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THE CONTRIBUTION OF THE TROPICAL DRY FOREST TO THE QUANTIFICATION OF FOREST BIOMASS AND CARBON IN THE SICARARE WETLAND: A PATH TOWARD ENVIRONMENTAL SUSTAINABILITY

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ABSTRACT: The Tropical Dry Forest (TDF) is one of the ecosystems most vulnerable to the effects of climate change and environmental degradation processes. In Colombia, its capacity to capture and store carbon has been progressively diminished as a result of deforestation, land-use change, and the expansion of the agricultural frontier. In this context, the present study focuses on the Sicarare Wetland, located in Valledupar, with the aim of analyzing its role as a carbon sink. This research is particularly relevant due to the limited existing information on forest biomass and carbon storage in wetlands associated with the Tropical Dry Forest of the Colombian Caribbean region, which highlights the need to deepen our ecological and environmental understanding of these ecosystems (Chaturvedi et al., 2011; IDEAM, 2011).

In line with the above, the main objective of the research was to estimate the biomass and carbon stored in the Tropical Dry Forest present in the Sicarare Wetland, based on a forest inventory aimed at generating information on the area's biodiversity and developing predictive models tailored to local conditions. To this end, a non-experimental quantitative approach was adopted, involving the delineation of 400 m² plots, within which tree individuals were measured and allometric equations were applied to estimate biomass (IDEAM, 2011). Complementarily, geographic information systems were used to spatially represent the distribution of biomass, as well as biodiversity indices, including the Shannon and Simpson indices, to characterize the floristic composition and diversity of the studied ecosystem (Shannon, 1964; Simpson, 1949).

The results showed that the wetland is home to a total of 457 trees belonging to 40 different species, with an estimated biomass of 75,438 tons and a carbon storage capacity of 552,373 tons. Likewise, a significant correlation was identified between tree diameter and accumulated biomass, which confirms the importance of the Sicarare Wetland as a carbon sink of high ecological significance. Consequently, this ecosystem is positioned as a strategic component for climate change mitigation, biodiversity conservation, and the maintenance of ecosystem services in the region (Cavender-Bares et al., 2022; Jucker et al., 2014; Hooper et al., 2005).

KEYWORDS: Forest biomass, carbon, Tropical Dry Forest, Sicarare Wetland, biodiversity, conservation, climate change, allometric models.

1. Introduction

The Tropical Dry Forest (TDF) is considered one of the most threatened ecosystems globally and nationally, due to its high vulnerability to environmental degradation, habitat fragmentation, and the effects of climate change. Its marked climatic seasonality and its ability to adapt to prolonged periods of drought do not diminish its ecological importance; on the contrary, this ecosystem harbors significant biological diversity and provides essential ecosystem services, including water regulation, habitat maintenance, and carbon storage. In Colombia, landscape transformation due to factors associated with agricultural expansion, un d land use, and other anthropogenic processes has significantly reduced the remaining areas of these ecosystems, affecting their ecological integrity and environmental function. In this context, the

Sicarare Wetland, located in Valledupar, Cesar, takes on special relevance, as it integrates a remnant of BST with a wetland ecosystem of high ecological value, making it a strategic site for the conservation and study of ecosystem processes associated with carbon (Pizano and García, 2014; Pizano et al., 2017).

This research stems from the need to assess the capacity of the Sicarare Wetland in the city of Valledupar to act as a carbon sink, given that wetlands play a fundamental role in climate regulation, carbon storage, and the preservation of multiple ecological functions. These ecosystems store carbon in both plant biomass and soils, and their conservation is key to reducing emissions resulting from environmental degradation. However, in the Colombian Caribbean region, there remain gaps in information regarding biomass and carbon stored in wetlands associated with the Tropical Dry Forest, which highlights the scientific and environmental relevance of this study. Added to this are growing anthropogenic pressures, such as logging, pollution, and land-use changes, which compromise the ecological stability of the wetland and necessitate the formulation of conservation strategies grounded in technical and scientific evidence (Ramsar Convention Secretariat, 2012; Pizano and García, 2014).

Regarding the methodological background, biomass and carbon estimation in tropical forest ecosystems has been conducted primarily using indirect methods, such as forest inventories and allometric equations—tools widely recognized for their utility in quantifying above-ground biomass without resorting to destructive techniques. Although the Tropical Dry Forest typically has lower tree density compared to other

forested ecosystems, this does not imply low carbon storage capacity, given that the presence of species with dense wood and specific structural adaptations can favor biomass accumulation over time. However, to improve the accuracy of estimates, it is essential to conduct site-specific studies so that the models used reflect the ecological, floristic, and structural conditions of the local ecosystem (Picard et al., 2012; IDEAM, 2022).

In line with the above, the purpose of this study is to estimate the biomass and carbon of the Tropical Dry Forest present in the Sicarare Wetland, located in Valledupar, Cesar, through a forest and tree inventory, the development of predictive models for biomass and carbon, and the formulation of actions aimed at the conservation of the wetland. To this end, a forest inventory was conducted to obtain information regarding the forest's composition, structure, and diversity—fundamental variables for understanding its ecological functioning and for supporting the development of estimation models tailored to local conditions. Thus, the research not only provides technical knowledge about the wetland's potential as a carbon sink but also generates relevant inputs for the environmental management and conservation of this strategic ecosystem (Picard et al., 2012; Pizano and García, 2014)

2. Objectives

The overall objective of this study is to estimate forest biomass and carbon in the Tropical Dry Forest of the Sicarare Wetland, located in Valledupar, Cesar, in order to generate scientific information relevant to the sustainable management of this ecosystem.

In this regard, the research seeks to provide technical elements that strengthen environmental conservation processes and, at the same time, contribute to recognizing the role of these ecosystems in climate change mitigation, particularly due to their capacity to store carbon in plant biomass.

As part of the methodological development, a detailed inventory of the flora present in the Sicarare Wetland Tropical Dry Forest will be conducted, with the aim of obtaining ecological indicators associated with biodiversity, such as species composition, relative abundance, and forest structure. This information will allow us to characterize the biological richness of the study area, as well as to understand its ecological functionality and its potential for carbon storage, a fundamental aspect in strategic ecosystems subject to constant environmental pressures.

Likewise, we propose the development of predictive models aimed at estimating forest biomass and carbon. These models will be based on dendrometric variables of the trees, particularly their physical dimensions, and will be adjusted according to the specific conditions of the local ecosystem. This procedure will allow for more accurate estimates of the accumulated biomass and carbon stored in the forest, in accordance with methodologies widely used in forestry and carbon quantification studies.

Finally, based on the results obtained, strategies will be formulated aimed at the conservation and protection of the Sicarare Wetland Tropical Dry Forest, with the goal of preserving biodiversity, strengthening forest management, and promoting the ecological sustainability of the area. In this way, the research will not only contribute to scientific knowledge of the ecosystem but will also provide technical inputs for

decision-making regarding environmental management and conservation in the Valledupar region of Cesar.

3. Methodology

This study was conducted using a quantitative approach and a non-experimental cross-sectional design [1], with the aim of estimating the forest biomass and carbon present in the Tropical Dry Forest (TDF) of the Sicarare Wetland at a specific point in time, without intervening in or altering the study variables. In this regard, the study sought to establish quantifiable relationships between the physical dimensions of the trees and the amount of stored carbon, through the application of previously validated allometric models for estimating biomass and carbon.

The research is descriptive in nature, as it allowed for the quantification of biomass and carbon in the evaluated ecosystem, and is also exploratory, as it addresses an ecosystem for which there is limited local data, thereby generating information relevant to environmental conservation and forest management. The study population consisted of the trees present in the BST of the Sicarare Wetland, for which stratified random sampling was used, taking into account the heterogeneity of the ecosystem and the topographic characteristics of the area. To this end, 400 m² plots were delineated, following the methodological recommendations of [2]. The sample size was determined based on tree density, ensuring that the selected individuals would allow for reliable estimates of biomass and carbon.

Field data collection was conducted using conventional instruments for measuring dendrometric variables. Forestry measuring tapes were used to determine diameter at breast height (DBH), a Pressler drill was used to extract wood samples and estimate their density, and a global positioning system (GPS) was used for the georeferencing of the plots. These measurements formed the basis for the application of allometric equations aimed at estimating forest biomass.

Subsequently, species-specific allometric relationships, previously established in scientific research, were applied to relate the dry weight of the wood to total biomass. Stem biomass was estimated using the following equation:

$$Biomasa = \frac{(V \text{ m}^3) \left(\text{Densidad} \frac{g}{\text{cm}^3} \right)}{(100)^3} \quad (1)$$

Subsequently, above-ground biomass was calculated using the allometric relationship established in IDEAM's "Protocol for the National and Subnational Estimation of Biomass and Carbon in Colombia." The specific formula for the Tropical Dry Forest was:

$$\ln(BA) = a + b \ln(D) + c (\ln(D))^2 + B1 \ln(p) \quad (2)$$

Forest carbon was calculated from the biomass obtained by multiplying the above-ground biomass (BA) by 0.5 to obtain the carbon content:

$$CA = (BA)(0,5) \quad (3)$$

Once the field data were collected, they were processed using Microsoft Excel, where calculations such as the mean, standard deviation, and other statistical indicators were performed. Additionally, the normality of the data and the correlation between the dendrometric variables (DBH, height, and biomass) were verified by applying statistical tests to confirm the relationship between tree diameter and stored biomass and carbon.

Furthermore, biodiversity indices were calculated to analyze forest structure, such as the Shannon Index, Simpson Index, and Margalef Index, which were used to measure species richness and abundance in the sample plots:

Shannon Index

$$H = - \sum (\pi * \ln(\pi)) \quad (4)$$

Simpson Index

$$D = \sum \frac{[n(n-1)]}{[N(N-1)]} \quad (5)$$

Margalef Index

$$D = \frac{S-1}{\ln(N)} \quad (6)$$

During the analysis phase, Geographic Information System (GIS) tools were also incorporated to georeference the sampling plots and create thematic maps representing the spatial distribution of biomass and forest carbon in the wetland.

4. Results

The research was based on field measurements and statistical analyses aimed at calculating biomass, carbon, and biodiversity indices. The results obtained were supported by key methodological references, which validate both the techniques applied and the validity of the findings.

In the first phase of the study, a forest and tree inventory of the Tropical Dry Forest (TDF) in the Sicarare Wetland was conducted to obtain biodiversity indicators and assess the ecosystem structure. To this end, a systematic methodological procedure was implemented for the collection of field information and data. In total, eight transects were established (see Figure 1), each with an average area of 2,000 m², in which fundamental dendrometric variables, such as diameter at breast height (DBH) and total tree height, were measured.

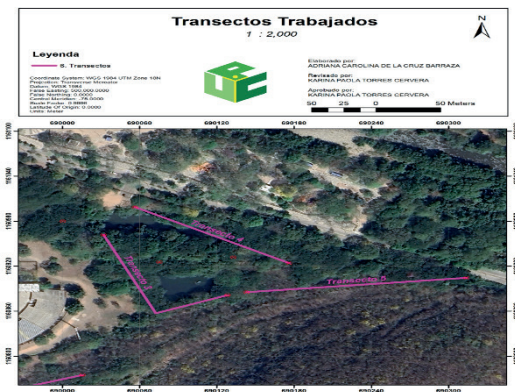


Figure 1. Transects Studied in the Sicarare Wetland of Valledupar, Cesar

The selection of transects was based on the guidelines proposed by Chaturvedi, R., Raghubanshi, A., and Singh, J. [3], who recommend an approximate length of 100 meters per transect, with a 20-meter-wide perpendicular strip on each side to facilitate the sampling process. This methodology

allows for coverage of a sufficiently large area to adequately record the ecosystem's variability, including tree individuals at different stages of development. Likewise, the transects were strategically distributed along different topographic gradients to ensure that the collected data was representative of the entire study area.

The forest inventory of the Tropical Dry Forest (TDF) was conducted over five days of fieldwork. On the first day, a team consisting of three environmental engineers and a forestry specialist conducted a preliminary survey of the area to assess terrain conditions and determine the location of the transects. On the second day, the tree inventory and the georeferencing process began in transects 1 and 2. On the third day, activities were extended to transects 3, 4, and 5, covering a considerable portion of the study area. Subsequently, on the fourth day, data collection was completed in transects 6, 7, and 8. Finally, on the fifth day, wood samples were collected for further analysis.

As a result of the inventory process, 457 tree individuals belonging to 40 different species were recorded (see Figure 2). This work involved the detailed identification of each tree present in the sampling units, which allowed not only for quantifying the abundance of individuals but also for accurately characterizing the floristic diversity existing in the evaluated area. In this way, a solid information base was obtained for the analysis of the forest's composition and structure in the Sicarare Wetland.

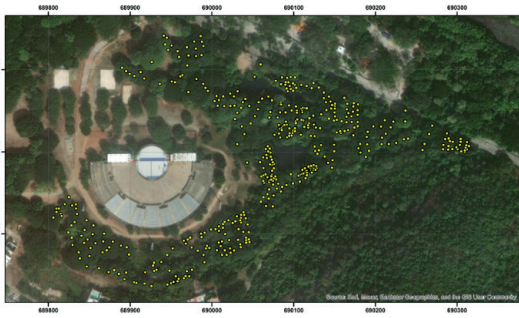


Figure 2. Georeferencing of the 457 Trees Inventoried in the TDS.

As a result of the forest inventory conducted in the Tropical Dry Forest (TDF) of the Sicarare Wetland, 457 tree individuals belonging to 40 different species were recorded, as shown in Table 1. This floristic diversity is a fundamental element for the ecological functionality of the ecosystem, in that a greater variety of species promotes processes such as primary production, ecological stability, and the forest's ability to respond to environmental variations. Similarly, the genetic and functional diversity present among species contributes to maintaining ecosystem productivity by reducing its susceptibility to pests and diseases and promoting its adaptation to changing environmental conditions [4].

Likewise, the presence of species with different ecological functions—particularly regarding microclimatic regulation, carbon sequestration, and the filtration of atmospheric pollutants—significantly contributes to improving environmental quality and providing essential ecosystem services. These benefits not only support forest conservation but also have a positive impact on surrounding communities. Furthermore, species diversity increases the ecosystem's stability in the face of disturbances such as fires, droughts, or climate change, as different species respond in distinct ways to such changes, thereby strengthening the ecological system's resilience [5].

In this regard, the floristic composition identified in the study area not only allows us to recognize the biological richness of the Sicarare Wetland but also constitutes a fundamental basis for analyzing forest structure and estimating ecological variables associated with biomass and forest carbon. Based on this information, it is possible to delve deeper into the relationship between ecosystem diversity and its carbon storage capacity, a key aspect for understanding its environmental importance and its potential contribution to climate change mitigation.

No.	Nombre común	Nombre Científico	No.	Nombre común	Nombre Científico
1	Algarrobbillo	<i>Platymiscium pinnatum</i>	21	Macurutu	<i>Muelleria sanctae-marthae</i> o <i>Lonchocarpus sanctae-marthae</i>
2	Barriga de culebre	<i>Chloroleucon mangense</i>	22	Majagua	<i>Pseudobombax septenatum</i>
3	Camajon	<i>Sterculia apetala</i>	23	Mamón cotoprix	<i>Melicoccus oliviformis</i>
4	Cañaguante	<i>Handroanthus chrysanthus</i>	24	Mango	<i>Mangifera indica</i>
5	Caracoli	<i>Anacardium excelsum</i>	25	Naranjuelo	<i>Crataeva tapia</i>
6	Caranganito	<i>Senna atomaria</i>	26	Neen	<i>Azadirachta indica</i>
7	Cedro	<i>Cordia alliodora</i>	27	Orejero	<i>Enterolobium cyclocarpum</i> (Jacq.) Griseb.
8	Ceiba bruja	<i>Hura crepitans</i>	28	Palma Real	<i>Roystonia regia</i>
9	Ceiba leche	<i>Ceiba pentandra</i>	29	Pereguetano	<i>Cochlospermum vitifolium</i>
10	Chibato	<i>Delonix regia</i>	30	Piñique	<i>Sapium glandulosum</i>
11	Chicho	<i>Senegalia tamarindifolia</i>	31	Puy	<i>Handroanthus billbergia</i>
12	Chiminango	<i>Pithecellobium dulce</i>	32	Roble	<i>Quercus humboldtii</i>
13	Corazon fino	<i>Platymiscium pinnatum</i>	33	Sapo	<i>Stemmadenia grandiflora</i>
14	Guacamayo	<i>Albizia niopoidis</i>	34	Dividivi	<i>Libidibia coriaria</i>
15	Guacharaco	<i>Cupania americana</i>	35	Uvita brasileña	<i>Syzygium cumini</i>
16	Guarumo	<i>Cecropia peltata</i>	36	Uvito	<i>Cordia alba</i>
17	Guasimo	<i>Guazuma Ulmifolia</i>	37	Vara de humo	<i>Cordia thaisiana</i>
18	Guayacan amarillo	<i>Bulnesia arborea</i>	38	Volador	<i>Ruprechtia ramiflora</i>
19	Higueron	<i>Ficus insipida</i>	39	Acacia	<i>Acacia collinsii</i>
20	Laurel	<i>Nectandra turbacensis</i>	40	Mulato	<i>Bursera simaruba</i>

Table 1. Species identified through the inventory conducted in the Sicarare Wetland

According to Chave et al. [6], in small forest areas, the use of transects for data collection is not always essential, as the size of the area may allow for other, less complex sampling schemes. However, in the case of the Sicarare Wetland, the specific terrain conditions, environmental heterogeneity, and variability in vegetation cover distribution made it necessary to implement this type of design in order to ensure more representative coverage of the study area. Consequently, although the approach of these authors constitutes an important methodological reference, in this study the use of transects responded to the specific characteristics of the evaluated ecosystem and the need to obtain more precise and reliable information.

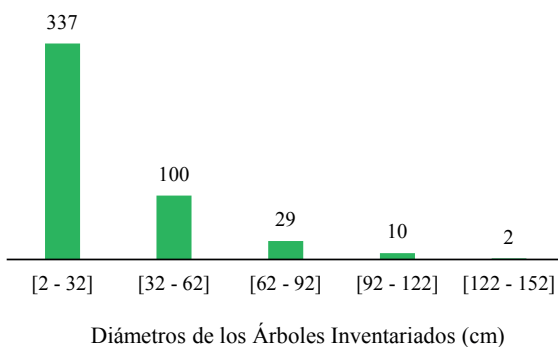


Figure 3. Classification of the diameters of the inventoried trees

Breast height diameter (BHD), commercial height, and volume.

The descriptive statistics obtained from the forest inventory conducted in the Sicarare Wetland reveal a general trend in the diameter at breast height (DBH) of the 457 trees evaluated. The mean DBH was 29.85 cm, indicating that, in general terms, the trees exhibit intermediate dimensions. However, the median of 23.87 cm and the mode of 15.92 cm show that a significant proportion of the trees are concentrated in smaller diameter classes, which may be asso-

ciated with a greater presence of young trees or trees in the process of growth. In turn, the standard deviation of 21.40 cm indicates considerable variability in the size of the inventoried trees.

Similarly, the positive skewness coefficient of 2.22 indicates that the data distribution is skewed toward smaller diameter values, while the kurtosis of 6.00 reflects a leptokurtic distribution, characterized by a higher concentration of individuals around small diameters and the presence of a small number of trees with significantly larger dimensions. Taken together, these results suggest that the forest's diameter structure is dominated by smaller individuals, although there are also some large specimens that increase the dispersion of the data.

Furthermore, the classification of trees by DBH classes, presented in Figure 3, shows that the largest proportion of individuals, corresponding to 337 trees (70.95%), is concentrated in diameters less than 32 cm. In particular, the diameter class between 17 and 32 cm comprises 188 trees, followed by the class between 2 and 17 cm, with 149 individuals, confirming the predominance of small to medium-sized trees in the wetland. In contrast, only 10.53% of the trees exceeded 47 cm in DBH, and barely 0.42% reach diameters greater than 107 cm.

These results suggest that the forest of the Sicarare Wetland is composed mainly of young or intermediate-sized individuals, with a low proportion of large trees. The recorded diameter range varied from a minimum of 2.80 cm to a maximum of 152.15 cm, confirming the high structural variability present in the ecosystem. Furthermore, the total sum of DBH values reached 14,300.45 cm, which serves as a general indicator of the magnitude of the tree biomass assessed in the study area.

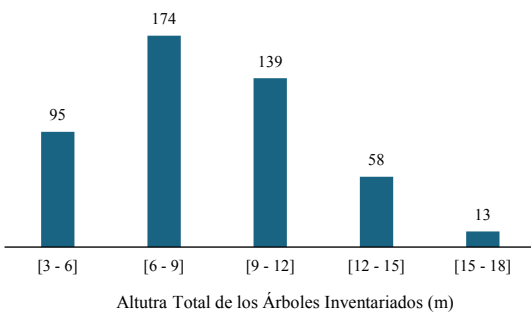


Figure 4. Classification of the total vertical size of the inventoried trees

Total height (TH).

The descriptive statistics corresponding to the total height (TH) of the trees assessed in the Sicarare Wetland reveal a vertical structure dominated by medium-sized individuals. The recorded mean was 9.26 m, while the median and mode reached values of 9 m and 8 m, respectively, indicating that most trees are concentrated at moderate heights within the ecosystem. Likewise, the standard deviation of 3.08 m reflects moderate variability in the distribution of this variable, suggesting relative homogeneity in the height of the sampled individuals.

Meanwhile, the positive skewness coefficient of 0.52 indicates a slight tendency toward higher values, while the kurtosis of -0.41 shows a slightly platykurtic distribution, that is, with a lower concentration of values around the mean compared to a normal distribution. Taken together, these results suggest that, although trees of medium height predominate, there is also a smaller proportion of individuals that reach greater heights, contributing to the heterogeneity of the forest's vertical structure. The height range ranged from 4 m to 18 m (), highlighting the structural diversity of the canopy in the study area. Similarly, the total sum of the recorded heights was 4,437.3 m.

The classification by height ranges, presented in Figure 4, shows that the highest concentration of individuals is found in the lower categories. In particular, 36.33% of the trees fell within the 6–9 m range, while 19.83% were grouped in the 3–6 m range. In contrast, only a small fraction of the individuals reached heights exceeding 15 m, indicating a predominance of young or intermediate-stage trees within the Sicarare Wetland.

This height distribution suggests that the forest may be in a regeneration phase or, alternatively, that factors exist that limit the development of large trees, whether due to human intervention, environmental conditions specific to the wetland, or the ecosystem's successional dynamics. In this regard, the observed vertical structure is an important element for understanding the forest's organization and its relationship with variables such as biomass, stored carbon, and the ecological recovery capacity of the assessed area.

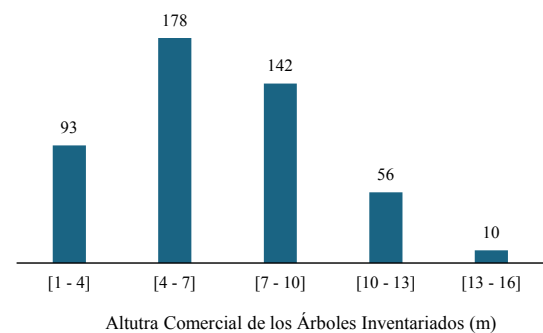


Figure 5. Classification of the commercial vertical height of inventoried trees

Descriptive data on the Commercial Height (CH) of trees in the Sicarare Wetland show a mean of 7.16 m, with a median of 7 m and a mode of 6 m, indicating that most trees have an average commercial height. The standard deviation is 2.93 m,

reflecting moderate variability, while the positive skewness coefficient (0.54) suggests a slight tendency toward taller heights. The kurtosis of -0.26 indicates a slightly flatter distribution, suggesting a lower concentration around the mean. Commercial heights range from 2 m to 16 m, with a total sum of 3,431.5 m, which gives an idea of the trees' exploitable potential in terms of their usable height.

The classification of commercial heights by ranges presented in Figure 5 shows that most trees are concentrated in the lower categories, with 37.16% of individuals in the 4–7 m range and 19.42% in the 1–4 m range. Only 2.09% of the trees reach a commercial height greater than 13 m, suggesting a predominance of young or developing trees in the area. This height structure reflects a regenerating population or one with a limited presence of trees of significant commercial height, likely due to human interventions or environmental factors that constrain growth in the wetland.

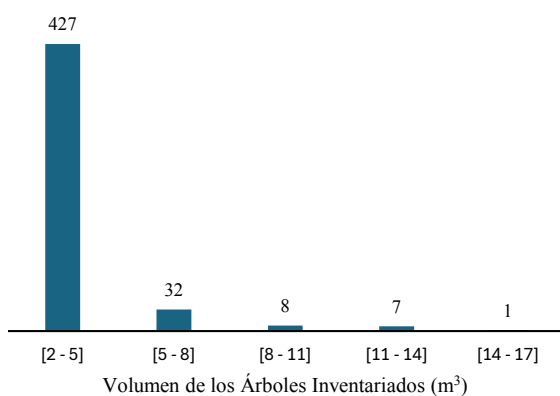


Figure 6. Classification of the individual volume of inventoried trees

Forest volume.

Descriptive studies of the forest volume of the trees inventoried in the Sicarare Wetland show a distribution dominated by individuals with relatively low volumes. The recorded mean was 0.87 m³, while both the median and mode reached a value of 0.23 m³, indicating that most trees have a small volume. Likewise, the standard deviation of 1.93 m³ reflects considerable data dispersion, suggesting marked heterogeneity in the volumetric size of the assessed individuals.

Similarly, the high kurtosis of 26.47 and the positive skewness coefficient of 4.66 indicate a distribution strongly skewed toward high values, due to the presence of a few trees with volumes significantly above the average. The volume range varied from a minimum of 0.005 m³ to a maximum of 16.62 m³, while the total sum reached 417.31 m³, a value that provides a general reference for the total tree volume present in the studied ecosystem.

The classification by volume ranges, presented in Figure 6, shows that the largest proportion of trees is concentrated in the lower volume classes. In this regard, the predominance of small-sized individuals confirms a forest structure composed mainly of young or medium-sized trees. In contrast, only a small fraction of the individuals reach higher volumes, indicating a low representation of large trees within the wetland. This distribution could be associated with natural regeneration processes, as well as ecological or anthropogenic factors that have limited growth and biomass accumulation in the forest.

In a second phase of the study, various ecological indicators were evaluated, and allometric models were constructed to explain the behavior of tree volume and density—fundamental variables for estimating forest biomass and carbon. These variables are particularly relevant, as they allow for the establishment of quantitative relationships between tree structure and the ecosystem's carbon storage capacity.

Biodiversity indices.

Based on the forest inventory conducted, various biodiversity indices were obtained, which allowed for the following ecological interpretations:

Margalef Index (richness) – 6.53.

This value indicates a high species richness in the assessed community. In ecological terms, a Margalef index greater than 5 is typically interpreted as evidence of a diverse community, suggesting that the ecosystem harbors a considerable number of different species. This condition may be associated with factors such as habitat heterogeneity, resource availability, and the variability of ecological niches present in the area [7].

Simpson's index (diversity) – 0.93.

The value obtained for the Simpson's index was 0.93, a figure close to 1, reflecting a high level of diversity in the ecosystem. This result indicates that the probability of two randomly selected individuals belonging to different species is high, suggesting a relatively balanced community structure with low dominance by a single species. Consequently, this high diversity can be interpreted as a favorable indicator of ecological resilience in the face of environmental disturbances [8].

Shannon Index (equity) – 3.10.

The Shannon index reached a value of 3.10, suggesting a relatively even distribution of species within the assessed plant community. Values above 3 are typically associated with good ecological evenness, implying that there is no excessive dominance of a few species over the others. This characteristic promotes ecosystem stability, as it allows for the coexistence of multiple species and reduces the likelihood of ecological imbalances resulting from disproportionate competition [9].

Density of individuals per forest area – 19.87 individuals/ha.

The density of individuals per forest area was 19.87 individuals per hectare, that is, approximately 20 individuals/ha in the evaluated area. Although this value may be considered low compared to dense tropical forests, it could correspond to the characteristics typical of a recovering forest or an ecosystem influenced by specific edaphic, hydrological, and climatic factors. In this regard, the observed density suggests a certain degree of fragmentation or a successional process in which not the entire surface of the area exhibits homogeneous tree cover.

Determination of wood density.

In the next phase of the research, the objective was to determine the wood density of specific species for which no information was available in the scientific literature. To do this, wood cores were extracted using a Pressler auger, an instrument that allows samples to be obtained without causing significant damage to the tree. Once collected, the subsamples were stored in airtight bags and subsequently transported to the laboratory for analysis.

In the laboratory, the samples were processed following established protocols for this type of study [10]. Initially, green volume was determined using the water displacement method, based on Archimedes' principle. This procedure involved submerging the samples in water for 48 hours to ensure complete moisture absorption and obtain an accurate measurement of their volume in cubic centimeters (cm³).

The wood density (DM) was calculated using the following expression:

$$DM=(PS(g))/(V(cm^3)) \quad (7)$$

Where **PS** corresponds to the dry weight of the sample in grams and **V** to the green volume determined from the displacement of water. Subsequently, the wet weight of the samples was recorded using an electronic scale, before subjecting them to an oven-drying process at 100 °C for 72 hours, in order to completely eliminate the moisture content. Finally, the dry weight of the wood was determined, from which the specific densities of each subsample were calculated (see Table 2).

Nombre Común	Peso Humedo	Peso Seco	Peso del Agua	Volumen	Densidad gr/cm ³
Caranganito	5,77	1,95	3,82	3,82	0,510471204
Chicho	5,04	1,91	3,13	3,13	0,610223642
Macurutu	4,22	1,75	2,47	2,47	0,708502024
Mamón cotoprix	3,06	0,98	2,08	2,08	0,471153846
Naranjuelo	1,21	0,27	0,94	0,94	0,287234043
Palma Real	3,03	0,904	2,126	2,126	0,425211665
Pereguetano	4,67	1,82	2,85	2,85	0,638596491
Roble	1,19	0,263	0,927	0,927	0,283710895
Sapo	4,66	1,95	2,71	2,71	0,719557196
Tío toño	6,45	2,4	4,05	4,05	0,592592593
Uvita brasileña	0,77	0,237	0,533	0,533	0,444652908
Vara de humo	6,7	2,3	4,4	4,4	0,522727273
Volador	0,95	0,146	0,804	0,804	0,18159204

Table 2. Estimated densities of each tree subsample

Forest biomass and stored carbon.

The calculation of forest biomass and stored carbon in the Sicarare Wetland was performed using Microsoft Excel, following the methodologies and equations established in the *Protocol for the National and Subnational Estimation of Biomass and Carbon in Colombia*, developed by IDEAM. Based on the previously determined wood densities and the physical characteristics of each tree, particularly diameter and volume, the total biomass of the ecosystem was estimated.

Based on the calculations performed, the total biomass of the wetland was estimated at 75,438.276 tons. From this value, the stored forest carbon was determined, yielding a total of approximately 552,373 tons. These results highlight the ecological importance of the Sicarare Wetland as a carbon sink, underscoring its contribution to climate change mitigation and its strategic value for biodiversity conservation in the region.

In this same phase of the study, predictive allometric models were implemented to more accurately estimate the forest biomass and carbon stored in the Sicarare Wetland ecosystem. These models constitute a fundamental tool for strengthening the interpretation of the results and for supporting future strategies for

ANÁLISIS DE VARIANZA

	Grados de libertad	Suma de cuadrados	Promedio de los cuadrados	F	Valor crítico de F
Regresión	1	38035340,65	38035340,65	1394,889808	1,03E-143
Residuos	477	13006660,02	27267,63107		
Total	478	51042000,67			

	Coefficientes	Error típico	Estadístico t	Probabilidad
Intercepción	-233,7735233	12,96044197	-18,03746538	7,8158E-56
DAP (m)	1318,283634	35,29709063	37,34822362	1,0323E-143

Table 3. Analysis of variance and coefficient estimates for the forest biomass predictive model

The equation for the predictive model of forest biomass (in tons) is:

$$Biomasa (Ton) = -233.773523 + 1318.283634 \times DAP (m) \quad (8)$$

Predictive model for forest biomass.

The forest biomass predictive model revealed a strong relationship between diameter at breast height (DBH) and the biomass of the assessed individuals. This association is reflected in a correlation coefficient of 0.86 and an adjusted coefficient of determination (adjusted R²) of 0.74, indicating that 74.46% of the observed variability in biomass can be explained by DBH. These results confirm that this dendrometric variable is a highly representative predictor in estimating forest biomass within the Sicarare Wetland Tropical Dry Forest.

Similarly, the analysis of variance (ANOVA) showed an F-value of 1394.89, accompanied by a significance value of 1.03E-143, demonstrating that the model is statistically significant and that the proba-

bility that this relationship is due to chance is practically zero. Consequently, the results support the robustness of the statistical fit and the reliability of the proposed model for estimating biomass in the study area.

Furthermore, the coefficient associated with DBH suggests that, for every additional meter in trunk diameter, biomass increases by 1,318.28 tons, reaffirming the importance of this variable as an explanatory factor for forest biomass growth. Although the intercept of the model has a negative value, which lacks direct practical interpretation from an ecological standpoint, this condition does not affect the overall validity of the fit or the predictive utility of the model.

In summary, the developed model constitutes a statistically robust and technically reliable tool for estimating forest biomass and, indirectly, the carbon stored in the ecosystem. Its application is of great relevance for strengthening the processes of assessment, management, and sustainable conservation of the Sicarare Wetland Tropical Dry Forest, as well as for supporting future strategies aimed at climate change mitigation.

ANÁLISIS DE VARIANZA

	Grados de libertad	Suma de cuadrados	Promedio de los cuadrados	F	Valor crítico de F
Regresión	1	1477,3074	1477,3074	2649,06786	7,3749E-197
Residuos	477	266,0089009	0,557670652		
Total	478	1743,316301			

	Coefficientes	Error típico	Estadístico t	Probabilidad
Intercepción	-1,299636123	0,058611792	-22,17362875	2,15052E-75
DAP (m)	8,215814824	0,159626173	51,46909617	7,3749E-197

Table 4. Analysis of variance and estimation of coefficients for the forest carbon prediction model

The predictive equation for forest carbon (in tons) is:

$$\text{Carbono Forestal (Ton)} = -1.29963612326 + 8.2158148235564 \times \text{DAP (m)} \quad (9)$$

The forest carbon predictive model, expressed in tons and estimated based on diameter at breast height (DBH), demonstrated a strong statistical relationship between the two variables. In particular, the correlation coefficient ($R = 0.92$) demonstrates that DBH is a highly reliable predictor of carbon stored in trees. Additionally, the adjusted coefficient of determination ($R^2 = 0.8471$) indicates that 84.71% of the observed variability in forest carbon can be explained by this dendrometric variable. Furthermore, the analysis of variance (ANOVA) yielded an F-value of 2649.06786 and an extremely low p-value ($7.3749E-197$), which confirms the model's high statistical significance and reinforces its validity for the accurate estimation of carbon stored in the forest.

In this regard, the estimated coefficient of 8,215 tons per additional meter of DBH highlights a directly proportional relationship between tree size and its carbon sequestration capacity, a finding consistent with previous research in forest ecology. Although the model's intercept has a negative value—a situation that lacks practical interpretation in biological terms—this does not compromise the robustness of the statistical fit or its predictive utility. Consequently, this model establishes itself as a robust tool for estimating forest carbon in the Tropical Dry Forest, providing relevant information for the sustainable management of forest resources and for the formulation of strategies aimed at mitigating climate change.

This research is part of a Clean Development Mechanism (CDM), whose main purpose is to contribute to the reduction of greenhouse gases (GHGs) through carbon sequestration in this strategic ecosystem. From this perspective, the study's central objective is to accurately estimate the biomass and carbon stored in the wetland-associated tropical dry forest through field measurements and the application of allometric models based on international protocols, such as those established by IDEAM (2011) and the IPCC (2006). In this way, the initiative seeks to strengthen environmental conservation policies and reaffirm the wetland's role as a carbon sink, in line with the commitments made by the municipality of Valledupar and the relevant environmental authorities.

Additionally, the project projects a reduction of 2,027,209 tons of CO_2 , along with the generation of complementary environmental benefits derived from ecological restoration actions, including the reforestation of the wetland's water perimeter and the establishment of a forest nursery. These measures not only promote carbon sequestration but also contribute to strengthening the ecosystem's biodiversity. Similarly, the proposal involves the participation of strategic stakeholders such as CORPOCESAR, the Universidad Popular del Cesar, the Cesar Governor's Office, and the local community, thereby promoting a coordinated and participatory approach to the conservation and sustainable use of natural resources.

In line with the above, the project aligns with the Sustainable Development Goals by promoting environmental protection and providing a consistent scientific basis for future conservation interventions. With a total budget of \$999,000,000, of which

30% is expected to be requested from the CDM, this initiative not only addresses the need to mitigate climate change but also establishes a conducive environment for local and regional development, generating benefits for both biodiversity and the communities that depend on the ecosystem services provided by the wetland.

Discussion

The results obtained in this research reaffirm the importance of the Sicarare Wetland as a carbon sink of high ecological significance and as a strategic ecosystem in climate change mitigation processes. The estimate of 75,438 tons of biomass and 552,373 tons of stored carbon is consistent with previous studies that argue that tropical dry forests, even though they have lower tree density than other forest types, possess a considerable carbon storage capacity due to the presence of species with dense wood [11]. In this context, the findings of the present study coincide with those reported in other dry tropical forests in Latin America, where a notable capacity for carbon sequestration has also been documented [12].

Furthermore, the biodiversity analysis conducted in the wetland yielded Margalef index values of 6.53, Simpson's index of 0.93, and Shannon index of 3.10—results suggesting a balanced ecological structure with high levels of diversity and evenness. These values are comparable to those reported by Ruiz-Benito [13], who highlights that biodiversity contributes significantly to the stability and resilience of forest ecosystems in the face of various disturbances. In turn, the coexistence of multiple species in the Sicarare Wetland promotes ecosystem stability and efficiency in resource use, as

indicated by Loreau's [14] arguments regarding the relationship between biodiversity and ecosystem functioning.

Regarding the methodology employed, the use of transects was essential for capturing the spatial heterogeneity of the study area. Although Chave et al. [6] suggest that this type of strategy is not always necessary in small forest areas, in this case the specific characteristics of the terrain and the variability of environmental conditions made its implementation indispensable to achieve sufficiently representative coverage. This methodological decision aligns with studies such as that by Gibbs et al. [15], who emphasize the need to adapt measurement methods to the topographic and climatic context in order to obtain more accurate estimates of biomass and carbon in heterogeneous forests.

Likewise, a significant correlation was identified between diameter at breast height (DBH) and the storage of both biomass and carbon, which is consistent with previous research. Various authors [11] and [16] have documented that DBH is a reliable predictor of biomass and accumulated carbon in tropical trees, and the results of this study confirm this relationship. In particular, the predictive model used, with a correlation coefficient of 0.86 for biomass and 0.92 for carbon, demonstrates that this dendrometric variable is a key indicator for estimating these components in the Tropical Dry Forest.

Similarly, the estimation of CO₂ equivalent in the Tropical Dry Forest of the Sicarare Wetland revealed a reduction potential of nearly 2,027,209 tons of CO₂, a finding that highlights the significance of this ecosystem as a natural carbon sink. Despite having a lower tree density than other forest systems, tropical dry forests can accumu-

late significant amounts of carbon due to the presence of species with dense wood, as documented in studies conducted in Latin America [17]; [18]. Consequently, these results confirm the importance of the wetland in climate change mitigation strategies.

Furthermore, the conversion of stored carbon to CO₂ equivalent is an essential procedure for quantifying the actual impact of these ecosystems on greenhouse gas reduction. Tropical forests, which store approximately 55% of terrestrial carbon [19], together with wetlands—whose ecological characteristics give them a remarkable capacity for carbon sequestration—play a decisive role in global carbon regulation [20].

The findings of this study demonstrate that the Sicarare Wetland not only plays a prominent role as a carbon sink but also represents a biodiversity reservoir of great ecological value. The high diversity recorded suggests significant ecosystem resilience, an essential condition for ensuring its long-term conservation [6]. Furthermore, these results have significant implications for the sustainable management of natural resources, highlighting the need to design and implement conservation strategies grounded in scientific evidence, aimed at both protecting the wetland and strengthening its ecosystem services

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