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Research article

Reference sites for the restoration of mining-affected peri-urban forests in the *Inambari* district, Peruvian Amazon

Sitios de referencia para la restauración de bosques periurbanos afectados por la minería en el distrito de Inambari, Amazonía peruana

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Abstract

Peri-urban forests affected by mining activities can provide ecological benchmarks to guide the restoration of degraded areas when they retain representative attributes of composition, diversity, and structure. This study evaluated the potential of six mining concessions in the *Inambari* River basin, in the Peruvian Amazon, to serve as reference sites for future restoration efforts. Rectangular plots of 0.1 ha were established, and all tree individuals with a diameter at breast height ≥10 cm were recorded. Taxonomic richness, Hill's *q*-numbers for orders *q*=0, *q*=1, and *q*=2, diameter, height, basal area, Importance Value Index, and floristic similarity were determined using the Jaccard and Bray-Curtis indexes, along with a non-metric multidimensional scaling (*NMDS*) analysis. A total of 2 063 individuals were recorded, grouped into 57 families, 172 genera, and 404 species. *Edmilot* I had the greatest observed richness and basal area; Washington III had the highest effective number of common species, while *Yesica* had the highest effective number of dominant species. *Yhon Hittler* and *Juan Raul*

2 showed lower effective diversity and a marked dominance of *Iriartea deltoidea*. Washington III and *Sarayacu* had very similar *NMDS* results, and so did *Yhon Hittler* and *Juan Raul* 2. The complementary use of multiple sites allows for the establishment of more representative benchmarks of the landscape's ecological variability to guide the restoration of peri-urban forests affected by mining.

Keywords: Effective diversity, forest structure, Importance Value Index, gold mining, Hill's numbers, floristic similarity.

Resumen

Los bosques periurbanos afectados por actividades mineras pueden aportar referencias ecológicas para orientar la recuperación de áreas degradadas cuando conservan atributos representativos de composición, diversidad y estructura. En este estudio se evaluó el potencial de seis concesiones mineras de la cuenca del Río Inambari, Amazonía peruana, para funcionar como sitios de referencia en futuras acciones de restauración. Se establecieron parcelas rectangulares de 0.1 ha y se registraron todos los individuos arbóreos con diámetro a la altura del pecho ≥10 cm. Se determinaron la riqueza taxonómica, números de *Hill* de órdenes q=0, q=1 y q=2, el diámetro, la altura, área basal, Índice de Valor de Importancia y la similitud florística mediante los índices de *Jaccard* y *Bray-Curtis*, además de una ordenación de escalamiento multidimensional no métrico (*NMDS*). Se registraron 2 063 individuos, agrupados en 57 familias, 172 géneros y 404 especies. Edmilot I presentó la mayor riqueza observada y área basal; respecto al número efectivo de especies comunes en *Washington* III se registró el valor más alto, mientras que en Yesica ocurrió lo mismo, pero para el número efectivo de especies dominantes. Yhon Hittler y Juan Raul 2 mostraron menor diversidad efectiva y una marcada dominancia de *Iriartea deltoidea*. *Washington* III y Sarayacu tuvieron una *NMDS* muy semejante, y entre Yhon Hittler y Juan Raul 2. El uso complementario de varios sitios permite establecer referencias más representativas de la variabilidad ecológica del paisaje para orientar la restauración de bosques periurbanos afectados por la minería.

Palabras clave: Diversidad efectiva, estructura forestal, Índice de Valor de Importancia, minería aurífera, números de *Hill*, similitud florística.

Introduction

Ecosystem restoration encompasses a range of actions aimed at halting and reversing degradation, from impact reduction and remediation to rehabilitation and ecological restoration. The latter aims to support the recovery of a native ecosystem based on its composition, structure, functioning, and ability to sustain itself over time. In this context, reference sites, reference models, and reference ecosystems serve different functions.

A reference site is a real-world area that provides data on an ecosystem's composition, structure, and functioning. The reference model integrates information from one or more sites, historical records, and other sources to represent the

expected condition and variability during recovery. The reference ecosystem corresponds to the ecological condition that guides the long-term restoration goal. Because ecosystems exhibit spatial and temporal variation, reference points should not be understood as rigid representations of the past, but rather as a basis for defining recovery pathways consistent with the ecological history and current conditions of the landscape (Higgs et al., 2014).

In the Peruvian Amazon, alluvial gold mining causes loss of forest cover, soil removal and redistribution, changes in drainage, and a reduction in sources of regeneration—changes that result in mosaics composed of forest remnants, severely degraded areas, and secondary communities at various stages of development (Caballero-Espejo et al., 2018). Research in *Madre de Dios* shows that recovery of biomass, diversity, and structure depends on the type of mining, disturbance intensity, and the time since the site was abandoned. Native species also show contrasting survival and growth responses when planted in areas degraded by gold mining (Garate-Quispe et al., 2024; Román-Dañobeytia et al., 2021).

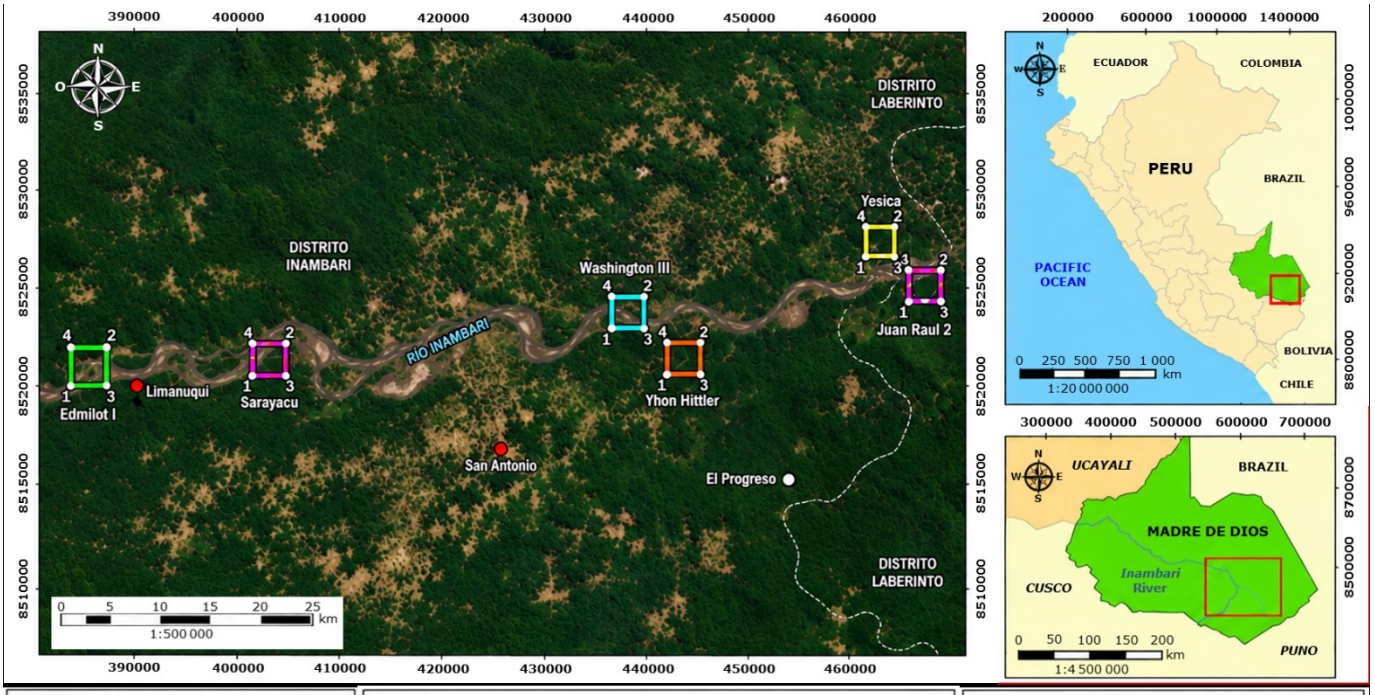
Identifying key sites in these landscapes requires information on species richness and diversity, tree structure, dominance, and floristic similarity between areas. The floristic composition and structure are therefore not the ultimate goal of the analysis, but rather the basis for selecting local reference points, defining initial attributes, and guiding future restoration efforts. Floristic studies conducted in Peruvian Amazonian forests and in previously reforested areas confirm the value of these indicators for interpreting vegetation reorganization and establishing recovery criteria (Alvarez-Montalván et al., 2021).

In this context, this study aimed to identify, among six peri-urban forests affected by mining in the *Inambari* District, those with the greatest potential to serve as reference sites for future restoration efforts by characterizing their floristic composition, diversity, tree structure, and the ecological importance of the species.

Materials and Methods

Study area

The study was conducted at six mining concessions located in the *Inambari* River basin, in the district of *Inambari*, *Tambopata* province, *Madre de Dios* Department, in the southeastern part of the Peruvian Amazon. The evaluated area is located in the UTM coordinate system, datum WGS 84, zone 19S, between 387743-465417 m E and 8504406-8535240 m N (Figure 1). The concessions are distributed along the *Inambari* River corridor, near the following population centers: *Limamoj*, *Asnai*, *Inambari Centro*, *El Progreso*, *Ancamayo Bajo*, and *Puerto Maltas*. Alluvial gold mining has shaped the landscape, causing vegetation loss, soil removal, river-channel changes, and hydrological alterations that have created a mosaic of remaining forests, degraded areas, and sections with secondary vegetation (Velásquez-Ramírez et al., 2020).



STUDY AREAS		
No.	**Site**	**Surface área (ha)**
1	*Edmilot* I	100
2	Washington III	100
3	*Sarayacu*	100
4	*Yhon Hittler*	100
5	*Juan Raul* 2	100
6	*Yesica*	100
Total		**600**

KEY

Population centers
Vertices
District boundaries
Main rivers
Secondary rivers

ASSESSED FORESTS

Edmilot I
Washington III
Sarayacu
Yhon Hittler
Yesica
Juan Raul 2

TOTAL: 6 FORESTS

PERI-URBAN FORESTS OF *INAMBARI*
Location map and peri-urban context

Province: *Tambopata*
Department: *Madre de Dios*
Datum: WGS 84 **Zone:** 19S
Date: April 2025 **Scale:** As indicated

Distrito *Inambari* = District of *Inambari*; Distrito Laberinto = District of *Laberinto*. *Limanuqui* = *Limanuqui* town; San Antonio = *San Antonio* town; El Progreso = El Progreso town. *Río Imambari* = *Inambari* River. O = West.

Figure 1. Location of the six mining concessions evaluated in the *Inambari* River basin, *Madre de Dios*, Peru.

Sampling design and database

Rectangular plots measuring 100×10 m, equivalent to 0.1 ha, were established and distributed across the six mining concessions. In each plot, all trees with a diameter at breast height of or above 10 cm (*DBH*≥10 cm) were recorded. For each individual, the

family, genus, species, *DBH* (model 283D Forestry Suppliers® diameter tape), and total height (model PM-5/360 PC Suunto® clinometer) were recorded. Taxonomic identification was conducted in the field with the assistance of specialists. Subsequently, the scientific names were reviewed in the World Checklist of Vascular Plants to verify accepted names, update synonyms, correct spelling inconsistencies, and standardize the taxonomic classification in the records (Govaerts et al., 2021).

Floristic composition and taxonomic richness

The floristic composition was described based on the number of families, genera, and species recorded in each concession and across the entire study area.

Structural analysis of the forest

The structure of the tree vegetation was assessed using mensuration variables, primarily diameter at breast height (*DBH*) and total height (*H*). Based on the *DBH*, the individual basal area (*BA*) of each tree was calculated using the following expression (Equation 1) (Pretzsch et al., 2015):

$$BA = \frac{(\pi \times DBH^2)}{40\,000} \quad (1)$$

Where:

BA = Individual basal area (m^2)

DBH = Diameter at breast height (cm)

π = 3.1416

The total basal area per concession was calculated as the sum of individual basal areas and standardized to m^2 ha^{-1} based on the area actually sampled. In restoration studies, comparing the structure, diversity, and composition across different areas makes it possible to establish baseline values and identify the ecological variation that must be taken into account when defining recovery goals (Beauchamp & Shafroth, 2011; Ruiz-Jaén & Aide, 2005).

Importance Value Index (*IVI*)

The ecological importance of the species was assessed using the Importance Value Index (*IVI*), calculated as the sum of relative abundance, relative frequency, and relative dominance (Equation 2) (Curtis & McIntosh, 1951):

$$IVI = RA + RF + RD \qquad (2)$$

Where:

IVI = Importance Value Index

RA = Relative abundance

RF = Relative frequency

RD = Relative dominance

Relative abundance (Equation 3):

$$RA = \left(\frac{N_i}{N_t}\right) \times 100 \qquad (3)$$

Where:

N_i = Number of individuals of the *i* species

N_t = Total number of the registered individuals

Relative frequency (Equation 4):

$$RF = \frac{F_i}{\sum F} \times 100 \qquad (4)$$

Where:

F_i = Frequency of the *i* species

$\sum F$ = Sum of the frequencies of all species

The frequency of each species was determined based on the number of plots in which it was present.

Relative dominance (Equation 5):

$$RD = \left(\frac{BA_i}{BA_t}\right) \times 100 \qquad (5)$$

Where:

BA_i = Total basal area of the *i* species

BA_t = Total basal area of all the species

Alpha and beta diversity analysis

Alpha diversity was assessed using Hill indexes of orders q=0, q=1, and q=2 (Equations 6 to 8). The value q=0 corresponds to the observed species richness; q=1 represents the effective number of common species and was obtained using the exponential of the Shannon index; and q=2 expresses the effective number of dominant species and was calculated as the inverse of Simpson's concentration. This approach allows diversity to be expressed in comparable units of effective species and avoids the interpretive limitations of traditional indexes (Jost & González-Oreja, 2012).

$$D_0 = S \qquad (6)$$

$$D_1 = e^{-\sum_{i=1}^{S} p_i nl(p_i)} \qquad (7)$$

$$D_2 = \frac{1}{\sum_{i=1}^{S} p_i^2} \qquad (8)$$

Where:

D_0 = Effective number of species of order 0 or observed species richness

D_1 = Effective number of common species

D_2 = Effective number of dominant species

S = Total number of recorded species

p_i = Proportion of individuals belonging to the i species

nl = Natural logarithm

Hill's figures were calculated directly from the abundances recorded in each concession. Due to differences in sampling effort, the observed richness (q=0) was interpreted with caution and in conjunction with q=1 and q=2, which incorporate the distribution of abundances. Beta diversity was assessed using the Jaccard and Bray-Curtis similarity indexes (Bray & Curtis, 1957; Jaccard, 1912).

Criteria for identifying reference sites

The potential of each concession as a reference site was assessed by integrating four attribute groups: effective richness and diversity, tree structure, ecological importance of species, and floristic similarity. Sites with high diversity values or notable structural attributes were considered relevant, as were those with specific compositions that increased the range of variability represented. The selection was not based on a single score, but rather on the ecological complementarity among concessions, so as to establish a more representative benchmark of the landscape.

Statistical and multivariate analysis

Statistical analyses were performed using SAS version 9.4 (SAS Institute Inc., 2016). Descriptive statistics were calculated, and the normality of the variables was tested using the Shapiro-Wilk test. Because this assumption was not met, the Kruskal-Wallis test was used to analyze the differences between concessions in the *DBH* and total height. When significant differences were detected, the Dwass-Steel-Critchlow-

Fligner multiple comparison test was applied (Zhen et al., 2022). The results are expressed as mean±standard error, and statistical groups are denoted by different letters. A significance level of α=0.05 was used in all analyses.

Jaccard and Bray-Curtis similarity matrices were calculated in *PAST* (Hammer et al., 2001), based on the species composition and abundance of each concession. For the *NMDS* analysis, Bray-Curtis similarity was transformed into dissimilarity. The *NMDS* was performed in Python version 3.13.5 (Python Software Foundation, 2026) using the Bray-Curtis dissimilarity matrix, and the quality of the ordination was evaluated using the stress value. The *NMDS* was used because of its suitability for representing differences in composition based on abundance data and ecological dissimilarity (Clarke, 1993).

Results and Discussion

Floristic composition and taxonomic richness

In the six concessions evaluated, 2 063 tree individuals were recorded, representing 57 families, 172 genera, and 404 species (Table 1).

Table 1. Taxonomic diversity of the tree community in six mining concessions in the *Inambari* River basin in *Madre de Dios*, Peru.

Study area	Plots	Individuals	Families	Genera	Species
Edmilot I	10	553	44	114	158
Washington III	10	562	38	103	154
Sarayacu	10	582	39	105	156
Yhon Hittler	3	112	23	39	41
Juan Raul 2	3	120	23	41	42
Yesica	3	134	32	56	83
Total	39	2 063	57	172	404

From a conservation perspective, the main contribution lies not only in the high richness of species, but also in the documentation of the identity, abundance, and distribution of the recorded species. This information, combined with data on forest diversity and structure, makes it possible to identify representative plant communities and establish local benchmarks for selecting species, defining restoration goals, and subsequently evaluating the progress of restored areas. The ecological integrity of secondary forests should be assessed using several complementary attributes, as no single indicator can on its own represent the composition, structure, and functioning of the ecosystem (Rosenfield et al., 2023).

Diversity indexes and structural attributes

Hill's data revealed marked differences in tree diversity across the concessions (Table 2). Species richness (q=0) was highest at *Edmilot* I, *Sarayacu*, and Washington III, with 158, 156, and 154 species, respectively; *Yesica* registered 83, while *Juan Raul* 2 registered 42 species, and *Yhon Hittler*, 41. Due to differences in sampling intensity,

these values should be interpreted with caution. The orders q=1 and q=2 provided complementary information by incorporating the distribution of abundances and reducing the relative weight of rare species (Jost & González-Oreja, 2012).

Table 2. Hill's indexes of tree diversity in six mining concessions in the *Inambari* River basin, in *Madre de Dios*, Peru.

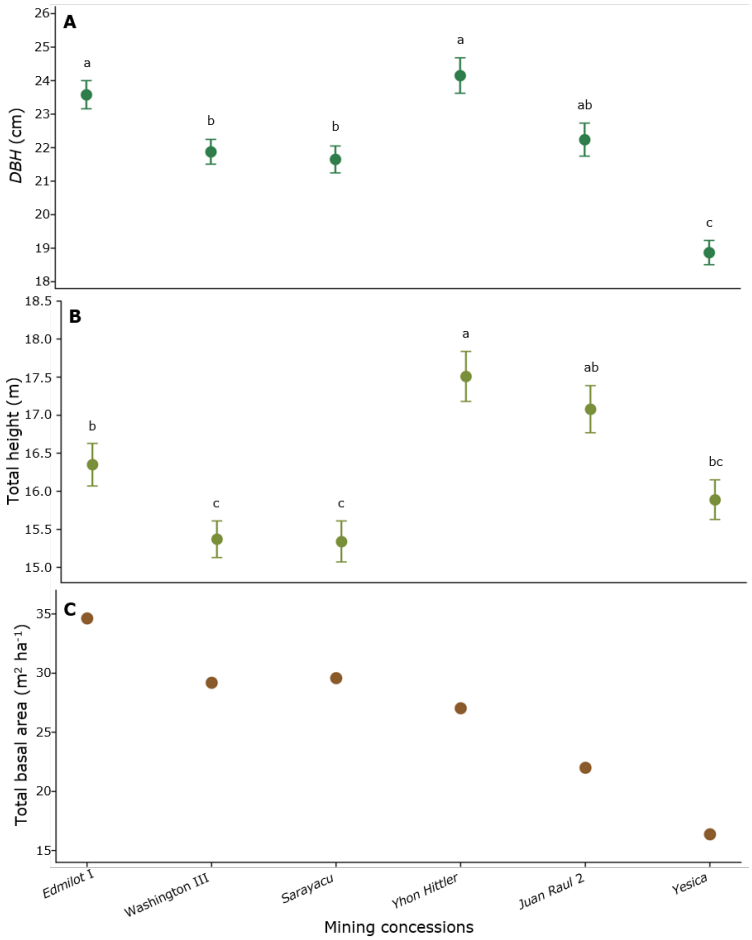
Study area	q=0	q=1	q=2
Edmilot I	158	69.38	30.06
Washington III	154	81.26	43.05
Sarayacu	156	79.03	40.32
Yhon Hittler	41	14.27	5.33
Juan Raul 2	42	16.01	6.39
Yesica	83	67.82	53.44

q=0 represents the observed richness; *q=1*, the effective number of common species, and *q=2*, the effective number of dominant species.

From a restoration perspective, Washington III and *Sarayacu* provide relevant examples because they combine high biodiversity with a broad representation of common species. *Yesica* provides a complementary measure, as it reported the highest effective number of dominant species (q=2), which reflects a more balanced distribution of abundances. *Edmilot* I stood out for its greater taxonomic breadth. These differences show that no single concession encompasses the full range of floristic variation in the landscape; therefore, the combined use of several sites allows for the creation of a more representative benchmark for potential recovery trajectories. In disturbed tropical landscapes, comparing communities with different compositions and levels of diversity makes it possible to set restoration goals that are consistent with local variability (Chazdon et al., 2009; Rother et al., 2019).

Structural attributes varied among the concessions. The standardized basal area per hectare was highest in *Edmilot* I (34.64 m^2 ha^{-1}), followed by *Sarayacu* (29.59 m^2 ha^{-}

^{1}), Washington III (29.19 m^2 ha^{-1}), and *Yhon Hittler* (27.03 m^2 ha^{-1}). *Juan Raul* 2 and *Yesica* registered 22.00 and 16.37 m^2 ha^{-1}, respectively (Figure 2).



A = Diameter at breast height; B = Total height; C = Total standardized basal area. In figures A and B, the dots represent the mean±standard error. Different letters indicate significant differences (p<0.05).

Figure 2. Diameter at breast height, total height, and total standardized basal area per hectare in six mining concessions in the *Inambari* River basin, *Madre de Dios*, Peru.

The observed pattern indicates that the average tree size and basal area per hectare did not necessarily follow the same trend. *Yhon Hittler* had higher *DBH* and height

values, but a smaller basal area than that recorded for *Edmilot* I, Washington III, and *Sarayacu*. In restoration, these attributes are interpreted in a complementary manner to assess how closely the recovering vegetation resembles the reference forests in terms of structure (Ssekuubwa et al., 2022). Differences in *DBH*, height, and basal area have also been documented among secondary forests undergoing different recovery trajectories within the same district (Nytch et al., 2023).

Importance Value Index and dominant species

Analysis of the Importance Value Index (*IVI*) showed that, within each concession, a small set of species accounted for the highest relative importance values; however, their composition and ranking varied between sites (Table 3). This pattern is consistent with the oligarchic structure described in forests of the Upper Amazon, where a small number of common species can account for a significant proportion of the individuals and the forest structure (Pitman et al., 2013).

Table 3. Species with the highest Importance Value Index (*IVI*) by study area in the *Inambari* River basin, *Madre de Dios*, Peru.

Study area	Species	*IVI* (%)
Edmilot I	*Iriartea deltoidea* Ruiz & Pav.	7.25
	Otoba parvifolia (Markgr.) A. H. Gentry	5.12
	Hevea guianensis Aubl.	3.30
Washington III	*Euterpe precatoria* Mart.	5.41
	Iriartea deltoidea Ruiz & Pav.	4.68
	Tetragastris altissima (Aubl.) Swart (sinonimia de *Protium altissimum* (Aubl.) Marchand)	3.76
Sarayacu	*Euterpe precatoria* Mart.	5.66
	Iriartea deltoidea Ruiz & Pav.	4.89
	Tetragastris altissima(Aubl.) Swart (sinonimia de *Protium altissimum* (Aubl.) Marchand)	3.83
Yhon Hittler	*Iriartea deltoidea* Ruiz & Pav.	22.64
	Brosimum alicastrum Sw.	13.60
	Otoba parvifolia (Markgr.) A. H. Gentry	7.18
Juan Raul 2	*Iriartea deltoidea* Ruiz & Pav.	21.64
	Otoba parvifolia (Markgr.) A. H. Gentry	6.46
	Quararibea wittii K. Schum. & Ulbr.	5.89
Yesica	*Tachigali amarumayu* Huamantupa, H. C. Lima & D. B. O. S. Cardoso	7.96
	Cecropia sciadophylla Mart.	4.74
	Helicostylis tomentosa (Poepp. & Endl.) J. F. Macbr.	4.40

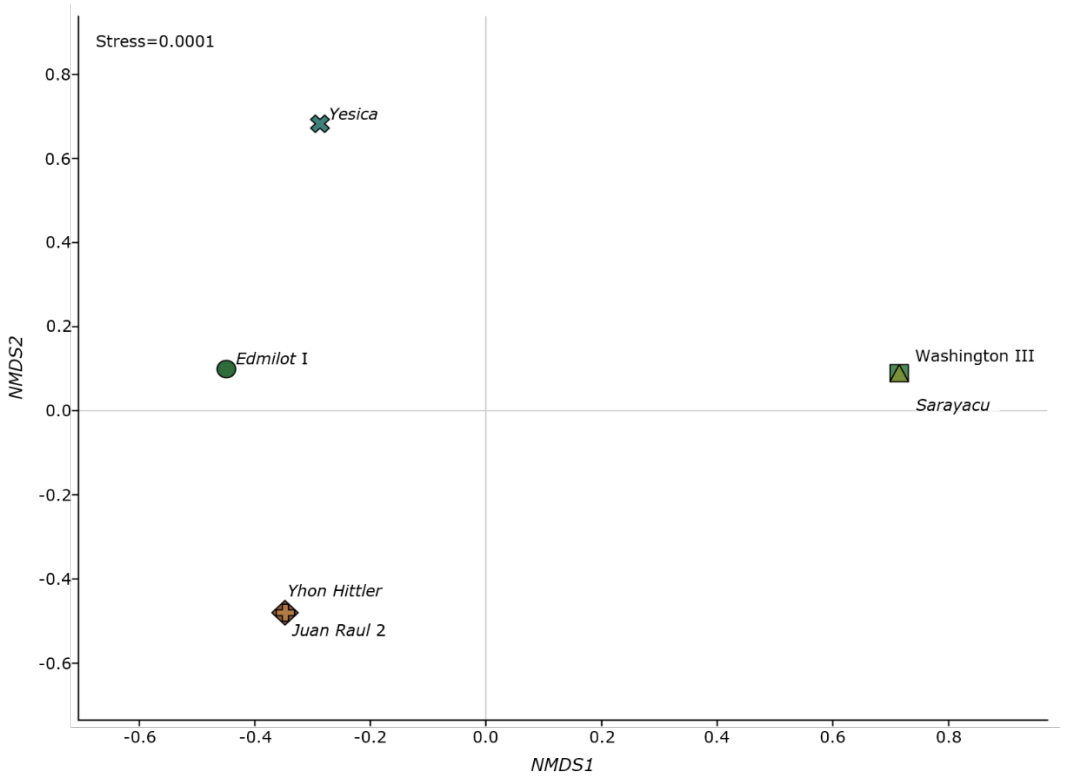
Yhon Hittler and *Juan Raul* 2 reported a much higher *IVI* for *Iriartea deltoidea* Ruiz & Pav., with values of 22.64 and 21.64 %, respectively. A few species often dominate recovering tropical communities, where a small group of taxa can account for a large portion of the forest's abundance and basal area (Asigbaase et al., 2019; Villa et al., 2019).

In *Yesica*, the greatest ecological importance was attributed *Tachigali amarumayu* Huamantupa, H. C. Lima & D. B. O. S. Cardoso (7.96 %), followed by *Cecropia sciadophylla* Mart. (7.74 %) and *Helicostylis tomentosa* (Poepp. & Endl.) J. F. Macbr.

(4.40 %). From a restoration perspective, the *IVI* makes it possible to identify species representative of the local structure, because it takes into account their abundance, spatial distribution, and contribution to the basal area. However, a high value alone is not proof of persistence, resilience, or the ability to accelerate succession. The selection of species for use in mining areas should complement the *IVI* with information on natural regeneration, tolerance to site conditions, and functional attributes related to establishment and growth (Gastauer et al., 2020). Consequently, *I. deltoidea* and *Euterpe precatoria* Mart. can be considered species that are structurally representative of several concessions, while *T. amarumayu* and *C. sciadophylla* provide evidence of a different local composition.

Floristic similarity

The floristic similarity revealed a marked differentiation among the six concessions. Washington III and *Sarayacu* showed the greatest similarity, with Jaccard values of 0.9620 and Bray-Curtis values of 0.9476 (Figure 3).



The closer the points are to each other, the greater the floristic similarity. *Stress*=0.0001.

Figure 3. *NMDS* clustering of six mining concessions based on Bray-Curtis dissimilarity.

In contrast, Washington III and *Sarayacu* showed virtually no similarities to *Juan Raul* 2, both in terms of both species presence and species abundance. These results indicate a considerable overlap in taxa among concession groups and show that similar species richness does not necessarily imply an equivalent floristic composition. A joint assessment of taxon identity and abundance is essential for identifying different trajectories of community reorganization, because changes in dominance may remain hidden when only richness or diversity values are compared (Chazdon et al., 2022).

Yhon Hittler and *Juan Raul* 2 reported a Jaccard similarity index of 0.2576, but a considerably higher Bray-Curtis similarity index of 0.6638. This difference indicates that they shared a limited proportion of taxa, although the common species had relatively similar abundances. This pattern is consistent with the high ecological

importance of *Iriartea deltoidea* in both concessions, where it accounted for more than 21 % of the *IVI*. The variation between the indexes shows that beta diversity reflects both species replacement and the distribution of species abundances—components that may respond differently to landscape configuration and heterogeneity (Juárez-Fragoso et al., 2024).

From a restoration perspective, these results indicate that a single concession does not represent the full range of plant diversity in the *Inambari* River basin. Washington III and *Sarayacu* can serve as examples of the same community structure, while *Edmilot* I, *Yesica*, and the group consisting of *Yhon Hittler* and *Juan Raul* 2 provide complementary floristic conditions. Selecting multiple reference sites incorporates spatial variability in the landscape and avoids setting restoration goals based on a single community, especially when connectivity, surrounding forest cover, and local conditions can influence vegetation establishment and composition during restoration (San-José et al., 2022).

The use of reference sites in restoration

The identified sites can be used complementarily to define reference attributes based on the conditions to be restored. Washington III and *Sarayacu* are examples of communities with high effective diversity and similar composition; *Edmilot* I provides values associated with greater species richness and basal area, and *Yesica* exhibits a distinct floristic composition with a more balanced distribution of dominant species. These attributes can be used to select native species, set composition and structure goals, and evaluate the progress of managed areas. Using multiple reference points accounts for the landscape's ecological variability and prevents setting restoration goals based on a single forest condition (Beauchamp & Shafroth, 2011; Ruiz-Jaén & Aide, 2005).

Conclusions

The six concessions differ in terms of effective diversity, structure, dominance, and floristic composition. Washington III and *Sarayacu* stand out for their high diversity of common species and high floristic similarity, while *Edmilot* I has the greatest observed species richness and basal area. *Yesica* complements these findings by reporting the highest effective number of dominant species and a distinct floristic composition. *Yhon Hittler* and *Juan Raul* 2 represent a condition of lower effective diversity and greater dominance of *Iriartea deltoidea*. The integration of these attributes allows identifying complementary reference sites that represent different ecological configurations of the landscape and provide comparative values to guide future restoration efforts in peri-urban forests affected by mining activities in the Peruvian Amazon.

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Conflict of interest

The authors declare that they have no conflicts of interest.

Contributions by author

Carlos Emerico Nieto Ramos and Luis Armando Nieto Ramos: conceptualization, fieldwork, and revision of the manuscript; Bayron Alexander Ruiz-Blandon: technical revision and editing of the manuscript; Efrén Hernández-Alvarez: analysis of information and fieldwork; Rosario Marilu Bernaola-Paucar: conceptualization, supervision, data analysis, and drafting of the manuscript. All authors reviewed and approved the final version of the manuscript.

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