecological interpretation. All measured soil properties were included in the descriptive assessment and were not selected or excluded according to the magnitude or direction of differences observed among plots. The complete set of original soil-property values is reported in Supplementary Table S4 (ESM 1).

To facilitate joint visualization of soil properties expressed in different units and numerical ranges, each property was additionally standardized across the four observed plots as

$$z_{ij} = \frac{x_{ij} - \overline{x}_j}{s_j} \quad (3)$$

where z_{ij} is the standardized value of soil property j in plot i, x_{ij} is the corresponding observed value, and $\bar{x}_j$ and s_j are the mean and sample standard deviation, respectively, of property j across the four plots. Standardization was used exclusively as a graphical scaling procedure to display relative variation within each soil property. Positive and negative z-scores therefore indicate observations above or below the four-plot mean for a given property and were not interpreted as favorable or unfavorable soil conditions, soil-health scores, restoration trajectories, or estimates of restoration success. Standardized values were not used to calculate ecological distances, quantify similarity among plots, or support statistical inference. Properties showing no variation among the four plots were retained in the original dataset and descriptive summaries but omitted from the standardized heatmap because their standard deviation was zero.

For the integrated heatmap, soil properties were arranged a priori according to physical, chemical, and biological/organic dimensions, and plots were maintained in the fixed order reference forest, pasture, active restoration, and passive restoration for consistency across the manuscript. No clustering, ordination, composite index, multivariate hypothesis testing, or ranking of plots was performed using the standardized values. Variables calculated mathematically from other measured properties were retained for descriptive completeness but were interpreted together with their component measurements rather than as independent signals. The heatmap was therefore used as an integrated visual summary, and

multidimensional patterns were described jointly from the standardized visualization and the corresponding original values and units. Data processing and visualization were performed in R version 4.2.1 [17].

3. Results

3.1. Landscape Context, Vegetation Structure, and Ground-Surface Conditions

Topographic setting and ground-surface composition differed among the four study plots (Table 1; Supplementary Table S2 (ESM 1)). The reference-forest and restored plots occurred on steep terrain (mean slopes of 39.0–47.3%), whereas the pasture plot occurred on gentler terrain (9.3%). Ground-surface composition also differed: the reference forest was dominated by litter (91.0%), the pasture by grasses and other herbaceous vegetation (excluding ferns) (97.5%), the active-restoration plot by a mixture of grasses and other herbaceous vegetation (excluding ferns) and litter, and the passive-restoration plot by ferns (74.3%). Litter depth was greatest in the reference forest, lowest in the pasture, and intermediate but more spatially variable in the passive-restoration plot. No grid cells were classified as bare soil or rock.

Woody-vegetation structure likewise differed among plots (Table 1; Supplementary Table S1 (ESM 1)). The reference-forest plot had the greatest woody-individual density, mean stem DBH, and basal area. Among the restored plots, the active-restoration plot had greater woody-individual density, mean stem DBH, and basal area than the passive-restoration plot, whereas the pasture had the lowest woody-individual density and basal area. Detailed vegetation-structural and ground-surface measurements are reported in Table 1 and Supplementary Tables S1–S2 (ESM 1).

Table 1 Topographic, ground-surface, and woody-vegetation descriptors of the four study plots

Descriptor	RF	PA	AR	PR
Mean elevation (m a.s.l.)	2646.8	2516.5	2528.3	2534.3
Slope (%), mean ± SD	46.3 ± 5.4	9.3 ± 2.2	47.3 ± 15.4	39.0 ± 9.8
Litter depth (cm), mean ± SD	17.3 ± 2.2	1.4 ± 0.5	4.8 ± 2.3	12.1 ± 6.9
Dominant ground-surface cover	Litter (91.0%)	Grasses/ herbaceous (97.5%)	Grasses/ herbaceous (43.8%); litter (40.3%)	Ferns (74.3%)
Woody individuals (n)	66	10	22	15
Measured stems (n)	71	10	22	17
Operational taxon richness	9	8	5	2
Woody-individual density (individuals ha^{-1})	1320	200	440	300
Mean stem DBH (cm)	12.53	4.10	10.17	5.01
Maximum stem DBH (cm)	30.24	5.79	17.51	7.00
Basal area (m^2 ha^{-1})	20.54	0.27	4.45	0.70

Notes: RF, reference forest; PA, pasture; AR, active restoration; PR, passive restoration. Elevation, slope, litter depth, and ground-surface cover were summarized from four nested 1 × 1 m subplots per 500 m² plot. Woody metrics were derived from the census of each entire 500 m² plot. Subplots and woody individuals are within-plot observations and not independent replicates of landscape context. "Grasses/herbaceous" denotes grasses and other herbaceous vegetation excluding ferns. Full observations are provided in Supplementary Tables S1–S2 (ESM 1)

3.2. Physical Soil Properties

Physical soil properties showed different patterns among the four study plots (Fig. 2; Supplementary Table S4 (ESM 1)). The active-restoration plot had the lowest observed bulk density (0.54 Mg m^{-3}) and the highest total porosity (72.7%) and macroporosity. Aggregate stability was of similar magnitude in the reference-forest and restored plots (94.15–99.30%) and lower in the pasture plot (74.92%). The remaining physical properties followed different relative patterns, with no single ordering of the four plots shared across all measured variables.

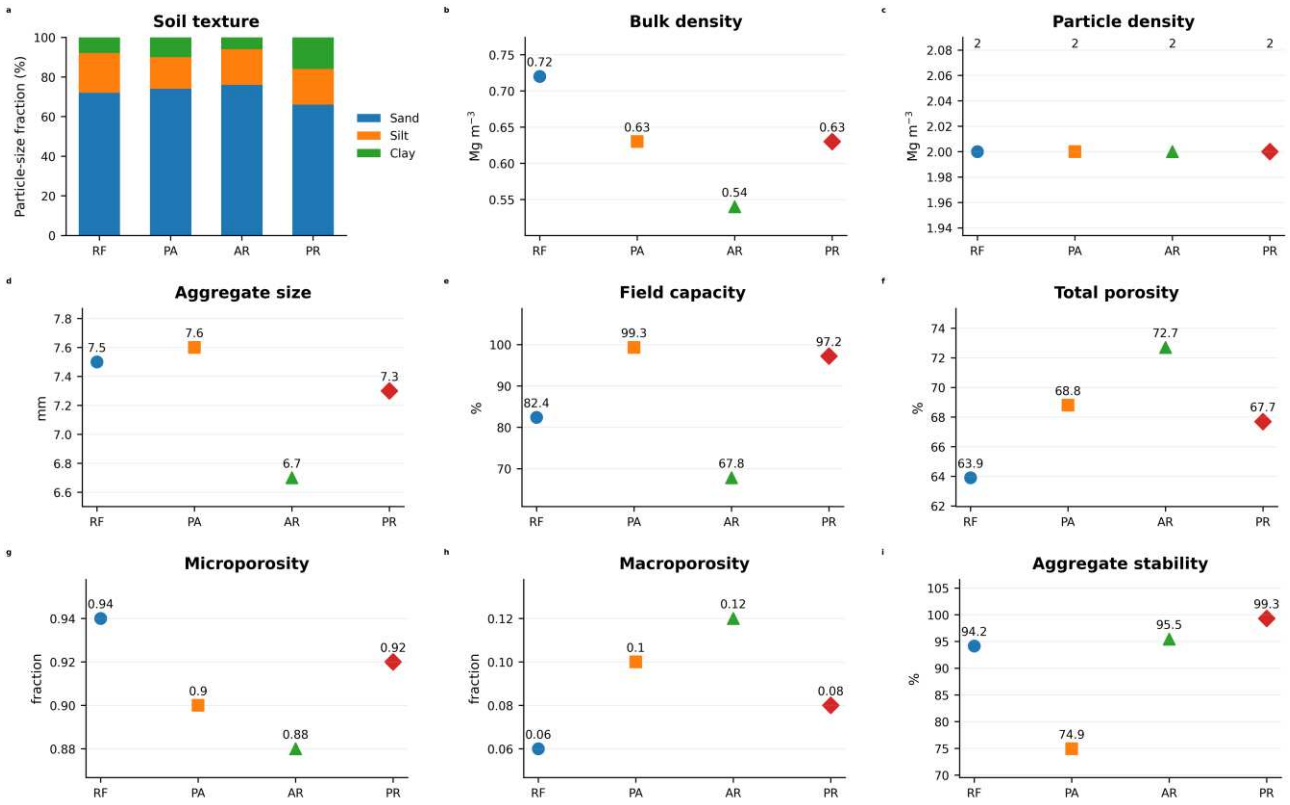

Fig. 2 Physical soil properties across the four study plots. (a) Particle-size distribution; (b) bulk density; (c) particle density; (d) aggregate size; (e) field capacity; (f) total porosity; (g) microporosity; (h) macroporosity; and (i) aggregate stability for the reference forest (RF), pasture (PA), active-restoration (AR), and passive-restoration (PR) plots. Panel a shows the relative proportions of sand, silt, and clay, whereas panels b–i show the plot-level value reported for each property

3.3. Chemical Soil Properties

Chemical soil properties varied among the four study plots (Fig. 3; Supplementary Table S4 (ESM 1)). The clearest observed difference occurred in the pasture plot, which had higher exchangeable Ca (7.80 cmolc kg^{-1}), Mg (2.30 cmolc kg^{-1}), and ECEC (13.03 cmolc kg^{-1}) than the other three plots. In contrast, Bray-extractable P reached its highest value in the passive-restoration plot (44 mg kg^{-1}), whereas nitrate was highest in the active-restoration plot (56.5 mg kg^{-1}). Soil pH varied from 4.3 to 4.8, and the remaining chemical properties showed different plot-specific patterns without a common ordering across plots.

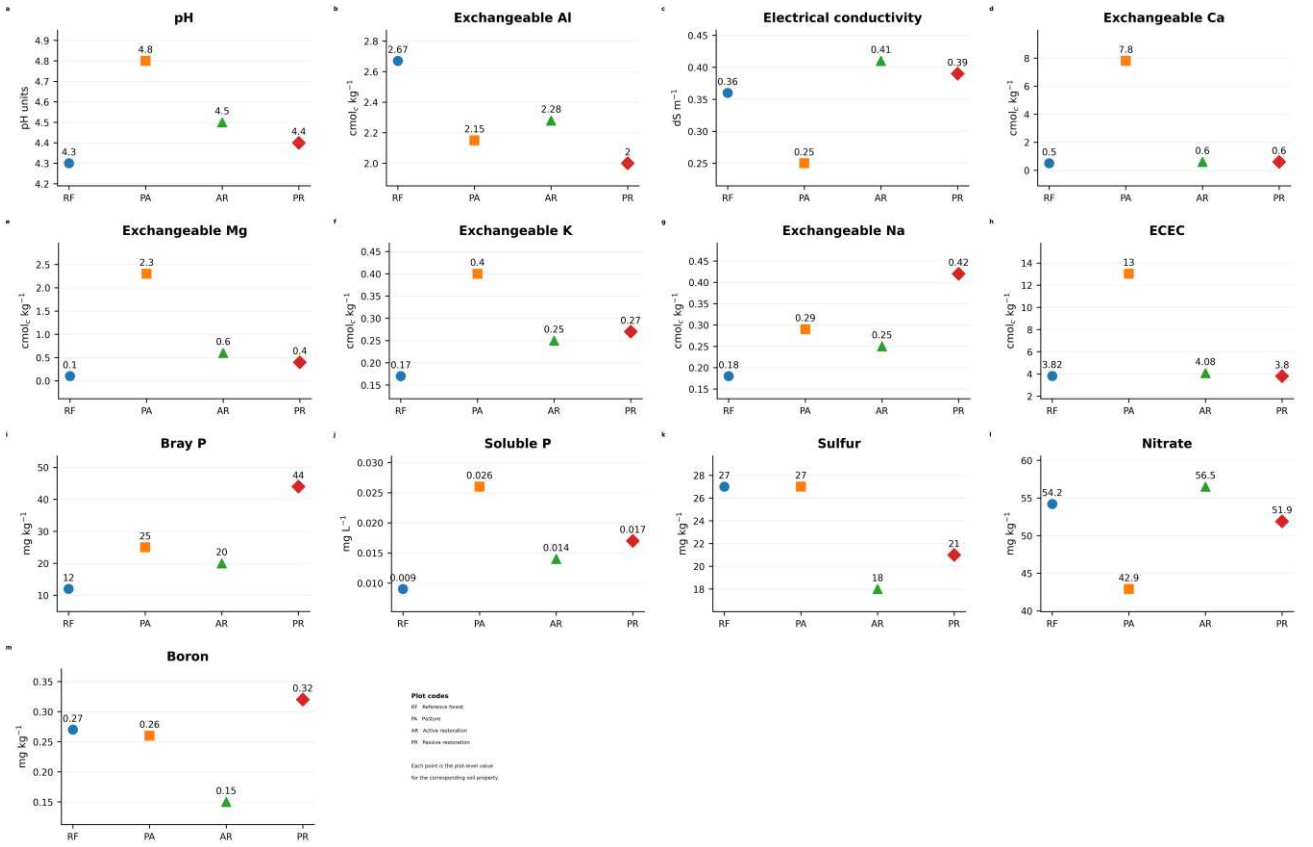

Fig. 3 Chemical soil properties across the four study plots. (a) Soil pH; (b) exchangeable Al; (c) electrical conductivity; (d) exchangeable Ca; (e) exchangeable Mg; (f) exchangeable K; (g) exchangeable Na; (h) effective cation exchange capacity (ECEC); (i) Bray-extractable P; (j) soluble P; (k) sulfur; (l) nitrate; and (m) boron in the reference forest (RF), pasture (PA), active-restoration (AR), and passive-restoration (PR) plots. Each point represents the plot-level value reported for the corresponding soil property

3.4. Biological and Organic Soil Properties

Biological and organic soil properties showed different patterns among the four study plots (Fig. 4; Supplementary Table S4 (ESM 1)). Total organic matter varied from 21.07% to 24.38%, whereas active carbon, microbial respiration, and potentially mineralizable N followed different relative patterns among plots. The active-restoration plot had the lowest observed active carbon and potentially mineralizable N, while the passive-restoration plot had the highest soil-borne AMF spore abundance (246 spores g^{-1} versus 151–159 spores g^{-1} in the other plots). Complete values are reported in Supplementary Table S4 (ESM 1).

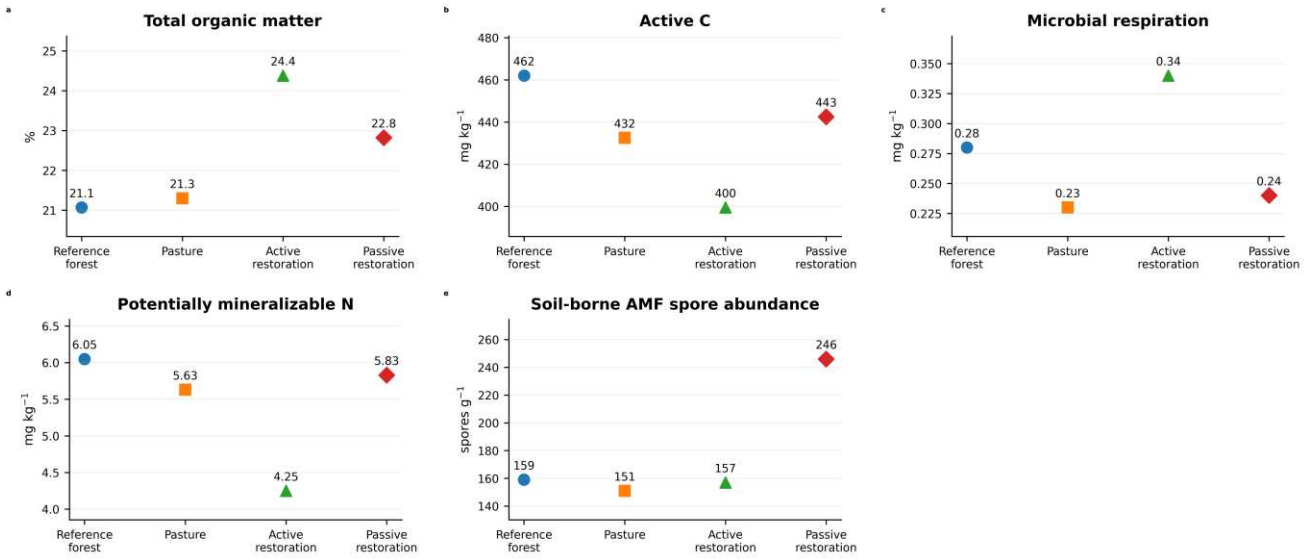

Fig. 4 Biological and organic soil properties across the four study plots. (a) Total organic matter; (b) active carbon; (c) microbial respiration; (d) potentially mineralizable N; and (e) soil-borne arbuscular mycorrhizal fungal (AMF) spore abundance in the reference forest (RF), pasture (PA), active-restoration (AR), and passive-restoration (PR) plots. Each point represents the plot-level value reported for the corresponding soil property

3.5. Multidimensional Soil-Property Configurations

The standardized heatmap summarized the property-specific variation among the four study plots across physical, chemical, and biological/organic dimensions (Fig. 5). No single relative pattern was shared across soil properties: the physical pattern associated with the active-restoration plot, the exchangeable-base pattern of the pasture, and the aggregate-stability, Bray-P, and AMF-spore values of the passive-restoration plot occurred in different combinations across dimensions. The standardized visualization therefore reflected the heterogeneous property-specific patterns evident in the original-scale measurements rather than a common ordering of the four plots.

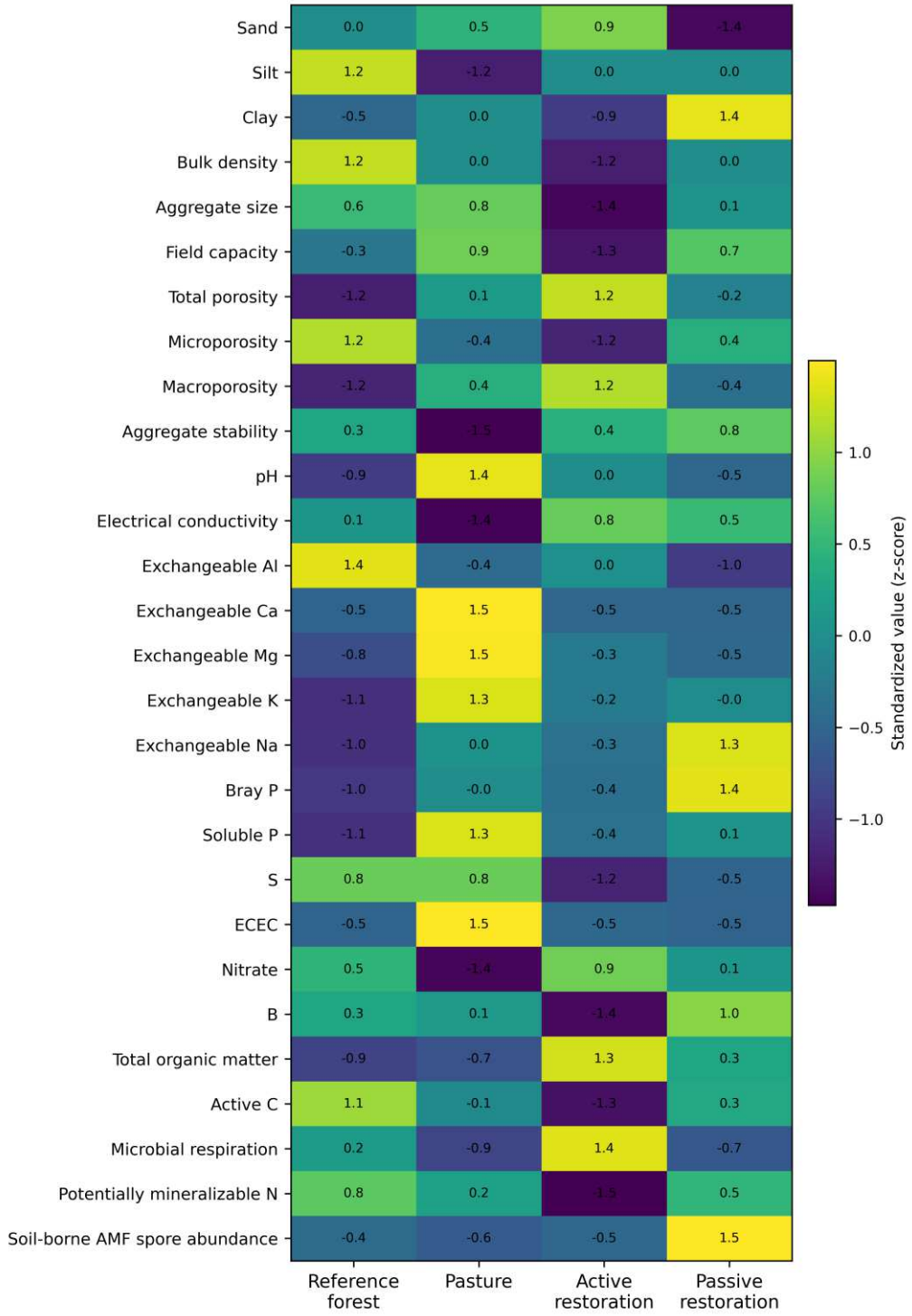

Fig. 5 Standardized multidimensional soil-property configurations across the four study plots. Heatmap of physical, chemical, and biological/organic soil properties for the reference forest (RF), pasture (PA), active restoration (AR), and passive restoration (PR). Each soil property was standardized separately across the four observed plots using z-scores. Positive and negative values indicate observations above or below the four-plot mean, respectively, for a given property. The color scale represents relative variation within individual soil properties and should not be interpreted as favorable or unfavorable soil conditions, soil-health scores, ecological

distances or statistical similarities among plots, rankings of plots, or estimates of restoration success

4. Discussion

4.1. Property-Specific Differentiation of Contemporary Soil Condition

The central pattern across the four study plots was that contemporary soil condition was not represented by a single ordering of the pasture, restored, and reference-forest plots. Physical, chemical, and biological/organic properties differentiated the plots in different ways, indicating that these dimensions provided complementary rather than interchangeable information. This pattern is consistent with broader restoration evidence showing that soil dimensions can differ in their degree of resemblance to reference forests. A global meta-analysis found that differences between restoring and reference forests varied among physical, chemical, and biological properties, with biological properties generally showing greater departures from reference conditions than several physical and chemical attributes [7]. Reviews of forest-restoration monitoring similarly emphasize that individual soil indicators capture different components of soil condition and that broader integration across soil dimensions is needed to avoid conclusions based on a restricted subset of properties [5,6]. Integrated ecosystem assessments further show that combining aboveground and belowground indicators can provide a more comprehensive representation of ecosystem status than isolated metrics [18,19].

The vegetation and soil observations in Orquídeas de Jardín further illustrate this non-parallel pattern. Among the two restored plots, the active-restoration plot had greater woody-individual density, mean stem DBH, and basal area, together with lower bulk density and higher total porosity and macroporosity. However, this greater observed woody structure did not correspond to a consistent ordering across the remaining soil properties. The passive-restoration plot, despite its lower woody structural metrics, had higher observed aggregate stability and soil-borne AMF spore abundance than the active-restoration plot, while chemical and other biological/organic properties followed additional property-specific patterns. Soil-borne AMF spore abundance is interpreted here as a measure of the spore pool in soil and not as evidence of root colonization or mycorrhizal activity [20]. The two restored plots therefore combined different aboveground and belowground configurations rather than differing consistently in the same direction across measured dimensions. This pattern is consistent with broader evidence that aboveground and belowground attributes may show non-parallel responses during tropical forest restoration and that vegetation-based assessments may capture only part of the variation expressed belowground [5]. In Colombian moist forests, a recent meta-analysis likewise reported clearer differences among restoration methods for vegetation structure than for soil nutrients, although the available soil-nutrient evidence was comparatively limited [9].

These observations do not imply that physical, chemical, and biological soil properties operate independently. Rather, they indicate that contemporary soil condition in the four study plots was not captured consistently by any single measured dimension. Aggregate stability provides a clear example: values were of similar magnitude in the two restored plots and the local reference-forest plot, while other physical, chemical, biological, vegetation, and ground-surface attributes showed different relative patterns. Resemblance in one property therefore

did not imply equivalent resemblance across the broader set of measured attributes. In this landscape, integrating multiple soil dimensions with vegetation structure distinguished complementary aspects of contemporary soil condition that were not represented consistently by any single soil property or aboveground structural metric.

4.2. Ecological Context of Soil-Property Configurations

The property-specific soil patterns observed in this study are best interpreted within the ecological settings in which they occurred. In tropical montane landscapes, vegetation structure and ground-surface cover can influence organic inputs, soil-surface protection, and near-surface environmental conditions, while topography can affect drainage, erosion, and lateral redistribution of water and soil materials [4,10,11]. More broadly, evidence from Neotropical forest succession indicates that soil responses can retain land-use legacies and vary with local environmental conditions, reinforcing the importance of site context when interpreting belowground change [21]. Because the ecological settings differed among the four sampled plots, the observed soil-property contrasts should therefore be interpreted in relation to the vegetation, surface conditions, topographic setting, and management history associated with each landscape context rather than as isolated responses to restoration pathway. The measured soil configurations represent contemporary conditions embedded within a heterogeneous montane landscape.

The pasture illustrates why this contextualization matters. Its higher exchangeable Ca and Mg were also reflected in higher ECEC, defining a distinctive exchangeable-base signature. However, this pattern did not extend consistently across the broader set of chemical properties: soil pH remained acidic across all plots, while Bray-extractable P, nitrate, and the other measured elements followed different relative patterns. Rather than indicating a uniformly richer or poorer chemical condition, the pasture therefore exhibited a particular chemical configuration characterized by elevated exchangeable bases. Such property-specific variation is consistent with evidence that tropical soil nutrient pools and their responses after land-use change reflect interacting effects of soil properties, land-use history, vegetation, and nutrient cycling rather than a uniform response across chemical attributes [4,21].

The same reasoning applies to the restored plots. Their contrasting vegetation structure and ground-surface composition indicate different contemporary ecological settings within which the measured soil properties were expressed. The present design does not allow the individual contributions of vegetation, topography, management history, or surface conditions to particular soil properties to be separated. Active and passive restoration are therefore most appropriately interpreted here as descriptors of contrasting intervention histories embedded within different local contexts rather than as isolated explanatory variables. This interpretation is consistent with viewing active and passive restoration as positions along a continuum of intervention rather than as discrete ecological states [12]. Accordingly, the observed soil configurations are best interpreted jointly with their local ecological context rather than from restoration labels alone.

4.3. Reference-Based Interpretation of Multidimensional Soil Condition

The property-specific patterns observed across the four plots also shape how the local reference forest can be used for interpretation. The reference-forest plot provided a site-

specific ecological benchmark, yet the restored plots showed different patterns of qualitative resemblance to it depending on the property considered. This is consistent with reference-based restoration frameworks in which ecosystem condition is evaluated across multiple ecosystem attributes and their variation rather than through individual indicators considered in isolation [22]. Integrated assessments of ecosystem recovery likewise show the value of jointly evaluating multiple aboveground and belowground components [18]. Agreement with the reference plot in an individual soil property therefore describes resemblance in that component of the system but does not establish comparable resemblance across the broader set of measured attributes.

This distinction is important because individual properties in a restored plot may match or exceed values observed in the reference plot while other soil, vegetation, or ground-surface attributes remain different. Reference-based interpretation is therefore better framed as a multidimensional pattern of property-specific resemblance and divergence than as uniform convergence toward reference values across properties. Because only one local reference-forest plot was characterized, it represents a local ecological benchmark rather than a reference model encompassing the natural variability of the ecosystem. Within that scope, comparison across complementary soil dimensions provides a structured basis for describing how contemporary restored-plot conditions relate to the local reference context without reducing that relationship to any single indicator. These comparisons characterize contemporary, site-specific configurations and should not be interpreted as temporal recovery trajectories or generalized effects of active versus passive restoration.

5. Conclusions

In this tropical Andean cloud-forest restoration landscape, the four sampled contexts did not show a common ordering of contemporary soil condition from pasture through restored patches to the local reference forest. Physical, chemical, and biological/organic dimensions highlighted different contrasts among plots, and the greater woody structure observed in the active-restoration plot was not mirrored consistently across the broader set of soil properties. Likewise, the restored plots resembled the local reference forest in some properties while differing from it in others. In this case study, contemporary soil condition was therefore better represented as a multidimensional, property-specific configuration than as a single axis of similarity to the reference condition.

These findings highlight the value of interpreting complementary soil properties alongside vegetation and local environmental context in heterogeneous restoration landscapes. The reference-forest plot serves as a site-specific ecological benchmark for identifying patterns of resemblance and divergence among components, rather than as a model encompassing the natural variability of the ecosystem. The main contribution of this study is to document that aboveground and belowground attributes can provide non-parallel descriptions of contemporary condition and that no single measured dimension consistently summarizes the broader soil configuration. Because the study is cross-sectional and site-specific, the observed patterns characterize the sampled landscape contexts rather than temporal recovery trajectories or generalized effects of active versus passive restoration.

Supplementary Information

The online version contains supplementary material: ESM 1, Supplementary Tables S1–S4 (taxonomic composition and woody vegetation structure; subplot-level topographic and ground-surface observations; soil analytical methods, units, and operational definitions; and original soil-property values); ESM 2, Figure S1 (field procedures used for ground-surface characterization and soil sampling); and ESM 3, Dataset S1 (individual-level woody vegetation census, data dictionary, and taxonomic dictionary).

Author contributions

Conceptualization, Santiago Vásquez, Laura Osorno; Methodology, Santiago Vásquez, Laura Osorno; Investigation, Santiago Vásquez, Laura Osorno, Luisa Marín, Maikol Martinez, and Jackeline Marin; Data Curation, Santiago Vásquez and Laura Osorno; Formal Analysis, Santiago Vásquez; Visualization, Santiago Vásquez; Writing—Original Draft Preparation, Santiago Vásquez; Writing—Review and Editing, Santiago Vásquez, Laura Osorno, and Luisa Marín; Supervision, Santiago Vásquez, Laura Osorno; Project Administration, Santiago Vásquez, Laura Osorno; Funding Acquisition, Santiago Vásquez, Laura Osorno. All authors read and approved the final manuscript.

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Data availability

The data supporting the findings of this study are provided within the article and its Supplementary Information. Individual-level woody vegetation records and associated taxonomic information are available in Dataset S1 (ESM 3), while the original plot-level soil-property dataset is provided in Supplementary Table S4 (ESM 1). Additional vegetation, ground-surface, and analytical information is provided in Supplementary Tables S1–S3 (ESM 1).

Ethics declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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