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Research Article

Composición y almacenamiento de carbono en palmas del *Hotspot* Andino-Amazónico, bosque piemontano ecuatoriano

Carbon composition and storage in palms of the Andean-Amazonian hotspot, Ecuadorian piedmont forest

Héctor Reyes-Morán[1,2]*, Bolier Torres-Navarrete[2,3], Cristhian Tipán-Torres[4,3], Erika Zambrano-Alcívar[5], Carlos Bravo-Medina[2], Antón García-Martínez[1]

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[1]Universidad de Córdoba. Programa de Doctorado en Recursos Naturales y Gestión Sostenible. España.
[2]Universidad Estatal Amazónica (UEA). Ecuador.
[3]Ochroma Consulting & Services. Ecuador.
[4]Instituto Superior Tecnológico Ciudad de Valencia. Ecuador.
[5]Conservación Internacional (CI). Ecuador.

*Autor para correspondencia; correo-e: hreyes.hr85@gmail.com
*Corresponding author; e-mail: hreyes.hr85@gmail.com

Abstract

Within the context of climate change, Ecuador's forest palms are crucial both for biodiversity and for the local communities that depend on them for food and building materials. This study analyzes the diversity of palms and their carbon storage capacity in an Ecuadorian Amazon forest, and highlights their socioeconomic importance. An allometric measurement methodology adapted to local conditions was used to determine biomass and carbon stocks. The diameter at breast height and total height revealed that *Iriartea deltoidea* and *Oenocarpus bataua* are the species with the highest carbon sequestration rates, especially in low altitude areas. A notable decrease in carbon storage capacity was observed with increasing altitude, with averages of 11.20 Mg ha^{-1} in the area at 600 to 701 masl, and 3.11 Mg ha^{-1} within an altitude interval of 901 to 1 000 masl. In addition to their relevance for climate change mitigation, these species are essential for local communities, providing them with food, building materials, and materials for handicraft products. There is a considerable need to develop conservation strategies focused on low altitude areas with high palm density and promote the sustainable use of their derived resources for local economic benefits. Also, it is urgent to implement more accurate allometric models to improve biomass and carbon stock estimates in order to reinforce their integration into global conservation policies.

Key words: Carbon storage, Ecuadorian Amazon, Arecaceae, conservation, altitudinal gradient, *Iriartea deltoidea* Ruiz & Pav.

Resumen

En el contexto del cambio climático, las palmas de los bosques de Ecuador son cruciales, tanto para la biodiversidad como para las comunidades locales que dependen de ellas para obtener alimentos y materiales de construcción. En este estudio se analiza la diversidad de palmas, su capacidad de almacenamiento de carbono en un bosque amazónico ecuatoriano, y se resalta su importancia socioeconómica. Se utilizó una metodología de medición alométrica adaptada a las condiciones locales, se determinó la biomasa y el carbono almacenado. Las mediciones de diámetro a la altura del pecho y la altura total revelaron que *Iriartea deltoidea* y *Oenocarpus bataua* son las especies con las mayores tasas de captura de carbono, especialmente en zonas de baja altitud. Se observó una disminución notable en la capacidad de almacenamiento de carbono al aumentar la altitud, con promedios de 11.20 Mg ha^{-1} en la zona de 600 a 701 msnm, y de 3.11 Mg ha^{-1} en el intervalo de 901 a 1 000 msnm. Además de su relevancia para la mitigación del cambio climático, estas especies son fundamentales para las comunidades locales, ya que les proveen alimentos, materiales de construcción y productos artesanales. Se subraya la necesidad de desarrollar estrategias de conservación enfocadas en áreas de baja altitud con alta densidad de palmas y promover el uso sostenible de sus recursos derivados para beneficios económicos locales. Destaca la urgencia de implementar modelos alométricos más precisos que mejoren las estimaciones de biomasa y carbono almacenado, para fortalecer su integración en políticas de conservación global.

Palabras clave: Almacenamiento de carbono, Amazonía Ecuatoriana, Arecaceae, conservación, gradiente altitudinal, *Iriartea deltoidea* Ruiz & Pav.

Introduction

Amazon rainforests are crucial carbon sinks that contribute to mitigating climate change (Malhi & Grace, 2000; Phillips et al., 1998). Within these ecosystems, the Andean-Amazonian Hotspot stands out for its biodiversity and its role in carbon cycling. Ecuador, one of 17 megadiverse countries (Bravo, 2014), is home to about 17 000 higher plant species, including 4 000 endemic (Neill, 2012). However, agricultural expansion and other human activities have drastically reduced forest cover in the region (Balslev et al., 2015).

The Arecaceae family (palms) plays a fundamental role in these ecosystems due to its abundance, diversity and ability to store carbon (Kristiansen et al., 2009). Species like *Iriartea deltoidea* Ruiz & Pav. and *Oenocarpus bataua* Mart. stand out for the large amount of biomass that they accumulate in altitudinal gradient areas (Balslev et al., 2017; Goodman et al., 2013). However, their contribution has been underestimated due to some of their particular morphological characteristics (Goodman et al., 2013).

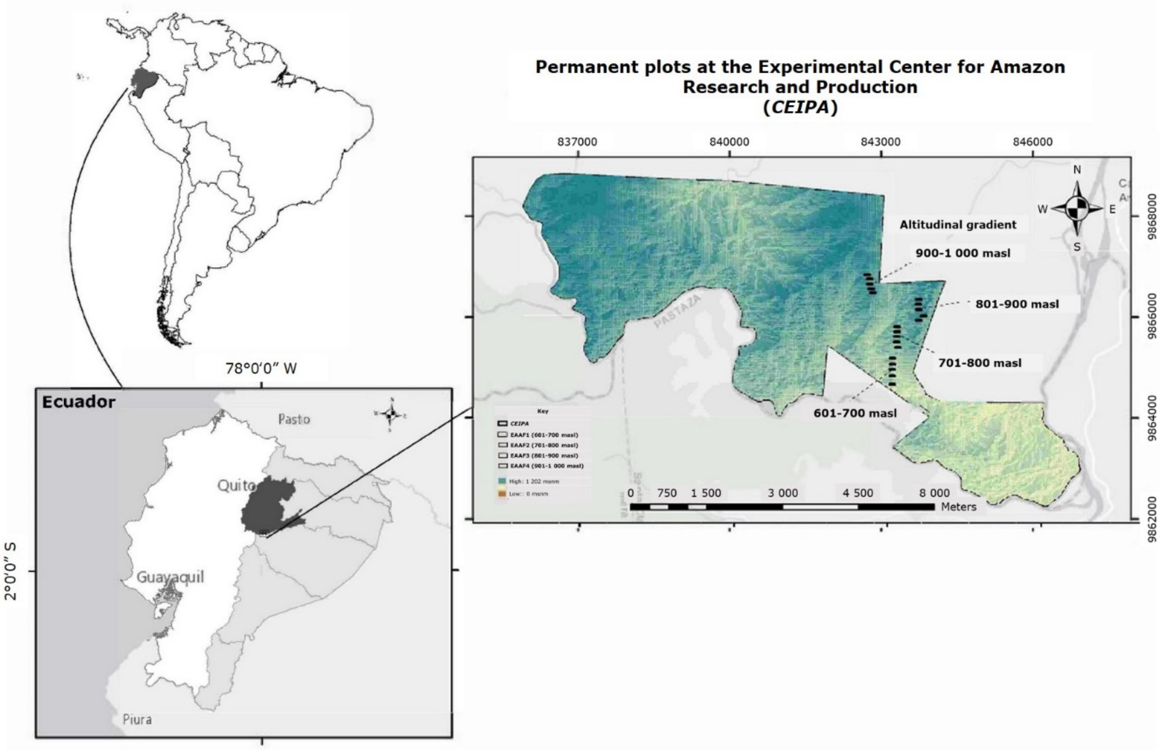
Palm diversity varies with altitude, soil type and rainfall (Alvez-Valles et al., 2018). This suggests that the altitudinal gradients present in the Andean-Amazonian Hotspot have a determining influence on the structure of palm communities, as they condition their distribution and composition (Balslev et al., 2015).

Palm species are crucial not only for climate change mitigation (Miranda et al., 2025) but also for local communities because they provide essential resources such as food and various materials (Zambrano et al., 2021). Given its ecological and economic value, it is essential to study how altitudinal gradients affect their structure and biomass (Torres et al., 2020). The objectives of this study were: (A) To evaluate the diversity and richness of the Arecaceae family in an altitudinal gradient of the piedmont evergreen forest that is part of the Andean-Amazonian Hotspot; and (B) To quantify the carbon stock in aboveground biomass and in the soil.

Materials and Methods

Study area

The study was carried out in the Andean-Amazonian forests of the *Napo* Province, Ecuador, in collaboration with the Experimental Center for Amazonian Research and Production (*CEIPA* in Spanish), located in the *Pastaza* Province, *Carlos Julio Arosemena Tola Canton*, at 44 km from the *Puyo-Tena* road (Figure 1).



Guayaquil = *Guayaquil* City; *Quito* = *Quito* City; *Piura* = *Piura* City; *Pasto* = *Pasto* Province.

Figure 1. Location map of the plots under study.

The study area is located in a mountainous region dominated by high ridges and hills composed of volcanic and sedimentary rocks of recent origin (Galeas & Guevara, 2012). Predominant bioclimatic conditions range from humid pluvial to hyper-humid (Galeas & Guevara, 2012). The altitude of the area varies from 580 to 1 120 m; the average annual temperature is 23 °C, the annual rainfall is 4 119 mm, and the relative humidity is 77 % (Galeas & Guevara, 2012).

For the establishment of the 20 permanent plots (PP), a preliminary reconnaissance of the area was carried out using orthophotos obtained from the database of the Military Geographic Institute (*Instituto Geográfico Militar*, *IGM*) of Ecuador, satellite images provided by the Copernicus Sentinel-2 website, and cartographic bases of the Geographic Information System of the Ministry of Environment and Water of Ecuador (Galeas & Guevara, 2012). The plots were established at four altitudes of the Andean-Amazonian Evergreen Forest (EAAF), with slopes ranging from 3 to 12 % and a slope angle of 3 to 30 % (Table 1).

Table 1. Number of palms and species on four small-scale altitudinal gradients.

Code	Altitude (masl)	Sampling area (m)	Coordinates	Number of species	Individuals ha^{-1}
EAAF1	601-700	100×10	S 1.223822° W 77.917784°	6	275
EAAF2	701-800	100×10	S 1.212358° W 77.916004°	5	297
EAAF3	801-900	100×10	S 1.211196° W 77.912133°	8	364
EAAF4	901-1 000	100×10	S 1.206227° W 77.920118°	8	980

EAAF = Andean-Amazonian Evergreen Forest.

Sampling protocol

Permanent transects, generally used in a rapid exploratory sampling called Gentry-type sampling, were installed (Gentry, 1982; Montufar & Pintaud, 2006), by modifying the original 500×2 m plots to 100×10 m plots (Figure 2), *i. e.*, 0.1 ha^{-1} (García-Cox et al., 2023). The number of individuals of the species of the Arecaceae family was recorded in each plot; these were marked, collected, herborized and deposited in the ECUAMZ-Ecuador Amazon Herbarium. Taxonomic identification was carried out with the support of keys, illustrated catalogs, and digital resources such as Tropicos (Bravo, 2014) and *The Plant List* (Neill, 2012), to ensure accuracy in nomenclature (Cazzolla et al., 2022; Gentry, 1982; Ter Steege, 1998).

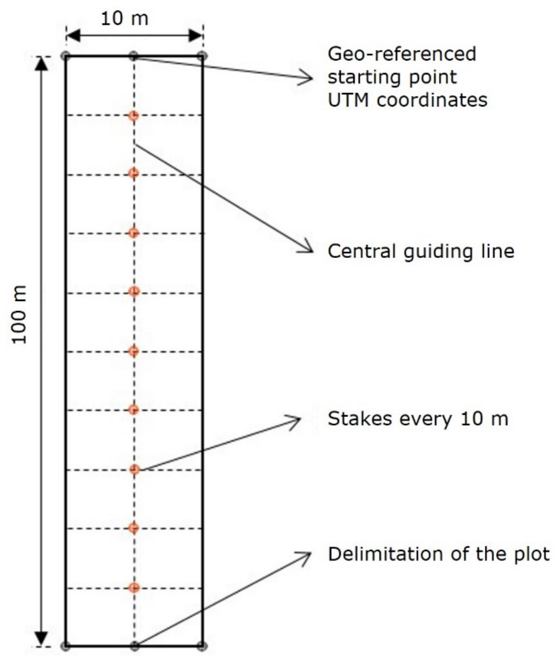


Figure 2. Diagram of the permanent transects implemented for the inventory and diversity and carbon calculations within the gradient.

The height (m) and diameter at breast height, *i. e.*, at 1.3 m from the ground (*DBH*, cm), of the individuals were measured using a model Vertex IV Haglöf® hypsometer and a model Mantax Blue Haglöf® caliper. Differentiated measurements were made for those individuals with a *DBH*≥10 cm and for smaller individuals.

Determination of floristic composition and carbon

The species richness (*S*), Shannon-Wiener diversity index (*H'*), Simpson's index (*λ*), Pielou's evenness index (*J'*), and Simpson's dominance index (*Eλ*) were estimated (Table 2) (Jost & González-Oreja, 2012). The ecological weight of the species was determined using the Ecological Importance Value Index (Medrano et al., 2017).

Table 2. Assessed ecological parameters and Importance Value Index.

Parameters	Equations	References	
Shannon-Wiener index (*H'*)	$H' = -\sum(pi \times \frac{log\ pi}{log^2})$	García-Cox et al. (2023)	(1)
Margalef index (*D*)	$D = \frac{S-1}{nlN}$	García-Cox et al. (2023)	(2)
Simpson's index (*λ*)	$\lambda = \Sigma(\ Pi)2$	Aryal et al. (2019)	(3)
Pielou's index (*J'*)	$J' = \frac{H'}{H'max}$	Medrano et al. (2017)	(4)
Relative abundance (*RA*)	$RA = (\frac{n_i}{N}) \times 100$	García-Cox et al. (2023)	(5)
Relative dominance (*Dr*)	$Dr = (\frac{g_i}{G}) \times 100$	García-Cox et al. (2023)	(6)
Basal area (*G*)	$G = \sum_{i-1}^{N} g_i$	García-Cox et al. (2023)	(7)

Relative frequency (*RF*)	$RF = (\frac{m_i}{M}) \times 100$	García-Cox et al. (2023)	(8)
Importance Value Index (*IVI*)	$IVI = \frac{Ar + Dr + Fr}{3}$	García-Cox et al. (2023)	(9)

pi = Proportion of individuals of species *i*; *S* = Number of species; log = Logarithm; *ni* = Number of individuals of the *i-esima* species; *Pi* = Proportional abundance of the number of individuals of each species (*ni)* among the total number of individuals (*N*); *N* = Total number of individuals in the *i-esimo* gradient; g_i = Basal area of each individual tree; m_i = Number of elements belonging to the category; *M* = Total number of elements or individuals in the data set or total sample.

Soil sampling

In each plot, five soil subsamples were collected at two different soil depths (0-10 and 10-30 cm) and were subsequently homogenized to obtain a representative soil sample for each soil depth (Bravo-Medina et al., 2021). For this study, the total carbon stock (*TCS*) was the sum of the following components: aboveground carbon (*AGC*), belowground root carbon (*BGRC*), litter biomass carbon (*LBC*), and soil organic carbon (*SOC*) (López-Santiago et al., 2019). However, this equation (Equation 10) may consist of more or fewer components, depending on the criteria and interest of the researchers (Dantas et al., 2021; Pradhan et al., 2012).

$$TCS\ (Mg\ C\ ha^{-1}) = AGC + BGRC + LBC + SOC \qquad (10)$$

Where:

TSC = Total carbon stock in Mg C ha^{-1}, and Mg CO_2 ha^{-1} results from the product of Mg C ha^{-1} and 3.67, which corresponds to the molecular weight of CO_2.

To estimate the carbon stored in the palms along the altitudinal gradient, we used the allometric equation proposed by Chave et al. (2005), adapted to include all palms with a diameter at breast height *DBH*≥10 cm. The Equation 11 is based on the wood density (ρ, in g cm^3) and the *DBH* (in cm), and is expressed as follows:

$$AGB = (\rho \times exp(-1.499 + (2.148 \times nl\,(DBH)))) + (0.207 \times nl\,(DBH)^2) - (0.0281 \times nl\,(DBH)^3) \times 0.001 \qquad (11)$$

Where:

AGB = Aboveground biomass per palm in Megagrams (Mg)

ρ = Specific weight of the species in g cm^3

DBH = Diameter at breast height (cm) for individuals with a *DBH*≥10 cm

Aboveground biomass values (*AGB*) were extrapolated per hectare to estimate the total aboveground biomass in Megagrams per hectare. For species without specific data (Chave et al., 2009) on wood density, the average of 0.632 g cm^3 in the Montufar and Pintaud (2006) database was used.

In this study, a comprehensive literature review was carried out to understand the traditional uses and socio-economic value of Amazonian palms (Borchsenius & Moraes, 2006) —a process incorporated to provide a more complete context on the importance of palms, covering the ecological and socioeconomic perspectives (De la Torre et al., 2008). This integrative approach allowed us to develop a broad picture of how palms contribute to the well-being of local communities and to their global conservation (Miranda et al., 2025); thereby ensuring that the discussion on their conservation will take into account both biological and socio-cultural aspects.

Statistical analysis

The data analysis included two main approaches: (1) Characterization of the floristic composition along an altitudinal gradient, assessing the diversity of the species, with the Shannon-Wiener index, and their effective number (Alvez-Valles et al., 2018; Balslev et al., 2015); and (2) Estimation of the contribution of Arecaceae species to carbon sequestration. The assumptions of normality and homoscedasticity were verified with the Kolmogorov-Smirnov and Bartlett tests (Berlanga & Rubio, 2012) ($p<0.001$), which allowed applying an analysis of variance (ANOVA). For those variables that did not meet the assumptions of normality, the Kruskal-Wallis nonparametric test was used as an alternative (Berlanga & Rubio, 2012).

The ANOVA compared palm diversity and density indices along the gradient, using superscript letters for significant differences between categories. The analyses were performed with RStudio (version 3.6.0) (de Lima et al., 2023), using the BiodiversityR version 2.16-1 and Vegan version 2.6-10 packages to calculate and analyze the diversity indices (Fernandez, 2019).

Results and Discussion

Diversity and richness along the altitudinal gradient

A total of 1 916 individuals were recorded, distributed among 11 palm species. The highest diversity was recorded between 801 and 1 000 masl, while the lowest values were obtained between 701 and 800 masl (Table 3). This pattern suggests that climate conditions of humidity and moderate temperatures favor diversity, consistently with the results of previous studies on the subject (Alvez-Valles et al., 2018; Balslev et al., 2017).

Table 3. Averages±standard deviation and Richness, Shannon, Simpson's, Margalef, Pielou's, and Density indices of the family Arecaceae.

Indexes	All	601-700 masl	701-800 masl	801-900 masl	901-1 000 masl	*p*-value[†]
Richness	4.65 ±1.03	3.80[a] ±0.45	3.80[a] ±0.45	5.40[b] ±0.54	5.60[b] ±0.89	***
Shannon	1.03 ±0.29	0.91[a] ±0.21	0.82[a] ±0.24	1.00[a] ±0.23	1.38[b] ±0.15	**
Simpson's	0.51 ±0.15	0.48[a] ±0.12	0.43[a] ±0.14	0.47[a] ±0.13	0.68[b] ±0.04	**
Margalef	1.33 ±0.38	1.03[a] ±0.16	1.03[a] ±0.20	1.56[b] ±0.20	1.69[b] ±0.36	***
Pielou's	0.67 ±0.14	0.68[a] ±0.11	0.61[a] ±0.15	0.60[a] ±0.14	0.80[b] ±0.03	*
Density (palms ha^{-1})	95.80 ±73.20	55.00[a] ±36.84	59.40[a] ±48.68	72.80[a] ±33.43	196.00[b] ±60.49	***

[†]ANOVA. *p*-value: * = *p*<0.05; ** = *p*<0.01; *** = *p*<0.001; n. s. = Non-significant difference between groups. Different letters represent significant differences between the means of the different altitudes (*p*<0.05)

At altitudes of 801 to 900 and 901 to 1 000 masl, the Margalef and Shannon indices reached their highest values, indicating diverse and balanced communities (Alvez-Valles et al., 2018). Pielou's index reflected high evenness in these areas, suggesting a balanced and resilient ecosystem in which species are evenly distributed and play important roles in the functionality of the forest (Pintaud et al., 2008).

Palm density was highest between 901 and 1 000 masl (196 palms ha^{-1}). The ability of the species to thrive in stable environmental conditions and its crucial role in carbon storage are prominent (Torres et al., 2020). Dominant species such as *Iriartea deltoidea* and *Oenocarpus bataua* contribute significantly to carbon sequestration and ecological sustainability of the Amazonian forest (Goodman et al., 2013). These findings underscore the importance of protecting critical areas at higher altitudes to conserve the biodiversity and optimize carbon storage in the Ecuadorian Amazon (Balslev et al., 2017; Malhi & Grace, 2000).

Abundance and ecological Importance Value (*IVI*)

The analysis of the Importance Value Index (*IVI*) highlights *Iriartea deltoidea* as the dominant species along the studied altitudinal gradient, with high values for relative abundance, frequency and dominance, with values of 39.25 between 600 and 700 masl, and of 56.03 from 801 to 900 masl (Table 4). This pattern reflects the ability of this species to adapt to diverse microenvironmental conditions and its importance in the structure of tropical rainforests (Balslev et al., 2017). At altitudes ranging between 901 and 1 000 m, *Oenocarpus bataua* stands out, with an *IVI* value of 30.14, due to its high relative abundance (43.06 %) and its significant contribution to the forest biomass (Goodman et al., 2013).

Table 4. Importance value index of the Arecaceae family species.

Species	*RA* (%)	*RF* (%)	*RD* (%)	*IVI*
EAAF1 (601-700 masl)				
***Iriartea deltoidea* Ruiz & Pav.**	21.45	69.98	26.32	39.25
***Wettinia maynensis* Spruce**	51.27	5.38	15.79	24.15
***Oenocarpus bataua* Mart.**	10.55	21.71	21.05	17.77
***Geonoma macrostachys* Mart.**	15.64	0.00	26.32	13.98
***Ceroxylon amazonicum* Galeano**	0.73	2.21	5.26	2.73
***Astrocaryum murumuru* Mart.**	0.36	0.72	5.26	2.12
EAAF2 (701-800 masl)				
***Iriartea deltoidea* Ruiz & Pav.**	45.12	93.87	26.32	55.10
***Wettinia maynensis* Spruce**	39.39	6.13	21.05	22.19
***Geonoma macrostachys* Mart.**	11.45	0.00	26.32	12.59
***Oenocarpus bataua* Mart.**	3.70	0.00	21.05	8.25
***Phytelephas tenuicaulis* (Barfod) A. J. Hend.**	0.34	0.00	5.26	1.87
EAAF3 (801-900 masl)				
***Iriartea deltoidea* Ruiz & Pav.**	56.87	92.71	18.52	56.03
***Oenocarpus bataua* Mart.**	18.68	1.20	18.52	12.80
***Geonoma macrostachys* Mart.**	15.66	0.00	18.52	11.39
***Phytelephas tenuicaulis* (Barfod) A. J. Hend.**	5.77	0.00	14.81	6.86
***Wettinia maynensis* Spruce**	1.37	0.00	11.11	4.16
***Socratea exorrhiza* (Mart.) H. Wendl.**	0.82	3.86	7.41	4.03
***Euterpe precatoria* Mart.**	0.55	2.23	7.41	3.39

***Aiphanes ulei* (Dammer) Burret**	0.27	0.00	3.70	1.33
EAAF4 (901-1 000 masl)				
***Iriartea deltoidea* Ruiz & Pav.**	38.98	61.94	17.86	39.59
***Oenocarpus bataua* Mart.**	43.06	29.52	17.86	30.14
***Geonoma macrostachys* Mart.**	9.59	0.00	17.86	9.15
***Euterpe precatoria* Mart.**	1.12	7.03	14.29	7.48
***Aiphanes ulei* (Dammer) Burret**	1.12	0.00	14.29	5.14
***Wettinia maynensis* Spruce**	5.61	1.51	7.14	4.76
***Socratea exorrhiza* (Mart.) H. Wendl.**	0.31	0.00	7.14	2.48
***Bactris gasipaes* Kunth**	0.20	0.00	3.57	1.26

RA = Relative abundance; *RF* = Relative frequency; *RD* = Relative density; *IVI* = Importance Value Index; EAAF = Andean-Amazonian Evergreen Forest.

Species such as *Geonoma macrostachys* Mart. and *Wettinia maynensis* Spruce showed greater variability in their contribution; they were more abundant at intermediate altitudes, but occur with a lower relative frequency compared with *Iriartea deltoidea*. This more dispersed distribution reinforces the resilience of the ecosystem through a high functional diversity (Alvez-Valles et al., 2018). The results emphasize the essential role of palms in the carbon cycle and the importance of conservation policies to preserve the dominant species and their storage capacity in tropical ecosystems (Balslev et al., 2017; Keeling & Phillips, 2007; Montufar & Pintaud, 2006).

Carbon stocks within the altitudinal gradient

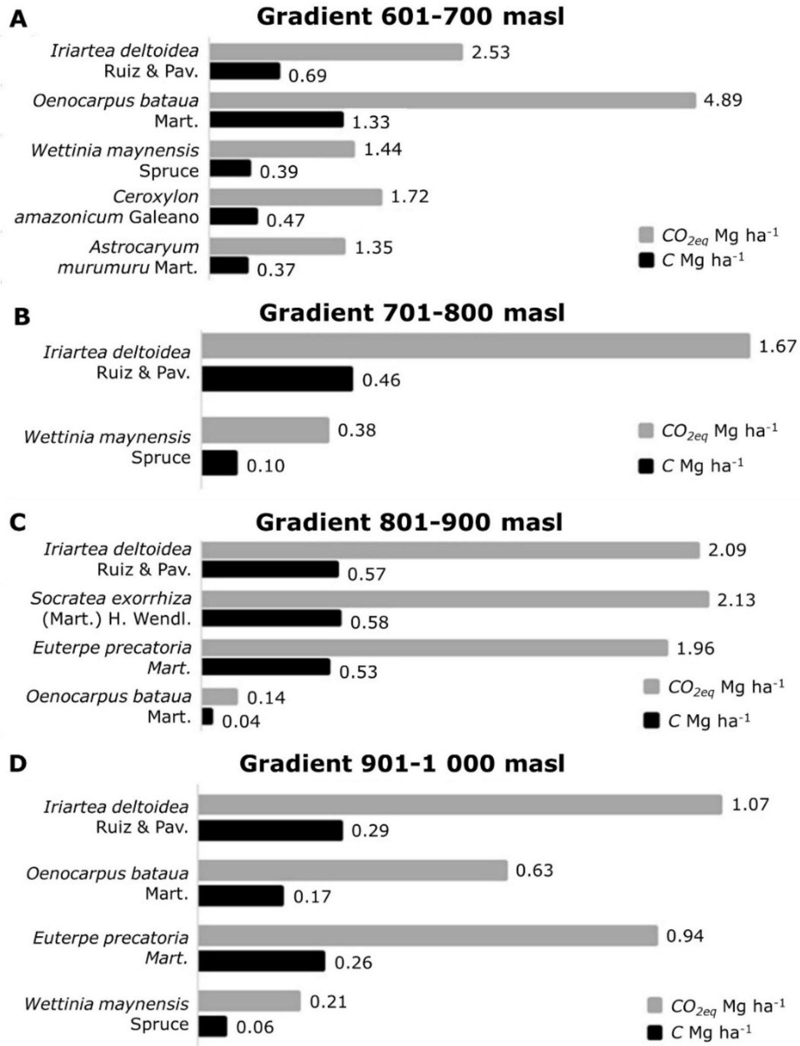
Carbon in palms is higher at 601-700 masl (11.20 Mg ha^{-1}, p<0.05), decreases at intermediate altitudes of 701-800 masl (6.26 Mg ha^{-1}), and is even lower at higher altitudes: 801-900 masl (7.80 Mg ha^{-1}) and from 901 to 1 000 masl (3.11 Mg ha^{-1}) (Table 5). These results highlight the relevance of lowland areas in carbon sequestration and reinforce the key role of palms in carbon cycling in the studied forests (Balslev et al., 2015; Dauber et al., 2000).

Table 5. Averages±standard deviation of the estimated variables.

Variables (Mg ha^{-1})	All	(601-700 masl)	(701-800 masl)	(801-900 masl)	(901-1 000 masl)	*p*-value†
$Carbon_{palms}$	7.10 ±4.98	11.20^{b} ±6.14	6.26^{a,b} ±5.09	7.80^{a,b} ±3.16	3.11^{a} ±1.36	*
CO_{2eq_palms}	26.03 ±18.27	41.14^{b} ±22.52	22.97^{a,b} ±18.65	28.58^{a,b} ±11.58	11.42^{a} ±4.97	*
$Carbon_{soil}$	29.69 ±7.33	25.82 ±1.76	31.02 ±10.52	31.63 ±10.48	30.29 ±2.43	n. s.
CO_{2eq_soil}	108.96 ±26.92	94.75 ±6.45	113.83 ±38.62	116.08 ±38.46	111.17 ±8.92	n. s.
$Carbon_{total}$	36.79 ±9.02	37.04 ±6.30	37.28 ±15.27	39.43 ±9.04	33.40 ±2.96	n. s.
CO_{2eq_total}	134.98 ±33.10	135.89 ±23.10	136.80 ±56.04	146.67 ±33.17	122.58 ±10.86	n. s.

$Carbon_{palms}$ = Carbon in palms; CO_{2eq_palms} = Carbon dioxide equivalent in palms; $Carbon_{soil}$ = Carbon in soil; CO_{2eq_soil} = Soil carbon dioxide equivalent; $Carbon_{total}$ = Total carbon; CO_{2eq_total} = Total carbon dioxide equivalent. †ANOVA. *p-value*: * = p<0.05; n. s. = Non-significant difference between groups. Different letters represent significant differences between the means of the different altitudes (p<0.05).

Iriartea deltoidea and *Oenocarpus bataua* represent 65 % of the registered palms; they stand out for their high biomass and contribution to carbon storage, since they accumulate between 3.11 and 11.20 Mg ha^{-1} of aboveground carbon along the assessed altitudinal gradient (Figure 3; Table 4), a fact that reflects their predominance in the low and medium altitudes. These observations are consistent with previous studies in the Ecuadorian Amazon (García-Quintana et al., 2021), which have shown that palms, despite being less studied than timber species, contribute substantially to carbon storage in tropical forests (Torres et al., 2020).



Gradient (masl): A = 601 a 700; B = 701 a 800; C = 801 a 900; D = 901 a 1 000.

Figure 3. Contribution of palm species to the carbon pool within an altitudinal gradient.

The carbon stored in the soil exhibited greater stability along the gradient (25.82-31.63 Mg ha^{-1}, p>0.05), which balanced the total reserves of the ecosystem. The total carbon (the sum of carbon in the palms and soil) presented a limited variation (33.40-39.43 Mg ha^{-1}). This indicates that, although palms contribute in a significant way to the aboveground carbon, the soil plays a key role in the overall carbon balance in the studied forests (Bravo-Medina et al., 2021).

CO_{2eq} stored in palm species

The CO_2 equivalent reached a maximum of 41.14 Mg ha^{-1} at low altitudes, and decreased to 22.97 and 28.58 Mg ha^{-1} at intermediate altitudes. Species like *Oenocarpus bataua* and *Iriartea deltoidea* stand out for their carbon sequestration capacity, which is essential for conservation and climate change mitigation strategies. Between the heights of 601 to 700 masl, *Oenocarpus bataua* stores 4.89 Mg ha^{-1} of CO_{2eq} and 1.33 Mg ha^{-1} of C, followed by *Iriartea deltoidea*, with 2.53 Mg ha^{-1} of CO_{2eq} and 0.69 Mg ha^{-1} of C, reflecting favorable conditions for the accumulation of biomass. Other species, such as *Wettinia maynensis*, *Ceroxylon amazonicum* Galeano and *Astrocaryum murumuru* Mart. contribute to a lesser extent, with CO_{2eq} values ranging between 1.35 and 1.72 Mg ha^{-1}, and C values of 0.37 to 0.47 Mg ha^{-1} (Figure 3A).

At 701 to 800 masl, carbon storage decreases, with *Iriartea deltoidea* as the dominant species (1.67 Mg ha^{-1} de CO_{2eq}) (Figure 3B). From 801 to 900 masl, a slight recovery is observed, with *Socratea exorrhiza* (Mart.) H. Wendl. (2.13 Mg ha^{-1} of CO_{2eq}) and *Iriartea deltoidea* (2.09 Mg ha^{-1}) as main contributors; while *Oenocarpus bataua* shows a significant drop with only 0.14 Mg ha^{-1} (Figure 3C). Finally, within the altitudinal interval of 901 to 1 000 masl, carbon storage decreases in all species, but *Iriartea deltoidea* remains dominant with 1.07 Mg ha^{-1} de CO_{2eq} (Figure 3D).

These results coincide with studies that highlight the value of palms in tropical forests as effective carbon sinks, due to the amount of aerial biomass they are capable of storing and their rapid regeneration (Keeling & Phillips, 2007). Their presence at different levels of the canopy, from herbaceous to arboreal, ensures continuous carbon storage: an essential aspect of climate change mitigation (Goodman et al., 2013).

Traditional uses and socioeconomic value of Amazonian palms

Arecaceae species play a crucial role in the livelihood of Amazonian human populations (Cámara-Leret et al., 2014). Its leaves are used in the elaboration of roofs and baskets, in addition to some traditional medicinal uses to treat fevers (Vormisto et al., 2004). They are highly appreciated for their oil-rich fruits; they are also used in the preparation of personal care products and in food, as well as for their medicinal applications for the treatment of skin conditions (Gutsche et al., 2008). These multiple uses highlight the importance of palms in the daily life of Amazonian communities, in addition to their ecological value (Table 6).

Table 6. Main uses recorded for palms in Amazonian communities along the studied gradient.

Species	Common name	Uses			
		Human and livestock food	Medicinal	Handicrafts	Construction
Iriartea deltoidea **Ruiz & Pav.**	*Pambil*, *Chonta*	√		√	√
Geonoma macrostachys **Mart.**	*Suqui-suqui*, *Pashaco*		√	√	√
Oenocarpus bataua **Mart.**	*Ungurahua*, *Seje*	√	√	√	√
Wettinia maynensis **Spruce**	*Cashapona*, White palm	√		√	√
Ceroxylon amazonicum **Galeano**	Wax palm	√		√	√
Astrocaryum murumuru **Mart.**	*Murumuru*	√	√	√	√

Source: De la Torre et al. (2008).

Conclusions

This study highlights the role of the Arecaceae family in carbon storage in the evergreen piedmont forest of the Ecuadorian Amazon. Altitudes between 901 and 1 000 masl have the highest density of palms (196 palms ha^{-1}) and carbon sequestration capacity, with significant contributions also within the range of 601 to 700 masl. Dominant species such as *Oenocarpus bataua* and *Iriartea deltoidea* stand out for their levels of carbon sequestration in Ecuadorian Amazonian forests. Between the altitudinal gradient of 601 to 700 masl, *Oenocarpus bataua* exhibits the highest storage with 4.89 Mg ha^{-1} of CO_{2eq} and 1.33 Mg ha^{-1} of C, while *Iriartea deltoidea* stores 2.53 Mg ha^{-1} of CO_{2eq} and 0.69 Mg ha^{-1} of C. At higher altitudes, *Iriartea deltoidea* continues to contribute consistently, with 1.67 Mg ha^{-1} of CO_{2eq} at 701 to 800 masl and 1.07 Mg ha^{-1} at 901 to 1 000 masl. *Oenocarpus bataua* is more efficient at low altitudes, while *Iriartea deltoidea* maintains its importance in all gradients, proving to be key for carbon restoration and sequestration in the Amazon ecosystem at different altitudes.

The diversity and even distribution of palms ensure carbon storage in the gradient, which is vital for ecological stability and climate change mitigation. The socioeconomic benefits that they bring, such as the provision of food, construction materials, and materials for handicraft products, render management strategies that balance their conservation and sustainable use more necessary, particularly among the local communities that depend on the palms. This study also emphasizes the importance of developing allometric models specific to palms that will improve the estimates of their biomass and carbon sequestration capacity to facilitate their effective inclusion in conservation and carbon offset programs such as REDD+.

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Conflict of interest

The authors declare that they have no conflict of interest with any company or institution related to this work.

Contributions by author

Héctor Reyes-Morán, Bolier Torres-Navarrete, Cristhian Tipán-Torres and Erika Zambrano-Alcívar: study idea, collection of field data, analysis of results and drafting of the manuscript; Carlos Bravo-Medina and Antón García-Martínez: revision of the manuscript; Héctor Reyes-Morán: field data collection and database formulation.

References

Alvez-Valles, C. M., Balslev, H., Garcia-Villacorta, R., Carvalho, F. A., & Menini N., L. (2018). Palm species richness, latitudinal gradients, sampling effort, and deforestation in the Amazon region. *Acta Botanica Brasilica*, *32*(4), 527-539. https://doi.org/10.1590/0102-33062017abb0400

Aryal, D. R., Gómez-González, R. R., Hernández-Nuriasmú, R., & Morales-Ruiz, D. E. (2019). Carbon stocks and tree diversity in scattered tree silvopastoral systems in Chiapas, Mexico. *Agroforestry Systems*, *93*, 213-227. https://doi.org/10.1007/s10457-018-0310-y

Balslev, H., Copete, J.-C., Pedersen, D., Bernal, R., Galeano, G., Duque, Á., Berrio, J. C., & Sanchez, M. (2017). Palm diversity and abundance in the Colombian Amazon. In R. W. Myster (Ed.), *Forest structure, function and dynamics in Western Amazonia* (pp. 101-123). John Wiley & Sons Ltd. https://doi.org/10.1002/9781119090670.ch5

Balslev, H., Pedersen, D., Navarrete, H., y Pintaud, J.-C. (2015). Diversidad y abundacia de palmas. En H. Balslev, M. J. Marcía y H. Navarreta (Edits.), *Cosecha de palmas en el noreste de Suramérica: bases cientícas para su manejo y conservación* (pp. 13-25). Pontificia Universidad Católica del Ecuador. https://www.researchgate.net/publication/294548512_Cosecha_de_palmas_en_el_noroeste_de_Suramerica_bases_cientificas_para_su_manejo_y_conservacion

Berlanga S., V., y Rubio H., M. J. (2012). Clasificación de pruebas no paramétricas. Cómo aplicarlas en SPSS. *REIRE, Revista d'Innovació i Recerca en Educació*, *5*(2), 101-113. https://doi.org/10.1344/reire2012.5.2528

Borchsenius, F., y Moraes R., M. (2006). Diversidad y usos de palmeras andinas (Arecaceae). En M. Moraes R., B. Øllgaard, L. P. Kvist, F. Borchsenius y H. Balslev (Edits.), *Botánica Económica de los Andes Centrales* (pp. 412-433). Universidad Mayor de San Andrés. https://www.researchgate.net/publication/228761462_Diversidad_y_usos_de_palmeras_andinas_Arecaceae

Bravo V., E. (2014). *La biodiversidad en el Ecuador*. Universidad Politécnica Salesiana. https://dspace.ups.edu.ec/bitstream/123456789/6788/1/La%20Biodiversidad.pdf

Bravo-Medina, C., Goyes-Vera, F., Arteaga-Crespo, Y., García-Quintana, Y., & Changoluisa, D. (2021). A soil quality index for seven productive landscapes in the Andean-Amazonian foothills of Ecuador. *Land Degradation & Development*, *32*(6), 2226-2241. https://doi.org/10.1002/ldr.3897

Cámara-Leret, R., Paniagua-Zambrana, N., Balslev, H., Barfod, A., Copete, J. C., & Macía, M. J. (2014). Ecological community traits and traditional knowledge shape palm ecosystem services in northwestern South America. *Forest Ecology and Management*, *334*, 28-42. https://doi.org/10.1016/j.foreco.2014.08.019

Cazzolla G., R., Reich, P. B., Gamarra, J. G. P., Crowther, T., Hui, C., Morera, A., Bastin, J.-F., de-Miguel, S., Nabuurs, G.-J., Svenning, J.-C., Serra-Diaz, J. M., Merow, C., Enquist, B., Kamenetsky, M., Lee, J., Zhu, J., Fang, J., Jacobs, D. F., … Liang, J.

(2022). The number of tree species on Earth. *PNAS Proceedings of the National Academy of Sciences*, *119*(6), Article e2115329119. https://doi.org/10.1073/pnas.2115329119

Chave, J., Andalo, C., Brown, S., Cairns, M. A., Chambers, J. Q., Eamus, D., Fölster, H., Fromard, F., Higuchi, N., Kira, T., Lescure, J.-P., Nelson, B. W., Ogawa, H., Puig, H., Riéra, B., & Yamakura, T. (2005). Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia*, *145*, 87-99. https://doi.org/10.1007/s00442-005-0100-x

Chave, J., Coomes, D., Jansen, S., Lewis, S. L., Swenson, N. G., & Zanne, A. E. (2009). Towards a worldwide wood economics spectrum. *Ecology Letters*, *12*(4), 351-366. https://doi.org/10.1111/J.1461-0248.2009.01285.X

Dantas, D., Terra, M. de C. N. S., Rodrigues P., L. O., Calegario, N., & Maciel, S. M. (2021). Above and belowground carbon stock in a tropical forest in Brazil. *Acta Scientiarum. Agronomy*, *43*, Article e48276. https://doi.org/10.4025/actasciagron.v43i1.48276

Dauber, E., Terán, J., y Guzmán, R. (2000). Estimaciones de biomasa y carbono en bosques naturales de Bolivia. *Revista Forestal Iberoamericana*, *1*(1), 1-10. https://www.forest.ula.ve/rforibam/archivos/DOC2.pdf

De la Torre, L., Navarrete, H., Muriel M., P., Macía, M. J., y Balslev, H. (Edits.). (2008). *Enciclopedia de las plantas útiles del Ecuador*. Herbario QCA de la Escuela de Ciencias Biológicas de la Pontificia Universidad Católica del Ecuador y Herbario AAU del Departamento de Ciencias Biológicas de la Universidad de Aarhus. https://bibdigital.rjb.csic.es/records/item/16016-enciclopedia-de-las-plantas-utiles-del-ecuador

De Lima, R. A. F., Sánchez-Tapia, A., Mortara, S. R., ter Steege, H., & de Siqueira, M. F. (2023). plantR: An R package and workflow for managing species records from biological collections. *Methods in Ecology and Evolution*, *14*(2), 332-339. https://doi.org/10.1111/2041-210X.13779

Fernandez, D. S. (2019, febrero 18). *Laboratorio de Ecología de Comunidades: Biodiversidad. Análisis de Biodiversidad con vegan y BiodiversityR*. RPubs by RStudio. http://rpubs.com/dsfernandez/468964

Galeas, R., y Guevara, J. E. (Eds.). (2012). *Sistema de clasificación de los ecosistemas del Ecuador Continental*. Ministerio de Ambiente del Ecuador. https://www.ambiente.gob.ec/wp-content/uploads/downloads/2012/09/LEYENDA-ECOSISTEMAS_ECUADOR_2.pdf

García-Cox, W., López-Tobar, R., Herrera-Feijoo, R. J., Tapia, A., Heredia R., M., Toulkeridis, T., & Torres, B. (2023). Floristic composition, structure, and aboveground biomass of the Moraceae Family in an Evergreen Andean Amazon Forest, Ecuador. *Forests*, *14*(7), 1406. https://doi.org/10.3390/f14071406

García-Quintana, Y., Arteaga-Crespo, Y., Torres-Navarrete, B., Bravo-Medina, C., y Robles-Morillo, M. (2021). Biomasa aérea de familias botánicas en un bosque siempreverde piemontano sometido a grados de intervención. *Colombia Forestal*, *24*(1), 45-59. https://doi.org/10.14483/2256201X.15939

Gentry, A. H. (1982). Patterns of Neotropical plant species diversity. In M. K. Hecht, B. Wallace & G. T. Prance (Edits.), *Evolutionary Biology* (Vol. 15, pp. 1-84). Springer New York. https://doi.org/10.1007/978-1-4615-6968-8_1

Goodman, R. C., Phillips, O. L., del Castillo T., D., Freitas, L., Tapia C., S., Monteagudo, A., & Baker, T. R. (2013). Amazon palm biomass and allometry. *Forest Ecology and Management*, *310*, 994-1004. https://doi.org/10.1016/j.foreco.2013.09.045

Gutsche, A., Smith, N., y Wust, W. H. (2008). *Frutas amazónicas, postres peruanos de vanguardia*. Ministerio de Comercio Exterior y Turismo e Instituto de Investigaciones de la Amazonía Peruana. https://repositorio.iiap.gob.pe/handle/20.500.12921/137

Jost, L., y González-Oreja, J. A. (2012). Midiendo la diversidad biológica: más allá del índice de Shannon. *Acta Zoológica Lilloana*, *56*(1-2), 3-14. https://lillo.org.ar/revis/zoo/2012/v56n1_2/v56n1_2a01.pdf

Keeling, H. C., & Phillips, O. L. (2007). The global relationship between forest productivity and biomass. *Global Ecology and Biogeography*, *16*(5), 618-631. https://doi.org/10.1111/j.1466-8238.2007.00314.x

Kristiansen, T., Svenning, J.-C., Grández, C., Salo, J., & Balslev, H. (2009). Commonness of Amazonian palm (Arecaceae) species: Cross-scale links and potential determinants. *Acta Oecologica*, *35*(4), 554-562. https://doi.org/10.1016/j.actao.2009.05.001

López-Santiago, J. G., Casanova-Lugo, F., Villanueva-López, G., Díaz-Echeverría, V. F., Solorio-Sánchez, F. J., Martínez-Zurimendi, P., Aryal, D. R., & Chay-Canul, A. J. (2019). Carbon storage in a silvopastoral system compared to that in a deciduous dry forest in Michoacán, Mexico. *Agroforest Systems*, *93*, 199-211. https://doi.org/10.1007/s10457-018-0259-x

Malhi, Y., & Grace, J. (2000). Tropical forests and atmospheric carbon dioxide. *Trends in Ecology & Evolution*, *15*(8), 332-337. https://doi.org/10.1016/S0169-5347(00)01906-6

Medrano M., M. de J., Hernández, F. J., Corral R., S., y Nájera L., J. A. (2017). Diversidad arbórea a diferentes niveles de altitud en la región de El Salto, Durango. *Revista Mexicana de Ciencias Forestales*, *8*(40), 57-68. https://doi.org/10.29298/rmcf.v8i40.36

Miranda, F., Coronel-Chugden, J.-W., Veneros, J., García, L., Guadalupe, G. A., & Arellanos, E. (2025). Species diversity of the Family Arecaceae: What are the implications of their biogeographical representation? An analysis in Amazonas, Northeastern Peru. *Forests*, *16*(1), 76. https://doi.org/10.3390/f16010076

Montufar, R., & Pintaud, J.-C. (2006). Variation in species composition, abundance and microhabitat preferences among western Amazonian *terra firme* palm communities. *Botanical Journal of the Linnean Society*, *151*(1), 127-140. https://doi.org/10.1111/j.1095-8339.2006.00528.x

Neill, D. A. (2012). ¿Cuántas especies nativas de plantas vasculares hay en Ecuador? *Revista Amazónica Ciencia y Tecnología*, *1*(1), 70-83. https://doi.org/10.59410/RACYT-v01n01ep08-0001

Phillips, O. L., Malhi, Y., Higuchi, N., Laurance, W. F., Núñez, P. V., Vásquez, R. M., Laurance, S. G., Ferreira, L. V., Stern, M., Brown, S., & Grace, J. (1998). Changes in the carbon balance of tropical forests: evidence from long-term plots. *Science*, *282*(5388), 439-442. https://www.science.org/doi/10.1126/science.282.5388.439

Pintaud, J.-C., Galeano, G., Balslev, H., Bernal, R., Borchsenius, F., Ferreira, E., de Granville, J.-J., Mejía, K., Millán, B., Moraes, M., Noblick, L., Stauffer, F. W., & Kahn, F. (2008). Las palmeras de América del Sur: diversidad, distribución e historia evolutiva. *Revista Peruana de Biología*, *15*(S1), 7-29. http://www.scielo.org.pe/scielo.php?pid=S1727-99332008000000003&script=sci_abstract&tlng=en

Pradhan, B. M., Awasthi, K. D., & Bajracharya, R. M. (2012). Soil organic carbon stocks under different forest types in Pokhare khola sub-watershed: a case study from Dhading district of Nepal. *WIT Transactions on Ecology and the Environment*, *157*, 535-546. https://www.witpress.com/elibrary/wit-transactions-on-ecology-and-the-environment/157/23310

Ter Steege, H. (1998). The use of forest inventory data for a National Protected Area Strategy in Guyana. *Biodiversity and Conservation*, *7*(11), 1457-1483. https://doi.org/10.1023/A:1008893920157

Torres, B., Vasseur, L., López, R., Lozano, P., García, Y., Arteaga, Y., Bravo, C., Barba, C., & García, A. (2020). Structure and above ground biomass along an elevation small-scale gradient: case study in an Evergreen Andean Amazon forest, Ecuador. *Agroforestry Systems*, *94*, 1235-1245. https://doi.org/10.1007/s10457-018-00342-8

Vormisto, J., Svenning, J.-C., Hall, P., & Balslev, H. (2004). Diversity and dominance in palm (Arecaceae) communities in *terra firme* forests in the western Amazon basin. *Journal of Ecology*, *92*(4), 577-588. https://doi.org/10.1111/j.0022-0477.2004.00904.x

Zambrano, E., Torres, B., Ochoa-Moreno, S., Reyes, H., Torres, A., Velasco, C., y Heredia R., M. (2021). Determinantes socioeconómicas del uso forestal maderable en la zona de amortiguamiento del Parque Nacional Sumaco Napo Galeras, Amazonía Ecuatoriana. *Ecosistemas*, *30*(3), 2216. https://doi.org/10.7818/ECOS.2216