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**Criseyda Román Córdova**
criseydaroman@alunos.utfpr.edu.br
Universidade Tecnológica Federal do Paraná
**Fabio Friso**
Centro Takiwasi
**Deayana Montenegro Bravo**
Universidad Nacional Agraria La Molina
**Edward Isla Ramírez**
Conservation International
**Juan Rubén Julca Torres**
University of Córdoba
**Joel Donazzolo**
Universidade Tecnológica Federal do Paraná

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# Agroforestry restoration led by Awajún Indigenous women: biodiversity patterns, carbon stocks and soil quality in degraded landscapes of the Peruvian Amazon

Criseyda Román Córdova[1*], Fabio Friso[2], Deayana Montenegro Bravo[3], Edward Isla Ramírez[4], Juan Rubén Julca Torres[5], Joel Donazzolo[1]

[1] Graduate Program in Agroecosystems, Federal University of Technology – Paraná (UTFPR), Dois Vizinhos, Paraná, Brazil
[2] Centro Takiwasi, Tarapoto, San Martín, Peru
[3] Faculty of Forest Sciences, Universidad Nacional Agraria La Molina, Lima, Peru
[4] Conservation International, Rioja, San Martín, Peru
[5] School of Agricultural and Forestry Engineering (ETSIAM), University of Córdoba, Córdoba, Spain
*Corresponding author: criseydaroman@alunos.utfpr.edu.br

**ORCID:** C. Román Córdova 0009-0004-1655-4582; F. Friso 0000-0001-5427-956X; D. Montenegro Bravo 0009-0005-5214-0165; E. Isla Ramírez 0009-0005-3097-6594; J. R. Julca Torres 0009-0008-8478-9593; J. Donazzolo 0000-0002-6331-0378

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**Author contributions**

**CRC:** Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **FF:** Project administration, Resources, Writing – review & editing. **DMB**: Project administration, Writing – review & editing. **EIR:** Project administration, Writing – review & editing. **JRJT**: Investigation, Writing – review & editing. **JD**: Supervision, Validation, Writing – review & editing.

**ABSTRACT:** Agroforestry systems (AFS) can serve as restoration strategies that integrate production, biodiversity conservation, and climate change mitigation; however, integrated empirical assessments of restoration-oriented AFS remain scarce in the Amazon. This study assessed biodiversity, carbon stocks and soil quality in AFS managed by Awajún Indigenous women in the Peruvian Amazon. Between 2022 and 2024, we compared a 2-year-old restoration AFS (SAF-R), an 8-year-old cacao AFS (SAF-C) and a reference primary forest (FP).

SAF-R stored 101.44 Mg C $ha^{-1}$, 5.2% more than SAF-C (96.39 Mg C $ha^{-1}$), with soil organic carbon (SOC) accounting for 96.7% of the total; in the absence of a baseline, the fraction attributable to restoration could not be quantified. FP stored 152.02 Mg C $ha^{-1}$. Tree diversity was higher in SAF-R (Shannon $H' = 2.74$; 63 species, including 17 morphospecies) than in SAF-C ($H' = 2.34$; 72 species, including 36 morphospecies). Over two years, SAF-R soil organic matter increased by 40.1% and available phosphorus by 34.3%, while exchangeable aluminum decreased by 57.1%; these trends require longitudinal monitoring.

The exploration of the convergence between Awajún traditional ecological knowledge and agroecological principles, through the Multiple Evidence Base approach, suggests that AFS led by Indigenous women are promising strategies for multifunctional restoration, with relevance to restoration policies, REDD+ (Reducing Emissions from Deforestation and Forest Degradation) mechanisms, and nature-based solutions.

**Keywords:** Agroforestry; Traditional ecological knowledge; Indigenous women; Soil quality; Carbon stocks

## 1. INTRODUCTION

The accelerated degradation of Amazonian ecosystems is one of the greatest socioecological challenges of the 21st century. The Amazon may be approaching an irreversible ecological tipping point that would compromise essential functions including global climate regulation, biodiversity conservation, and human well-being (Lovejoy and Nobre 2018). These changes, driven mainly by increasing deforestation, intensifying droughts, altered rainfall regimes, and wildfires, undermine the resilience of the Amazon (Barlow et al. 2016; Flores et al. 2024; Nobre et al. 2016; Silva et al. 2018). Since 2002, approximately 33.7 million hectares of primary forest have been degraded across the Amazon basin, with 4.5 million hectares lost in 2024 alone, driven mainly by agricultural and cattle ranching expansion (Finer et al. 2025). These critical transformations reduce the functional connectivity of ecosystems and sociocultural systems, thereby endangering the livelihoods of Indigenous peoples and local communities in the Amazon (Peña-Claros et al. 2025).

In the face of this multidimensional crisis, agroforestry systems (AFS) have emerged as a key strategy for reversing degradation, restoring ecosystem functionality, and supporting food security in the Amazon (Brancalion et al. 2019; Villa et al. 2020). Mature AFS can store three to four times more carbon than conventional croplands, with soil as the main reservoir, followed by aboveground biomass (Mazumder et al. 2025; Somarriba et al. 2013). AFS also have a large global restoration potential, with considerable benefits for climate adaptation and mitigation when strategically scaled up (Zomer et al. 2022). Successful restoration, however, requires more than planting trees (Holl and Brancalion 2020), and calls for multicriteria approaches that consider multiple ecosystem services, such as carbon storage, biodiversity, water regulation and social resilience, while avoiding reductionist solutions focused solely on carbon sequestration (Brancalion et al. 2019; Poorter et al. 2021a; Strassburg et al. 2020) or on the production of one or a few economically important species.

In this context, the traditional ecological knowledge (TEK) of the Awajún Indigenous people is an essential component of successful restoration, although it has historically been marginalized (Reyes-García et al. 2022). Indigenous peoples manage or hold tenure rights over about 25% of the global land surface and overlap with approximately 40% of protected areas and 36% of intact forest landscapes, highlighting their importance for biodiversity conservation (Fa et al. 2020; Garnett et al. 2018). This effectiveness is not accidental: over millennia, Amazonian Indigenous peoples have developed integrated management systems that create anthropogenic forests with a greater diversity of useful species than unmanaged ecosystems, challenging Western paradigms (Clement et al. 2021; Levis et al. 2024). The Awajún people of the Peruvian Amazon exemplify how TEK can be integrated into agroforestry practices, ecosystem restoration and territorial governance, guided by the principles of Tajimat Pujut ("good living" in the Awajún worldview), which integrates ecological, social and spiritual dimensions in sustainable land management (Federación Regional Indígena Awajún del Alto Mayo 2025). These principles align with agroecological tenets such as functional diversity, agroecological facilitation, and adaptive management, as proposed by Altieri and Toledo (2011), as well as with a participatory, transdisciplinary, and action-oriented agroecological approach (Méndez et al. 2013).

These knowledge systems are implemented in the Shampuyacu community, where the Asociación Bosque de las Nuwas (ABN), led by Awajún women, has, since 2014, developed a model that integrates the management of traditional knowledge with agroforestry production and community-based conservation (Enrico 2024). Awajún women combine ecological, technical, and spiritual dimensions in sustainable agricultural practices, which are key to improving livelihoods through biodiversity-based value chains (Bussmann and Sharon 2006; Navas Del Águila and Florida García 2025). Their work challenges one-size-fits-all, technocratic approaches to restoration and suggests that integrating Amazonian worldviews and traditional practices can broaden Western sustainability paradigms (Cassino et al. 2025; Clement et al. 2021; Mistry and Berardi 2016). Despite these contributions, management systems led by Indigenous women remain underrepresented in the scientific literature (Schmink and Gómez-Garcia 2015).

Although AFS are increasingly recognized as nature-based solutions (Álava-Núñez et al. 2025), studies that simultaneously address multidimensional indicators of biodiversity, soil quality recovery, aboveground and soil carbon stocks, and the role of women's TEK in Indigenous communities of the Amazon remain scarce.

This gap limits the recognition of Indigenous management systems in public policies as effective strategies for conservation, restoration and sustainable income generation.

In a degraded landscape managed by Awajún women of the ABN in the Shampuyacu native community (northern Peru), we compared a multistrata restoration AFS, a cacao AFS and a reference primary forest to analyze patterns of biodiversity, carbon stocks, and soil quality indicators along a restoration trajectory. Our specific objectives were to: a) characterize floristic composition and biodiversity indicators across land-use systems; b) quantify and compare carbon stocks in aboveground biomass and soil organic carbon; c) assess changes in soil quality associated with the different management systems; and d) explore the convergence between Awajún traditional ecological knowledge and the biophysical indicators of agroforestry management.

## 2. MATERIALS AND METHODS

### 2.1 Study area

The study was conducted in the Peruvian Amazon, in the Shampuyacu native community (5°47'48.2"S; 77°23'30.84" W), Awajún district, Rioja province, San Martín region, at 850 m a.s.l. (Fig. 1). The community has flat, non-flooding topography and lies within the tropical premontane moist forest life zone, with a mean annual precipitation of 1,800 mm, a mean temperature of 23 °C, and two well-defined seasons (dry and rainy). The predominant soils are Inceptisols (Fluventic Eutrudepts subgroup), developed from ancient alluvial materials on intermediate terraces of a well-drained plain, and are characterized by high acidity, low fertility and high aluminum saturation (Escobedo Torres 2007). The community, officially recognized in 1975, belongs to the Awajún Indigenous people and covers 4,926 ha (Ministerio de Cultura del Perú 2025). Migrant settlement brought illegal deforestation and urban and agricultural expansion (Ichikawa et al. 2014), converting a primary forest mosaic into agricultural landscapes of coffee, cacao, banana, and pineapple in an advanced state of degradation.

The ecosystems of the Awajún territory are of exceptional ecological value, with more than 600 bird, 80 mammal and 60 fish species recorded, in addition to the provision of essential ecosystem services for the entire Alto Mayo valley (Federación Regional Indígena Awajún del Alto Mayo 2025). The primary forest of Bosque de las Nuwas, used as the reference ecosystem in this study, is one of the last continuous forest remnants in a landscape more than 90% deforested (Vásquez Romero 2020).

These ecosystems face growing pressure from agricultural expansion, territorial conflicts, illegal logging and agrochemical use, which also accelerate the loss of traditional management practices (Federación Regional Indígena Awajún del Alto Mayo 2025). The women-led ABN initiative emerged as a local restoration response to this context.

### 2.2 Characterization of the study areas

The study systems are associated with the ABN restoration initiative, implemented by Centro Takiwasi and Conservation International (2022–2024). It promotes forest conservation and agroforestry restoration based on traditional knowledge, together with value chains for medicinal plants and other products. We compared (Fig. 1A–C): (i) a multistrata restoration agroforestry system (SAF-R), (ii) a cacao-based agroforestry system (SAF-C), and (iii) a primary forest used as the reference ecosystem (FP). Their characteristics are summarized in Table 1.

**Table 1. Characterization of the land-use types selected for this study**.

| Land-use type | Description |
|---|---|
| | ABN assisted-restoration and resilient-farm model, established in 2022 on 1.36 ha. History: >20 years of intensive use under rotational monocultures (coffee, banana, pineapple), resulting in degraded soils. Multistrata design (herbaceous, shrub and tree layers) mimicking natural succession. High density and diversification: 9,913 individuals of all species (including herbs and shrubs) were planted in the initial restoration phase, prioritizing medicinal (*Zingiber* sp., *Tynanthus polyanthus*, |

| | |
|---|---|
| Multistrata Agroforestry Restoration System (SAF-R) | *Physalis* sp., *Vanilla pompona*, *Stevia* sp.), food (*Manihot esculenta*, *Solanum sessiliflorum*, *Calathea allouia*, *Colocasia esculenta*, *Musa* spp.) and service species (*Erythrina edulis*, *Inga* spp.). Management includes continuous incorporation of living biomass, rotational green manuring (*Phaseolus vulgaris*, *Tithonia diversifolia*, *Erythrina poeppigiana*, *Tynanthus polyanthus*), and organic amendments (Bokashi) to restore organic matter and fertility and reduce acidity. |
| Cacao Agroforestry System (SAF-C) | System established in 2016 on 0.73 ha, with market-oriented production and traditional Awajún management: regular pruning, annual fertilization, and maintenance of vegetation cover. Established on a former coffee monoculture that had replaced the primary forest. Its composition and structure reflect low-intensity management and moderate diversification, typical of Amazonian family farming systems. |
| Primary Forest Reference Ecosystem (FP) | Fragment of Amazonian tropical moist forest (560.64 ha) surrounded by an intensive agricultural matrix (coffee, banana, pineapple). Dominated by timber species of ecological and commercial importance (*Calophyllum brasiliense*, *Cedrelinga cateniformis*, *Hieronyma oblonga*, *Aniba* sp., *among others*). It shows signs of historical selective logging and edge effects. As a descriptive reference, we used five 40 × 50 m plots with 20 × 20 m subplots, sampled by Vásquez Romero (2020), in an 8.9 ha area that was then managed by ABN; since 2024, the association has managed the entire 560.64 ha. |

**Note:** FP data come partly from secondary sources (aboveground biomass: Vásquez Romero 2020; soil organic carbon: Díaz Chuquizuta et al. 2016), and soil sampling depth differs between systems (FP: 0–20 cm; AFS: 0–30 cm).

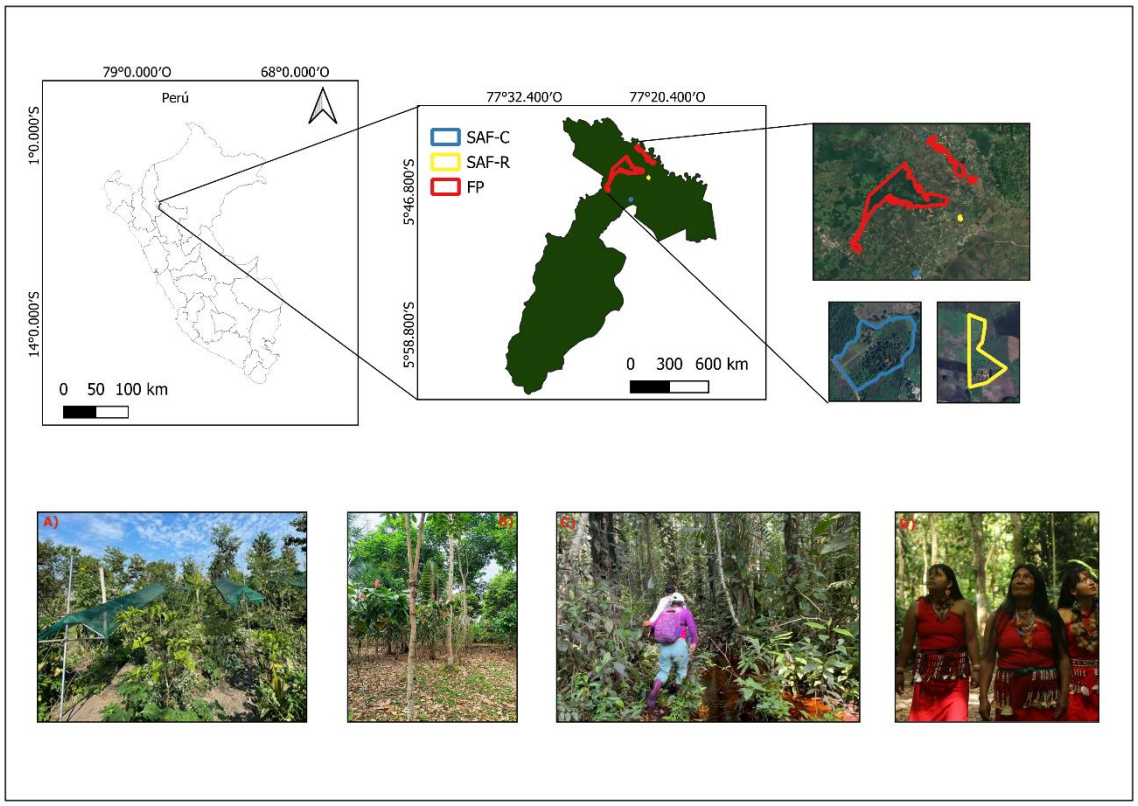



**Fig. 1.** Location of the study area and studied systems. Shampuyacu native community (San Martín, Peru) and sampled systems: SAF-R (1.36 ha), SAF-C (0.73 ha) and FP (Bosque de las Nuwas; 1.0 ha plot). Photographs: (A) SAF-R; (B) SAF-C; (C) FP; (D) an Awajún woman in the forest. Map lines delineate study areas and do not necessarily depict accepted national boundaries.

### 2.3 Floristic composition

Floristic diversity in the agroforestry systems (SAF-C and SAF-R) was assessed through complete censuses of the 0.73-ha and 1.36-ha plots, respectively. All woody individuals present in the plots were recorded in the floristic composition, regardless of size. Diameter, commercial height and total height were recorded for each individual. *Musa spp., individuals outside the validity range of the allometric equations, woody individuals with diameter at breast height (DBH) < 5 cm and palms < 0.5 m tall were included in the floristic composition but not in the aboveground biomass (AGB) estimate; short-cycle herbaceous species were excluded.* Botanical identification was carried out in the field using vernacular names validated by local Awajún experts and subsequently verified against taxonomic databases (Missouri Botanical Garden n.d.; Royal Botanic Garden n.d.). Species were classified into functional groups following the framework proposed by Nair (1993) and regional Amazonian authors (Barbosa et al. 2026; Guimarães et al. 2025; Isaac et al. 2024). Each unidentified individual was treated as a distinct morphospecies (operational taxonomic unit, OTU; coded R-NN-01 to R-NN-17 in SAF-R and C-NN-01 to C-NN-36 in SAF-C; Table S1) and included in species richness (S) to avoid underestimation. Primary forest reference data came from five 40 × 50 m plots (1.0 ha; DBH ≥ 30 cm) with nested 20 × 20 m subplots (0.20 ha; DBH ≥ 10 cm) in Bosque de las Nuwas, sampled by Vásquez Romero (2020). Diversity was quantified with the Shannon–Wiener index with Miller–Madow bias correction (H′; Eq. 1), the Simpson index (1−D; Eq. 2), Pielou's evenness (J′; Eq. 3) and the Margalef richness index (SR; Eq. 4) (Magurran 2003; Margalef 1993; Pielou 1974; Simpson 1949).

### 2.4 Estimation of carbon stocks

AGB was estimated from census data with species-specific allometric equations (Eqs. 5–11, Table S2; Andrade et al. 2008; Rueda Arana 2014; Rügnitz Tito et al. 2009; Segura et al. 2006, 2018), applied only to woody individuals within each equation's size range and using its required predictor variable. Equation 9, applied to *Erythrina edulis*, is a generic model for small trees in tropical moist forest, calibrated for diameters of 2.0–12.0 cm ($R^2 = 0.63$). Of the 673 individuals of this species, 605 (89.9%) fell within this range; estimates for the remaining 68 were extrapolated and are therefore more uncertain. The predictor variables were DBH for trees in general, diameter at 30 cm above the ground for *Theobroma cacao* and *Coffea arabica*, and diameter at 5 cm above the ground (DAC) for *Inga* spp. Basic wood density (ρ) was assigned in order of priority (species, genus, or regional value), with $\rho = 0.614$ g cm$^{-3}$ for the Amazon (Chave et al. 2006). AGB was thus estimated for 94.0% of individuals in SAF-C and 41.2% in SAF-R; the remaining individuals (*Musa* spp., non-woody plants, and individuals below the size thresholds) are included in the floristic composition but not in the biomass estimate. AGB data were converted to carbon using a conversion factor of 0.47, according to the Intergovernmental Panel on Climate Change (2019), yielding the aboveground biomass carbon stock (Mg C) (Eq. 12, Table S2).

Soil organic carbon (SOC) was estimated from composite soil samples collected at a depth of 0–30 cm, following the sampling protocol of the Peruvian Ministry of the Environment. In a sampling campaign specific to carbon stocks, conducted in 2024 independently of the physicochemical analysis described in Section 2.5, three composite samples per system were analyzed at the Instituto de Cultivos Tropicales (ICT) to determine the organic carbon concentration (%) and bulk density (g cm$^{-3}$). SOC stock (Mg C ha$^{-1}$) was calculated with Eq. 13 and total carbon dioxide equivalent ($CO_2e$) stock (Mg $CO_2e$ ha$^{-1}$) as (AGB carbon + SOC) × 44/12 (Eq. 14, Table S2).

For the primary forest, AGB values were taken from Vásquez Romero (2020), who reported 58.90 Mg C ha$^{-1}$ in five 40 × 50 m plots (2,000 m² each; 1.0 ha in total) following the ICRAF methodology. Because SOC values were not available for FP, we used data from Díaz Chuquizuta et al. (2016), who reported 93.12 Mg C ha$^{-1}$ for a forest with soil characteristics similar to those of the study site. Combining these sources involves three caveats: the AGB of Vásquez Romero (2020) considered individuals with DBH ≥ 30 cm in the plots and DBH ≥ 10 cm in the subplots, versus DBH ≥ 5 cm in this study; the SOC refers to 0–20 cm, versus 0–30 cm in the AFS; and primary forest necromass (16.74 Mg C ha$^{-1}$) was not included. All three caveats lead to an underestimation of the primary forest carbon stock.

## 2.5 Soil quality assessment of the agroforestry systems

Soil analyses covered two land-use units (SAF-R and SAF-C), with a time series only for SAF-R, using topsoil samples (0–30 cm) collected in accordance with the national soil sampling protocol (Ministerio del Ambiente 2014). Three samples were collected in SAF-R on October 8, 2022, at the start of the restoration project. During the monitoring campaign on May 29, 2024, one composite sample was collected in each of SAF-R and SAF-C. In SAF-R, this sample is a composite of the entire plot, unlike the three 2022 samples, which were collected separately from individual cultivation lots; this difference in sampling schemes should be considered when interpreting the 2022–2024 variation. Soil quality was assessed through physicochemical analyses (Table S3), including texture, pH, organic matter (OM), nitrogen (N), phosphorus (P), potassium (K), and exchangeable aluminum ($Al^{3+}$). All analyses were carried out at the ICT. For comparative purposes, the physicochemical parameters of the primary forest (FP) come from a survey by the Oficina Nacional de Evaluación de Recursos Naturales (ONERN), cited by Escobedo Torres (2007), and refer to the surface horizon (0–20 cm) of the Naranjillo locality in the Awajún territory of Shampuyacu. These data were used only as a descriptive reference.

## 2.6 Documentation of traditional agroecological principles

TEK documentation (2022–2024) followed free, prior and informed consent (FPIC) protocols developed by Centro Takiwasi and the ABN. The systematization of TEK was based on three complementary sources: (i) participatory field records in which Awajún women described practices, species and management criteria; (ii) the project's quarterly technical reports (2022–2024); and (iii) the Tajimat Pujut concept sheet (Federación Regional Indígena Awajún del Alto Mayo 2025).

The systematization and integration of documented TEK followed the Multiple Evidence Base (MEB) approach proposed by Tengö et al. (2014), which recognizes different knowledge systems as complementary sources for understanding social–ecological systems (Hill et al. 2020). Three analytical management axes were defined to link Awajún agroecological principles with measurable ecological indicators (Table S4): (i) biodiversity management (species management), associated with species diversity and the structural complexity of vegetation; (ii) land management (soil care), associated with SOC, organic matter and soil physicochemical attributes; and (iii) productive diversification (polycultures), associated with species richness and aboveground biomass. These indicators were integrated into a convergence matrix (Table S5). Axis–indicator associations were defined by the research team from field records and project reports and reviewed by all co-authors.

## 2.7 Data analysis

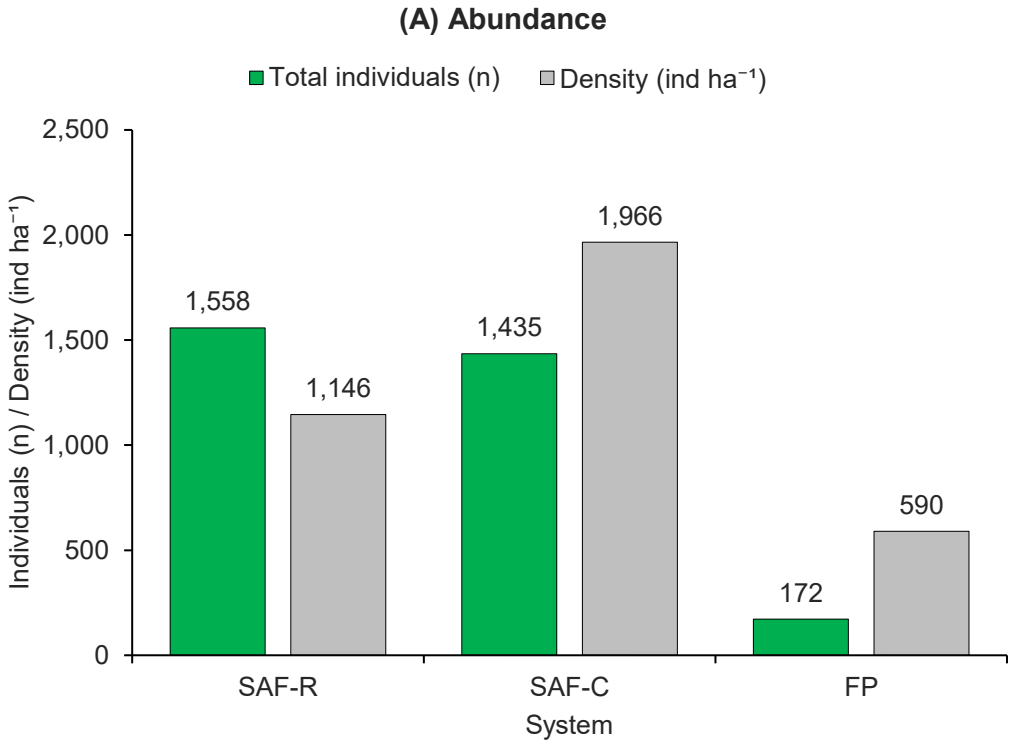
Because sampling followed the project's operational protocols, each land-use type (SAF-R, SAF-C, FP) was represented by a single management unit, as is typical of full-scale restoration case studies (Chazdon et al. 2016; Meli et al. 2017). Soil monitoring in 2024 had one composite sample per system (n = 3 for SAF-R in 2022). Given this design and the different sampled areas (FP = 1.0 ha, with 0.20 ha subplots; SAF-C = 0.73 ha; SAF-R = 1.36 ha), differences between systems were analyzed descriptively, without causal inference or statistical testing. To control for differences in sampling effort, species richness was compared using individual-based rarefaction curves standardized to the smallest observed sample size (n = 172 individuals). Floristic diversity indices were calculated in PAST v4.17 (Hammer et al. 2021), and the floristic composition and diversity plots (Figs. 2–4) and convergence matrix (Table S5) were produced in Microsoft Excel. The AGB of unidentified individuals (morphospecies) was estimated with the pantropical equation of Chave et al. (2014). Soil attributes were summarized descriptively (mean ± SD for SAF-R in 2022, n = 3; single values in 2024, n = 1). Ecological indicators were normalized using min–max scaling (0–1), with the minimum and maximum being the values observed in SAF-R, SAF-C and FP, and reclassified into four ordinal levels (1 = very low, ≤ 0.25; 2 = low, ≤ 0.50; 3 = moderate, ≤ 0.75; 4 = high, > 0.75). This classification does not represent absolute values but relative positions among systems (Chergui and Jiménez-Martín 2024) and was integrated into a convergence matrix following the MEB

approach (Díaz et al. 2015; Tengö et al. 2014). The soil texture triangle (Fig. S1) was produced in R v4.3.2 (R Core Team 2024), using the soiltexture package (Moeys 2024).

## 3. RESULTS

### 3.1 Floristic composition and functional groups

The multistrata restoration agroforestry system (SAF-R; 1.36 ha) contained 1,558 individuals (Fig. 2), 17 of which were morphospecies, belonging to 63 species and 24 botanical families, and distributed across five functional groups (Table S1). Among the 1,541 identified individuals, ecosystem-service species were the most represented (600), followed by food (424) and timber (395) species (Fig. 3). The richest families were Fabaceae (7 species), Rutaceae (5) and Arecaceae (4). The cacao agroforestry system (SAF-C; 0.73 ha) contained 1,435 individuals, 36 of which were morphospecies, belonging to 72 species and 21 botanical families, likewise organized into the five functional groups (Table S1). Productive species were strongly dominant, particularly *Theobroma cacao* (42.3% of total abundance), followed by *Erythrina edulis* (14.6%) and *Cedrelinga cateniformis* (6.9%), which together accounted for 63.8% of individuals. Food-production species dominated the 1,399 identified individuals (771; Fig. 3); the richest families were Arecaceae (7 species) and Fabaceae (5). Morphospecies accounted for only 1.1% of individuals in SAF-R and 2.5% in SAF-C and, because no function could be assigned to them, they were excluded from the functional group analysis. The primary forest reference ecosystem (FP; 1.0 ha, with nested 0.20 ha subplots) contained 172 individuals belonging to 15 species and 10 families, with timber species being the most abundant (63 individuals), followed by ecosystem services (53) and multipurpose (34) species. Stem density, which is comparable across plot sizes, was 1.7 times higher in SAF-C (1,966 ind $ha^{-1}$) than in SAF-R (1,146 ind $ha^{-1}$). In FP, the stratum-based density estimate was 590 ind $ha^{-1}$ (DBH ≥ 10 cm), which is not directly comparable with the AFS.



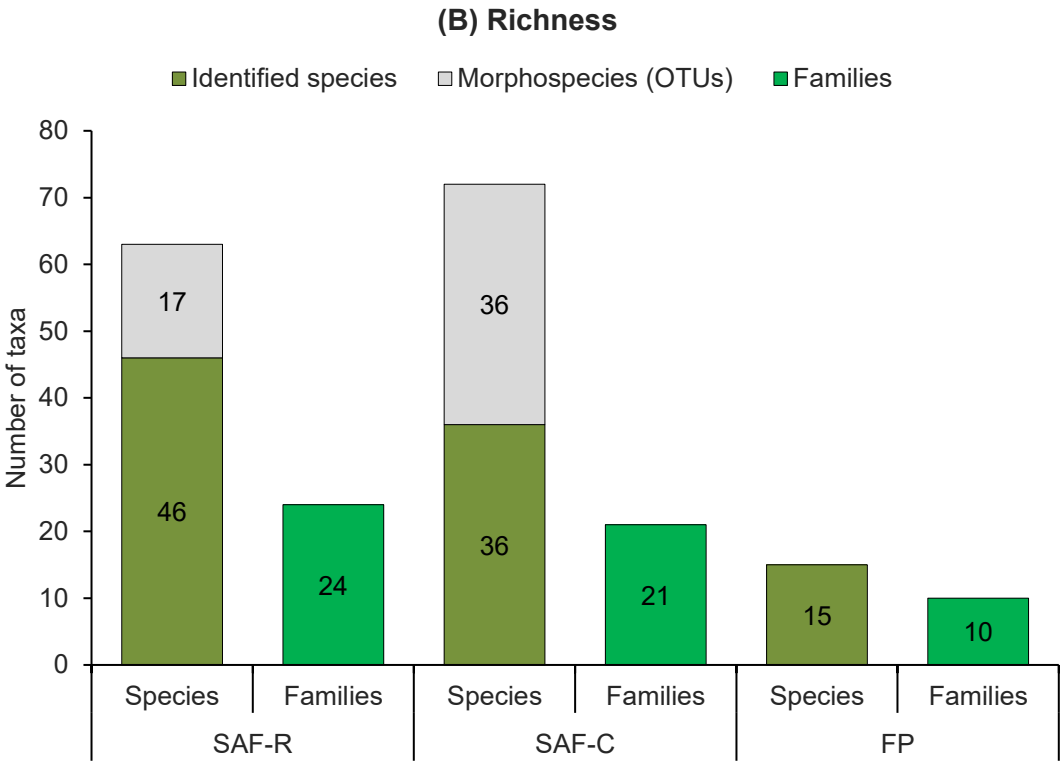
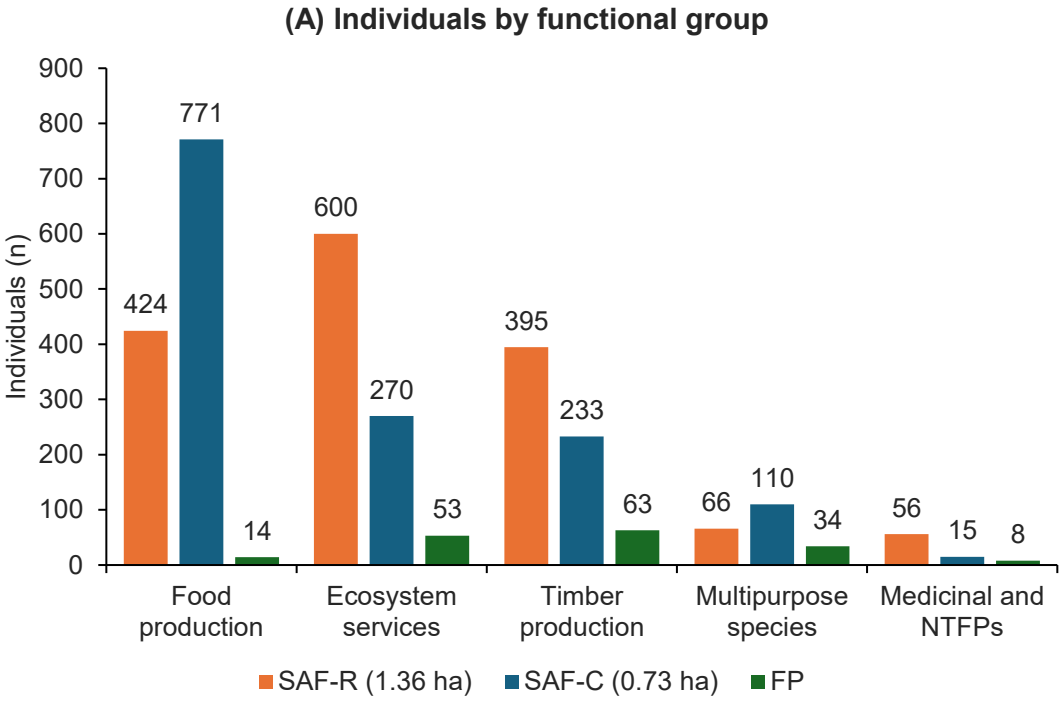



**Fig. 2.** Floristic composition of the study systems. (A) Total number of individuals and density (ind ha$^{-1}$), including morphospecies (OTUs); for FP, density stratified by DBH class. (B) Species richness, distinguishing identified species and morphospecies (OTUs), and number of botanical families (excluding OTUs). SAF-R: multistrata restoration agroforestry system; SAF-C: cacao agroforestry system; FP: primary forest.



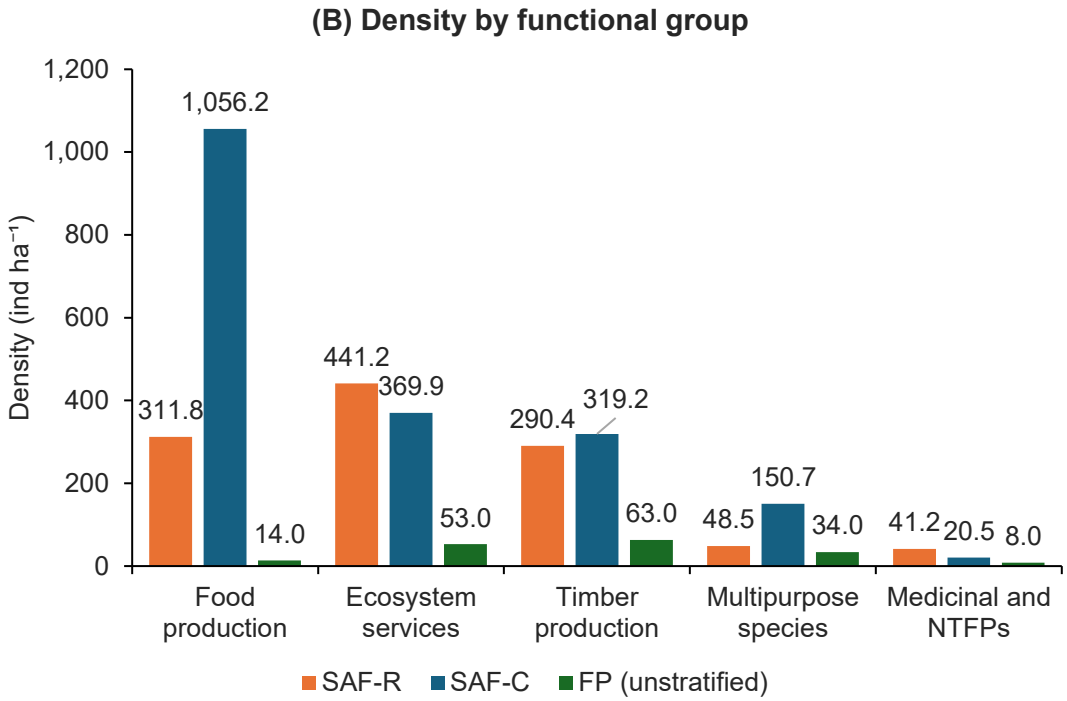



**Fig. 3.** Distribution of identified individuals by functional group: (A) number of individuals and (B) density (ind ha$^{-1}$). Morphospecies (17 in SAF-R and 36 in SAF-C) were excluded because no function could be assigned to them; hence, AFS densities differ slightly from those shown in Fig. 2. For FP, density by functional group was not stratified by DBH class (individuals / 1.0 ha); the total stratified density of FP is 590 ind ha$^{-1}$ (Section 3.1).

### 3.2 Tree species diversity

Individual-based rarefaction curves revealed differences in species richness among land-use systems (Fig. 4). After standardizing sampling effort to 172 individuals (FP), SAF-R showed higher expected richness than SAF-C. Observed richness was 63 species in SAF-R (46 identified and 17 morphospecies) and 72 in SAF-C (36 identified and 36 morphospecies); the higher raw richness of SAF-C is therefore largely explained by its high proportion of morphospecies, each represented by a single individual.

SAF-R showed the highest diversity (Table 2; H′ = 2.74) and intermediate evenness (J′ = 0.66). SAF-C showed lower diversity (H′ = 2.34) and evenness (J′ = 0.55), reflecting stronger dominance by productive species, particularly cacao. The primary forest showed H′ = 2.44 and J′ = 0.90, values presented as a descriptive reference from the Vásquez Romero (2020) inventory. Although the Margalef index indicated higher species richness in SAF-C (SR = 9.77), this index does not correct for sampling effort and is inflated by the 36 morphospecies in SAF-C (half of its observed richness). When OTUs are excluded, SAF-R exceeds SAF-C on all indices, including Margalef (6.13 vs. 4.83).

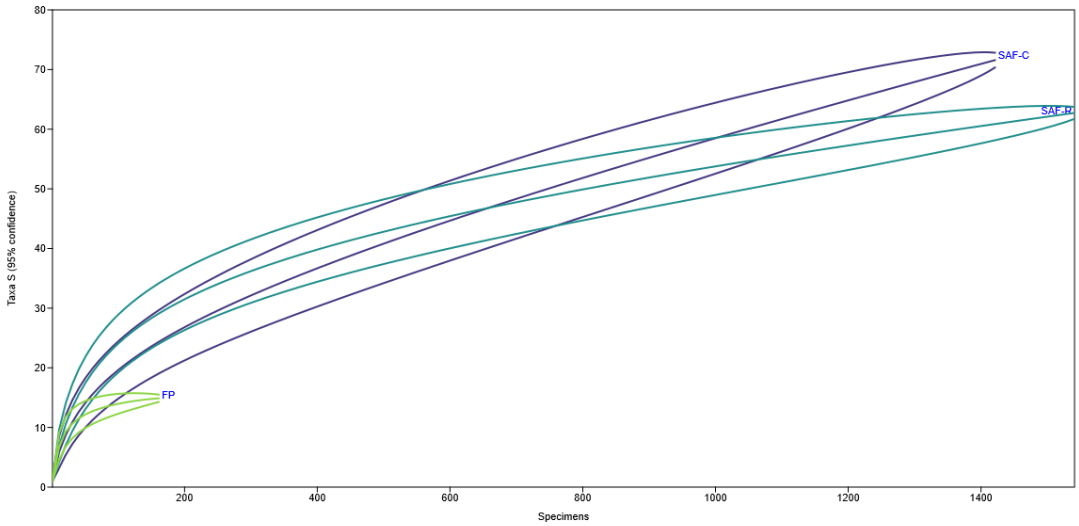



**Fig. 4.** Individual-based rarefaction curves of tree species richness in the study systems (SAF-R = 1.36 ha; SAF-C = 0.73 ha; FP = 1.0 ha, with 0.20 ha subplots). Curves were standardized to the smallest sample size (172 individuals). Solid lines represent expected species richness (Taxa S) and shaded bands the 95% confidence intervals. Morphospecies (OTUs) were included in the richness calculation. The FP curve (DBH ≥ 10 cm) is presented only as a descriptive reference.

**Table 2. Tree species diversity indices in the study areas**

| System | N | S | H′ | 1−D | J′ | SR |
|---|---|---|---|---|---|---|
| **SAF-R** | 1,558 | 63 | 2.74 | 0.87 | 0.66 | 8.43 |
| **SAF-C** | 1,435 | 72 | 2.34 | 0.79 | 0.55 | 9.77 |
| **FP** | 172 | 15 | 2.44 | 0.89 | 0.90 | 2.72 |

**Note:** N = number of individuals; S = species richness (including morphospecies); H′ = Shannon index with Miller–Madow bias correction; 1−D = Simpson index; J′ = Pielou evenness, calculated from the corrected H′; SR = Margalef richness index. AFS values are based on complete censuses of all individuals regardless of DBH; primary forest (FP) values were adapted from Vásquez Romero (2020) (DBH ≥ 10 cm; descriptive reference).

### 3.3 Carbon stocks and $CO_2e$ mitigation

Total carbon stocks were similar in the two agroforestry systems: SAF-R stored 101.44 Mg C $ha^{-1}$ (371.93 Mg $CO_2e$ $ha^{-1}$) and SAF-C 96.39 Mg C $ha^{-1}$ (353.45 Mg $CO_2e$ $ha^{-1}$), a difference of 5.2%, despite marked differences in age and management history (Table 3). However, carbon distribution among pools differed: aboveground biomass contributed 17.48 Mg C $ha^{-1}$ in SAF-C but only 3.37 Mg C $ha^{-1}$ in SAF-R. Soil organic carbon (SOC) was the main storage pool in both systems: 98.07 Mg C $ha^{-1}$ in SAF-R and 78.91 Mg C $ha^{-1}$ in SAF-C. However, in the absence of a 2022 SOC baseline, the SAF-R stock cannot be attributed to the restoration period. FP had the largest total stock (152.02 Mg C $ha^{-1}$; 557.39 Mg $CO_2e$ $ha^{-1}$), distributed between aboveground biomass (58.90 Mg C $ha^{-1}$) and SOC (93.12 Mg C $ha^{-1}$).

**Table 3. Carbon stocks by pool in the study ecosystems. Primary forest values are a lower bound (Section 2.4).**

| System | Area (ha) | AGB (Mg C ha⁻¹) | SOC (Mg C ha⁻¹) | Total carbon (Mg C ha⁻¹) | Total $CO_2e$ (Mg $CO_2e$ ha⁻¹) |
|---|---|---|---|---|---|
| **SAF-R** | 1.36 | 3.37 | 98.07 | 101.44 | 371.93 |
| **SAF-C** | 0.73 | 17.48 | 78.91 | 96.39 | 353.45 |
| **FP** | 1 | 58.90 | 93.12 | 152.02 | 557.39 |

**Note:** SAF-R and SAF-C: primary data. FP: AGB adapted from Vásquez Romero (2020), whereas soil organic carbon (SOC) was obtained from Díaz Chuquizuta et al. (2016).

### 3.4 Soil physicochemical attributes and quality

At the start of restoration (2022), the SAF-R soil had a sandy loam texture, high acidity (pH 4.54 ± 0.15), low nutrient availability, and high exchangeable aluminum content ($Al^{3+}$: 2.33 ± 0.59 cmolc $kg^{-1}$) (Table 4). By 2024, we observed increases in organic matter (+40.1%), nitrogen (+41.2%) and available phosphorus (+34.3%), as well as a marked reduction in exchangeable aluminum (−57.1%) and a slight increase in pH (from 4.54 to 4.90; +8.0%). Organic matter, nitrogen, and phosphorus contents approached or exceeded those of the reference FP, whereas pH remained well below (6.8); this comparison is only indicative, given the difference in sampling depth (0–30 vs. 0–20 cm). In contrast, despite its longer establishment time, SAF-C maintained high aluminum levels (3.50 cmolc $kg^{-1}$), low pH (4.30), and low calcium (0.50 cmolc $kg^{-1}$) and magnesium (0.13 cmolc $kg^{-1}$; Table S3) contents. Texture analysis (Fig. S1) showed that both AFS retained sandy loam textures (>60% sand), whereas FP had a more balanced distribution of sand, silt, and clay, consistent with a clay loam texture class. These differences probably reflect land-use history and past erosion rather than current management.

**Table 4. Soil physicochemical parameters in the study land-use systems and percentage change in SAF-R between 2022 and 2024 (full data in Table S3).**

| Parameter | Unit | SAF-R 2022 Mean ± SD | SAF-R 2024 | Δ % | SAF-C 2024 | FP (ref.) |
|---|---|---|---|---|---|---|
| pH | – | 4.54 ± 0.15 | 4.90 | +8.0% | 4.30 | 6.8 |
| OM | % | 3.37 ± 1.01 | 4.72 | +40.1% | 4.15 | 4.48 |
| N | % | 0.17 ± 0.05 | 0.24 | +41.2% | 0.21 | 0.20 |
| P | mg $kg^{-1}$ | 9.24 ± 1.68 | 12.41 | +34.3% | 9.54 | 13.3 |
| $Al^{3+}$ | cmolc $kg^{-1}$ | 2.33 ± 0.59 | 1.00 | −57.1% | 3.50 | n.d. |

**Note:** AFS data were obtained from laboratory analyses (0–30 cm). Primary forest (FP) data refer to the surface horizon (0–20 cm) and were adapted from Escobedo Torres (2007). Mean ± standard deviation for SAF-R (2022, n = 3); single values for SAF-R (2024) and SAF-C (2024, n = 1). n.d. = not determined.

### 3.5 Convergence between Awajún traditional management and biophysical indicators

The convergence analysis between the Awajún traditional management axes and the SAF-R biophysical indicators (Tables S4–S5) showed that relative classes varied among indicators within the same axis. On the biodiversity management axis, SAF-R obtained the highest classes for Shannon diversity (H′; class 4) and species richness (S; class 4), whereas Pielou evenness (J′; class 2) and aboveground biomass (class 1)

fell in the lower classes. The productive diversification (polyculture) axis reproduced this contrast: high species richness (class 4) and low aboveground biomass (class 1). On the land and soil care axis, SAF-R reached class 4 for soil organic carbon (SOC), organic matter (OM), and available phosphorus (P; normalized value of 0.76, close to the boundary between classes 3 and 4), whereas pH and exchangeable potassium (K) remained in class 1; for K, this class reflects a tie with SAF-C (0.05 cmolc $kg^{-1}$) rather than a lower value. No axis reached the highest class for all of its indicators. The observed values used for normalization are shown in Table 5.

**Table 5. Observed values of the biophysical indicators used in the convergence analysis for each land-use system.**

| System | Indicator | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | AGB C (Mg C $ha^{-1}$) | SOC (Mg C $ha^{-1}$) | OM (%) | pH | H′ | J′ | S | P (mg $kg^{-1}$) | K (cmolc $kg^{-1}$) |
| **SAF-R** | 3.37 | 98.07 | 4.72 | 4.90 | 2.74 | 0.66 | 63 | 12.41 | 0.05 |
| **SAF-C** | 17.48 | 78.91 | 4.15 | 4.30 | 2.34 | 0.55 | 72 | 9.54 | 0.05 |
| **FP** | 58.90 | 93.12 | 4.48 | 6.8 | 2.44 | 0.90 | 15 | 13.30 | 0.25 |

**Note:** SAF-R and SAF-C: data observed in 2024; FP: reference data (Vásquez Romero 2020; Díaz Chuquizuta et al. 2016; Escobedo Torres 2007). These values were used for the min–max normalization in Table S5. Abbreviations as in Table S5.

## 4. DISCUSSION

### 4.1 Floristic composition and functional diversity

The higher Shannon diversity of SAF-R (H′ = 2.74) compared with SAF-C (H′ = 2.34) is consistent with its restoration-oriented design, based on diversified agroecological principles (Altieri et al. 2015), and suggests that such systems can sustain high levels of biodiversity from the early stages. In diversified systems, the intentional introduction of multiple species promotes greater taxonomic and functional richness than in predominantly production-oriented systems (Niether et al. 2020; Somarriba et al. 2013).

The high-density multistrata design of SAF-R may accelerate functional recovery. In Neotropical secondary forests, the functional composition of communities progressively converges toward that of mature forests during succession (Poorter et al. 2021b), and early occupation of multiple spatial and temporal strata can accelerate this trajectory (De Souza Dutra et al. 2026). Similar intentional early-stage species selection has been described in Indigenous systems of the Brazilian Xingu, paralleling the diversification practices of Awajún women (Schmidt et al. 2021).

In contrast, SAF-C prioritizes short-term production for income generation. This reflects a trade-off between profitability and multifunctionality, as simpler systems provide fewer ecosystem services (Grass et al. 2020). Nevertheless, the retention of shade trees and associated tree species distinguishes these systems from monocultures, allowing them to conserve relatively high levels of biodiversity and carbon stocks (Isaac et al. 2024; Quaedvlieg and Lagneaux 2026).

The high levels of diversity recorded in SAF-R also reflect the TEK of Awajún women, who intentionally select food, medicinal, timber, multipurpose and ecosystem-service species (Levis et al. 2024). This structural heterogeneity increases niche complementarity, enhances nutrient cycling and strengthens the ecological stability of ecosystems in the face of environmental disturbances (Altieri and Toledo 2011; Méndez et al. 2013), a dynamic similar to that reported in tropical agroforests by Mazumder et al. (2025), in which species diversification contributed to restoring ecological processes typically associated with natural forests.

Although SAF-C shows lower diversity, both systems incorporate native tree species, such as *Cedrelinga cateniformis* and *Ocotea* sp., which, in fragmented tropical landscapes, supports their role as biodiversity reservoirs and ecological corridors between forest remnants (Barlow et al. 2016; Díaz-Cháux et al. 2025; Montagnini 2020).

The FP reference (n = 172 individuals; DBH ≥ 10 cm; 1.0 ha) covers a minimal fraction of the 560 ha of the Bosque de las Nuwas; the actual richness of the forest is probably much higher. Rarefaction is therefore used to compare the two AFS, not to rank them against FP.

### 4.2 Carbon stocks and climate mitigation potential along a restoration trajectory

The SOC of FP (93.12 Mg C $ha^{-1}$; 0–20 cm) is consistent with the estimates of Mendoza-Lopez et al. (2024), who reported SOC stocks of up to 131.4 Mg C $ha^{-1}$ at the same depth. The FP aboveground biomass value adopted (58.90 Mg C $ha^{-1}$; Vásquez Romero 2020) was chosen for its proximity to the study plots but is lower than other regional estimates (84.5–300.3 Mg C $ha^{-1}$), so the AFS–FP comparison is a lower bound of the actual gap.

The total carbon stock of SAF-R (101.44 Mg C $ha^{-1}$) was already comparable to that of SAF-C (96.39 Mg C $ha^{-1}$), despite being about 6 years younger. High species diversity, permanent soil cover and intensive organic management may accelerate carbon recovery; however, in the absence of a baseline, part of the SOC in SAF-R may have been inherited from previous land use.

Their carbon pools, however, differed: in SAF-R, SOC accounts for 96.7% of total carbon, reflecting inherited soil carbon and organic inputs from litter, fast-growing species (*Tynanthus polyanthus*, *Tithonia diversifolia*, *Erythrina edulis*, *Inga* spp.) and Bokashi. SAF-C showed a more balanced distribution (SOC 81.9%; AGB 18.1%), reflecting eight years of tree growth, including *Cedrelinga cateniformis*, *Theobroma cacao,* and *Erythrina edulis*. This contrast suggests that soil is the main carbon pool in early restoration stages (96.7% in SAF-R), while the contribution of aboveground biomass increases progressively as the system matures, as described for tropical agroforests (Somarriba et al. 2013; Zomer et al. 2022).

The aboveground biomass stocks observed in SAF-C fall within the range reported for cacao agroforestry systems in the Peruvian Amazon (Goñas et al. 2022). At only 8 years, SAF-C held 17.48 Mg C $ha^{-1}$, above the 13.64 Mg C $ha^{-1}$ reported for young systems (8–15 years) and below the 24.86 Mg C $ha^{-1}$ of mature ones (30–40+ years), possibly reflecting its high density of associated trees.

In contrast, the SOC stocks observed in SAF-C (78.91 Mg C $ha^{-1}$) and SAF-R (98.07 Mg C $ha^{-1}$) remained below the values reported by Goñas et al. (2022) (119.96–131.96 Mg C $ha^{-1}$). These differences probably reflect soil texture, floristic composition and management history.

Together, the three systems suggest a recovery trajectory, represented by the conceptual gradient SAF-R → SAF-C → primary forest (Fig. 5). Similar trajectories, with carbon, biodiversity and functionality increasing together, have been described for tropical forest restoration (Brancalion et al. 2019; Chazdon et al. 2016; Poorter et al. 2021a).

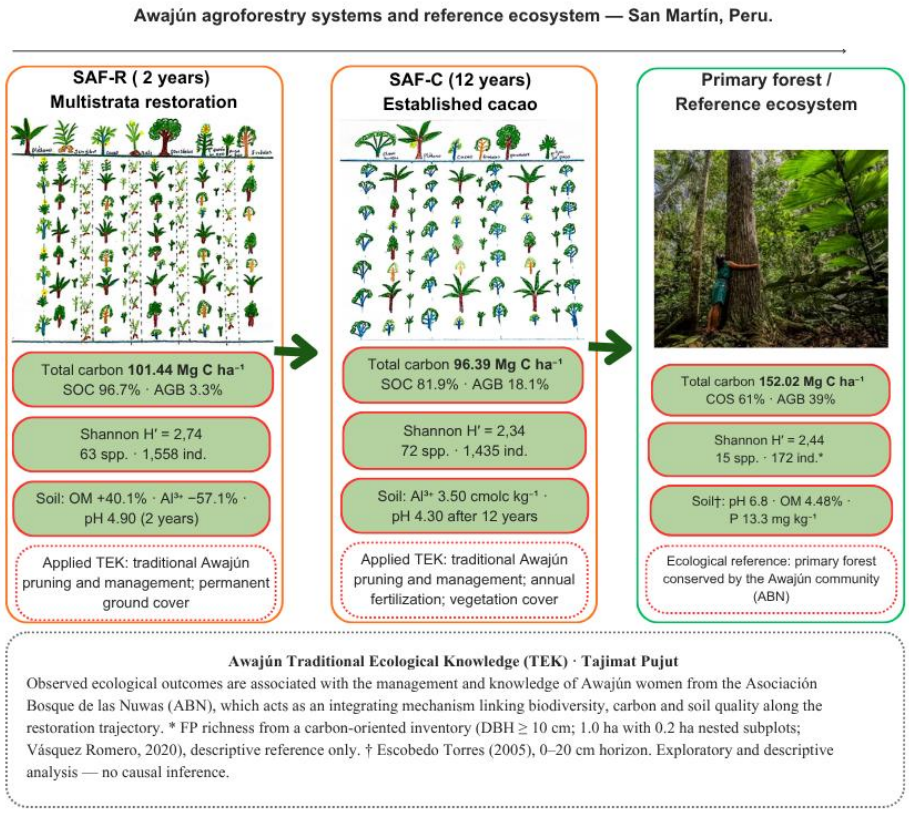



**Fig. 5. Conceptual trajectory of biodiversity and carbon recovery across managed agroforestry systems and primary forest in the Awajún community of Shampuyacu.**

As SAF-R matures, aboveground biomass gains should raise its total stock further. Stocks of 353–372 Mg $CO_2e$ $ha^{-1}$ make these systems relevant for climate mitigation and local economies, especially in Amazonian Indigenous territories that act as important carbon reservoirs (Bodin et al. 2025). As an illustration, 100 ha under the SAF-R model would store about 10,144 Mg C (37,193 Mg $CO_2e$), of which only the aboveground biomass (about 337 Mg C; 1,235 Mg $CO_2e$ in two years) can be confidently attributed to restoration.

Diversified AFS managed on the basis of Awajún TEK can thus be a promising nature-based climate solution for Amazonian agricultural landscapes (Álava-Núñez et al. 2025; Brancalion et al. 2019; Zomer et al. 2022).

### 4.3 Soil quality improvement under agroforestry management

The early improvements observed in the soil chemical attributes of SAF-R suggest that diversified agroforestry systems can initiate edaphic recovery processes within a few years of establishment. In tropical ecosystems, soil quality responds more quickly to changes in vegetation cover and management practices than structural components such as tree biomass, making it one of the earliest indicators of ecological restoration (Marques et al. 2025; Souza et al. 2025).

The 57.1% reduction in exchangeable aluminum ($Al^{3+}$) is the clearest sign of soil chemical recovery in this study, although the 2024 value is based on a single sample. In acidic tropical soils, $Al^{3+}$ is the main phytotoxic form of aluminum, restricting root growth, nutrient uptake, and microbial activity (Bojórquez-Quintal et al. 2017; Kochian et al. 2015). The continuous incorporation of organic matter through green manures, Bokashi and plant residues promotes the formation of stable organo-aluminum complexes, thereby reducing $Al^{3+}$ activity in the soil solution and improving cation exchange capacity (Antonangelo and Koenig 2026; Castro et al. 2015). This process may explain the simultaneous decrease in $Al^{3+}$ and

increase in pH, organic matter and available phosphorus in SAF-R, even without conventional liming, consistent with results obtained in cacao agroforestry systems (Arévalo-Gardini et al. 2015) and in family-farm AFS in the Amazon (Marques et al. 2025; Souza et al. 2025).

In contrast, SAF-C maintained high $Al^{3+}$ levels (3.50 cmolc $kg^{-1}$) and acidic pH (4.30) after 8 years of establishment, possibly reflecting lower organic inputs and plant diversity, although land-use history and initial soil conditions may also contribute. These results suggest that the chemical recovery of tropical soils depends not only on the presence of trees but also on the intensity and quality of the agroecological management adopted (Altieri et al. 2015; Mazumder et al. 2025; Somarriba et al. 2013).

Although texture and exchangeable bases remain far from FP values, the two-year improvements in SAF-R suggest that intensive agroecological practices can accelerate fundamental processes of soil functional recovery (Poorter et al. 2021a; Souza et al. 2025).

### 4.4 Convergence between Awajún traditional ecological knowledge and agroecological principles

The high diversity and initial soil improvements in SAF-R are consistent with intentional species diversification, biomass recycling and multistrata arrangement, mechanisms that increase the multifunctionality and resilience of agroecosystems (Altieri et al. 2015; Nicholls and Altieri 2018). Similar principles underpin Indigenous land management systems, where functional diversity sustains productivity and ecological stability (Galhena et al. 2013; Gonçalves et al. 2021; Mijatović et al. 2013).

In the Awajún context, these practices express Tajimat Pujut, a principle of reciprocity between people and nature: the selection of food, medicinal, and service species, the continuous incorporation of biomass into the soil, and the multistrata arrangement of crops integrate production, ecological restoration, and collective well-being (Federación Regional Indígena Awajún del Alto Mayo 2025; Gudynas 2011; Navas Del Águila and Florida García 2025). In Awajún communities of the Imaza district, this knowledge still guides species selection and cacao agroforestry management (Gurbillón et al. 2025).

Awajún TEK is transmitted orally across generations, especially by women, through everyday practice; according to participants, it incorporates cultural norms that regulate the timing and manner of plant propagation, the selection of vegetative material and the relationship with species regarded as “mother plants.” These practices include traditional protocols related to women's life cycles that guide the planting or collection of certain species, as well as practices of respect and requests for permission before collecting propagules or planting species such as cassava (*Manihot esculenta*). Although rarely documented in the scientific literature, these norms show that Awajún TEK encompasses not only knowledge about species and ecological processes but also social and cultural norms that regulate interactions among people, plants and territory.

The convergence between Awajún TEK and agroecology also resonates with the concept of biocultural restoration, according to which ecosystem recovery is intrinsically linked to the maintenance of knowledge systems and reciprocal relationships between human communities and their territories (Cassino et al. 2025; Kimmerer 2011; Mistry and Berardi 2016).

A central dimension of this process is the leading role of Awajún women. As the main managers of food, medicinal and multipurpose species, they are key to maintaining the functional diversity of agroforestry systems, a pattern widely documented in Indigenous and traditional communities (Galhena et al. 2013; Howard 2003; Mijatović et al. 2013). Although this contribution often remains underrepresented in restoration and territorial governance policies (Schmink and Gómez-Garcia 2015), the results suggest that strengthening the role of Indigenous women can increase the effectiveness of restoration strategies in the Amazon.

### 4.5 Implications for Amazon restoration policies, gender equity and scalability

Our results are consistent with the recognition of AFS as nature-based solutions capable of integrating climate change mitigation, biodiversity conservation and rural development (Brancalion et al. 2019; Strassburg et al. 2020; Zomer et al. 2022). Their carbon stocks could also open access to climate finance, including voluntary carbon markets and REDD+. However, implementing these instruments in Indigenous territories must ensure free, prior, and informed consent, strengthen community governance, and guarantee a fair and equitable distribution of the benefits generated (Bodin et al. 2025; Osborne et al. 2024).

A central contribution of this study is to document ecological outcomes achieved under the leadership of Awajún women in planning and managing the agroforestry systems, consistent with evidence that women's participation strengthens food security, biodiversity conservation, and the resilience of agri-food systems (Njuki et al. 2022; Quisumbing et al. 2023).

Restoration policies in the Amazon may thus be more effective when they explicitly incorporate TEK and promote the participation of Indigenous women in governance and decision-making processes. Although this is a case study, its management principles could be adapted to other Amazonian Indigenous communities with similar socio-ecological conditions. Scaling up requires participatory monitoring and financing instruments that recognize the ecological, social and cultural benefits of Indigenous AFS.

### 4.6 Methodological limitations and future research agenda

This exploratory case study relied on data from a restoration project whose sampling was set by operational objectives and budget. Without system-level replication, differences among systems describe patterns consistent with management but do not support causal inference or generalization (Chazdon et al. 2016; Meli et al. 2017). Soil changes should be read as trends: 2024 monitoring relied on one sample per system, and baseline coefficients of variation in SAF-R (18–30% for organic matter, N, $Al^{3+}$ and P) were of the same order as the reported changes. The two campaigns (October 2022 and May 2024) also differed in season, which may affect moisture-sensitive parameters such as pH and $Al^{3+}$.

Primary forest data came from previous studies with different diameter thresholds and soil depths (Section 2.4), so AFS–FP comparisons are indicative and underestimate the FP stock, and the lack of a 2022 SOC baseline prevents attributing SAF-R SOC to restoration. The absence of biological soil quality indicators, such as microbial biomass, enzymatic activity, and macrofauna, limits understanding of the ecological mechanisms underlying improvements in edaphic attributes (Souza et al. 2025).

Future studies should incorporate replicated plots, long-term monitoring, standardized sampling protocols and biological indicators, and extend research to other Awajún communities and Amazonian Indigenous peoples.

## 5. CONCLUSIONS

This case study suggests that agroforestry restoration led by Awajún women in the Peruvian Amazon can deliver measurable ecological outcomes across multiple dimensions within the first two years of implementation. SAF-R reached a total carbon stock comparable to that of an 8-year-old cacao system, mostly held as SOC, and showed initial improvements in soil quality and higher species diversity ($H' = 2.74$ vs. 2.34) than the established cacao system — all within a framework explicitly guided by Awajún TEK and the Tajimat Pujut principle of well-being. The exploration of the convergence between Awajún TEK and contemporary agroecological science, through the Multiple Evidence Base approach, suggests that Indigenous management systems are not only culturally valuable but also potentially effective strategies for landscape restoration. SOC was the dominant carbon pool across all systems; because its dynamics under restoration could not be quantified without a baseline, soil monitoring from establishment onward is essential to assess short-term AFS restoration trajectories. These findings support the recognition of Indigenous-led, women-managed AFS as promising nature-based solutions for biodiversity conservation, climate change mitigation and sustainable land management in the Amazon. Integrating them into REDD+ frameworks, conservation strategies and payment for ecosystem services programs, with mechanisms that recognize and compensate Indigenous women's contributions, is both scientifically and ethically important.

## Statements and Declarations

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**Data availability** The data supporting this study are included in the Supplementary Information. Additional data are available from the corresponding author on reasonable request, subject to the community's FPIC for traditional knowledge.

**Competing interests** This work was carried out without any conflict of interests between the authors, structures and institutions involved.

**Ethics approval and consent to participate** The Shampuyacu community granted free, prior and informed consent for this study, including the use of images.

**Artificial intelligence (AI):** Claude (Anthropic) was used for language editing and translation; the authors reviewed all content and take full responsibility for the manuscript.

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