Carbon storage in the branchless trunk of the black mangrove *Avicennia germinans* (L.) in the mangroves of the Gulf of Mexico

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ABSTRACT

Objective: To estimate the aboveground biomass and carbon storage of black mangrove (*Avicennia germinans*).

Design/methodology/approach: Field measurements were conducted at 24 monitoring sites within the UMA, each encompassing 30×10 meter plots. Tree height and diameter at breast height (DBH) of *A. germinans* were recorded to estimate aboveground biomass using established allometric equations. Simulations and correlation analysis were performed using Wolfram Mathematica® software.

Results: Carbon storage was derived by applying a biomass-to-carbon conversion factor. The average aboveground biomass across the study sites was 41.04 $\mathrm{Mg \cdot ha^{-1}}$, corresponding to an average carbon stock of 19.70 $\mathrm{MgC \cdot ha^{-1}}$. The simulation yielded a coefficient of determination (R^2) of 0.734465.

Limitations/implications: The study did not comprehensively account for environmental variables such as salinity, water level, and temperature, which may significantly influence biomass accumulation and carbon storage estimates.

Findings/conclusions: The results underscore the role of *A. germinans* in climate change mitigation, highlighting its substantial carbon sequestration potential within the mangrove ecosystems of the Gulf of Mexico.

Keywords: biomass, salinity, climate change

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INTRODUCTION

Mangroves are ecosystems that thrive in tropical and subtropical coastal zones, occupying the intertidal fringe of areas shielded from direct wave action. They are characterized by flat, muddy soils that are periodically flooded by tides and exhibit high salinity levels (Manrow-Villalobos & Vilchez-Alvarado, 2012). These ecosystems offer a wide range of ecological services, including coastal protection against sea-level rise, wave erosion, and hurricanes. Moreover, mangroves possess a significant capacity to store biomass and carbon, positioning them as key contributors to climate change mitigation (Salum *et al.*,

2020; Vasconcelos *et al.*, 2015). Recognized as some of the most productive ecosystems globally, mangroves exhibit an average carbon production of 2.5 $gC/m^2/day$ and are notable for their substantial carbon sequestration potential, with storage values exceeding 1,000 MgC/ha. Despite representing less than 1% of tropical forests and under 0.4% of global forest cover, their high productivity underscores their critical role in mitigating global warming. In this context, allometric equations serve as essential tools for quantifying carbon stocks and fluxes within mangrove ecosystems (Yepes *et al.*, 2016). In Mexico, mangrove forests are primarily composed of four species: red mangrove (*Rhizophora mangle*), white mangrove (*Laguncularia racemosa*), black mangrove (*Avicennia germinans*), and button mangrove (*Conocarpus erectus*). Other species, such as *Rhizophora harrisonii* and *Avicennia bicolor*, occur in lower abundance (Hernández & Junca-Gómez, 2020). The section of the trunk from its base to the first live branch termed the branchless trunk is a critical metric in forest mensuration (Romahn *et al.*, 1994). High salinity levels in mangrove ecosystems impose physiological stress that can alter forest structure, leading to reduced tree height, trunk diameter, and leaf size, ultimately resulting in stunted forest formations. However, species of the genus *Avicennia* L. are among the most salt-tolerant, albeit their growth and carbon assimilation capacity diminish under extreme salinity. *Avicennia germinans* L., in particular, exhibits remarkable resilience, thriving across a broad salinity gradient due to its diverse morphological and ecophysiological adaptations (Virgulino-Júnior *et al.*, 2020). It develops pneumatophores that can extend up to 20 cm above the substrate and can withstand salinities as high as 90 ppt (Niño-Martínez & León-Ledesma, 2011).

Given their ecological significance, it is imperative to conduct research that accurately quantifies carbon storage in mangrove ecosystems. Such data support informed policy-making and the development of carbon offset strategies that benefit both the environment and local communities. This, in turn, promotes the conservation and restoration of mangroves, ensuring their long-term sustainability. Therefore, the objective of this study is to estimate, using dasometric variables, the aboveground biomass and carbon storage of Avicennia germinans in the ejido "La Solución Somos Todos," located in Paraíso, Tabasco, Mexico.

MATERIALS AND METHODS

Study sites

The study was conducted in the ejido "La Solución Somos Todos," located in Paraíso, Tabasco, Mexico (Figure 1). The mangrove forest in this area covers approximately 1,936 hectares and is composed of three dominant species: red mangrove (*Rhizophora mangle*), white mangrove (*Laguncularia racemosa*), and black mangrove (*Avicennia germinans*).

Avicennia germinans is a species adapted to saline environments, exhibiting specialized mechanisms such as salt excretion through its leaves and the development of pneumatophores for gas exchange in waterlogged soils. However, its habitat is increasingly threatened by interspecific competition for ecological niches. Notably, *L. racemosa* can encroach upon areas typically occupied by *A. germinans*, particularly where shifts in environmental conditions such as changes in salinity, hydrology, or soil composition favor the establishment and spread of the white mangrove.

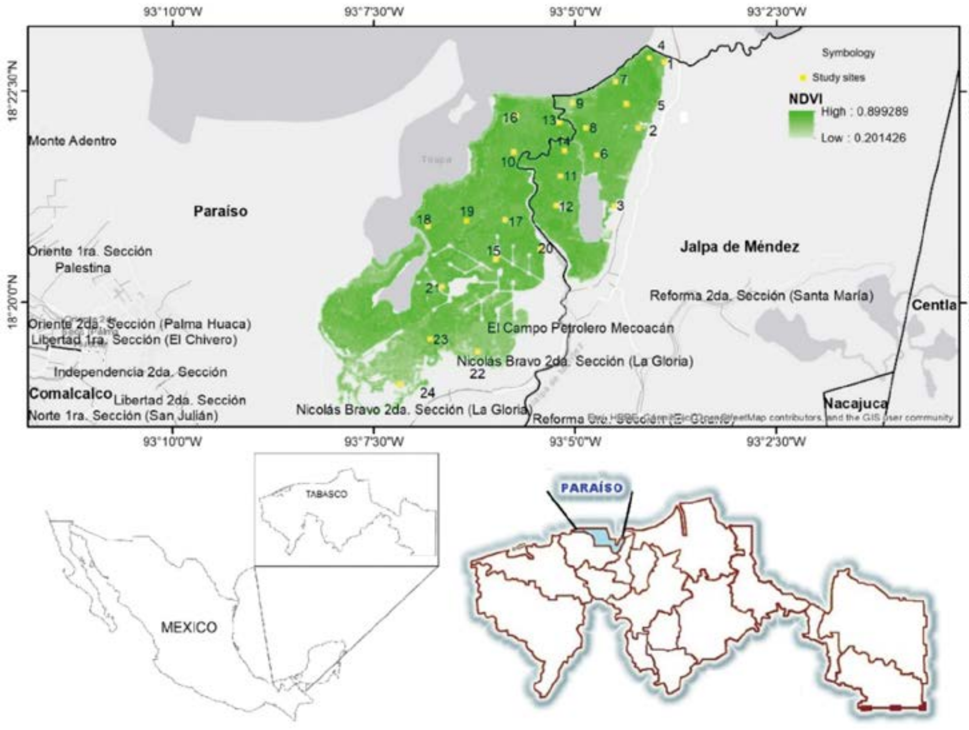


Figure 1. Location of the ejido "La Solución Somos Todos," Paraíso, Tabasco, México. Source: Modified from CONABIO (2021).

Data collection and inventory

The data used to estimate biomass in the branchless trunk and subsequently determine carbon storage in the mangrove ecosystem were obtained through field measurements carried out in 2020 and 2021. This effort was supported by ejido members with in-depth knowledge of the condition of each plot. A total of twenty-four monitoring sites were established, each consisting of a 30×10 m plot (Marín-Cruz, 2019).

Measurements of dasometric variables

At each tree site within the sampling units, diameter at breast height (DBH) was measured at 1.30 m using a model 283D/5M diameter tape. Tree height was recorded using a Haga altimeter (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:

$$BT = 0.140 \times DBH^{2.4} \text{ (for } A.\ germinans\text{)}$$

Where: BT = Total biomass; DBH = Diameter at breast height.

A biomass-to-carbon conversion factor (Fc) of 0.48 was applied.

The biomass of the branchless trunk obtained for *A. germinans* was multiplied by the 0.48 conversion factor, as recommended by Velázquez-Pérez *et al.* (2019) and Kauffman *et al.* (2013). The average biomass values in the branchless trunk ($Mg{\cdot}ha^{-1}$) were calculated and then converted to carbon storage using this factor.

Estimation of the uncertainty of the selected model through simulation

Mathematical simulations were performed using Wolfram Mathematica® software. After running the computational simulations for n cases, the results were exported for further analysis. To identify the best-fitting model, four growth models were evaluated: Combined Variable, Generalized Combined Variable, Australian Näslund, and Modified Meyer.

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

Model fitting was conducted based on the statistical criterion of the coefficient of determination (R^2). In this study, a correlation test was applied to assess the degree of association between dasometric variables (tree diameter and height) and the estimated biomass of the branchless trunk in *Avicennia germinans* mangroves.

RESULTS AND DISCUSSION

Diameter-height distribution

Diameter distribution ranged from 1.31 to 26.89 cm, while tree height varied between 1.5 and 35 m (Figure 2). This variation reflects the presence of individuals from early sapling stages to mature stems across the sampled sites. As shown in Figure 2, the majority of trees exhibit diameters below 18 cm, suggesting that the area is in an advanced stage of ecological recovery. Similarly, most tree heights are below 15 m, further indicating the developmental status of the ecosystem.

In mature mangrove forests, trees typically exhibit larger DBH values as a result of long-term growth, thereby playing a more substantial role in carbon sequestration. Conversely, regenerating mangroves are characterized by smaller DBH values, reflecting the prevalence

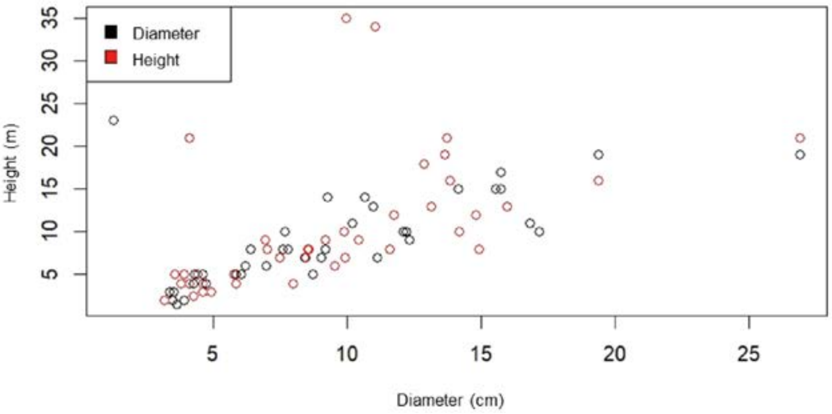


Figure 2. Height and diameter distribution of *Avicennia germinans* trees.
Source: Own elaboration.

of younger or early-stage individuals. While these younger trees do contribute to carbon storage, their impact is less significant compared to that of mature specimens.

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

The study recorded maximum biomass values of up to 129.03 Mg·ha^{-1} and carbon storage of 61.93 MgC·ha^{-1} in sites dominated by mature trees. Higher DBH values in these individuals indicate greater carbon sequestration capacity, as they reflect a larger volume of accumulated woody biomass. In contrast, regenerating mangrove sites exhibited smaller DBH values, with carbon storage as low as 2.03 MgC·ha^{-1} (Table 1).

This study focused on *Avicennia germinans* as a case species, with the highest aboveground biomass recorded at 129.03 Mg·ha^{-1} and carbon storage reaching 61.93 MgC·ha^{-1} across

Table 1. Average branchless trunk biomass and carbon storage of black mangrove (*Avicennia germinans*) at the study sites.

Site	Average biomass in the branchless trunk (Mg ha^{-1})	Stored carbon (Mg C ha^{-1})
1	7.58	3.63
2	15.05	7.22
3	0	0
4	0	0
5	4.23	2.03
6	63.52	30.48
7	129.03	61.93
8	8.28	3.97
9	71.81	34.46
10	0	0
11	22.56	10.82
12	52.39	25.14
13	79.59	38.20
14	35.12	16.85
15	56.29	27.01
16	0	0
17	0	0
18	41.02	19.68
19	50.40	24.19
20	27.17	13.04
21	0	0
22	0	0
23	6.85	3.288
24	26.89	12.90
	$\bar{x} = 41.04$	$\bar{x} = 19.70$

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

the study sites. These findings are consistent with global studies. For instance, Virgulino-Júnior *et al.* (2020) reported an average aboveground biomass of 88.26 $\mathrm{Mg \cdot ha^{-1}}$ and carbon storage of 36.98 $\mathrm{MgC \cdot ha^{-1}}$ for *A. germinans* in mangrove areas along the Amazonian coast of Brazil. Similarly, Salum *et al.* (2020) found an average aboveground biomass of 164.38 $\mathrm{Mg \cdot ha^{-1}}$ on Guarás Island at the mouth of the Amazon River. In West Africa, Vasconcelos *et al.* (2015) documented an aboveground biomass of 89.5 $\mathrm{Mg \cdot ha^{-1}}$ for the same species in Guinea-Bissau. Additionally, Yepes *et al.* (2016) reported an average branchless trunk biomass of 64.4 $\mathrm{Mg \cdot ha^{-1}}$ in the mangroves of Cispatá Bay, Colombian Caribbean.

In this study, the average aboveground biomass across all sites was 41.04 $\mathrm{Mg \cdot ha^{-1}}$, with an average carbon storage of 19.70 $\mathrm{MgC \cdot ha^{-1}}$, based on a single species, *Avicennia germinans*. These findings are consistent with results from other national studies. For example, Bautista-Olivas *et al.* (2018) reported an aboveground biomass of 47.9 $\mathrm{Mg \cdot ha^{-1}}$ and an estimated carbon stock of 23.9 $\mathrm{MgC \cdot ha^{-1}}$ for *A. germinans* in Bahía del Sargento, Sonora, Mexico. Four years later, Mendoza-Cariño *et al.* (2022) recorded an increased aboveground biomass of 71.7 $\mathrm{Mg \cdot h^{-1}}$ and a carbon stock of 35.9 $\mathrm{MgC \cdot ha^{-1}}$ at the same site. Similarly, in Bahía de La Paz, Baja California Sur, Ochoa-Gómez *et al.* (2019) reported an average aboveground biomass of 45.6 $\mathrm{Mg \cdot ha^{-1}}$ and a carbon storage value of 22.8 $\mathrm{MgC \cdot ha^{-1}}$ for the same species. Regional and local research has been conducted in La Caleta, located in Ciudad del Carmen, Campeche, Mexico, Hernández-Nava *et al.* (2022) estimated for *A. germinans* an aboveground biomass of 119.2 $\mathrm{Mg.\ ha^{-1}}$ and an estimated carbon stock of 59.6 $\mathrm{MgC.ha^{-1}}$. In the Úrsulo Galván mangroves in Tabasco, Mexico, Ávila-Acosta *et al.* (2024) report an aboveground biomass of 0.32 $\mathrm{Mg.\ ha^{-1}}$ for *A. germinans*.

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, expressed as:

$$Biomass = 0.355104 + 0.358937D^2 - 0.927267h + 0.008849D^2h$$

Where: a = 0.355104: Constant or intercept, representing the baseline biomass value when diameter (D) and height (h) are zero. b = 0.358937: Coefficient for D^2, indicating the change in biomass with increasing diameter squared, holding other variables constant. c = −0.927267: Coefficient for height, showing the biomass variation with increasing tree height, all else equal. d = 0.008849: Coefficient for the interaction term D^2h, reflecting the combined effect of diameter and height on biomass.

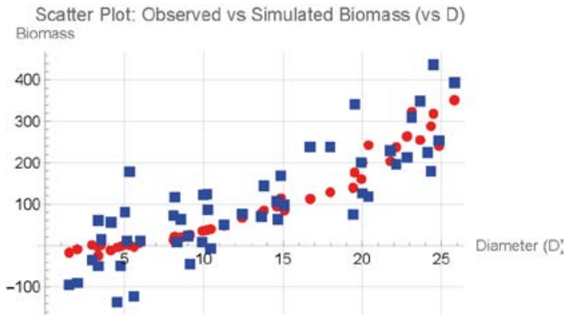
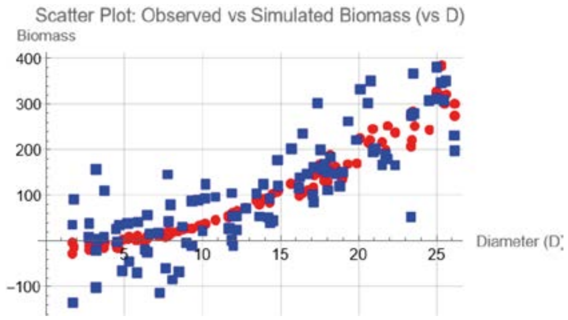
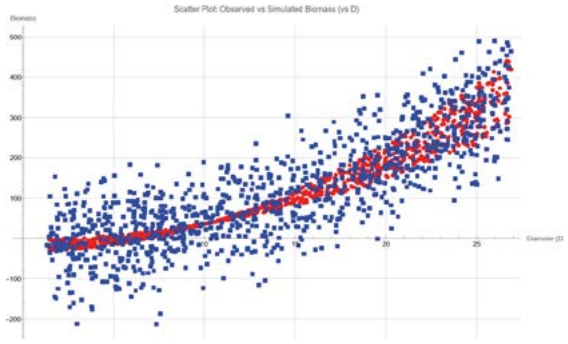
The model achieved a coefficient of determination of $R^2 = 0.99651$, indicating that 99.65% of the variability in biomass is explained by the model making it the best-fitting among those evaluated. The standard error (s = 4.07792) was also the lowest, indicating a high level of accuracy in the model's predictions.

The simulation process, conducted using Wolfram Mathematica®, allowed for fitting and validating complex mathematical models that relate dasometric variables such as tree diameter and height to biomass. Through allometric equations, the software enabled highly accurate estimations of branchless trunk biomass. In this study, the simulation yielded a correlation coefficient of $R^2 = 0.734465$, demonstrating a strong agreement between simulated and observed data, and thus reliable predictive accuracy.

Table 2 presents biomass simulation results for sample sizes of 50, 100, and 1,000. The corresponding correlation coefficients were R^2=0.689555, 0.734465, and 0.727649, respectively, all of which confirm a good model fit.

Previous models developed for *Laguncularia racemosa* have demonstrated high accuracy with relatively small sample sizes. For instance, Correa (2002) achieved a correlation

Table 2. Biomass simulation and adjusted curves according to the number of sample sizes generated.

Sample	R^2	Sd	Graphic representation
50	0.689555	73.093	
100	0.734465	61.2985	
1000	0.727649	69.7306	

D^2H represents the composite variable, where D is diameter and H is height.
Blue dots indicate curve fitting with simulated data; orange dots represent simulated biomass values with standard deviation (SD). X-axis: Composite Variable (D^2H); Y-axis: Total Biomass.
Source: Own elaboration.

coefficient of $R^2=0.97$ with a sample size of n=21, while Fromard *et al.* (1998) reported the same R^2 value using a sample of n=45. These results highlight that highly accurate models can be constructed even with limited sample sizes.

CONCLUSIONS

This research makes a significant contribution to the understanding of carbon storage in the mangroves of the Gulf of Mexico, with a focus on *Avicennia germinans*. The diameter-height distribution observed in the study area indicates the coexistence of both regenerating and mature mangrove stands, with higher carbon storage levels associated with mature individuals. Although regenerating mangroves contribute less to carbon storage, they represent the potential for ecosystem recovery.

The findings underscore the critical importance of conserving and restoring *A. germinans* mangroves not only for their carbon sequestration capacity but also for their ecological resilience in saline environments. Effective conservation strategies should account for ecological dynamics, such as interspecific competition, particularly the encroachment of white mangroves into black mangrove habitats.

The results are consistent with both national and international studies, reinforcing the need for continued research to inform and refine mangrove conservation and sustainable management strategies. Additionally, this study highlights the remarkable resilience of black mangroves under adverse environmental conditions and their role in mitigating climate change through carbon storage. These insights should be considered by policymakers to enhance protection and restoration efforts, ensuring the long-term preservation and ecological functionality of these vital coastal ecosystems in the face of global climate change.

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