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REVEALING POTENTIAL PLANTS FOR ECOLOGICAL RESTORATION OF DEGRADED AREAS IN THE SOUTHWESTERN ANDES OF COLOMBIA

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Abstract

The remnants of the sub-Andean forest in Colombia are key ecosystems due to their high biodiversity and the ecosystem services they provide to communities. However, human activities such as deforestation and fragmentation have put them at risk, highlighting the need for conservation and restoration strategies. Although neotropical forests have been studied, there remains a knowledge gap regarding species with potential for the restoration of degraded areas in this life zone. Therefore, the objective of this study was to characterize species with ecological restoration potential in a forest remnant. Floristic surveys and structural analyses were conducted using 14 Gentry-type transects. A total of 181 vascular plant species were identified, distributed across 72 families, with Piperaceae and Lauraceae being the most diverse. Nineteen species with high restoration potential were selected based on ecological and biocultural attributes such as structural capacity and seed production. The study highlights the value of sub-Andean remnants as biodiversity reservoirs and restoration tools. The integration of local and biocultural knowledge is essential to ensuring the long-term sustainability of these processes.

Keywords: *Sub-Andean forest; Biodiversity; Ecological restoration; Vegetation structure; conservation*

Introduction

The biodiversity of mountain ecosystems in Colombia stands out, particularly in sub-Andean and tropical Andean forests, which host remarkable species richness and endemism [1]. These characteristics result from complex geological and climatic processes that have occurred over the last two million years [2]. These biomes represent approximately 24.9% of the country's forests, covering an estimated 61,035,628 hectares, of which nearly 60% corresponds to the national flora [3, 4]. However, these areas face significant pressures due to the high population density in the Andean region, which concentrates 70.4% of the national population.

Demographic growth, urbanization, and other anthropogenic activities, such as livestock farming, agriculture, and logging, have subjected these ecosystems to negative transformations [5, 6]. These alterations include deforestation, biodiversity loss, and fragmentation into isolated

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mosaics, compromising both their ecological functionality and the ecosystem services they provide [7]. In this context, restoration and conservation have become fundamental priorities [8, 9].

Ecological restoration (ER) emerges as a key discipline in designing specific strategies that integrate floristic characterization, essential for assessing species composition and structure [10]. This initial information allows the identification of species with key attributes that facilitate ecological regeneration, promoting biotic interactions and habitat adaptations [11, 12].

Species selection is a critical aspect of restoration processes, prioritizing those with favorable successional trajectories and attributes suitable for the sites to be restored [12-14]. However, knowledge gaps persist regarding the species with the greatest potential for restoration in sub-Andean forest remnants.

Given this scenario, the present study aims to characterize species with ecological restoration potential in degraded areas within sub-Andean life zones. The information obtained will serve as a foundation for classifying species with high potential for implementing management, conservation, and ecological restoration strategies, contributing to the recovery of similar areas [15].

Materials and Methods

Study area

The study was conducted in a 12.5-hectare forest remnant located in the village of La Cuchilla (02° 11’ N, 76° 44’ W), in the municipality of La Sierra, Cauca, Colombia. This remnant belongs to the premontane humid forest (bh-P) life zone according to Holdridge’s classification [16]. The altitudinal gradient ranges between 1785 and 1903 meters above sea level (Fig. 1).

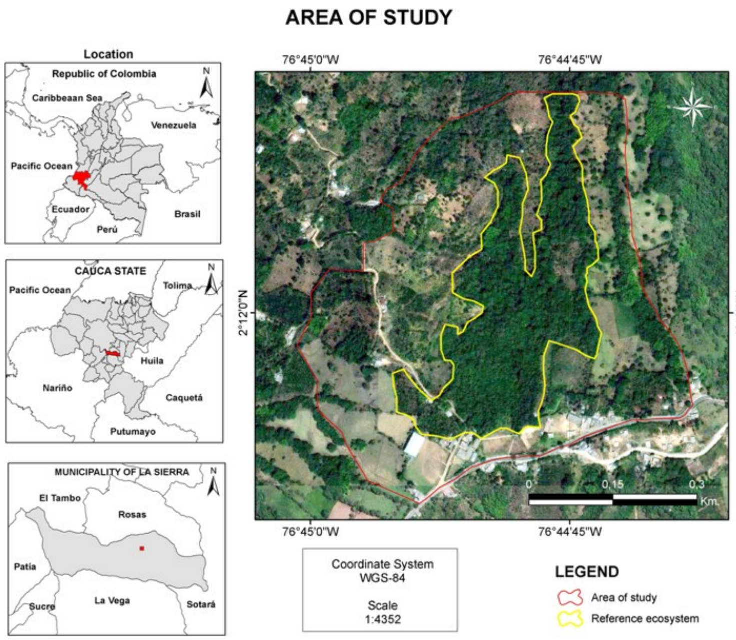

Fig. 1. Location map of the study area, sub-Andean forest remnant, municipality of La Sierra, Colombia

The village of La Cuchilla is part of the municipality of La Sierra, located in the central region of the department of Cauca, on the western flank of the Central Cordillera, within the Colombian Massif. The altitude of the municipality varies between 700 and 3000 meters above sea level, with predominantly rugged terrain and slopes ranging between 25% and 75%. The average annual precipitation is 2440mm, with a bimodal distribution pattern characterized by two rainy periods and two dry periods per year. The temperature ranges between 16°C and 24°C [17].

The municipality is irrigated by the sub-watersheds of the Esmita and San Pedro rivers, tributaries of the Patía River basin. The soils in this region are covered by a layer of volcanic ash, which softens the abrupt shapes of the underlying rock and favors mixed land use, including areas dedicated to agriculture, pastures, fallow lands, and forested zones. Among the main crops in the region are coffee, plantain, and sugarcane [17].

Methods

Floristic Composition

During the study, four field trips were conducted to collect fertile vascular plant samples through free collection. During this process, data were recorded on growth habit, size, coloration of vegetative and reproductive parts, and photographic records [18]. The collected material was pressed, alcohol-preserved, and processed at the Herbarium of the Universidad del Cauca (CAUP).

The identification of the samples was carried out by comparing them with exsiccata from the CAUP Herbarium, complemented by consulting online databases such as Tropicos, Plants of the World Online (POWO), and World Flora Online (WFO). Scientific names were verified using these sources.

To estimate expected richness and assess sampling effort, the iNEXT package [19] was used, applying a non-asymptotic approach based on interpolation and extrapolation, which allowed for the construction of the corresponding accumulation curve.

Vegetation Structure

The structural characterization of the forest remnant was conducted using 14 Gentry-type transects of 50×2m (totaling 1100m², equivalent to 0.14ha). The transects were distributed with a 25m separation to avoid overlaps.

In each transect, individuals with a diameter at breast height (DBH) ≥ 1cm were recorded, documenting species, morphology, circumference at breast height (CBH), total height, canopy coverage, and Cartesian coordinates for geolocation [20].

Based on the collected data, the main structural parameters were calculated, including abundance (A), relative abundance (AR), frequency (F), relative frequency (FR), dominance (Do), relative dominance (DoR), and the importance value index (IVI) [20]. Additionally, tree height and canopy coverage area in relation to the total area and spatial distribution of vegetation were evaluated, allowing for the generation of idealized vertical and horizontal profiles based on the most diverse transect.

Selection of Species with Restoration Potential

To identify species with the highest potential for ecological restoration, a pre-selection process was carried out considering ecological attributes, life cycles, and biocultural knowledge. The evaluation was conducted using a scale from 1 to 5 based on ten vital attributes, following the methodology proposed by Vásquez-Valderrama & Solorza-Bejarano [21].

Based on the obtained scores, species were classified into two main categories: those corresponding to pioneer trees and shrubs with rapid growth, and those characterized as slow-growing interior forest species.

The selection of these species was based on key criteria, such as social behavior, constructive capacity, sociability, foliage coverage, and high renewal rate. Attributes related to vegetative reproduction capacity, seed production, resprouting ability after damage, pioneer aptitude, resilience, and competitiveness were also considered. All these factors are essential for facilitating ecological succession and ensuring the success of restoration processes [21] (Table 1).

Table 1. Vital attributes used in the selection of species with potential for ecological restoration (adapted from Vásquez-Valderrama & Solorza-Bejarano [21])

Vital Attribute	Description
Social Behavior	Individuals are distributed close to each other.
Constructive Capacity	The size of individuals significantly contributes to the structural construction of vegetation.
Sociability	Tendency to associate with other species (does not form pure stands).
Foliage Coverage	Dense foliage with wide coverage (provides good shade), enabling microclimate transformations in its surroundings.
High Renewal Rate	Frequent removal of parts such as leaves, twigs, branches, and roots, which have a short life cycle, depositing dead material that contributes to soil formation and improvement.
Vegetative Reproduction	Natural conditions for cloning through rhizomes, stolons, layering, cuttings, or stakes.
High Seed Production	Species that generate a large number of propagules, embryos, or spores.
Tenacious Resprouting	Rapid and repeated regrowth after physical damage (partial cutting and burning).
Pioneer Aptitude and Hardiness	Ability to colonize, reproduce, and develop without subsidies or assistance in recently disturbed environments, mainly bare substrates.
Aggressiveness	Species capable of effectively competing with opportunistic species from disturbed environments, human-introduced species, or dominant native species from a given successional stage; they disrupt the existing floristic balance and drive succession toward primary ecosystems.

Results and discussion

Floristic Composition

In the sub-Andean forest remnant, 180 species were identified, distributed across 127 genera and 72 families, reflecting remarkable floristic diversity for a small and fragmented area. Dicotyledons were the most prominent group, with 108 species, followed by monocotyledons (29), bryophytes (24), and lycophytes, monilophytes, and horsetails (20) (Table 2). This predominance of dicotyledons is consistent with the typical structure of sub-Andean forests and highlights their essential role in the floristic composition of these ecosystems.

Table 2. Number of species, genera, and families by determined group

Group	Species	Genera	Families
Dicotyledons	108	71	38
Monocotyledons	29	23	9
Lycophytes, Monilophytes, and Equisetums	20	15	10
Bryophytes	24	18	15
Total	181	127	72

The families Piperaceae (12 species), Lauraceae (9), Asteraceae (8), Fabaceae (8), Araceae (7), and Orchidaceae (7) proved to be the most diverse, which aligns with previous reports identifying them as key components in both conserved areas and disturbed zones [18]. Similarly, genera such as Piper, Nectandra, and Anthurium stood out for their species richness, demonstrating high ecological adaptability and a broad distribution in the Andes [22, 23]. On the other hand, Neckeraceae, Polypodiaceae, and Aspleniaceae accounted for 44.3% of the species among monilophytes and bryophytes, reflecting their relevance in the ecological dynamics of the remnant (Supplementary file 1).

The rarefaction curve showed high sampling representativeness (89.2%), indicating that a significant portion of the present floristic diversity was recorded (Fig. 2A). However, extrapolation suggests that additional species could be incorporated with increased sampling effort. Nevertheless, this analysis should be interpreted cautiously due to the impact of fragmentation and selective logging, which have likely reduced species richness compared to an intact sub-Andean forest.

The estimated q-order diversity revealed a decline in evenness as the value increases (Fig. 2B). This suggests a community dominated by a few frequent and rare species. This pattern, characteristic of fragmented ecosystems, highlights the need for management strategies that prioritize the conservation of less common species.

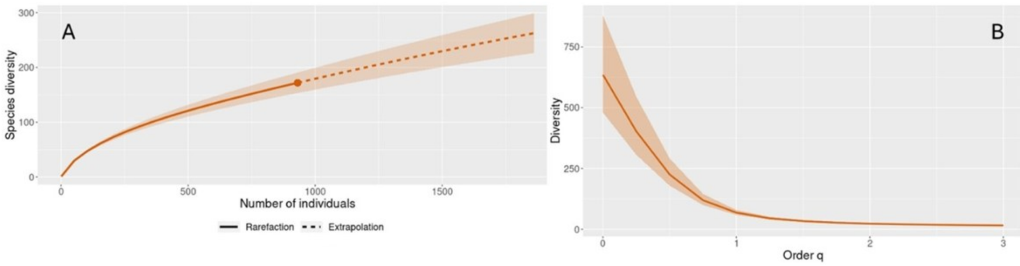

Fig. 2. Sampling curve by extrapolation and rarefaction based on sample size (A) and estimated diversity profiles of order q (B)

In terms of growth habit, herbs represented 47% of the species richness, followed by trees and small shrubs (24%), epiphytes (15%), shrubs and subshrubs (11%), lianas and climbers (2%), and one palm and one tree fern (1%). This predominance of herbaceous elements aligns with the findings of Gentry and Dodson [24], who identified similar trends in the tropics, where herbs can account for up to 50% of vascular plant richness. This pattern is influenced by factors such as historical disturbances, local climatic conditions, and the availability of water sources and dispersers [18].

Despite its fragmentation, the sub-Andean forest remnant maintains a species richness comparable to the minimum values proposed by Gentry [25] for neotropical forests between 1500 and 2000m in altitude. This result highlights the ecosystem's resilience and its value as a propagule source for restoration and conservation processes. Furthermore, families such as Asteraceae and Fabaceae were particularly relevant in open areas, acting as pioneers in early succession stages, while Lauraceae and Orchidaceae were associated with more humid and shaded sites, characteristic of intact sub-Andean forests [26, 27].

Vegetal Structure

In the 14 evaluated transects, a total of 829 individuals belonging to 77 species, distributed across 52 genera and 33 families, were recorded. The species with the highest Importance Value Index (IVI) were *Palicourea thyrsiflora*, *Saurauia scabra*, *Oreopanax albanensis*, *Cupania americana*, *Cecropia angustifolia*, and *Myrcia popayanensis*. At the family level, *Piperaceae, Lauraceae, Primulaceae, Rubiaceae,* and *Melastomataceae* stood out due to their structural and functional contributions to the ecosystem (Supplementary files 2 and 3).

Five altimetric strata were identified based on height classes (Figs. 3 and 4):

- The herbaceous stratum (*<1.49m*) was dominated by *Besleria solanoides*.
- The shrub stratum (*1.5 to 3.9m*) was characterized by *Oreopanax albanensis, Miconia theizans, Geissanthus sp1, Piper crassinervium,* and *Acalypha macrostachya*.
- The lower tree stratum (*4 to 9.9m*) included *Saurauia scabra, Clusia ellipticifolia,* and *Palicourea thyrsiflora*.
- The intermediate tree stratum (*10 to 19.9m*) was dominated by *Saurauia scabra, Miconia caudata, Palicourea thyrsiflora, Cecropia angustifolia, Ficus caucana,* and three species of the genus *Nectandra*.
- The upper tree stratum (*≥20m*) was represented by *Inga sp., Quercus humboldtii,* and *Cecropia angustifolia*.

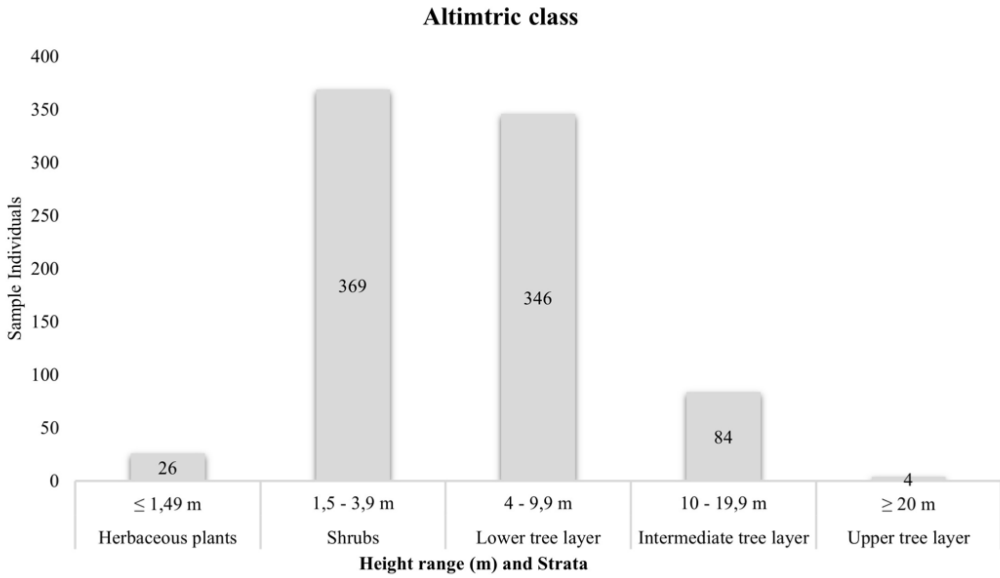

Fig. 3. Vegetation stratification based on altimetric classes

Fig. 4. Vertical profile representing the heights of the most diverse transect:
1. *Palicourea thyrsiflora;* **2.** *Piper aequale;* **3.** *Nectandra sp5.;* **4.** *Croton hibiscifolius;* **5.** *Nectandra sp1.;* **6.** Sapindaceae sp.; **7.** *Cupania americana;* **8.** *Geissanthus sp2;* **9.** *Geissanthus sp2.;* **10.** *Miconia sp2;* **11**. *Piper hartwegianum;* **12.** *Nectandra sp1.;* **13.** *Piper aduncum;* **14.** *Ficus caucana;* **15.** *Clusia ellipticifolia;* **16.** *Alchornea latifolia;* **17.** *Toxicodendron sp.;* **18.** *Piper crassinervium;* **19.** *Heliocarpus americanus;* **20.** *Besleria solanoides;* **21.** *Myrcia popayanensis;* **22.** *Acalypha macrostachya;* **23.** *Trichanthera gigantea;* **24.** *Asteraceae sp1.;* **25**. *Xylosma benthamii;* **26.** *Billia rosea;* **27.** *Oreopanax albanensis;* **28.** *Miconia caudata;* **29.** *Viburnum sp.;* **30.** *Eugenia sp.;* **31.** *Lauraceae sp2.*

The relationship between diameter and height classes reflected the active regeneration of the forest remnant, with high abundance in the lower diameter at breast height (DBH) categories (*1.1–3cm* and *3.1–10cm*). This pattern indicates a predominance of young individuals and the impact of anthropogenic practices such as selective logging and fragmentation, which limit the development of mature trees.

Species with the highest canopy coverage values, such as *Nectandra sp1, Toxicodendron sp., Ficus caucana,* and *Heliocarpus americanus*, form a semi-open canopy, fostering stable microclimates essential for the regeneration of epiphytic species and other specific growth habits [28, 29].

The high IVI values for *Palicourea thyrsiflora, Saurauia scabra, Cupania americana,* and *Myrcia popayanensis* highlight their ecological importance and contribution to the forest canopy. These species exhibit morphological traits, such as high CAP values and tall stature, that are fundamental to ecosystem dynamics. Furthermore, the presence of *Myrcia popayanensis* and *Palicourea thyrsiflora* in similar remnants emphasizes their role as indicators of regeneration processes [23].

The secondary succession stage of the remnant, evidenced by the dominance of the shrub and lower tree strata (369 and 346 individuals, respectively), suggests a trajectory toward ecological maturity, provided that anthropogenic pressures are reduced. These characteristics are typical of regenerating secondary forests [30-32]. The canopy cover generated by the lower and intermediate tree strata is key to microclimate stability and habitat formation, promoting biodiversity and ensuring the success of restoration processes [33].

Potential Species for Ecological Restoration

The identification and selection of species with key attributes for ecological regeneration resulted in the preselection of 27 species, of which 19 obtained the highest scores in a vital attributes matrix (Table 3). These species were grouped into two main categories:

1. Pioneer trees and shrubs with rapid growth, and
2. Interior forest species with slow growth.

This classification enables the design of restoration strategies adapted to different successional stages, maximizing their positive impact in degraded areas.

Table 3. Matrix of Vital Attribute Relationships with Preselected Plant Species, with Assigned Values (1 = Low, 3 = Medium, and 5 = High). The (*) indicates species with the highest value; 1 represents fast-growing species, and 2 represents slow-growing species; (I) indicates interior forest species

ID	Habit	Scientific Name	Social Behavior	Constructive Capacity	Sociability	Foliage Coverage	High Renewal Rate	Vegetative Reproduction	High Seed Production	Tenacious Resprouting	Pioneer Aptitude	Aggressiveness	**TOTAL**
1	Tree - Shrub	*Trichanthera gigantea* (2) *	5	3	5	3	5	5	3	5	3	3	40 *
2	Tree - Shrub	*Euphorbia laurifolia* (1)	3	3	3	3	3	5	5	5	3	1	34
3	Tree	*Ochroma pyramidale* (1) *	5	5	5	5	5	1	5	3	5	5	44 *
4	Tree	*Nectandra acutifolia* (2)	5	3	5	5	3	3	3	3	3	3	36
5	Tree	*Lafoensia acuminata* (2)	3	3	3	5	3	1	5	3	3	3	32
6	Tree	*Ficus cucana* (2)	3	5	3	5	3	1	5	3	3	3	34
7	Tree	*Inga densiflora* (1) *	3	5	3	5	5	3	5	3	5	3	40 *
8	Tree - Shrub	*Erythrina edulis* (1) *	5	5	5	3	5	3	3	5	5	5	44 *
9	Tree	*Erythrina poeppigiana* (1) *	5	5	5	5	5	5	5	5	3	3	46 *

10	Tree	*Clusia ellipticifolia* (2) * (I)	5	5	5	3	5	3	5	5	3	3	42 *
11	Tree - Shrub	*Croton hibiscifolius* (1) *	5	5	5	3	5	3	5	5	5	5	46 *
12	Tree	*Heliocarpus americanus* (1) *	5	5	5	5	5	3	5	5	5	5	48 *
13	Tree	*Myrcia popayanensis* (1) *	5	5	5	5	3	3	5	3	5	3	42 *
14	Tree	*Cedrela montana* (1) *	5	5	5	5	5	3	5	3	3	5	44 *
15	Tree	*Cecropia angustifolia* (1) *	5	5	5	5	5	2	5	3	5	5	45 *
16	Tree - Shrub	*Cinchona pubescens* (2)	3	3	3	5	3	2	5	3	3	5	35
17	Tree	*Cupania americana* (1) *	5	5	5	5	5	3	5	5	3	3	44 *
18	Tree	*Cordia alliodora* (2)	5	3	3	5	3	1	5	3	3	3	34
19	Tree	*Quercus humboldtii* (2) *	5	5	3	5	3	3	5	3	3	5	40 *
20	Tree	*Eugenia sp.* (2) (I)	5	3	5	3	3	1	5	3	3	3	34
21	Tree – Small Tree	*Miconia caudata* (1)	3	3	3	5	3	5	5	3	3	3	36
22	Tree	*Saurauia scabra* (1) *	5	5	5	5	5	3	5	3	3	5	44 *
23	Tree – Small Tree	*Oreopanax albanensis* (2) * (I)	5	5	5	5	5	3	5	5	3	3	44 *
24	Shrub	*Piper aduncum* (1) *	5	5	5	3	3	5	5	5	5	5	46 *
25	Tree	*Juglans neotropica* (1) *	5	5	5	5	5	3	5	3	3	5	44 *
26	Tree	*Inga sp* (2) * (I)	5	5	5	5	3	3	5	3	3	5	42 *
27	Tree – Small Tree	*Mabea sp.* (1) * (I)	5	5	5	5	5	3	5	3	3	3	42 *

Among the selected species, *Heliocarpus americanus, Cecropia angustifolia, Erythrina poeppigiana, Trichanthera gigantea*, and *Piper aduncum* stand out for their high values in attributes such as social behavior, structural capacity, high seed production, and aggressiveness. These characteristics make them dynamogenic species, as they modify the microclimate, generate significant biomass, and promote ecological interactions between flora and fauna [34]. These dynamics are essential to facilitate successional processes and ensure the success of ecological restoration.

The importance of these species lies in their capacity to build most of the biomass, generate canopy coverage that stabilizes the microclimate, and facilitate environmental changes that support vegetation succession. This aligns with the findings of Rodríguez et al. [35], who emphasize the importance of identifying key species that promote the transition of plant communities toward more complex successional stages.

Furthermore, this research takes an integrative approach, recognizing the role of local communities in restoration processes. Incorporating traditional knowledge into the selection and management of species fosters sustainability and biocultural appropriation of restored areas. This approach ensures positive outcomes in the medium and long term, strengthening the relationship between communities and their natural environment.

A comparison with previous studies, such as Trujillo [36], reveals notable overlaps in the selection of key species, including *Cinchona pubescens, Quercus humboldtii, Cordia alliodora*, and *Piper aduncum*. These similarities underscore the usefulness of these species for restoring areas with comparable conditions, demonstrating that their inclusion can guide replicable restoration strategies in other sub-Andean forest remnants. This highlights the importance of developing restoration processes that not only restore ecosystems but also reinforce the biocultural connection between communities and their environment.

Conclusions

This study highlights the critical role of sub-Andean forest remnants as biodiversity reservoirs and drivers of ecological restoration in fragmented landscapes of the southwestern Andes of Colombia. Despite human pressures, these ecosystems demonstrate significant resilience and invaluable potential for the regeneration of degraded areas.

The research identified 180 plant species distributed across 72 families and 127 genera, with families such as Piperaceae, Lauraceae, and Asteraceae standing out due to their high richness and ecological adaptability. The structural characterization of the remnant allowed the definition of five altitudinal strata, with a higher concentration of individuals in the shrub and lower tree strata, reflecting an active secondary succession stage. Additionally, 19 key species with high restoration potential were selected based on attributes such as high seed production, pioneer behavior, and structural capacity. These species not only promote successional progress but also stabilize microclimates favorable for biodiversity.

The results go beyond the local scale, providing a replicable framework for identifying key species in restoration processes in similar sub-Andean areas. This approach can be incorporated into regional conservation programs and public policies, emphasizing the need to integrate biocultural knowledge as a tool to ensure the sustainability of restored ecosystems.

The study significantly contributes to restoration ecology by developing a robust methodology for selecting species with key functional traits that facilitate ecological regeneration. Moreover, it highlights the importance of sub-Andean remnants as functional hubs for biodiversity conservation and the restoration of fragmented ecosystems.

It is recommended to further explore the ecological dynamics of the selected species, evaluating their performance in different successional stages and under varying climatic conditions. Additionally, it would be valuable to investigate how land-use changes and community practices influence the long-term effectiveness of these species in restoration.

It is crucial for researchers, decision-makers, and local communities to collaborate in implementing these ecological restoration strategies. Integrating scientific and biocultural knowledge in these processes will not only strengthen ecosystem resilience but also foster sustainable stewardship of restored territories. This joint effort is key to ensuring the recovery of fragmented landscapes in the southwestern Andes and other highly biodiverse regions.

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