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Carbon storage in the branchless trunk of red mangrove *Rhizophora mangle* L. in the mangroves of the Gulf of Mexico

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ABSTRACT
Objective: To estimate the aboveground biomass and carbon storage of red mangrove (*Rhizophora mangle*) within a designated conservation area.
Design/Methodology/Approach: Data were collected from 24 monitoring sites within the UMA, using 30×10 meter plots. Measurements of diameter at breast height (DBH) and tree height were taken for *Avicennia germinans* individuals to estimate aboveground biomass via allometric equations. Simulations and correlation analyses were performed using Wolfram Mathematica® software.
Results: Aboveground biomass varied considerably across sites, ranging from 4.23 $Mg \cdot ha^{-1}$ at the lowest to 53.88 $Mg \cdot ha^{-1}$ at the highest, with an overall average of 10.64 $Mg \cdot ha^{-1}$. The mean carbon storage was 5.09 $MgC \cdot ha^{-1}$. The modeling approach yielded a high coefficient of determination (R^2=0.991984), indicating strong predictive accuracy and good model fit.
Study Limitations/Implications: The analysis was limited to carbon stored in the trunk, excluding other key compartments such as roots, foliage, and soil, which are important contributors to total carbon sequestration in mangrove ecosystems.
Findings/Conclusions: The red mangrove population in the ejido "La Solución Somos Todos" demonstrates meaningful carbon storage capacity, though values are lower compared to similar studies in other regions. The strength of the model and the reliability of the estimates underscore the importance of continued research on mangrove carbon dynamics. These findings can support targeted conservation and restoration strategies, reinforcing the role of mangroves in climate change mitigation.

Keywords: coastal protection, biodiversity, model.

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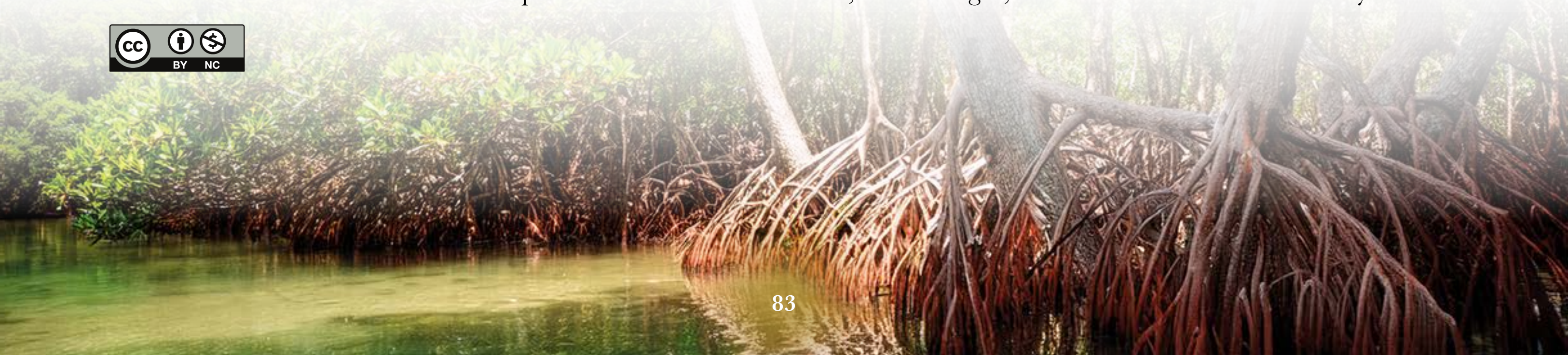
INTRODUCTION

Mangrove forests are among the most carbon-dense ecosystems on Earth, with the majority of their carbon stored in the soil. Globally, they contribute approximately 3% of the total carbon sequestration by tropical forests (Hernández & Junca-Gómez, 2020). Beyond their carbon-storing capacity, mangroves offer vital ecological services, including coastal protection from sea-level rise, storm surges, and wave erosion. Their ability to store



large quantities of biomass and carbon underscores their essential role in climate change mitigation (Salum *et al.*, 2020; Vasconcelos *et al.*, 2015). In Mexico, mangrove ecosystems are dominated by four main species: red mangrove (*Rhizophora mangle*), white mangrove (*Laguncularia racemosa*), black mangrove (*Avicennia germinans*), and buttonwood (*Conocarpus erectus*). Other species such as *Rhizophora harrisonii* and *Avicennia bicolor* are found in very low abundance. Mexican mangroves are typically composed of either a dominant species or an association of two to three species, depending on environmental conditions. These ecosystems occur across dynamic gradients influenced by salinity, temperature, oxygen levels, redox potential, and nutrient availability. Mexico ranks fifth globally in terms of mangrove coverage (Hernández & Junca-Gómez, 2020). *Rhizophora mangle*, or red mangrove, thrives in a wide range of intertidal wetland conditions, including highly saline and brackish environments. This species exhibits high tolerance to flooding, variable soil types, and other challenging physical factors (Duke & Allen, 2006). Unlike other mangrove species such as *Avicennia germinans* and *Laguncularia racemosa*, which absorb seawater and excrete salt through leaf glands, *R. mangle* regulates salt intake primarily through its roots by excluding salts during water absorption (Peel *et al.*, 2017). As a salt-excluding species, it avoids excessive uptake of sodium and chloride through a process of ultrafiltration at the root membrane level. The typical habitat of *R. mangle* is the protected intertidal fringe along tropical and subtropical coastlines, where it often becomes the dominant species. It develops aerial roots with thick periderm layers, which once anchored to the substrate, generate lateral roots above ground. These aboveground root systems not only provide structural support and facilitate nutrient uptake and gas exchange but also contribute significantly to the ecosystem by creating microhabitats for various wildlife species (Brooks & Bell, 2005). Quantifying forest aboveground biomass typically involves either direct methods (harvesting and measuring biomass) or indirect methods based on allometric models, which estimate biomass using tree attributes such as diameter at breast height (DBH), height, crown diameter, basal area, and wood density (Santos *et al.*, 2017; Thuy *et al.*, 2020). Aboveground biomass is a critical variable for estimating carbon storage and understanding the contribution of mangroves to carbon cycling. In this context, it is imperative to promote research that accurately estimates mangrove carbon stocks. Such data are fundamental for informed decision-making and the implementation of climate strategies that incorporate carbon offset mechanisms, providing environmental and socioeconomic benefits, especially for coastal communities. Enhancing our understanding of mangrove biomass and carbon storage is key to their long-term conservation and restoration. Therefore, the aim of this study is to estimate the aboveground biomass and carbon storage of red mangrove (*Rhizophora mangle*) using dasometric variables in the ejido "La Solución Somos Todos" in Paraíso, Tabasco, Mexico.

MATERIALS AND METHODS

Study sites

The study was carried out in the ejido "La Solución Somos Todos," located in Paraíso, Tabasco, Mexico (Figure 1). The mangrove forest in this area spans approximately 1,936 hectares. The ecosystem is composed of three main mangrove species: red mangrove

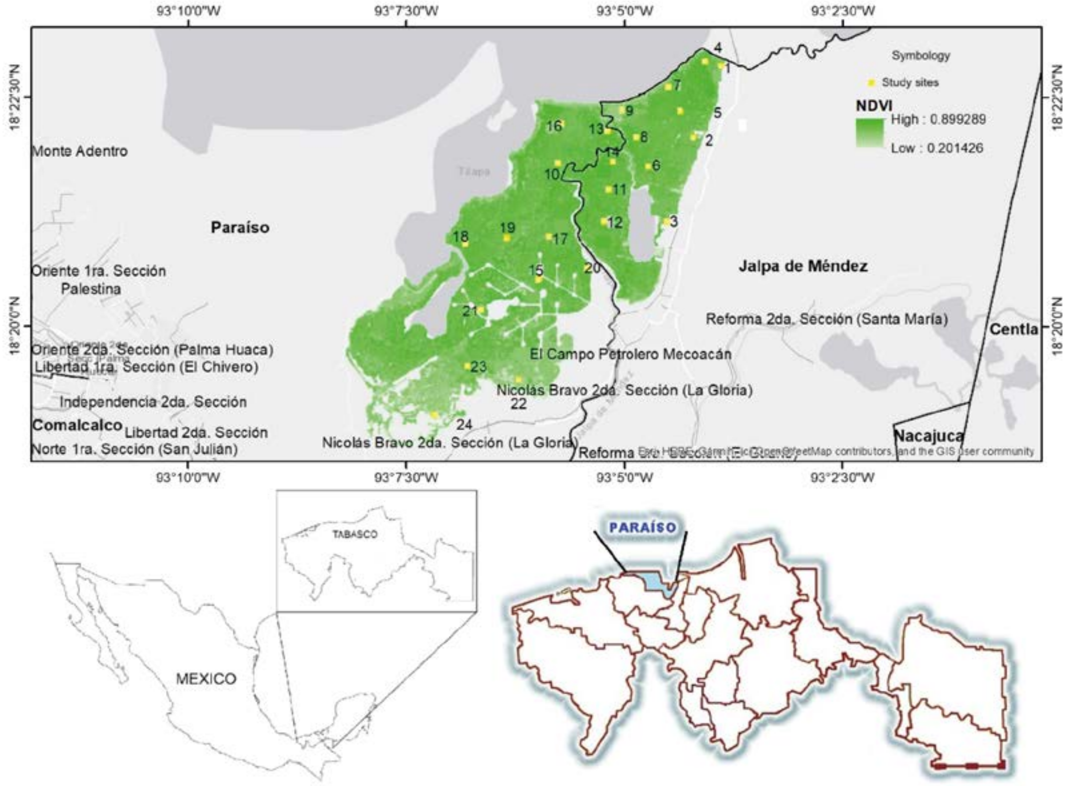


Figure 1. "Ejido la solución somos todos", Paraíso, Tabasco, México.
Source: Modified from CONABIO (2021).

(*Rhizophora mangle*), white mangrove (*Laguncularia racemosa*), and black mangrove (*Avicennia germinans*). Among them, *R. mangle* plays a particularly vital ecological role in coastal environments. Its distinctive aerial roots not only provide habitat for a diverse range of species but also serve as a natural barrier, dissipating wave energy and protecting shorelines from erosion.

Data collection and inventory

Biomass estimation of the branchless trunk —and the subsequent calculation of carbon storage in the mangrove ecosystem— was based on field measurements taken across designated plots. These measurements were carried out with the support of local ejido members, whose knowledge of the condition and history of each plot was invaluable. Data collection took place during the years 2020 and 2021 across twenty-four monitoring sites, each consisting of a 30×10 m plot, following the methodology outlined by Marín-Cruz (2019).

Measurements of dasometric variables

Within each sampling unit, the diameter at breast height (DBH) of every tree was measured at 1.30 meters above the ground using a 283D/5M diameter tape. Additionally, tree height was recorded using a Haga altimeter (height gun), following the methodology described by Kauffman *et al.* (2013).

Estimation of biomass in the branchless trunk and stored carbon

Tree biomass was estimated using the allometric equation proposed by Fromard *et al.* (1998) for neotropical mangroves with high structural development:

$$BT = 0.1282 \times DR^{2.6} \quad 6$$

where: BT=Total aboveground biomass (kg); DR=Diameter above the last root (cm).

To estimate carbon content, the biomass of the branchless trunk of *Rhizophora mangle* was multiplied by a carbon conversion factor of 0.48, as applied in previous studies on *Avicennia germinans* (Velázquez-Pérez *et al.*, 2019; Kauffman *et al.*, 2013). The average biomass values of the branchless trunk, expressed in megagrams per hectare ($Mg \cdot ha^{-1}$), were calculated and subsequently converted to carbon stock using this factor.

Estimation of the uncertainty of the selected model through simulation

Mathematical simulations were performed using Wolfram Mathematica® software. After conducting simulations for all cases (n), the results were exported for further analysis. To determine the best-fitting model for biomass estimation, four different allometric models were evaluated: The Combined Variable model, the Generalized Combined Variable model, the Australian Näslund model, and the Modified Meyer model.

Equation models for estimating biomass and its correlation coefficient R^2

Model fitting was assessed using the correlation coefficient (R^2) as the primary statistical criterion. In this study, a correlation analysis was conducted to evaluate the degree of association between the dasometric variables tree diameter and height and the estimated biomass of the branchless trunk in *Rhizophora mangle* mangroves.

RESULTS AND DISCUSSION

Diameter-height distribution

Within the UMA, *Rhizophora mangle* exhibited a diameter range of 2.48 to 14.32 cm and a height range of 3 to 16 m (Figure 2). Based on diameter values, the majority of individuals fall within the category of physiologically immature, non-reproductive trees. A significant proportion of these individuals those with diameters under 10 cm can be classified as saplings. This distribution pattern is expected, as mature red mangrove trees are predominantly found along the shores of the Mecoacán Lagoon and the Cuxcuchapa River, where they contribute to stabilizing the coastal edge.

In mature mangrove ecosystems, trees typically display larger DBH values as a result of prolonged growth. These larger, older individuals contribute substantially more to carbon storage. Conversely, in regenerating or younger mangroves, DBH values are smaller, reflecting earlier growth stages. While these younger trees do contribute to carbon sequestration, their contribution is comparatively lower than that of mature specimens.

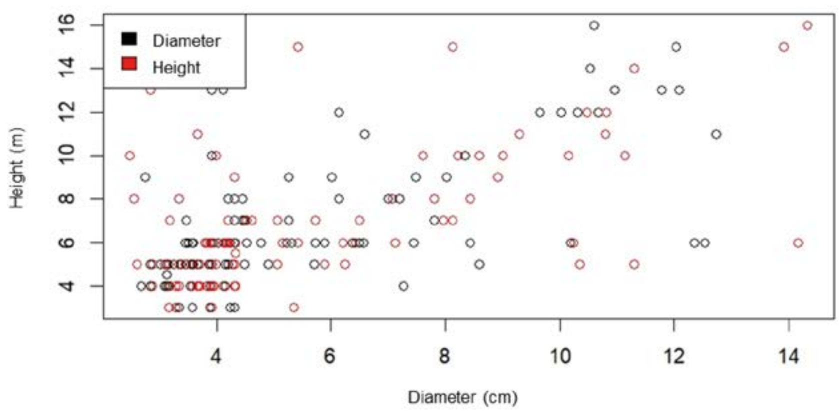


Figure 2. Height and diameter distribution of *R. mangle* trees.
Source: Own elaboration.

Biomass in the branchless trunk (AB) and estimation of stored carbon

The study recorded maximum aboveground biomass values of up to 53.88 Mg·ha^{-1} and corresponding carbon storage of 25.86 MgC·ha^{-1} at sites dominated by adult trees. The higher DBH observed in these individuals indicates a greater carbon sequestration capacity, as more woody biomass is accumulated in the trunk. In contrast, regenerating mangrove sites exhibited smaller DBH values and notably lower carbon storage, with values as low as 1.24 MgC·ha^{-1} (Table 1).

This study focused on *Rhizophora mangle* as a case study, with the highest observed aboveground biomass reaching 53.88 Mg·ha^{-1} and corresponding carbon storage of 25.86 MgC·ha^{-1} at select sites. These findings are comparable at the global scale with those reported by Komiyama *et al.* (2008), who documented average aboveground biomass values of 62.9 Mg·ha^{-1} for *R. mangle* in Puerto Rico and 12.5 Mg·ha^{-1} in Florida, USA. Similarly, Yepes *et al.* (2016) reported a branchless trunk biomass of 129.59 Mg·ha^{-1} and a carbon stock of 64.85 MgC·ha^{-1} for *R. mangle* in the Cispatá Bay mangroves, Colombian Caribbean. In the present research, the overall average aboveground biomass across all study sites was 10.64 Mg·ha^{-1}, with an average carbon stock of 5.09 MgC·ha^{-1} for *R. mangle*. These values are also comparable at the national and local levels. For example, Bautista-Olivas *et al.* (2018) reported an aboveground biomass of just 0.038 Mg·ha^{-1} for *R. mangle* in Bahía del Sargento, Sonora, Mexico. Four years later, Mendoza-Cariño *et al.* (2022) reported a significant increase at the same site, with biomass reaching 32.3 Mg·ha^{-1} and carbon storage estimated at 16.2 MgC·ha^{-1}. In La Paz Bay, Baja California Sur, Ochoa-Gómez *et al.* (2019) reported an average carbon stock of 11.2 MgC·ha^{-1} for *R. mangle*, while in the urban mangrove of Estero La Caleta in Ciudad del Carmen, Campeche, Hernández-Nava *et al.* (2022) estimated a carbon storage of 52.4 MgC·ha^{-1}. Additionally, in the Úrsulo Galván mangroves of Tabasco, Ávila-Acosta *et al.* (2024) reported an aboveground biomass of 20.33 Mg·ha^{-1} for the same species.

Table 1. Average branchless trunk biomass and carbon storage of red mangrove (*Rhizophora mangle*) across study sites.

Site	Average biomass in the branchless trunk (Mg ha^{-1})	Stored carbon (MgC ha^{-1})
1	31.58	15.15
2	53.88	25.86
3	36.00	17.28
4	16.41	7.8
5	5.64	2.7
6	3.41	1.63
7	3.99	1.91
8	3.31	1.58
9	4.36	2.09
10	4.09	1.96
11	4.43	2.12
12	0	0
13	3.71	1.7
14	4.21	2.02
15	0	0
16	0	0
17	5.56	2.66
18	4.10	1.96
19	4.74	2.27
20	4.60	2.20
21	5.67	2.72
22	2.60	1.24
23	0	0
24	0	0
	$\bar{x}=10.64$	$\bar{x}=5.09$

Mg·ha^{-1}=Megagrams per hectare. MgC·ha^{-1}=Megagrams of carbon per hectare.
Source: Own elaboration.

Estimation of the uncertainty of the selected model through simulation and correlation coefficient

The model that demonstrated the best fit for estimating biomass was the Generalized Combined Variable Model, defined by the following equation:

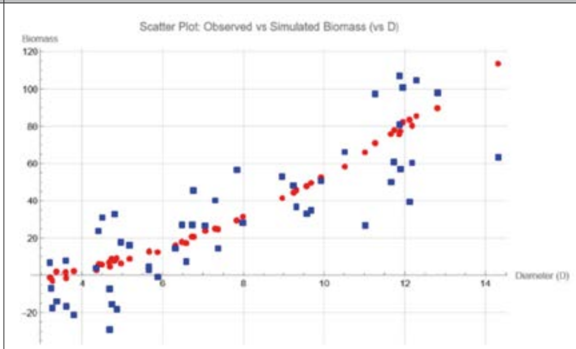
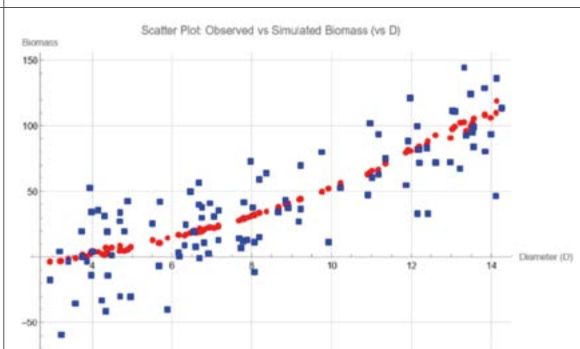
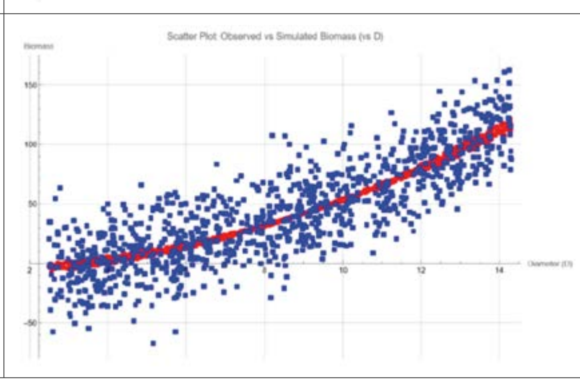
$$Biomass = -1.408362 + 0.532182D^2 - 0.613565h + 0.007642D^2h$$

Where: $a=-1.408362$: Intercept, representing the baseline biomass when all predictor variables are zero; $b=0.532182$: Coefficient indicating the change in biomass with respect to D^2 (diameter squared), holding other variables constant; $c=-0.613565$: Coefficient reflecting the inverse relationship between biomass and tree height (h), when other variables are constant; $d=0.007642$: Interaction term capturing the combined effect of D^2 and h on biomass.

The coefficient of determination (R^2) for this model was 0.991984, indicating that approximately 99.2% of the variability in biomass is explained by the model making it the best-fitting model among those evaluated. Additionally, the model showed the lowest standard error of estimate ($s = 2.140233$), further confirming its high predictive accuracy.

Simulations using Wolfram Mathematica® allowed for the adjustment and validation of complex allometric models relating dasometric variables (diameter and height) to biomass. The high R^2 value (0.991984) indicates excellent agreement between observed and simulated data, confirming the precision of biomass estimates for branchless trunks. Table 2 presents biomass simulations for different sample sizes (n=50, 100, and 1000). The resulting correlation coefficients for these simulations were R^2=0.689555,

Table 2. Simulated biomass values and adjusted model curves according to sample sizes.

Sample	R^2	Sd	Graphic representation
50	0.689555	19.4356	
100	0.734465	25.1614	
1000	0.727649	22.7592	

D^2H=Composite variable (D=diameter, H=height). *Blue dots: curve fitting with simulated data; orange dots: simulated biomass with standard deviation (Sd); X axis: Composite Variable; Y axis: Total biomass. Source: Own elaboration

0.734465, and 0.727649, respectivelyeach reflecting an acceptable model fit across varying sample sizes.

Previous studies, such as Fromard *et al.* (1998), have demonstrated that allometric models developed for *Laguncularia racemosa* with a small sample size (n=9) can achieve high levels of accuracy, reporting a correlation coefficient of R^2=0.92. This highlights the potential of well-constructed models to yield reliable results even with limited data.

CONCLUSIONS

This study, conducted in the ejido "La Solución Somos Todos" in Paraíso, Tabasco, provides valuable estimates of biomass and carbon storage for *Rhizophora mangle*. The findings are consistent with those reported in other regions of Mexico and globally, although local differences in site conditions and mangrove structure were observed. Mature individuals, characterized by larger diameters and greater height, were found to play a critical role in carbon sequestration, underscoring the importance of conserving these trees to maximize their contributions to climate change mitigation. While the estimated values are lower than those from some other regions, they are nonetheless representative of the natural variability found in Mexican mangrove ecosystems. The simulations yielded a strong model fit, indicating that the biomass estimates are robust. However, it is essential to consider the limitations of the models and the ecological variability among mangrove systems when interpreting the results. This research reinforces the need for continued studies on mangrove carbon dynamics to better support decision-making processes. The insights gained here can serve as a foundation for developing targeted conservation and restoration strategies, essential for the long-term sustainability of these critical coastal ecosystems.

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