



Original Papers

Structure, floristic and diversity from Laguna de San Diego (Samaná, Colombia)

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Abstract

The Magdalena Valley along the eastern slopes of the Central Andes in Colombia is characterized by both high biodiversity and endemism and human infrastructure development. In this study, we present the first botanical record from Distrito de Manejo Integrado Laguna de San Diego flora's, part of South America's northernmost active volcanic field. Here, we analyzed the diversity, structure, and composition in four different cover types (Dense forest: Bd, Mosaic of pastures with natural spaces: Mpen, Pastures: P, and Secondary vegetation: Vs). A total of 100 species and 42 botanical families were recorded. In Bd, the species with the highest IVI was *Pourouma bicolor* (20.9), while in the Mpen, was *Triplaris dugandii* (53.7); *Psidium guajava* (75.6) in P, and *Guatteria punctata* (21.2) in Vs. Bd exhibited the highest values of diversity across all measures (⁰D, ¹D, and ²D). We strongly advocate for increased efforts to enhance the protection status and safeguard local species to protect biodiversity. This research adds to baseline botanical knowledge and should be used to minimize impacts of ecotourism, and the potential for future mining exploitation in biodiverse landscapes.

Key words: conservation, Magdalena valley, protected areas, threatened species.

Resumo

O Vale do Magdalena, ao longo das encostas orientais dos Andes Centrais, na Colômbia, é caracterizado pela alta biodiversidade e endemismo e pelo desenvolvimento da infraestrutura humana. Neste estudo, apresentamos o primeiro registro botânico da flora do Distrito de Manejo Integrado Laguna de San Diego, parte do campo vulcânico ativo mais ao norte da América do Sul. Aqui analisamos a diversidade, estrutura e composição em quatro coberturas diferentes (Floresta Densa: Bd, Mosaico de pastagens com espaços naturais: Mpen, Pastagens: P e Vegetação Secundária: Vs. Um total de 100 espécies e 42 famílias botânicas foram registradas. No Bd, a espécie com maior IVI foi *Pourouma bicolor* (20,9), enquanto no Mpen, foi *Triplaris dugandii* (53,7); *Psidium guajava* (75,6) em P, e *Guatteria punctata* (21,2) em Vs. Bd exibiu os maiores valores de diversidade em todas as medidas (0D, 1D e 2D). Defendemos fortemente o aumento de esforços para aumentar seu status de proteção e a salvaguarda das espécies locais para proteger a biodiversidade. Esta pesquisa fornece uma linha de base botânica que deveria ser usada para minimizar os impactos do ecoturismo e a possível implementação da exploração mineira em paisagens biodiversas.

Palavras-chave: conservação, vale Magdalena, áreas protegidas, espécies ameaçadas.

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Introduction

Floristic diversity in neotropical ecosystems has been linked to local orographic effects of the regional climate as well as recent human impacts. Abrupt climate change on short time scales in neotropical forests may contribute to species losses and decreased biodiversity. However, neotropical forests host highly dynamic environments that support high rates of speciation and species adaptation (Van der Hammen & Hooghiemstra 2001; Antonelli *et al.* 2009; Bernal *et al.* 2016) and buffering against impacts from climate (Flantua *et al.* 2019). The Andean region has been key to Colombia's economic and cultural development during the past century (Alvear *et al.* 2010). Forest fragmentation from timber harvesting has contributed disproportionately to local species extinctions and adds to the growing evidence of long-term human use of these landscapes (Aceituno & Loaiza 2014; Álvarez *et al.* 2007).

Human-caused deforestation in Colombia is one of the clearest examples of how globalized pressure on natural resources leads to the exploitation and international consumption of those natural resources (Baumann & Kuemmerle 2016; Landholm *et al.* 2019). The accelerating rate and scale of deforestation and forest burning in Colombia during the last decade contributes to rapid biodiversity loss. For example, a sixfold increase in deforestation and burning within protected areas occurred after the 2016 peace agreement (JEP 2016), and a 52% increase in the probability of deforestation in National parks were driven by social changes linked to armed conflict and post-conflict boundary disputes and re-occupation (Armenteras *et al.* 2019; Negret *et al.* 2019). In Samaná, as armed groups withdrew, a wave of displaced landowners were able to return and re-activate economic activities, including the exponential growth of the cattle industry. These post-conflict economies are promoted by well-intentioned international agencies as a reparation strategy for local communities. Unfortunately, the consequences of these programs have accelerated deforestation, habitat loss and wildfire activity in many regions, including the DMI Laguna de San Diego. Therefore, this research views DMI laguna de San Diego as a local example of national trends impacting Colombia's unique biodiversity through unintended consequences following a period of rapid social change across Colombia.

The Magdalena's tropical humid ecoregion (Olson *et al.* 2001) exemplifies a human-disturbed

area within the Magdalena-Cauca river basin. This ecoregion is characterized as a region of high endemism and many threatened species (Benavides-Ossa *et al.* 2022). The Magdalena river valley, with its unique climate and topography, has an ancient and rich cultural heritage that is juxtaposed over one of Colombia's most biodiverse regions (Acosta-Galvis *et al.* 2006). Factors such as temperature, precipitation, winds (example: Choco Low-Level Jet), atmospheric humidity, altitude, and the orientation of mountains influence the regional climatology across the Magdalena River valley (Cardona *et al.* 2010). Fortunately, recent conservation efforts have been put in place by both national and regional initiatives that have resulted in the protection of hydrographic subzones of the La Miel, Samaná Sur, and Guarínó rivers, such as Parque Nacional Natural Selva de Florencia, the Distrito de Manejo Integrado (DMI) Laguna de San Diego in Samaná (Caldas department) and, the Distrito de Manejo Integrado Cuchilla de Bellavista in Victoria, Caldas (Herrera *et al.* 2018).

Efforts to capture the unique biodiversity of the Magdalena River valley during the past two decades has been the focus of several conservation groups conducting biological surveys in forested areas along rivers, streams, and man-made reservoirs (Rojas *et al.* 2008; Cardona *et al.* 2010; Roncancio *et al.* 2011; Mendoza-Cifuentes 2011; Calonje *et al.* 2021; Sierra-Giraldo *et al.* 2022). However, despite these regional efforts, there is a notable absence of biological baseline knowledge for Laguna de San Diego, likely because of the socio-political situation that discourages research activities in the region. Here, we present the first floristic assessment of this regional protected area. The objective of this study is to document the flora of the DMI Laguna de San Diego and analyze the diversity, structure, and composition of vegetation. This baseline data will serve as the foundation for future studies in this protected area and provide guidance for stakeholders pursuing land management decisions in this unique territory.

Materials and Methods

Study area

The San Diego-Cerro Machín Volcano Tectonic Province constitutes the northern most active volcanic field in South America (Murcia *et al.* 2018; Sánchez-Torres *et al.* 2019, 2022). The study was conducted at San Diego Volcano, declared in 2011 as a regional protected area by the regional environmental authority, Corpocaldas,

through administrative agreement number 19 of 2011. The protected area and San Diego volcano occurs between two geological features, La Laguna (maar lake) and El Cerro (tuff cone) (Monsalve *et al.* 2023) (Fig. 1), located on the eastern slope of the Central Mountain Range, between Samaná Sur and La Miel watersheds, at an altitude ranging between 720 to 1,100 meters of elevation in Samaná county (05.6524N, -74.9529W), Caldas, Colombia.

Laguna de San Diego has been the focus of volcanic studies as well as mining and energy explorations. These competing interests have generated several detailed studies on regional geology and geomorphology (Beltrán *et al.* 2016; Borrero *et al.* 2017; Monsalve *et al.* 2023). Potential explorations for uranium and geothermal energy, as well as unregulated ecotourism, pose an additional urgency for protecting that region's natural resources and were part of the motivation for this current assessment of Laguna de San Diego's biodiversity and ecological services.

The municipality of Samaná has a tetra-seasonal climate with a bimodal rainfall pattern caused by the annual latitudinal migration of the Inter Tropical Convergence Zone. The first rainy season occurs between April and May, and the second occurs between October and November, with an average annual rainfall of ~4,000 mm. There are two “dry” seasons, or periods of reduced rainfall, in January–February and July–August, and the average annual temperature is 26.4 °C. Torrential rains, characterized by clouds, and storm-like conditions, can potentially occur throughout all seasons.

Dataset

The definition of land cover units follows guidelines established in the CORINE Land Cover methodology adapted for Colombia (IDEAM 2010). The vegetation cover types identified included Dense forest (Bosque denso - Bd), Secondary vegetation (Vegetación secundaria - Vs), Mosaic of pastures with natural spaces (Mosaico de

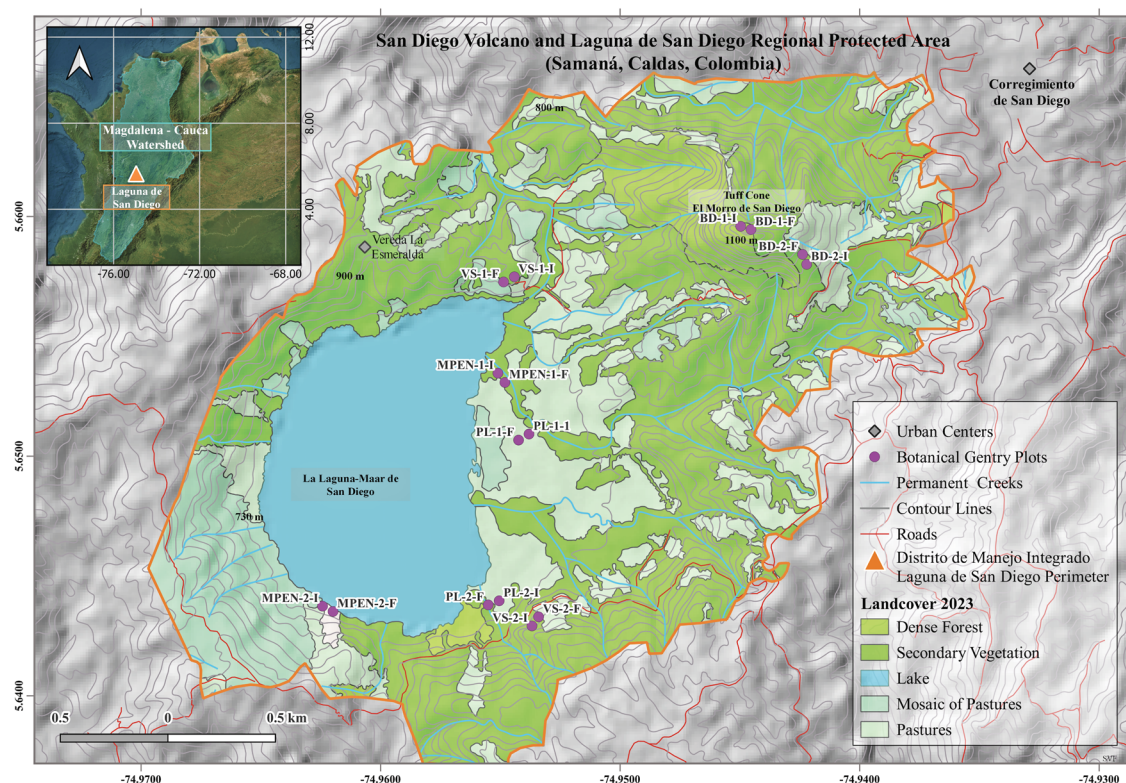


Figure 1 – Location of the four Gentry-type plots in the DMI Laguna de San Diego. Codes of the plots of each vegetation cover: Bd = Dense forest; Mpen = Mosaic of pastures with natural spaces; P = Pastures; Vs = Secondary vegetation. In each vegetation cover, two 50 × 10 m plots were made (For each plot the starting and ending point is observed).

pastos con espacios naturales - Mpen), and Pastures (Pastos limpios - P); these four categories (Bd, Vs, Mpen, P) are used to summarize our findings in the discussion.

Between September 2021 and September 2022, four plots of 0.1 ha established within each vegetation cover. Additionally, two 50 m × 10 m transects were created within each vegetation cover type, for a total of eight transects, following the methodology originally proposed by Gentry (1982) (Fig. 1). Each transects was established perpendicular to the slope of the terrain (Villarreal *et al.* 2006). In these plots, all woody individuals (excluding vines and herbs) with a diameter at breast height (DBH) ≥ 2.5 cm (principally trees, shrubs, palms and tree ferns), measured at 1.3 m above the ground, were recorded.

The botanical samples were identified using specialized literature (Gentry 1996; Vargas 2002; Cardona *et al.* 2010; David *et al.* 2014; Idárraga *et al.* 2016), consultation of virtual herbaria (ICN 2004; HUA 2017), and comparison with specimens from the herbarium of the University de Caldas (FAUC). Herbarium abbreviations follows Thiers (2023) and all nomenclature was validated in IPNI (2023).

The basal area was calculated using the equation $BA = (\pi/4) (DBH)^2$ (Franco-Rosselli *et al.* 1997). For each species, the relative density (RDe) was calculated as the number of individuals of that species divided by the total number of individuals in the community multiplied by 100. The relative frequency (RF) was calculated as the number of plots in which the species was found divided by the total number of plots, multiplied by 100 (Rangel-Ch. & Velásquez 1997). The relative dominance (RDo) was calculated as the sum of the basal area of all individuals of that species divided by the sum of the basal area of the entire community, multiplied by 100 (Finol 1976). This method was then used to calculate the Importance Value Index (IVI), using the formula: $RDe + RF + RDo$. To evaluate the diameter and height distribution, class intervals were constructed using the equation $C = (X_{max} - X_{min}) / m$, where C is the interval width, m is equal to $1 + 3.3 \log N$, and N is the number of individuals (Rangel-Ch. & Velásquez 1997).

Plant diversity was calculated using the effective number of species qD (Hill 1973; Jost 2006; Cultid-Medina & Escobar 2019), where qD corresponds to the effective richness, which is a measure of the number of unique and distinct species present in a community; 1D corresponds to

the effective number of equally common species and is equivalent to the exponential of Shannon's entropy; and 2D corresponds to the effective number of dominant species and is equivalent to the inverse of the Simpson's index (Jost 2006, 2018). Diversity was calculated using the entropart package (Marcon & Herault 2015) in the statistical software R (R Core Team 2022), and the online statistical software iNEXT (Chao *et al.* 2016). The sampling coverage was also calculated in R using the iNEXT package (Hsieh *et al.* 2022). The diversity profile was created with 95% confidence intervals based on 2000 bootstrap simulations using the entropart package (Marcon & Herault 2015).

Results and Discussion

Structure and floristic diversity

Botanical field surveys in 2020 and in 2022 identified a total of 517 individual, 100 species, and 42 families (Tab. S1, available on supplementary material <<https://doi.org/10.6084/m9.figshare.27207825.v1>>). The richest families were Melastomataceae (14 species, where *Graffenrieda galeottii* (Naudin) L.O. Williams and *Miconia elata* (Sw.) DC., are the most abundant with 32 and 15 individuals each), Lauraceae (7 species, *Nectandra* sp. 1 is the most abundant with 13 individuals) and Rubiaceae (7 species, *Schizocalyx bracteosus* Wedd., is the most abundant with 30 individuals). In Bd land-cover type, the species with the highest IVI values were *Pourouma bicolor* Mart. (20.9), *Marila podantha* Cuatrec. (18.1), and *Hedyosmum* cf. *racemosum* (Ruiz & Pav.) G. Don (14.6). In Mpen, the species with the highest IVI values were *Triplaris dugandii* Brandbyge (53.7), *Nectandra* sp. 1 (51.9), *Cedrela odorata* L. (42.4) and *Vismia macrophylla* Kunth (37.1). In P land-cover type, the species with the highest IVI values were *Psidium guajava* L. (75.6) and *Myrsine coriacea* (Sw.) Roem. & Schult. (59.4) and in Vs the species with the highest IVI values were *Guatteria punctata* (Aubl.) R.A. Howard (21.2), *Jacaranda copaia* (Aubl.) D. Don (20.2), and *Graffenrieda galeottii* (Naudin) L.O. Williams with 19.5 (Figs. 2;3;4).

The fact that heliophytic durable species (Finegan 1992, 1996) such as *H. cf. racemosum*, *M. podantha* and *P. bicolor* has the highest IVI values in Bd indicates that this vegetation type is likely an intermediate stage of succession (Fig. 2). These species have relatively long life spans, can exhibit rapid to moderate growth, and can reach

large dimensions in terms of diameter and height (Sánchez *et al.* 2007). This could be attributed to various types of disturbances characteristic of the area, including heavy precipitation and frequent lightning strike events during storms (Turner 2010; Albrecht *et al.* 2016; Torres-Sánchez *et al.* 2019), but also to human-caused deforestation and selective logging of valuable timber tree species used for construction that have occurred on crater and dome hillsides of the Distrito de Manejo Integrado Laguna de San Diego. However, the presence of obligate sciophytes, such as *Virola sebifera* Aubl. (Myristicaceae) and *Welfia regia* H. Wendl. (Arecaceae) suggests canopy closure and the establishment of shade-tolerant species (Yepes *et al.* 2010). Bd species such as these sciophytes are likely experiencing frequent disturbances that keep this vegetation cover in a dynamic state between intermediate and advanced succession stages (Holl 2023).

In Vs, ephemeral Heliophytes and durable Heliophytes (Finegan 1996) species prevail, such as *Alchornea costaricensis* Pax & K. Hoffm. (Euphorbiaceae), *G. galeottii* (Melastomataceae), *G. punctata* (Annonaceae), *Inga samanensis* Uribe (Fabaceae), and *J. copaia* (Bignoniaceae). These

species are characterized by their rapid and regular growth, relatively short to long life cycles, and are frequently found in recent clearings (Sánchez *et al.* 2007). They are present from early succession to secondary and late-stage forests (Montagnini 2000; Kunert *et al.* 2015; Sánchez *et al.* 2018), indicating that this vegetation type follows an appropriate course of plant succession, progressing towards more advanced stages where the forest canopy closes and allows the establishment of shade-tolerant species (Guariguata & Ostertag 2002).

The presence of ephemeral Heliophytes such as *T. dugandii* (Polygonaceae), *P. guajava* (Myrtaceae), and *M. coriacea* (Myrsinaceae) in Mpen indicates that these vegetation types are in the early successional stage, where pioneer species dominate and mature canopy is absent. Additionally, the presence of other sciophytes, including *C. odorata* (Meliaceae) suggests the land-use practices in these areas, including limited selective logging, is allowing large-diameter and tall trees to remain standing (Figs. 5-6).

The altitudinal and diametric classes (Figs. 5-6), both Bd and Vs, showed an inverted “J” pattern, where the most individuals were grouped into the initial diametric and altitudinal

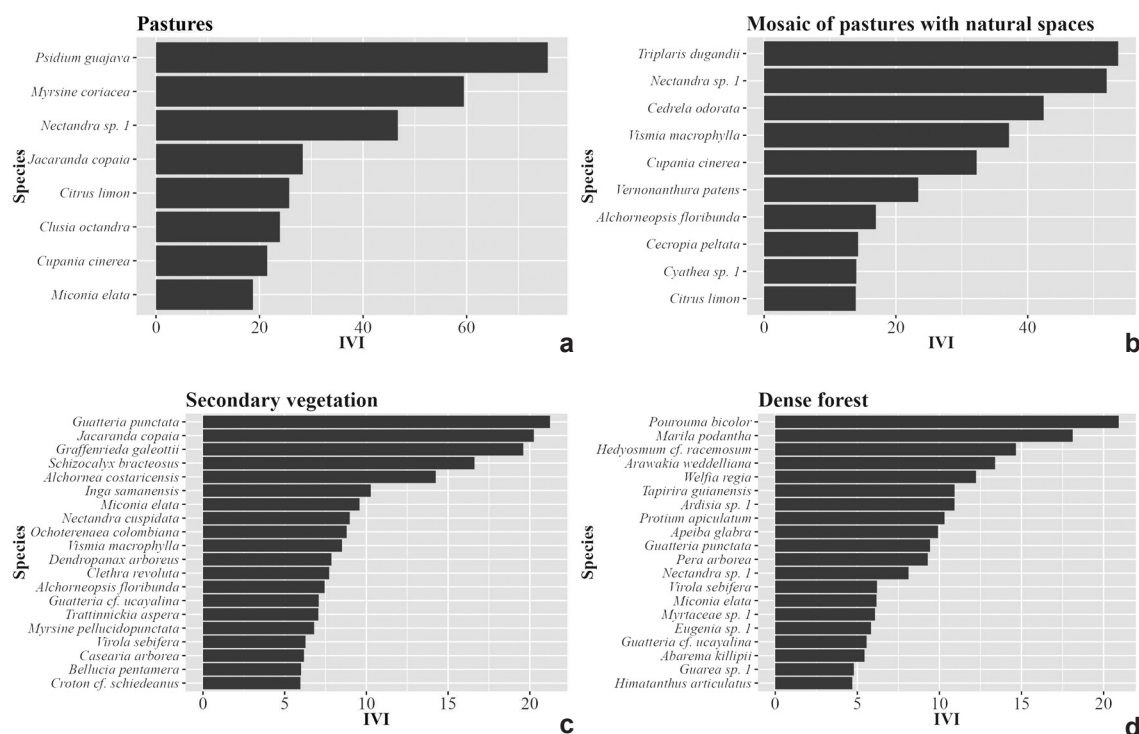


Figure 2 – Importance Value Index (IVI) of each evaluated vegetation cover type.



Figure 3 – a-i. Examples of species with high IVI values – a-b. *Cedrela odorata*; c-d. *Guatteria punctata*; e-g. *Pourouma bicolor*; h-i. *Psidium guajava*. (Photos: Julio Andrés Sierra-Giraldo).

categories, and tended to decrease in abundance as the categories increased (Galeano 2001). This pattern suggests the successful re-generation of a seedling bank, understory species, and canopy taxa, leading to greater structural complexity within these vegetation types (Guariguata & Ostertag 2002). In Mpen and P land-cover type, this inverted “J” pattern was less evident, with

tall individuals dominating in Class IV (Mpen) and large-diameter individuals in Class III (P). In these classes, isolated trees of large diameters and vertical heights persist because of selective logging and livestock activities.

Regarding diversity, it was estimated and compared under a sampling coverage of 76.03%. To compare diversity among vegetation covers, the

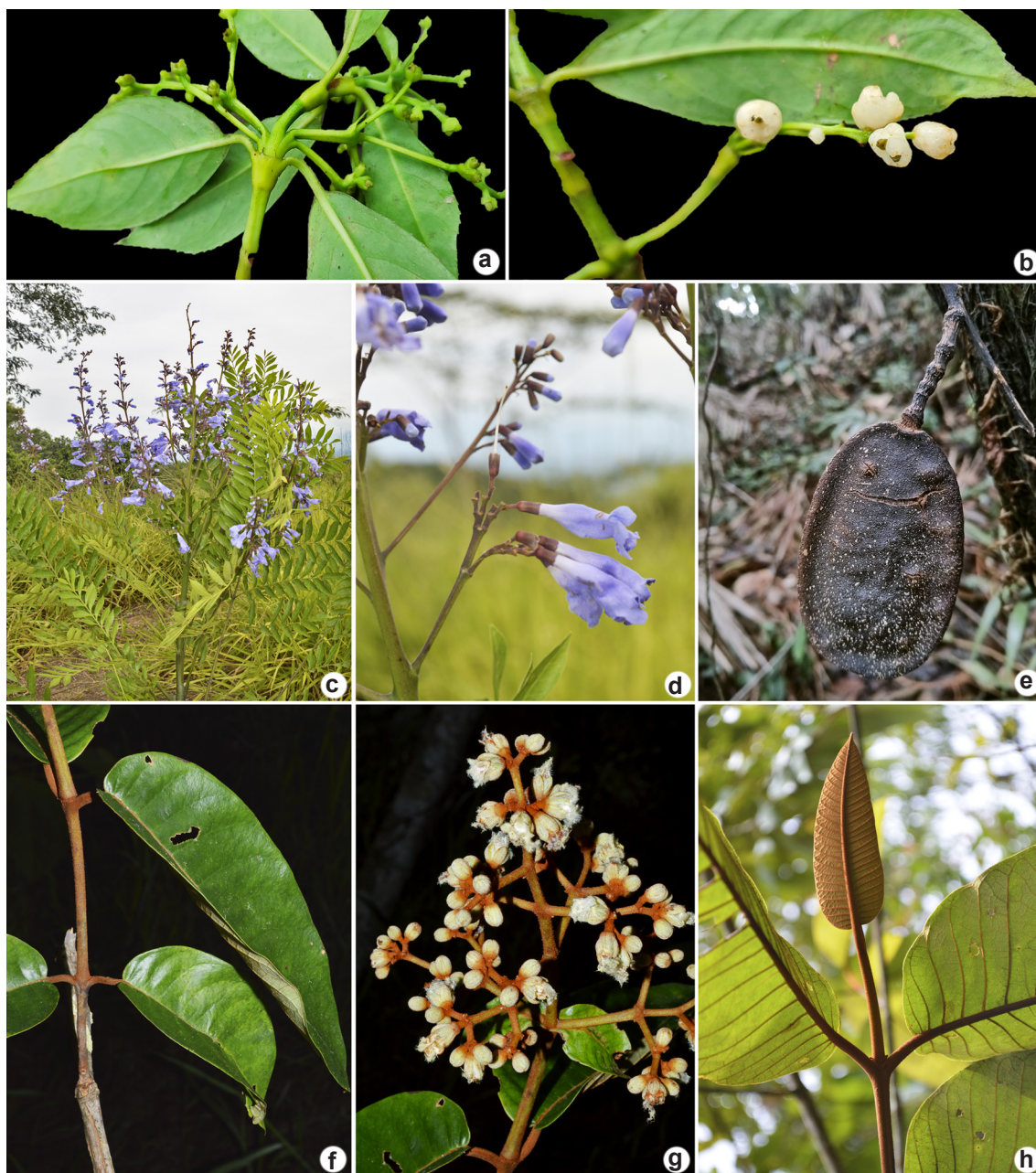


Figura 4 – a-h. Examples of species with high IVI values – a-b. *Hedyosmum* cf. *racemosum*; c-e. *Jacaranda copaia*; f-h. *Vismia macrophylla*. (Photos: Julio Andrés Sierra-Giraldo).

values must be calculated under the same sampling coverage percentage. Thus, the recommendations of Cultid-Medida & Escobar (2019) were followed, which state that extrapolated values associated with more than twice the abundances observed in the least complete samples should not be used and that the comparison should be made using the fewest possible extrapolated values. Therefore, the values reported in comparison scenario 2 were used (Tab. 1; Fig. 7). In Bd, the highest diversity values were recorded for all orders. (0D , 1D , and 2D), followed by Vs, while the lowest diversity values were recorded in Mpen and P land-cover type.

Effective richness (0D) provides a measure of the number of unique and distinct species present in a community, where a higher value of 0D indicates greater species diversity for a given community (Hill 1973; Jost 2006). Bd had the highest value of 0D (40.3), indicating that this vegetation cover has the highest effective species richness among the sampled covers, followed by Vs with a value of 32.6. Mpen had the lowest value of 0D , with 8.3 (Tab. 1; Fig. 7).

Regarding Shannon entropy, it is a measure that combines both species richness and evenness in species distribution. A higher Shannon entropy value indicates greater species diversity in a community. Bd had the highest 1D value (31.5), followed by Vs with a value of 23.5 (Tab. 1; Fig. 7). This suggests that these cover types have higher diversity regarding species richness and a more equitable distribution of abundance among them. In contrast, Mpen had the lowest 1D value (6.7).

Bd exhibits the highest 2D values (24.8), followed by Vs (16.9). These results suggest a greater evenness in species distribution and a

lower dominance of a few species, capturing a more diverse and balanced community structure (Hill 1973; Jost 2006) compared to P land-cover type (4.4) and Mpen (5.6). In these last two coverages (Mpen and P), there is a higher dominance with few species and a less equitable distribution of abundance among species. This pattern is characteristic of vegetation found in areas supporting agricultural and livestock activities.

The importance of promoting the conservation of Bd and Vs is highlighted, as these vegetation covers are mainly found surrounding El Morro (Bd) and the crater wall (Vs). These covers represent the most conserved and diverse ones in this study, where species characteristic of advanced stages of vegetation succession (Guariguata & Ostertag 2002) are recorded, such as *Aniba perutilis* Hemsl., *Gustavia speciosa* (Kunth) DC., *V. sebifera* and *W. regia*, additionally, these vegetation covers harbor 57 out of the 62 species that are categorized as at risk of extinction (IUCN 2022), meaning they support 92% of the threatened species in the Distrito de Manejo Integrado Laguna de San Diego (Tab. S1, available on supplementary material <<https://doi.org/10.6084/m9.figshare.27207825.v1>>).

DMI Laguna de San Diego is a unique natural value within the Andean forest, as it is part of the northernmost active volcanic field in South America and one of only two known Maar-type lakes in Colombia. However, plant diversity remains relatively unknown. In this study we are reporting the first-ever scientific vegetation survey conducted in the area after a recent period of high deforestation rates and decades of disturbances. There is an urgent need for increased efforts to enhance its protection status in order

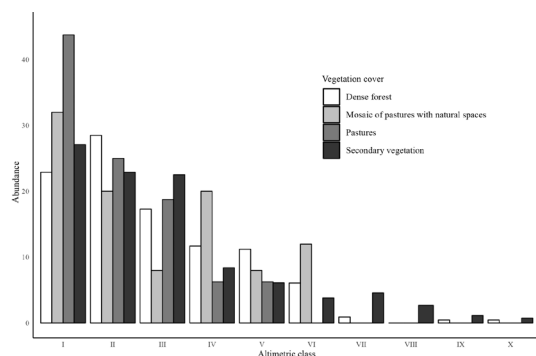


Figure 5 – Distribution of plant heights for woody individuals with DBH ≥ 2.5 cm in the different evaluated vegetation covers.

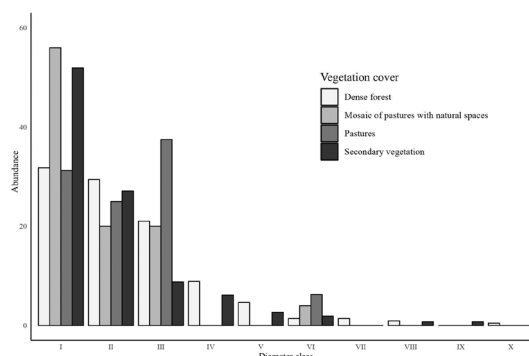


Figure 6 – Distribution of plant diameters for woody individuals with DBH ≥ 2.5 cm in the different evaluated vegetation covers.

Table 1 – Floristic diversity (qD) in the four sampled vegetation covers. Bd = Dense forest; Mpen = Mosaic of pastures with natural spaces; P = Pastures; Vs = Secondary vegetation; Cs = Comparison Scenario; Ext = Extrapolation; Int = Interpolation; Obs = Observed Diversity; Ab = Abundance; SCV = Sampling coverage value.

Cs	Vegetation Cover	Method	Ab	SCV	⁰ D	¹ D	² D
1	P	Obs	16	63.47 %	8 ± 5.5	5.6 ± 5.4	4 ± 3.7
	Mpen	Obs	25	80.32 %	10 ± 6.4	7.7 ± 4.0	6.2 ± 3.0
	Vs	Obs	262	91.24 %	58 ± 14.5	32.2 ± 5.6	20.1 ± 4.3
	Bd	Obs	214	91.66 %	59 ± 8.6	40.4 ± 5.6	29.8 ± 5.5
2	P	Ext	32	76.03 %	13.1 ± 11.0	7.6 ± 6.2	4.4 ± 4.5
	Mpen	Int	28	76.03 %	8.3 ± 5.8	6.7 ± 3.6	5.6 ± 2.8
	Vs	Int	74	76.03 %	32.6 ± 6.8	23.5 ± 4.7	16.9 ± 3.5
	Bd	Int	87	76.03 %	40.3 ± 5.8	31.5 ± 4.8	24.8 ± 4.3

to address issues such as predatory ecotourism, ranching, selective extraction, and the potential implementation of mining exploitation. We hope that the information presented in this paper will contribute to the promotion of conservation and restoration efforts aimed at fostering biodiversity

and its ecosystem services for many more centuries. Additionally, we believe that these efforts can potentially strengthen Laguna de San Diego as a key node for regional biological corridors, facilitating the migration of flora and fauna in future climate and environmental change scenarios.

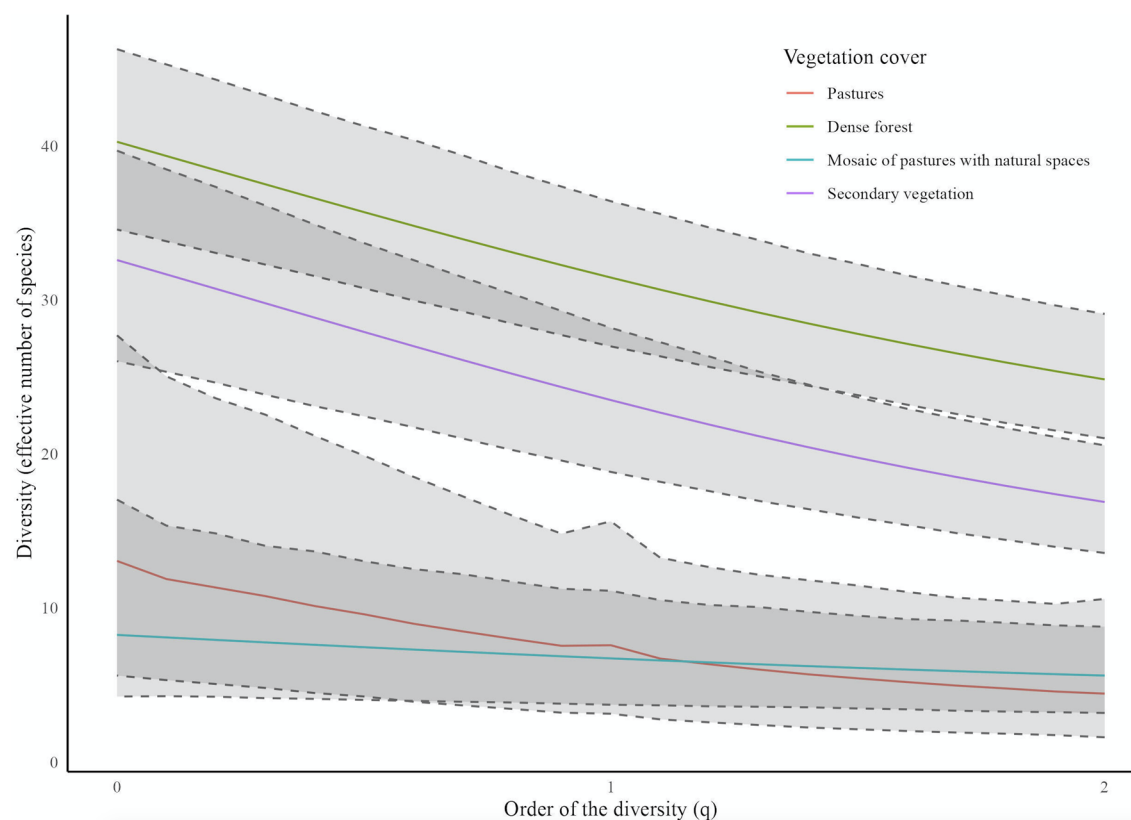


Figure 7 – Values of qD diversity in the different evaluated vegetation covers.

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Data availability statement

In accordance with Open Science communication practices, the authors inform that there is no data sharing of this manuscript.

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