Estimation of Biomass and Forest Carbon in the Tropical Dry Forest of the Sicarare Wetland in Valledupar, Cesar.

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Abstract: This study examines the role of the Sicarare Wetland as a carbon sink within the Tropical Dry Forest (TDF) of Valledupar, one of Colombia's ecosystems most impacted by climate change and deforestation. Using a quantitative approach, a forest inventory was conducted to gather data on tree dimensions and species diversity, estimating stored biomass and carbon. Measurement tools and allometric equations were applied, highlighting the wetland's value for environmental conservation and climate change mitigation.

Objectives: The primary objective of this study is to estimate the biomass and forest carbon of the Tropical Dry Forest in the Sicarare Wetland in Valledupar, Cesar. To achieve this, a forest and tree inventory will be conducted to obtain biodiversity indicators regarding the forest's composition and structure. Specific biomass and carbon prediction models for this ecosystem will also be defined, providing accurate estimates tailored to its local characteristics.

Method: This study employs a quantitative approach with a non-experimental cross-sectional design to estimate biomass and forest carbon in the Tropical Dry Forest (TDF) of the Sicarare Wetland at a specific point in time. The research, both descriptive and exploratory, aims to establish quantitative relationships between the physical dimensions of trees and stored carbon by applying pre-established allometric models. The study population includes trees in the TDF of the wetland, utilizing stratified random sampling with 2000 m² plots. Data collection involved conventional tools, such as forest measurement tapes for diameter at breast height (DBH), a Pressler borer for wood samples, and GPS for plot georeferencing, enabling accurate biomass estimates through allometric equations.

Results: The study's results, based on field measurements and statistical analyses, provide a comprehensive view of the biomass, carbon storage, and biodiversity within the Sicarare Wetland's Tropical Dry Forest (TDF). A forest inventory identified 457 trees across 40 species, with an estimated total biomass of 1,104,746 tons and carbon storage of 552,373 tons. Measurements of tree diameter, height, and volume revealed a predominance of young or medium-sized trees, with diameter and height distributions indicating a regenerating forest structure. Biodiversity indices, including Margalef (6.53), Simpson (0.93), and Shannon (3.10), reflect high species diversity and ecosystem resilience. Predictive models confirmed a strong correlation between diameter at breast height (DBH) and both biomass and carbon, highlighting the forest's significant role as a carbon sink. This research, part of a Clean Development Mechanism initiative, supports sustainable management efforts and aims to mitigate climate change through CO_2 reduction, reforestation, and community collaboration, with projected CO_2 reductions of over 2 million tons.

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

1. Introduction

The Tropical Dry Forest (TDF) is among the most threatened ecosystems worldwide due to its high susceptibility to degradation and climate change. This type of forest, characterized by marked seasonality and the ability to adapt to long periods of drought, harbors a great deal of biological diversity and provides essential ecosystem services, such as water cycle regulation and carbon storage. In Colombia, deforestation and agricultural expansion have significantly reduced TDF remnants, decreasing their capacity to counteract climate change. In this context, the Sicarare Wetland, located in Valledupar, Cesar, stands out as a key conservation area, as it combines a remnant of this ecosystem with a wetland of great ecological relevance.

This study addresses the need to assess the Sicarare Wetland's capacity to function as a carbon sink, which could significantly contribute to mitigating climate change both locally and regionally. Wetlands, known for their role in climate regulation, store large amounts of carbon in vegetation and soil. However, there is little information on the biomass and carbon stored in wetlands associated with tropical dry forests, especially in Colombia's Caribbean region, justifying the relevance of this research. Moreover, increasing human pressures, such as illegal logging, pollution, and land-use changes, threaten the integrity of the Sicarare Wetland, making the implementation of conservation strategies based on reliable scientific data urgent.

Previous studies on biomass and carbon in the TDF have focused on estimating these variables through indirect methods, such as allometric equations and forest sampling. Despite dry forests having lower tree density compared to other forest types, research has shown that they can store considerable amounts of carbon due to the presence of species with dense wood, allowing them to act as carbon reservoirs over long periods. However, it is crucial to conduct region-specific studies to adjust biomass and carbon estimation models to the particular conditions of local ecosystems.

This study aims to estimate the biomass and carbon of the Tropical Dry Forest in the Sicarare Wetland, located in Valledupar, Cesar, through a forest and tree inventory, the development of predictive biomass and carbon models, and the proposal of actions for the wetland's conservation. To achieve these objectives, a forest inventory was conducted to obtain biodiversity indicators, such as forest composition and structure, which are essential for developing biomass and carbon predictive models.

2. Objetives

The general objective of this study is to estimate the biomass and forest carbon in the Tropical Dry Forest of the Sicarare Wetland, located in Valledupar, Cesar. The research aims to provide key information for the sustainable management of this ecosystem, contributing to its conservation and to climate change mitigation.

A detailed inventory of the flora in the Tropical Dry Forest of the Sicarare Wetland will be conducted, with the aim of obtaining biodiversity indicators, such as species composition and forest structure. These data will allow for the characterization of the area's biological richness and its capacity to store carbon.

Predictive models will be developed to estimate the biomass and forest carbon. These models will be based on the physical dimensions of the trees and adjusted to the specific conditions of the local ecosystem, enabling accurate estimates of the biomass and carbon stored in the forest.

Based on the results obtained, strategies for the conservation and protection of the Tropical Dry Forest in the Sicarare Wetland will be formulated. These actions will focus on preserving biodiversity and improving forest management, contributing to the sustainability of this ecosystem in the Valledupar, Cesar region.

3. Method

This study uses a quantitative approach and a non-experimental cross-sectional design [1], with the objective of estimating biomass and forest carbon in the Tropical Dry Forest (TDF) of the Sicarare Wetland at a specific point in time, without altering the variables. It aims to establish quantitative relationships between the physical dimensions of the trees and the stored carbon by applying pre-established allometric models to obtain estimates of biomass and carbon.

The research is descriptive, as it quantifies the biomass and carbon of the ecosystem, and also exploratory, since it studies an ecosystem with limited previous local studies, generating valuable information for environmental conservation and forest management. The study population includes the trees of the TDF in the Sicarare Wetland, with a stratified random sampling based on the ecosystem's diversity and topographic characteristics. Plots of 400 m² were delineated following the recommendations of [2]. The sample size was calculated considering tree density, ensuring that the sampled trees provided accurate estimates of biomass and carbon.

Data collection used conventional tools to measure dendrometric characteristics. Forest measurement tapes were employed to calculate the diameter at breast height (DBH), the Pressler borer to obtain wood samples and measure density, and a GPS to georeference the plots. These data were fundamental for applying allometric equations that allowed for the estimation of biomass.

Specific allometric relationships were applied for each species, previously defined in scientific studies, which link the dry weight of the wood with the total biomass. The biomass of the stem was calculated using the formula:

$$\boldsymbol{Biomass} = \frac{(\boldsymbol{V\,m^3})\left(\boldsymbol{Density}\,\frac{\boldsymbol{g}}{\boldsymbol{cm^3}}\right)}{(\mathbf{100})^{\mathbf{3}}} \quad (1)$$

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

$$\ln(\boldsymbol{BA}) = \boldsymbol{a} + \boldsymbol{b}\ln(\boldsymbol{D}) + \boldsymbol{c}\,(\ln(\boldsymbol{D}))^{2} + \boldsymbol{d}\,(\ln(\mathbf{D}))^{3} + \boldsymbol{B1}\ln(\boldsymbol{p}) \quad (2)$$

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

$$\boldsymbol{CA} = (\boldsymbol{BA})(\mathbf{0,5}) \quad (3)$$

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 dendrometric variables (DBH, height, and biomass) were verified, applying statistical tests to confirm the relationship between tree diameter and the stored biomass and carbon.

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

Shannon Index:

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

Simpson Index:

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

Margalef Index:

$$\boldsymbol{D} = \frac{\boldsymbol{S}-\mathbf{1}}{\boldsymbol{Ln}\,(\boldsymbol{N})} \quad (6)$$

During the analysis phase, Geographic Information System (GIS) tools were also used to georeference the plots and generate maps illustrating the spatial distribution of biomass and forest carbon in the wetland.

4. Results

The research was based on field measurements and statistical analyses to calculate biomass, carbon, and biodiversity indices. The results were supported by key references that validate the techniques used and the findings obtained.

In the first stage, a forest and tree inventory of the Tropical Dry Forest (TDF) in the Sicarare Wetland was carried out with the aim of obtaining biodiversity indicators and evaluating the ecosystem's structure. A systematic methodological approach was used for data collection and fieldwork. Eight transects were worked on (see Figure 1), each with an average area of 2000 m², where key parameters such as diameter at breast height (DBH) and the total height of the trees were measured.

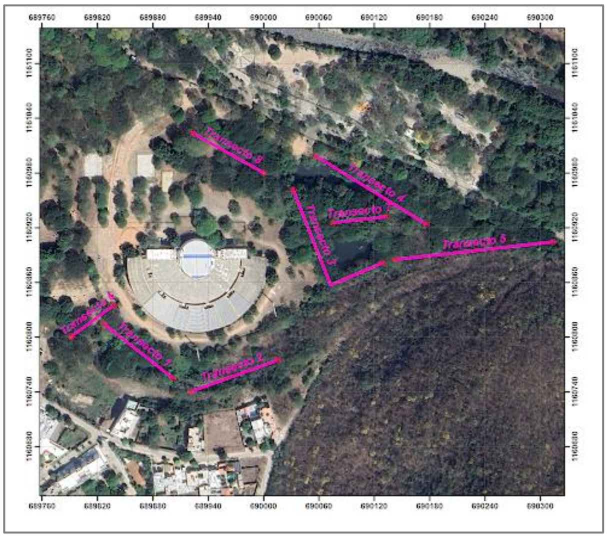

Figure 1. Transects Worked in the Sicarare Wetland, Valledupar, Cesar

The transects were selected in accordance with the guidelines of Chaturvedi, R., Raghubanshi, A., & Singh, J. [3], who suggest a length of approximately 100 meters per transect, with a perpendicular extension of 20 meters on both sides to facilitate sampling. This approach allows sufficient area coverage to capture the ecosystem's diversity, including trees of different ages. The transects were strategically placed along various topographic gradients to ensure that the data were representative of the total study area.

The forest inventory in the Tropical Dry Forest (TDF) was conducted over five sessions. In the first session, a team of three environmental engineers and a tree specialist made an initial visit to explore the area and define the transects. During the second session, the tree inventory and georeferencing began in transects 1 and 2. In the third session, work was done on transects 3, 4, and 5, covering most of the area, while in the fourth session, transects 6, 7, and 8 were completed. Finally, wood samples were taken for additional analysis.

During the inventory process, 457 individuals belonging to 40 different species were recorded (see Figure 2). This work included the meticulous identification of each tree, allowing not only for the counting but also for a detailed characterization of the species diversity in the study area.

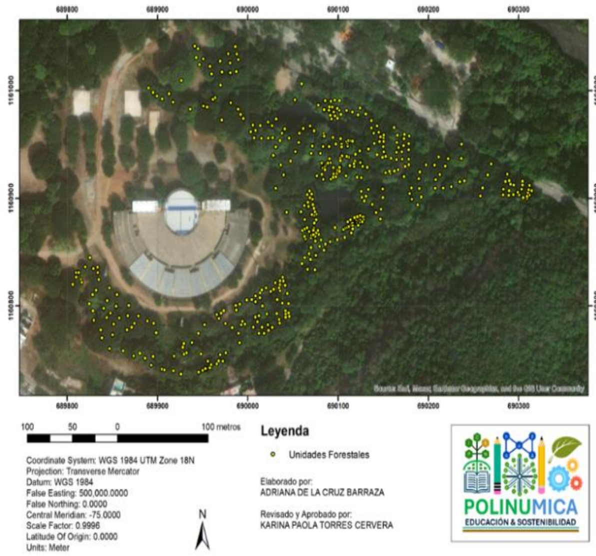

Figura 2. Georeferencing of the 457 Trees Inventoried in the TDF.

A total of 457 trees were identified, classified into 40 different species, as shown in Table 1. This species diversity within the ecosystem provides important benefits, as a greater variety of trees contributes to better ecosystem functioning, promoting primary production, stability, and the forest's ability to withstand environmental changes. Additionally, the genetic and functional diversity within species enhances ecosystem productivity by reducing susceptibility to pests and diseases and favoring adaptation to variable environmental conditions [4].

The presence of species with different capacities to regulate the climate, capture carbon, and filter air pollutants improves environmental quality and provides ecosystem services that benefit both the ecosystem and nearby communities. Furthermore, diversity increases ecosystem stability in the face of disturbances such as fires or climate changes, thanks to the varied responses of species [5].

Table 1. Species Identified through the Inventory Conducted in the Sicarare Wetland

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

According to Chave et al. [6], it is unnecessary to use transects to collect information in small forested areas, as their reduced size does not justify the complexity of sampling. However, the results obtained in this study differ from the conclusions of these authors, as the heterogeneity of the terrain and the environmental conditions in the Sicarare Wetland made the use of transects essential to ensure adequate coverage of the area.

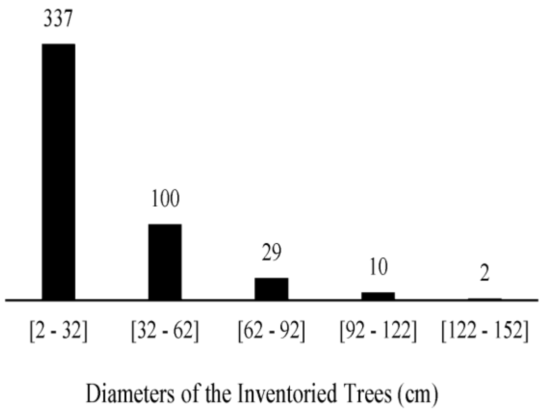

Figure 3. Classification of the Diameters of the Inventoried Trees

Total, Commercial Height, and Volume. The descriptive data from the forest inventory in the Sicarare Wetland show a general trend in the diameter at breast height (DBH) of the 457 trees evaluated. The average DBH is 29.85 cm, indicating that most trees are of intermediate size. However, the median, at 23.87 cm, and the mode, at 15.92 cm, suggest that a significant proportion of the trees have smaller diameters, which may be due to a higher density of young or growing individuals. The standard deviation is 21.40 cm, revealing considerable variation in tree size, with a positive skewness coefficient of 2.22, indicating that the data is skewed towards smaller values. This is confirmed by the kurtosis of 6.00, suggesting a leptokurtic distribution where most trees are concentrated in smaller diameters, with a few reaching significantly larger diameters.

The classification of trees by DBH class, as shown in Figure 3, indicates that the majority of the trees, specifically 337 (70.95%), have diameters smaller than 32 cm. The class with diameters between 17 and 32 cm contains 188 trees, followed by the class between 2 and 17 cm with 149 trees, highlighting the predominance of smaller trees in the wetland. Only 10.53% of the trees exceed 47 cm in DBH, and just 0.42% reach diameters greater than 107 cm. These results suggest that the forest in the wetland is primarily composed of young or medium-sized trees, with a limited number of large specimens. The diameter range extends from a minimum of 2.80 cm to a maximum of 152.15 cm, confirming the wide variability in the size of the trees present. The total sum of all DBHs is 14,300.45 cm, providing an estimate of the total trunk mass in the studied ecosystem.

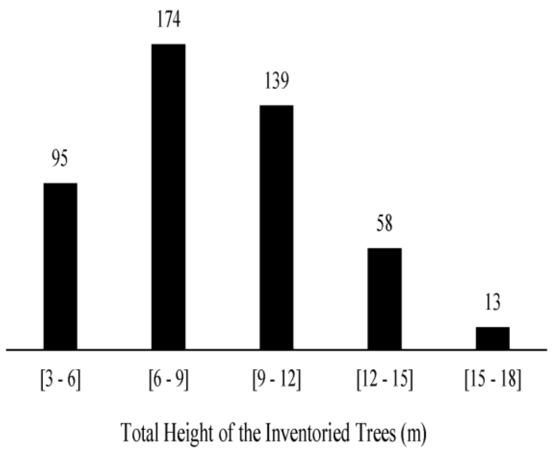

Figure 4. Classification of the Total Vertical Size of the Inventoried Trees

The descriptive data for the Total Height (TH) of the trees in the Sicarare Wetland show an average of 9.26 m, with a median of 9 m and a mode of 8 m, suggesting that most trees are of medium height. The standard deviation of 3.08 m indicates moderate variability, while the positive skewness coefficient (0.52) suggests a slight inclination towards greater heights. The kurtosis of -0.41 reflects a slightly flatter distribution, indicating less concentration of values around the mean. The heights range from 4 m to 18 m, revealing diversity in the canopy structure, and the total sum of heights is 4437.3 m.

The classification by height ranges presented in Figure 4 shows that most trees are in the lower categories, with 36.33% in the 6 to 9 m range and 19.83% in the 3 to 6 m range. Only a small percentage of trees reach heights greater than 15 m, suggesting a population dominated by young or medium-sized trees. This distribution reflects a possible regeneration phase or a limitation in the growth of large trees, either due to human intervention or environmental conditions.

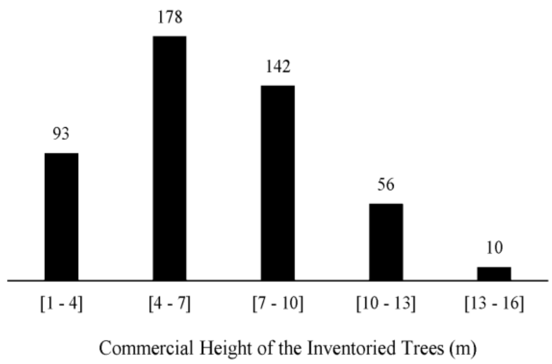

Figure 5. Classification of the Commercial Vertical Size of the Inventoried Trees

The descriptive data for the Commercial Height (CH) of the trees in the Sicarare Wetland show an average of 7.16 m, with a median of 7 m and a mode of 6 m, indicating that most trees have a medium commercial height. The standard deviation is 2.93 m, reflecting moderate variability, while the positive skewness coefficient (0.54) suggests a slight inclination towards taller heights. The kurtosis of -0.26 indicates a slightly flatter distribution, suggesting less concentration around the mean. Commercial heights range between 2 m and 16 m, with a total sum of 3431.5 m, providing an idea of the trees' exploitable height potential.

The classification of commercial heights by ranges, as shown in Figure 5, shows that most trees are concentrated in the lower categories, with 37.16% of individuals in the 4 to 7 m range, and 19.42% in the 1 to 4 m range. Only 2.09% of 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 limited presence of large commercial-height trees, likely due to human interventions or environmental factors affecting growth in the wetland.

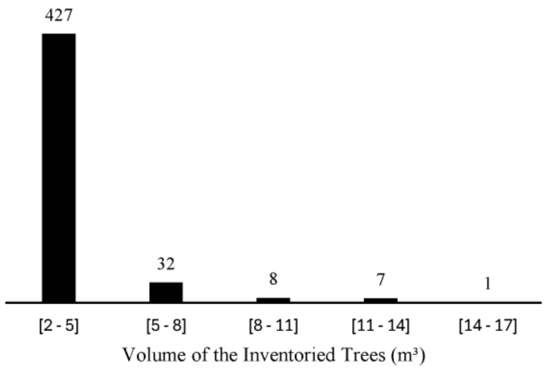

Figure 6. Classification of the Individual Volume of the Inventoried Trees

The descriptive data for the forest volume of the inventoried trees in the Sicarare Wetland show an average of 0.87 m^3, with a median of 0.23 m^3 and a mode of 0.23 m^3, indicating that most trees have relatively low volume. The standard deviation of 1.93 m^3 reflects considerable dispersion, and the extremely high kurtosis (26.47) along with the positive skewness coefficient (4.66) suggest a highly asymmetrical distribution towards elevated values, with a few trees reaching significantly higher volumes. Volumes range from a minimum of 0.005 m^3 to a maximum of 16.62 m^3, with a total sum of 417.31 m^3, providing an estimate of the total biomass volume in the ecosystem.

The classification by volume ranges, presented in Figure 6, shows that the vast majority of trees (89.14%) have volumes between 2 and 5 m^3, highlighting the predominance of smaller individuals. Only 32 trees (6.68%) have volumes between 5 and 8 m^3, while just a few reach volumes greater than 11 m^3. This suggests that the wetland is mainly composed of young or small trees, with a limited presence of large trees in terms of volume, which could indicate a regeneration process or the impact of limiting factors on biomass growth.

In the second stage of this work, indicators were evaluated, and allometric models were developed to explain both the growth of volume and tree density, as these variables are more relevant for the purpose of estimating forest biomass and carbon.

Various biodiversity indices were calculated in the forest inventory, from which the following inferences can be made:

Margalef Index (Richness) - 6.53: This value indicates a high species richness in the evaluated community. A Margalef index greater than 5 is generally interpreted as a sign of a diverse community, suggesting that the ecosystem harbors a large number of distinct species. This could reflect the ecosystem's capacity to support a wide variety of species, thanks to factors such as habitat heterogeneity and resource availability [7].

Simpson Index (Diversity) - 0.93: The obtained Simpson index (0.93) is close to 1, indicating that the ecosystem has high diversity. This value implies that the probability of two randomly selected individuals belonging to different species is high, indicating a balanced community structure with little dominance by a single species. High diversity suggests an ecosystem with good resilience to disturbances [8].

Shannon Index (Evenness) - 3.10: The Shannon index value of 3.10 suggests considerable evenness in species distribution. Values above 3 are generally interpreted as an indication of good evenness, implying that no species dominates the others significantly. This contributes to the ecological stability of the system, as evenness favors ecosystem sustainability, allowing multiple species to coexist without excessive competition [9].

Individual Density per Forest Area - 19.87 individuals/Ha: The calculated individual density per forest area shows that there are approximately 20 individuals per hectare in the evaluated area. This value is relatively low compared to dense tropical forests but may be characteristic of a recovering forest or an ecosystem with specific edaphic and climatic conditions. The appropriate density depends on the ecological context of the area and the conservation objective, but this value suggests a certain level of fragmentation or a regeneration process where not all areas are occupied by tree individuals.

In the next phase of the research, the goal was to determine the wood density for specific species that lacked available data in the literature. To achieve this, wood cores were extracted using a Pressler borer, which allows for samples to be obtained without significantly damaging the tree. The cores were stored in airtight bags, and once collected, the samples were transported to the laboratory for analysis.

Figure 7. Measurement of DBH, Heights, and Georeferencing of Tree Species and Sampling with the Pressler Borer.

Subsequently, the samples were taken to the laboratory, where the wood density analysis was performed following established protocols for this type of study [10].

Once the wood samples were collected and brought to the laboratory, the green volume was determined using the water displacement method, based on Archimedes' principle. This method involves submerging the samples in water for 48 hours to ensure they fully absorb moisture, allowing for an accurate measurement of their volume in cubic centimeters (cm³). The wood density (WD) was calculated using the formula:

$$\boldsymbol{DM} = \frac{\boldsymbol{PS(g)}}{\boldsymbol{V(cm^3)}} \quad (7)$$

Where PS represents the dry weight of the sample in grams, and V was the green volume determined through water displacement. Subsequently, the wet weight of the samples was measured using an electronic scale before placing them in an oven at 100°C for 72 hours to remove all moisture. Finally, the dry weight of the wood was determined, from which the specific densities of each sample were obtained (see Table 2).

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Table 2. Estimation of Densities for Each Tree Subsample

Species	Wet Weight (g)	Dry Weight (g)	Water Weight (g)	Volume (cm^3)	Density (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

The calculation of forest biomass and the carbon stored in the Sicarare Wetland was conducted using Excel software, following the methodologies and formulas established in the Protocol for the National and Subnational Estimation of Biomass and Carbon in Colombia, developed by IDEAM. Based on the previously obtained tree densities and the physical characteristics (diameter and volume) of each specimen, the total biomass was determined.

Based on the calculations performed, the total biomass of the wetland was estimated at 1,104,746 tons, using the equations and formulas from the protocol. From this value, forest carbon was estimated, and it was determined that the wetland stores approximately 552,373 tons of carbon. These results highlight the importance of the wetland as a carbon sink, significantly contributing to climate change mitigation and underscoring its ecological and strategic value in biodiversity conservation.

In this section of the study, predictive allometric models were implemented to accurately estimate the forest biomass and carbon stored in the Sicarare Wetland ecosystem.

Table 3. Analysis of Variance and Coefficient Estimation for the Forest Biomass Predictive Model

ANALYSIS OF VARIANCE

	Degrees of Freedom	*Sum of Squares*	*Mean Square*	*F*	*F Critical Value*
Regression	1	38035340.65	38035340.65	1394.889808	1.03E-143
Residual	477	13006660.02	27267.63107		
Total	478	51042000.67			

	Coefficients	*Standard Error*	*t Statistic*	*P-value*
Intercept	-233.7735233	12.96044197	-18.03746538	7.8158E-56
DBH (m)	1318.283634	35.29709063	37.34822362	1.0323E-143

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

$$\boldsymbol{Biomass\ (Ton) = -233.773523 + 1318.283634 \times DAP\ (m)} \quad (8)$$

The forest biomass predictive model shows a strong correlation between diameter at breast height (DBH) and biomass, with a correlation coefficient of 0.86 and an adjusted R^2 of 0.74, indicating that 74.46% of the variability in biomass can be explained by DBH. The analysis of variance (ANOVA) shows a high F-value of 1394.89, confirming the statistical significance of the model, supported by a p-value of 1.03E-143, indicating that these results are highly unlikely to be due to chance.

The DBH coefficient suggests that for each additional meter in trunk diameter, the biomass increases by 1318.28 tons, consolidating DBH as a key predictor of forest biomass in the Tropical Dry Forest. Although the model's intercept is negative, which has no direct practical interpretation, this adjustment does not compromise the model's overall validity. In summary, this model is a precise and significant tool for estimating biomass and carbon capture, crucial for the sustainable management and conservation of the forest ecosystem.

Table 4. Analysis of Variance and Coefficient Estimation for the Forest Carbon Predictive Model

ANALYSIS OF VARIANCE

	Degrees of Freedom	*Sum of Squares*	*Mean Square*	*F*	*F Critical Value*
Regression	1	1477.3074	1477.3074	2649.06786	7.3749E-197
Residual	477	266.0089009	0.557670652		
Total	478	1743.316301			

	Coefficients	*Standard Error*	*t Statistic*	*P-value*
Intercept	-1.299636123	0.058611792	-22.17362875	2.15052E-75
DBH (m)	8.215814824	0.159626173	51.46909617	7.3749E-197

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

$$\boldsymbol{Forest\ Carbon\ (Ton) = -1.29963612326 + 8.2158148235564 \times DAP\ (m)} \quad (9)$$

The forest carbon predictive model (in tons) based on diameter at breast height (DBH) shows a strong correlation with a correlation coefficient of 0.92, indicating that DBH is an excellent predictor of the carbon stored in trees. The adjusted coefficient of determination (R^2) of 0.8471 suggests that 84.71% of the variability in forest carbon can be explained by DBH. Additionally, the analysis of variance (ANOVA) with a high F-value of 2649.06786 and an extremely low p-value (7.3749E-197) confirms the statistical significance of the model, reinforcing confidence in DBH's ability to accurately predict the carbon stored in trees.

The coefficient of 8.215 tons for each additional meter of DBH highlights the direct relationship between tree size and its capacity to store carbon, which is consistent with previous studies in forest ecology. Although the model's intercept is negative, which has no direct practical interpretation, this does not affect the model's predictive validity. In conclusion, this model is a solid tool for estimating forest carbon in the Tropical Dry Forest, supporting the management of forest resources and the planning of climate change mitigation strategies.

This research is developed within the framework of a Clean Development Mechanism (CDM), with the purpose of contributing to the reduction of greenhouse gases (GHG) through carbon capture in this strategic ecosystem. The central objective is to achieve an accurate estimation of the biomass and carbon stored in the tropical dry forest of the wetland, through field measurements and the application of allometric models, following international protocols such as those from IDEAM (2011) and the IPCC (2006). This initiative aims to support environmental conservation policies and reinforce the wetland’s role as a carbon sink, in line with the commitments made by the municipality of Valledupar and local environmental authorities.

With a projected reduction of 2,027,209 tons of CO_2, the project also intends to generate additional benefits through ecological restoration activities, such as the reforestation of the wetland’s watercourse and the creation of a forest nursery. These actions not only contribute to carbon capture but also promote increased biodiversity in the ecosystem. The project involves key stakeholders such as CORPOCESAR, the Universidad Popular del Cesar, the Government of Cesar, and the local community, promoting a collaborative approach to the sustainable conservation and management of natural resources.

Additionally, the project is aligned with the Sustainable Development Goals, promoting environmental protection and providing a solid scientific basis for future conservation actions. With a total budget of $999,000,000, of which 30% will be requested from the CDM, this project not only addresses climate change mitigation but also establishes a platform for implementing local and regional development strategies that benefit both biodiversity and the communities that depend on the wetland's ecosystem services.

5. Discussion

The results obtained in this study emphasize the importance of the Sicarare Wetland as a significant carbon sink and a key ecosystem for climate change mitigation. The estimation of 1,104,746 tons of biomass and 552,373 tons of stored carbon is consistent with previous studies that indicate that tropical dry forests, although they have a lower tree density compared to other types of forests, can store large amounts of carbon due to the presence of dense wood species [11]. In this sense, our results align with observations in other tropical dry forests in Latin America, where a high capacity for carbon sequestration in these ecosystems has been documented [12].

The biodiversity analysis of the wetland revealed a Margalef index of 6.53, a Simpson index of 0.93, and a Shannon index of 3.10, suggesting an ecologically balanced structure with high diversity and evenness. These values are comparable to those reported by Ruiz-Benito [13], who indicated that biodiversity significantly contributes to the stability and resilience of forest ecosystems in the face of disturbances. The coexistence of multiple species in the Sicarare Wetland also favors stability and resource-use efficiency, as suggested by Loreau [14] in his studies on biodiversity and ecosystem functioning.

The use of transects in this study was essential to capture the heterogeneity of the area, despite the recommendations of Chave et al. [6], who suggested that transects are not necessary in small forested areas. In this case, the complexity of the terrain and the variability in environmental conditions made the use of transects essential to obtain representative coverage. This is consistent with studies like that of Gibbs et al. [15], which highlight the importance of using methods adapted to topographic and climatic contexts to obtain accurate biomass and carbon estimates in heterogeneous forests.

Additionally, a significant correlation was found between diameter at breast height (DBH) and the storage of biomass and carbon, which is consistent with previous research. [11] and [16] have documented that DBH is a reliable predictor of biomass and carbon stored in tropical trees, and our results reinforce this relationship. The predictive model used, which showed a correlation coefficient of 0.86 for biomass and 0.92 for carbon, indicates that DBH is a key indicator for estimating biomass and carbon in the Tropical Dry Forest.

The estimation of CO_2 equivalent in the Tropical Dry Forest of the Sicarare Wetland showed a potential reduction of approximately 2,027,209 tons of CO_2, highlighting the importance of this ecosystem as a carbon sink. Despite having lower tree density than other types of forests, tropical dry forests can store large amounts of carbon thanks to dense wood species, as demonstrated by previous studies in Latin America [17]; [18]. These results reinforce the value of the wetland for climate change mitigation.

The conversion to CO_2 equivalent is key to measuring the impact of carbon storage on the reduction of greenhouse gases. Tropical forests, which store around 55% of terrestrial carbon [19], along with wetlands that possess unique storage characteristics, play a crucial role in global carbon regulation [20].

Therefore, the findings of this study underscore the importance of the Sicarare Wetland not only as a carbon sink but also as a reservoir of critical biodiversity. The high diversity recorded in this ecosystem suggests that the wetland has significant resilience capacity, which is essential for its long-term conservation [6]. Additionally, these results have important implications for the sustainable management of natural resources, highlighting the urgent need to implement conservation strategies based on the data obtained in this study.

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