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Examining functional diversity in two plant communities under ecological restoration in Farallones de Cali, Colombia

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ABSTRACT

Introduction: Functional diversity is crucial in understanding species performance and monitoring ecological restoration processes. In Valle del Cauca, Colombia, where only a small percentage of tropical dry forest remains, ongoing ecological restoration efforts are vital. However, monitoring of restoration efforts is typically not conducted.

Objective: To compare the functional diversity of two plant communities, restored two and eight years ago, in the Loma Larga reserve, Colombia.

Methods: We assessed nine functional traits in the five most significant species of each community. The analysis included contrast tests for functional trait differences, as well as functional diversity indices.

Results: The 8-year community displayed greater values for maximum height, diameter at breast height, and specific leaf area. Conversely, the 2-year community exhibited higher leaf thickness. Moreover, the 8-year community presented the highest values in the functional indices: richness, evenness, divergence, dispersion, and specialization.

Conclusions: Ecological restoration had a positive impact on plant communities, as evidenced by increased functional diversity and structural complexity in the 8-year community compared to the 2-year community. This suggests that ecological succession processes advance significantly over time, leading to more resilient and functionally diverse communities. The analysis of functional traits stands out as an effective tool for monitoring the success of restoration and guiding future efforts in critically threatened ecosystems such as tropical dry forests.

Keywords: ecological succession; functional ecology; functional traits; plant communities; tropical dry forest.

RESUMEN

Examinando la diversidad funcional en dos comunidades vegetales bajo restauración ecológica en Farallones de Cali, Colombia

Introducción: La diversidad funcional se usa para entender el desempeño de las especies y monitorear procesos de restauración ecológica. En el Valle del Cauca, Colombia, solo queda un pequeño porcentaje del bosque seco tropical original, por lo que los planes de restauración ecológica son necesarios, pero no se realiza monitoreo de estos.

Objetivo: Comparar la diversidad funcional de dos comunidades vegetales, con dos y ocho años desde la restauración ecológica en la reserva Loma Larga, Colombia.

Métodos: Se midieron nueve rasgos funcionales para las cinco especies más importantes de cada comunidad. Los análisis incluyeron pruebas de contraste para diferencias entre los rasgos funcionales, e índices de diversidad funcional.

Resultados: La comunidad de 8 años presentó mayores valores de altura máxima, diámetro a la altura del pecho, y área foliar específica. La comunidad de 2 años exhibió mayores valores de grosor foliar. La comunidad de 8 años presentó los mayores valores en los índices funcionales: riqueza, equitatividad, divergencia, dispersión, y especialización.
Conclusiones: La restauración ecológica tuvo un impacto positivo en las comunidades vegetales, evidenciado por una mayor diversidad funcional y complejidad estructural en la comunidad de 8 años en comparación con la de 2 años. Esto sugiere que los procesos de sucesión ecológica avanzan significativamente con el tiempo, resultando en comunidades más resilientes y funcionalmente diversas. El análisis de rasgos funcionales se destaca como una herramienta efectiva para monitorear el éxito de las restauraciones y guiar futuros esfuerzos en ecosistemas críticamente amenazados como el bosque seco tropical.

Palabras clave: sucesión ecológica; ecología funcional; rasgos funcionales; comunidades vegetales; bosque seco tropical.

INTRODUCTION

Functional diversity (FD) examines the connection between ecosystem diversity, structure, and function. It assesses biological success by comparing functional traits (FTs) among species and calculating FD indices across communities (Mason & de Bello, 2013). FTs encompass individual measurements of morphological, physiological, and phenological characteristics that can be extrapolated to the community level (Córdova-Tapia & Zambrano, 2015). These traits enable the evaluation of species' growth, reproduction, and survival, as well as their responses to environmental factors and their impact on ecosystem processes (Tedesco et al., 2023). Salgado-Negret (2016) stated that FTs provide insights into the responsiveness of plant communities to climate change and the effects of environmental gradients on interspecific variation. This author also pointed out that plant FTs are categorized into vegetative, foliar, and regenerative traits. Vegetative traits offer information about persistence, competition, and longevity; foliar traits are linked to establishment; and regenerative traits are associated with dispersal and colonization (Rosell et al., 2022).

FD has emerged as an approach for monitoring and evaluating anthropogenic impacts on ecosystems, as it is more sensitive to environmental changes than species loss alone (Tedesco et al., 2023). FD has been used to assess the recovery of degraded areas during restoration processes by analyzing FTs and comparing FD indices (Qin et al., 2016; Rosell et al., 2022). Using FTs in restoration studies and projects has gained attention due to the ease of measuring soft traits and the important insights that they provide (Carlucci et al., 2020). For example, tree height (Ht) and diameter at breast height (DBH) are used to understand carbon storage dynamics within plant communities (Mensah et al., 2016). Similarly, leaf thickness (LT) correlates with hydric balance and herbivory protection (Sandoval-Granillo & Meave, 2023), while specific leaf area (SLA) is linked to light capture efficiency and water regulation (Mensah et al., 2016).

Building on these trait-based insights, functional diversity is quantified using indices that capture different aspects of trait distribution within communities. The main FD indices proposed by Mason et al. (2005) include richness (FRic), evenness (FEve), and divergence (FDiv). Other indices such as specialization (FSpe) (Villéger et al., 2010) and dispersion (FDis) (Laliberté & Legendre, 2010) have also been proposed. These indices provide insights into community functioning patterns and their variations along environmental gradients (Mason & de Bello, 2013). For example, high species richness and FEve are related to a low likelihood of losing functional groups in a plant community (Fonseca & Ganade, 2001). Although the FD field of research has increased in recent years, there are still information gaps in several ecosystems globally. Most conservation studies have focused on tropical moist forests, and tropical dry forests (TDFs) remain poorly understood in comparison (Siyum, 2020). Furthermore, TDFs are critically endangered, and the use of FD may give insights into the resilience of these ecosystems that are facing climate change and anthropic disturbances (Dexter et al., 2018).

Colombia's TDF has experienced a significant decline, with over 90 % of its original cover lost due to agricultural and livestock expansion, deforestation, and mining (Ruíz et al., 2023). The TDF ecosystem is highly fragmented and critically endangered, with Valle del Cauca having 6 303 ha of remaining natural state TDF and 53 184 ha of small, unconnected fragments (García & González-M., 2019). In the Loma Larga reserve, situated in the foothills of the Farallones de Cali, patches of TDF face various stressors, such as the invasion of species like bracken fern (*Pteridium aquilinum* (L.) Kuhn), forest fires, grazing, and deforestation. Ecological restoration efforts have aimed to mitigate TDF loss in the Loma Larga area. These efforts have included revegetation using native plant species and suppressing bracken fern in the restoration zones. However, systematic monitoring of these restoration areas to evaluate their progress and outcomes has yet to be conducted (Corredor, G., personal communication). Monitoring is a crucial component of restoration processes, as it enables the evaluation and potential adjustment of activities to enhance the long-term effectiveness and success of the restoration program (Ruíz et al., 2023).

Since FD is an effective tool for evaluating restored areas, this research aimed to evaluate and compare functional diversity traits and indices between two restored plant communities in the Loma Larga reserve, situated in the piedmont of Los Farallones de Cali. Additionally, this study sought to assess the progress of the restoration process in the examined plant communities by utilizing functional diversity as an analytical tool.

MATERIAL AND METHODS

Study area: We conducted the research in the ecological restoration areas of the Loma Larga Reserve (3°20' N & 76°33' W), located in El Peón village, foothills of the Farallones de Cali, township of Pance, municipality of Santiago de Cali, Valle del Cauca, Colombia. Fieldwork took place between March and May 2022. The reserve encompasses an altitudinal range of 1 100 to 1 350 m.a.s.l., with average temperatures between 17 and 24 °C, and annual rainfall from 1 220 to 1 640 mm (Sardi et al., 2018). The area represents a transitional zone between the TDF and premontane rainforest (Sardi et al., 2018). The plant species composition in the area includes *Jacaranda caucana* Pittier, *Calliandra pittieri* Standl., and *Cecropia angustifolia* Trécul, among others (Botina & García, 2005; Sardi et al., 2018).

Experimental design: We chose two zones within the ecological restoration areas to conduct our study, including an older community that had undergone restoration eight years ago and a more recent community that had undergone restoration two years ago. Native plant species were planted in both zones, while introduced species, specifically *Clitoria fairchildiana* R.A. Howard and *Acacia mangium* Willd., were used in the 8-year community. Ten rectangular plots measuring 25 x 4 m were randomly established in each community, resulting in a total area of 1 000 m^2 per community (Rangel & Velázquez, 1997). We calculated the Importance Value Index (IVI) in each community following the methodology proposed by Rangel and Velázquez (1997). We sampled individuals with a DBH greater than 1 cm and followed the measurement approach described by Leverett and Bertolette (2013). Likewise, we identified the species using the species guide by Botina and García (2005), with validation performed at the CUVC Herbarium of the Universidad del Valle.

To identify the most significant species, we ranked them using their IVI. Based on this ranking, we selected the top five species with the highest IVI in each community, ensuring that these five species collectively represented at least 50 % of the total IVI within each community. We then randomly selected five individuals from each of the five previously identified species per community, following the methodology outlined by Salgado-Negret et al. (2016), resulting in a total of 25 individuals sampled per community. Finally, we used reflective tape to mark these individuals and took measurements for three vegetative traits, five foliar traits, and two regenerative traits.

Functional traits: The vegetative FTs assessed for each species included bark type, classified according to Ramírez-Padilla and Goyes-Acosta (2004). We measured Ht and DBH following the approach proposed by Leverett and Bertolette (2013). Regarding foliar FTs, we employed the methodology outlined by Pérez-Harguindeguy et al. (2013). We collected ten leaves from each individual, for a total of 250 leaves per community. We characterized leaf type and the presence of indumentum for each species. Additionally, we measured LT using a REXBETI digital micrometer, dry weight using a Mettler Toledo® analytical balance, and leaf area using ImageJ software (Schneider et al., 2012). We calculated SLA following the methodology proposed by Salgado-Negret et al. (2016); for species with compound leaves, we randomly selected a leaflet for measurements (Pérez-Harguindeguy et al., 2013). For regenerative FTs, we characterized fruit type and dispersal syndrome based on a literature review, following guidelines by Pérez-Harguindeguy et al. (2013).

For quantitative FTs, we conducted two-sample tests to compare the mean values between the communities. We used Mann-Whitney tests to compare LT, Ht, and SLA; and a Student's t-test to compare DBH. These statistical analyses were performed using PaST (Hammer et al., 2001). For functional diversity analysis, we computed a PCA analysis, as well as the FRic, FEve, FDiv, FDis, and FSpe indices using the "mFD" package (Magneville et al., 2022) in R 4.4.1 with RStudio (R Core Team, 2024).

RESULTS

Community composition: The composition of plant communities differed between the 8-year and 2-year restoration areas at the landscape level. The 8-year community featured a closed canopy with abundant leaf litter in the understory and scattered patches of bracken fern. In contrast, the 2-year community had an open canopy with minimal leaf litter and was dominated by grass cover. A total of 494 individuals were identified across both areas, with 277 individuals belonging to 30 species in the 2-year community and 217 individuals belonging to 31 species in the 8-year community (SMT 1).

Figure 1 shows the distribution of diametric classes in both communities. The 2-year community had a higher proportion of individuals in diameter classes I (79 %) and II (16 %), with a significant decline in class III (5 %), and no individuals in classes IV and above. In contrast, the 8-year community had a lower percentage of individuals in classes I (58 %) and II (13 %), with a gradual decrease from class III to VIII: 8 % in class III, 8 % in class IV, 5 % in class V, 4 % in class VI, 3 % in class VII, and 1 % in class VIII. There were no individuals in class IX, and only one *Ladenbergia oblongifolia* (Mutis) L. Andersson individual in class X (0.5 %). Both communities exhibited a reverse J-shaped distribution pattern (Fig. 1).

Regarding the IVI, the five species with highest IVI (55.2 % in total) in the 2-year community were *Miconia rubiginosa* (Bonpl.) DC.-20.1 %, *Miconia minutiflora* (Bonpl.) DC.-12.5 %, *Erythroxylum citrifolium* A.St.-Hil.-9.4 %, *Miconia prasina* (Sw.) DC.-7.4 %, and *Persea caerulea* (Ruiz & Pav.) Mez.-5.7 %. In the 8-year community, the five species with the highest IVI (63.2 %) were *Didymopanax morototoni* (Aubl.) Decne. & Planch.-25.2 %, *Henriettea seemannii* (Naudin) L.O. Williams-11.4 %, *M. minutiflora*-9.9 %, *C. fairchildiana*-8.6 %, and *Eugenia egensis* DC-8.1 %. The only species

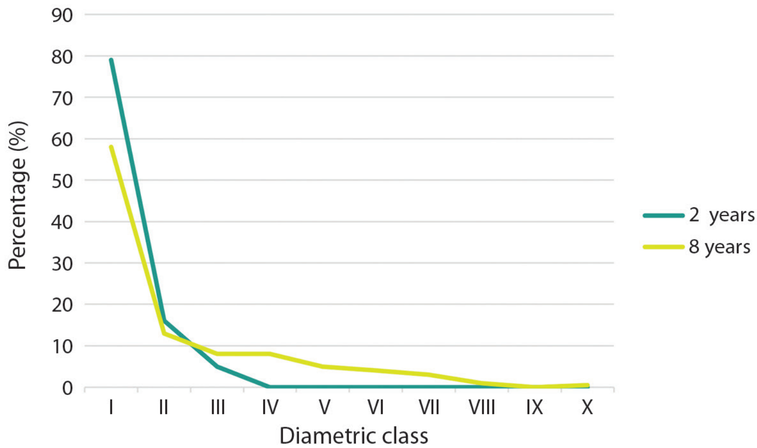

Fig. 1. Comparison of the diameter class distribution in each community.

Table 1
Summary of functional traits in the Loma Larga Reserve.

Species	IVI (%)	Lf	Im	Bk	Ft	Sd	LT (mm)	SLA (cm^2/g)	Ht (m)	DBH (cm)
8-year community										
D. morototoni	25.2	Co	Pu	Le	Be	Zo	0.27 ± 0.05	68.6 ± 33.4	10.2 ± 1.6	14.3 ± 5.5
H. seemannii	11.4	Si	Pu	Fi	Be	Zo	0.13 ± 0.02	209.9 ± 35.4	5.7 ± 2.0	8.8 ± 5.3
M. minutiflora	9.9	Si	Gl	Fi	Be	Zo	0.09 ± 0.02	196.9 ± 49.5	6.0 ± 0.5	5.8 ± 0.8
C. fairchildiana	8.6	Co	Gl	Le	Lg	Au	0.10 ± 0.01	226.2 ± 38.2	7.9 ± 2.3	15.6 ± 9.0
E. egensis	8.1	Si	Gl	Fi	Be	Zo	0.14 ± 0.02	117.1 ± 23.6	4.3 ± 1.2	3.1 ± 3.1
Trait's mean value							0.15 ± 0.07	163.7 ± 71	6.3 ± 2.9	9.5 ± 7.0
2-year community										
Species	IVI (%)	Lf	Im	Bk	Ft	Sd	LT (mm)	SLA (cm^2/g)	Ht (m)	DBH (cm)
M. rubiginosa	20.1	Si	Pu	Fi	Be	Zo	0.49 ± 0.08	70.7 ± 13.1	3.4 ± 0.4	6.1 ± 2.1
M. minutiflora	12.5	Si	Gl	Fi	Be	Zo	0.17 ± 0.03	130.6 ± 42.7	3.1 ± 2.0	3.1 ± 2.9
E. citrifolium	9.4	Si	Gl	Fi	Be	Zo	0.25 ± 0.02	11.2 ± 2.4	3.5 ± 1.1	2.5 ± 1.0
M. prasina	7.4	Si	Pu	Fi	Be	Zo	0.20 ± 0.02	84.5 ± 22.0	4.9 ± 1.3	6.0 ± 3.0
P. caerulea	5.7	Si	Gl	Le	Dr	Zo	0.21 ± 0.02	9.17 ± 12.8	2.5 ± 0.3	2.1 ± 0.6
Trait's mean value							0.27 ± 0.12	99.0 ± 31.7	4.1 ± 1.7	3.9 ± 2.4

Lf: Leaf type, Co: Compound leaves, Si: Simple leaves; Im: Indumentum presence, Gl: Glabrous, Pu: Pubescent; Bk: Bark type, Le: Lenticellate, Fi: Fissured; Ft: Fruit type, Lg: Legume, Be: Berry, Dr: Drupe; Sd: Seed dispersal, Au: Autochory, Zo: Zoochory; LT: Leaf thickness; SLA: Specific leaf area; Ht: Height; DBH: Diameter at breast height.

shared by both communities was *M. minutiflora*. The selected species were also the most abundant (SMT 1), except for *Genipa americana* L., whose individuals were smaller and had a limited impact on the IVI.

Functional traits and diversity indices: Table 1 summarizes the evaluated FTs, including qualitative traits with their corresponding character states for each species, and quantitative traits with average values and standard deviations for each species. The most frequent character states for the five qualitative FTs evaluated in the two communities were simple leaf, glabrous indumentum, fissured bark, berry-like fruit, and zoochorous dispersal. Regarding quantitative FTs, the contrast tests revealed significantly higher mean values of Ht

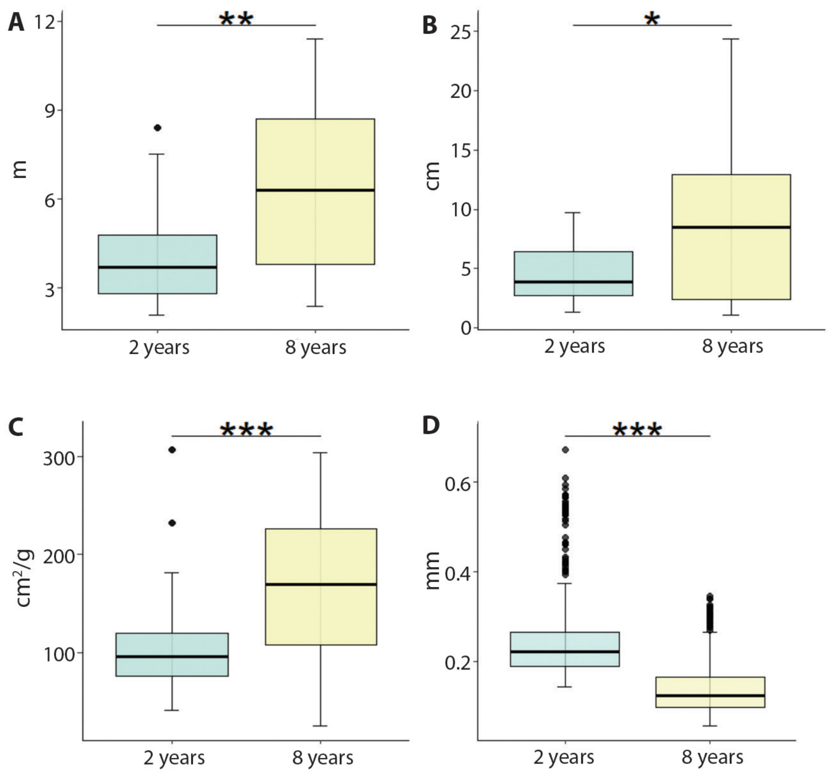

Fig. 2. Comparison between quantitative traits in each community. **A.** Height. **B.** Diameter at breast height. **C.** Specific leaf area. **D.** Leaf thickness. Significant differences are indicated by asterisks, where ** p ≤ 0.01, *** p ≤ 0.001.

(Fig. 2A), DBH (Fig. 2B), and SLA (Fig. 2C) in the 8-year community. Finally, the 2-year community exhibited a significantly higher mean LT value (Fig. 2D).

The position occupied by each species in the functional space is shown in Fig. 3A. The cumulative percentage of variance explained by PC1 and PC2 was 73.8 %. The values obtained for the FD indices (2-year community vs. 8-year community) were: 0.012 vs. 0.032 for FRic (Fig. 3B), 0.539 vs. 0.916 for FEve (Fig. 3C), 0.867 vs. 0.907 for FDiv (Fig. 3D), 0.308 vs. 0.784 for FDis (Fig. 3E), and 0.424 vs. 0.782 for FSpe (Fig. 3F). All indices exhibited higher values in the 8-year community compared to the 2-year community. Among the indices, FRic had the lowest values. The smallest difference between the two communities was obtained for the FDiv index, whereas the greatest differences between the two communities were found for the FDis, FEve, and FSpe indices.

DISCUSSION

Plant communities: The two areas studied exhibited a reverse J-shaped curve regarding the diametric classes, which is typical of early successional forests. As time progresses, the abundance of individuals shifts towards higher diameter classes due to biomass accumulation. This shift facilitates the replacement of younger individuals by older ones, reflecting the succession dynamics of a plant community (Imaña-Encinas et al., 2021). The species with highest IVI selected in the two communities represent the vegetation of the TDF ecosystem in Valle del Cauca, except for the introduced species *C. fairchildiana* (Fabaceae), according to Bernal

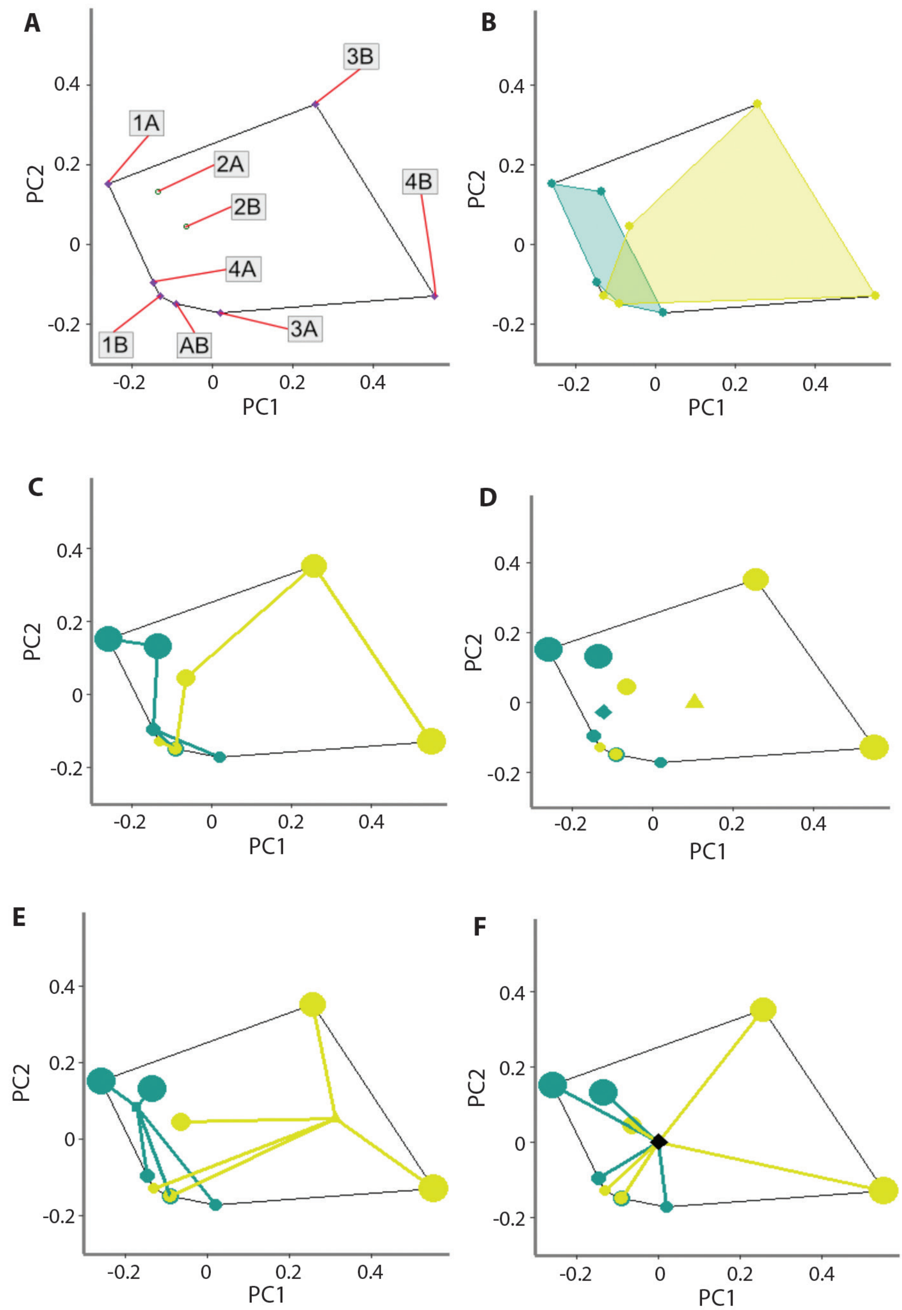

Fig. 3. Comparison of functional diversity indices between the two communities. **A.** Position of species in the functional space. **B.** Functional richness. **C.** Functional evenness. **D.** Functional divergence. **E.** Functional dispersion. **F.** Functional specialization. In Figure 3A, A denotes 2-year community species, B denotes 8-year community species, and AB denotes species occurring in the two communities. **1A.** *M. rubiginosa*, **2A.** *M. prasina*, **3A.** *P. caerulea*, **4A.** *E. egensis*, **1B.** *E. citrifolium*, **2B.** *H. seemannii*, **3B.** *D. morototoni*, **4B.** *C. fairchildiana*, **AB.** *M. minutiflora*. Bluish green represents the 2-year community, whilst olive yellow represents the 8-year community. The axes are the PCoA axes in the Functional Space: where PC1 is driven by DBH ($p = 0.0077$); Height ($p = 0.0230$); Leaf type ($p = 0.404$) and Bark type ($p = 0.0201$), whilst PC2 is driven by SLA ($p = 0.0457$) and Indumentum presence ($p = 0.0143$).

et al. (2016). Most of the sampled species are pioneer plants with a shrubby habit, except for *P. caerulea* (Lauraceae), *D. morototoni* (Araliaceae), and *C. fairchildiana*, which are arboreal, fast-growing species typically found in an intermediate successional stage (da Silva et al., 2020; Sardi et al., 2018). *D. morototoni* and *C. fairchildiana* were exclusively found in the 8-year community and exhibited the tallest height and largest DBH among the sampled individuals. Conversely, young *P. caerulea* individuals were only present in the 2-year community, resulting in lower Ht values for this species.

C. fairchildiana is a species native to Brazil and introduced to Colombia. It has been observed to form root nodules through symbiotic relationships with nitrogen-fixing bacteria, making it suitable for restoring areas with degraded soils (da Silva et al., 2020). These characteristics made it an appropriate choice for the initial stage of the restoration program in the Loma Larga reserve. *D. morototoni* is a fast-growing native tree with palmate compound leaves that accumulate as leaf litter in the understory (da Silva et al., 2020). The genus *Miconia*, from the family Melastomataceae, was represented by three species, all native and characterized by a fast-growing shrubby habit and high abundance in the TDF (Sardi et al., 2018). However, only *M. minutiflora* occurred in both communities. According to the restoration plan, a combination of native and introduced species, including *C. fairchildiana*, was initially used; the restoration plan was subsequently refined and focused solely on native species. According to information from Corredor (personal communication), no one intentionally planted *Miconia* or *D. morototoni* species, suggesting that their presence in the sampled areas resulted from natural establishment, indicating ecosystem recovery and a link with other patches (Ruíz et al., 2023). *E. citrifolium* (Erythroxylaceae), *E. egensis* (Myrtaceae), and *H. seemannii* (Melastomataceae) are native pioneer shrubs that are characteristic of the TDF species assemblage (Corredor-Londoño et al., 2020). *P. caerulea* is a native tree, reaching heights of up to 20 m, and is typical of the TDF. This is a valuable species for its landscape quality; it is used in various urban contexts (Núñez-Florez et al., 2019) and is commonly found in forests at an intermediate successional stage (Sardi et al., 2018).

Functional traits: The two communities differed in their structural composition, with the 8-year community exhibiting traits typical of a more advanced successional stage, compared with the younger community. However, the 8-year community was still at an early successional stage when compared to intermediate and advanced plant communities in the Colombian TDF (Ruíz et al., 2023). Younger individuals tend to invest more metabolic energy in vertical growth rather than in accumulation and secondary growth (Matsuo et al., 2021). This explains the lower SLA values found in the 2-year community as well as the greater LT, which aids in moisture retention and protection against herbivory, providing thus essential benefits in the early stages of succession (Ruíz et al., 2023), when plants are vulnerable to temperature shifts, droughts, and solar irradiance as occurs in the TDF (Sandoval-Granillo & Meave, 2023).

The dissimilarities in DBH values found in the two communities may be explained by the rapid growth of individuals in the 8-year community, along with light heterogeneity, which allows a higher interception of light by canopy trees (Matsuo et al., 2021). With a direct source of light and higher SLA values, as was seen in the 8-year community, individuals can perform further secondary growth that leads to differentiation in the diametric classes (Matsuo et al., 2021; Rosell et al., 2022). Furthermore, plant communities in early and intermediate successional stages are adapted to intense light conditions, and display a wide range of qualitative traits that improve dispersion and establishment (Carlucci et al., 2020). These species are mainly light-demanding species that create the canopy cover and the conditions for the establishment and growth of the shade-tolerant species that will replace them in later succession (Matsuo et al., 2021).

It is worth emphasizing that Ht, DBH, SLA, and LT are soft traits with straightforward, cost-effective measurement methods, making them valuable for incorporation into restoration project planning (Carlucci et al., 2020). These metrics provide an accurate representation of energy and carbon fluxes, as well as trends within plant communities (Carlucci et al., 2020; Pérez-Harguindeguy et al., 2013), and the analysis of these patterns can reveal the successional stage of plant communities (Matsuo et al., 2021; Rosell et al., 2022; Ruíz et al., 2023). Additionally, FTs can guide adjustments in restoration project planning. For example, if a community exhibits lower trait values, this might be indicative of incorrect species selection or of the influence of variables that may be identified and managed. The key is to identify a set of FTs that are easily measurable and highly informative about the specific conditions and dynamics of the community.

Functional Diversity Indices: The variation in FD indices between the two communities could be attributed to the structural complexity typically associated with advanced successional stages, driven by the temporal gradient (Ruíz et al., 2023). For instance, intermediate successional species such as *D. morototoni* and *C. fairchildiana* contributed significantly to the increased FD indices in the 8-year community. These species exhibited higher FT values linked to biomass accumulation, including Ht, DBH, SLA, and presence of compound leaves (Li et al., 2022).

The presence of *D. morototoni* and *C. fairchildiana* in the 8-year community also contributed to higher FSpe, which quantifies the differentiation among species within the community. Elevated FSpe values indicate a community composed of specialist species that exploit distinct ecological niches (Córdova-Tapia & Zambrano, 2015). Consequently, the specialized species in the older community increased Fric, which measures the volume of ecological space occupied by the community. This niche differentiation enhances resilience to environmental fluctuations and invasions by other species, while also increasing ecosystem productivity (Córdova-Tapia & Zambrano, 2015; Schleuter et al., 2010).

It is important to note that the relatively low FRic values observed in this study resulted from analyzing only five species in each community. However, the higher productivity observed in the 8-year community may be linked to the greater divergence in resource acquisition strategies among dominant species, as represented by FDiv (Córdova-Tapia & Zambrano, 2015; Schleuter et al., 2010). Although FDiv was slightly higher in the 8-year community, the difference with the 2-year community was minimal, suggesting that both communities contained species with considerable variability in resource acquisition strategies (Córdova-Tapia & Zambrano, 2015). This variability was further evidenced by FDis, which showed the most significant differences between the two communities. The higher FDis in the 8-year community reflected greater FT specialization and variability, indicating an enhanced capacity to respond to environmental changes and suggesting increased resilience (Cooke et al., 2019).

Additionally, the 8-year community displayed lower species dominance and a more equitable abundance distribution, as indicated by the higher FEve. This index reflects uniformity in resource use among species, as well as the distribution of species abundance within the community (Mason & de Bello, 2013). In contrast, the 2-year community exhibited lower FEve values, indicating the presence of species conglomerates where a few dominant species overshadowed others with poor representation (Córdova-Tapia & Zambrano, 2015; Schleuter et al., 2010).

Applications and limitations: The presence of key species with desirable functional traits (e.g. *D. morototoni* in Colombian TDF) can be an indicator of a more advanced successional stage. Additionally, integrating plant community metrics, such as the IVI, FTs, and FD indices would enhance restoration projects and their monitoring strategies. (Carlucci et al., 2020). Comparing plant communities across temporal gradients is essential for tracking functional trait dynamics and evaluating long-term community development, whereas high FD indices correlate with enhanced ecosystem services, which provide a wide range of benefits for local communities dependent on those ecosystems (Matsuo et al., 2021; Ruíz et al., 2023).

However, several limitations must be addressed. First, selecting FTs that accurately represent community dynamics is challenging, particularly in species-rich ecosystems. In such cases, IVI can help (Joshi et al., 2024; Rangel & Velázquez, 1997). Second, measuring FTs and obtaining FD indices often require years of data collection to become meaningful, and differences observed within specific communities may not be generalizable to others (Carlucci et al., 2020; Mason & de Bello, 2013; Rosell et al., 2022). Despite these challenges, further research is urgently needed, particularly in vulnerable ecosystems such as tropical dry forests, where effective and practical restoration protocols are critical for ecological and social resilience.

The results of this study emphasize the positive impact of ecological restoration efforts on the functional diversity and structural complexity of plant communities in the Loma Larga reserve. The 8-year community exhibited a more advanced successional stage characterized by higher functional trait values (e.g., Ht, DBH, and SLA) and elevated functional diversity. These metrics suggest that the older community has a broader functional niche, greater species differentiation, and more equitable distribution of species abundances compared to the 2-year community. The results emphasize the ecological benefits of using functional traits as indicators to monitor the progress and effectiveness of restoration initiatives. Functional diversity analysis provides insights into the contribution of species to ecosystem resilience, stability, and productivity. In particular, the presence of key species, such as *D. morototoni* and *C. fairchildiana,* highlights their significant role in shaping community dynamics and enhancing ecosystem functionality.

This research contributes to the growing understanding of ecological restoration in tropical dry forests, a critically endangered ecosystem. The temporal gradient revealed by the comparison of 2-year and 8-year restored communities highlights the importance of long-term monitoring to evaluate the effectiveness of restoration programs. Future efforts should focus on refining restoration protocols by prioritizing species selection based on functional traits, improving connectivity between restored patches, and addressing challenges such as invasive species management. By providing a robust framework for assessing restoration outcomes, this study supports the development of evidence-based strategies to restore and conserve tropical dry forests. It also underscores the need for further research to explore the role of functional diversity in enhancing ecosystem resilience and its applications in restoration ecology. Continuous investment in restoration initiatives and monitoring will be critical for safeguarding these ecosystems and the services they provide to both biodiversity and human communities.

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See supplementary material
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REFERENCES

Bernal, R., Gradstein, S. R., & Celis, M. (Eds.). (2016). *Catálogo de plantas y líquenes de Colombia: Capítulos introductorios—Líquenes a Lythraceae* (Vol. 1, 1a ed.). Editorial Universidad Nacional de Colombia.

Botina, J. R., & García, L. (2005). *Árboles y arbustos del Ecoparque Río Pance*. Editorial Sepia Ltda.

Carlucci, M. B., Brancalion, P. H. S., Rodrigues, R. R., Loyola, R., & Cianciaruso, M. V. (2020). Functional traits and ecosystem services in ecological restoration. *Restoration Ecology*, *28*(6), 1372–1383. https://doi.org/10.1111/rec.13279

Cooke, R. S. C., Bates, A. E., & Eigenbrod, F. (2019). Global trade-offs of functional redundancy and functional dispersion for birds and mammals. *Global Ecology and Biogeography*, *28*(4), 484–495. https://doi.org/10/gr4s9z

Córdova-Tapia, F., & Zambrano, L. (2015). La diversidad funcional en la ecología de comunidades. *Ecosistemas*, *24*(3), 78–87. https://doi.org/10/gkms3h

Corredor-Londoño, G. A., Beltrán, J. W., Torres-González, A. M., & Sardi-Saavedra, A. (2020). Phenological synchrony and seasonality of eight tree species in a fragmented landscape in the Colombian Andes. *Revista de Biología Tropical*, *68*(3), 987–1000. https://doi.org/10/gr4s99

da Silva, J. de J., da Silva-Braulio, C., Melo-Moreira, F., Sandos de Jesus-Cavalcante, A., Anda-Rocabado, J. M., & Simao-Nobrega, R. (2020). Crescimento inicial de *Clitoria fairchildiana* em substratos orgânicos. *Revista Brasileira de Agropecuária Sustentável*, *10*(1), 58–66. https://doi.org/10/gr4s9p

Dexter, K. G., Pennington, R. T., Oliveira-Filho, A. T., Bueno, M. L., Silva de Miranda, P. L., & Neves, D. M. (2018). Inserting tropical dry forests into the discussion on biome transitions in the tropics. *Frontiers in Ecology and Evolution*, *6*, 104. https://doi.org/10.3389/fevo.2018.00104

Fonseca, C. R., & Ganade, G. (2001). Species functional redundancy, random extinctions and the stability of ecosystems. *Journal of Ecology*, *89*(1), 118–125. https://doi.org/10/ds9zbx

García, H., & González-M., R. (Eds.). (2019). *Bosque seco Colombia: Biodiversidad y gestión* (1a ed.). Instituto Humboldt Colombia.

Hammer, Ø., Harper, D. A. T., & Ryan, P. (2001). PAST: Paleontological statistics software package for education and data analysis. *Palaeontologia Electronica*, *4*(1), 9.

Imaña-Encinas, J., Riesco-Munoz, G., Antunes-Santana, O., & de Camino, R. (2021). Análisis silvicultural del bosque tropical atlántico a partir de la distribución diamétrica y riqueza florística del arbolado. *Revista Forestal Mesoamericana Kurú*, *18*(42), 46–54. https://doi.org/10.18845/rfmk.v16i42.5538

Joshi, H. C., Pant, P., & Chauhan, H. K. (2024). Challenges and opportunities in scaling up plant functional trait-based approaches. In N. Kumar, & H. Singh (Eds.), *Plant functional traits for improving productivity* (pp. 301–327). Springer Nature. https://doi.org/10.1007/978-981-97-1510-7_16

Laliberté, E., & Legendre, P. (2010). A distance-based framework for measuring functional diversity from multiple traits. *Ecology*, *91*(1), 299–305. https://doi.org/10/d6rqtj

Leverett, B., & Bertolette, D. (2013). *American forests tree: Measuring guidelines*. American Forests.

Li, J., Chen, X., Niklas, K. J., Sun, J., Wang, Z., Zhong, Q., Hu, D., & Cheng, D. (2022). A whole-plant economics spectrum including bark functional traits for 59 subtropical woody plant species. *Journal of Ecology*, *110*(1), 248–261. https://doi.org/10/grc9jk

Magneville, C., Loiseau, N., Albouy, C., Casajus, N., Claverie, T., Escalas, A., Leprieur, F., Maire, E., Mouillot, D., & Villéger, S. (2022). mFD: an R package to compute and illustrate the multiple facets of functional diversity. *Ecography*, *2022*(1), e05904. https://doi.org/10/gqpf73

Mason, N. W. H., & de Bello, F. (2013). Functional diversity: A tool for answering challenging ecological questions. *Journal of Vegetation Science*, *24*(5), 777–780. https://doi.org/10/f46c77

Mason, N. W. H., Mouillot, D., Lee, W. G., & Wilson, J. B. (2005). Functional richness, functional evenness and functional divergence: The primary components of functional diversity. *Oikos*, *111*(1), 112–118. https://doi.org/10/cmwgjt

Matsuo, T., Martínez-Ramos, M., Bongers, F., van der Sande, M. T., & Poorter, L. (2021). Forest structure drives changes in light heterogeneity during tropical secondary forest succession. *Journal of Ecology*, *109*(8), 2871–2884. https://doi.org/10/gss33b

Mensah, S., Veldtman, R., Assogbadjo, A. E., Glèlè Kakaï, R., & Seifert, T. (2016). Tree species diversity promotes aboveground carbon storage through functional diversity and functional dominance. *Ecology and Evolution*, *6*(20), 7546–7557. https://doi.org/10.1002/ece3.2525

Núñez-Florez, R., Pérez-Gómez, U., & Fernández-Méndez, F. (2019). Functional diversity criteria for selecting urban trees. *Urban Forestry & Urban Greening*, *38*, 251–266. https://doi.org/10/gfvxn4

Pérez-Harguindeguy, N., Díaz, S., Garnier, E., Lavorel, S., Poorter, H., Jaureguiberry, P., Bret-Harte, M. S., Cornwell, W. K., Craine, J. M., Gurvich, D. E., Urcelay, C., Veneklaas, E. J., Reich, P. B., Poorter, L., Wright, I. J., Ray, P., Enrico, L., Pausas, J. G., Vos, A. C., … Cornelissen, J. H. (2013). New handbook for standardised measurement of plant functional traits worldwide. *Australian Journal of Botany*, *61*(3), 167–234. https://doi.org/10/gfgn82

Qin, H., Wang, Y., Zhang, F., Chen, J., Zhang, G., & Dong, G. (2016). Application of species, phylogenetic and functional diversity to the evaluation on the effects of ecological restoration on biodiversity. *Ecological Informatics*, *32*, 53–62.

R Core Team. (2024). *R: A language and environment for statistical computing* [Software]. R Foundation for Statistical Computing. Vienna, Austria. https://www.R-project.org/

Ramírez-Padilla, B., & Goyes-Acosta, R. I. (2004). *Botánica. Generalidades, Morfología y Anatomía de plantas superiores* (1a ed.). Editorial Universidad del Cauca.

Rangel, O., & Velázquez, A. (1997). Métodos de Estudio de la Vegetación. In O. Rangel (Ed.), *Tipos de Vegetación en Colombia* (pp. 59–87). Universidad Nacional de Colombia y Ministerio del Medio Ambiente.

Rosell, J. A., Olson, M. E., Martínez-Garza, C., & Martínez-Méndez, N. (2022). Functional diversity in woody organs of tropical dry forests and implications for restoration. *Sustainability*, *14*(14), 8362. https://doi.org/10/grz6rp

Ruíz, J., Vargas, O., & Rodríguez, N. (2023). Restoration priorities: Integrating successional states and landscape resilience in tropical dry forest compensation projects in Colombia. *Applied Geography*, *157*, 103021. https://doi.org/10/gsfztf

Salgado-Negret, B. (Ed.). (2016). *La ecología funcional como aproximación al estudio, manejo y conservación de la biodiversidad: Protocolos y aplicaciones* (1ª ed.). Instituto de Investigación de Recursos Biológicos Alexander von Humboldt.

Salgado-Negret, B., Pulido Rodríguez, E. N., Cabrera, M., Ruíz Osorio, C., & Paz, H. (2016). Protocolo para la medición de rasgos funcionales en plantas. In B. Salgado-Negret (Ed.), *La ecología funcional como aproximación al estudio, manejo y conservación de la biodiversidad: Protocolos y aplicaciones* (1a ed., pp. 36–80). Instituto de Investigación de Recursos Biológicos Alexander von Humboldt.

Sandoval-Granillo, V., & Meave, J. A. (2023). Leaf functional diversity and environmental filtering in a tropical dry forest: Comparison between two geological substrates. *Ecology and Evolution*, *13*(9), e10491. https://doi.org/10.1002/ece3.10491

Sardi, A., Torres, A. M., & Corredor, G. (2018). Floristic diversity in a rural landscape of the lower slope in Farallones of Cali, Colombia. *Colombia Forestal*, *21*(2), 142–160. https://doi.org/10/gr4s9v

Schleuter, D., Daufresne, M., Massol, F., & Argillier, C. (2010). A user's guide to functional diversity indices. *Ecological Monographs*, *80*(3), 469–484. https://doi.org/10/btbrks

Schneider, C. A., Rasband, W., & Eliceiri, K. W. (2012). NIH Image to ImageJ: 25 years of image analysis. Nature methods, *9*(7), 671–675. https://doi.org/10.1038/nmeth.2089

Siyum, Z. G. (2020). Tropical dry forest dynamics in the context of climate change: Syntheses of drivers, gaps, and management perspectives. *Ecological Processes*, *9*(1), 25. https://doi.org/10.1186/s13717-020-00229-6

Tedesco, A. M., López-Cubillos, S., Chazdon, R., Rhodes, J. R., Archibald, C. L., Pérez-Hämmerle, K.V., Brancalion, P. H. S., Wilson, K. A., Oliveira, M., Correa, D. F., Ota, L., Morrison, T. H., Possingham, H. P., Mills, M., Santos, F. C., & Dean, A. J. (2023). Beyond ecology: Ecosystem restoration as a process for social-ecological transformation. *Trends in Ecology & Evolution*, *38*(7), 643–653. https://doi.org/10/gsfztj

Villéger, S., Ramos-Miranda, J., Flores-Hernández, D., & Mouillot, D. (2010). Contrasting changes in taxonomie vs. functional diversity of tropical fish communities after habitat degradation. *Ecological Applications*, *20*(6), 1512–1522. https://doi.org/10/fbtqmr