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BIOMASS, CARBON STOCK, CARBON UPTAKE, AND OXYGEN PRODUCTION OF *SONNERATIA ALBA*: ESTIMATING VALUES FOR MANGROVE FOREST ENVIRONMENTAL SERVICE IN CAN GIO, VIETNAM

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Sonneratia alba J.E. Smith is a key mangrove species contributing to forest structure along tropical Southeast Asian coasts. This study aims to quantify the ecosystem service value of natural *S. alba* populations through biomass, carbon stock, carbon uptake, and oxygen production, using a case study in the Can Gio Mangrove Biosphere Reserve, Vietnam. To our knowledge, this is the first study to provide a species-specific economic valuation of both carbon uptake and oxygen production for *S. alba* in this region. Fifty sample plots were established to investigate above-ground biomass and carbon accumulation across diameter classes. Allometric equations were developed to estimate the above-ground biomass and carbon stock. Below-ground values were assessed using standard conversion factors. Carbon uptake and oxygen production were calculated based on total carbon accumulation. The results show a total biomass of 88.25 metric tons per hectare (t ha^{-1}), a total carbon stock of 37.95 t ha^{-1}, a carbon uptake of 139.27 t ha^{-1}, and an oxygen production of 101.32 t ha^{-1}. The estimated economic values of *S. alba* include 696.3 USD ha^{-1} for carbon uptake and 6079.2 USD ha^{-1} for oxygen production. These results contribute to the understanding of mangrove ecosystems and offer practical input for payment for environmental services schemes and conservation policies.

Keywords: *Sonneratia alba*, biomass, carbon stock, carbon uptake, oxygen production, forest environmental service

INTRODUCTION

Biomass, carbon stock, carbon uptake, and oxygen production of forests play critically essential roles in ecosystem services, helping to maintain environmental stability, regulate climate, and provide critical benefits to humans and other organisms. Especially in the context that fossil fuel combustion is the leading cause of increased atmospheric CO_2 and global warming (IPCC 1995), increasing CO_2 uptake during the lifetime of trees becomes a potential solution (Eamus 2000). Also, Chen et al. (2022) stated that oxygen produced by forest ecosystems is an ecosystem service and should be valued because of benefits to human wellbeing, such as health and attraction to tourists. Regarding mangrove forests, the ecosystem services of carbon sequestration and oxygen production have been considered. Several studies have shown that mangroves are an ecosystem with great potential for storing and absorbing carbon (Alongi 2012, Daniel et al. 2011, Mitra et al. 2011, Anjum et al. 2025), as well as producing oxygen (Pal et al. 2019).

The Can Gio Mangrove Biosphere Reserve, Vietnam, is a significant research area due to its diverse mangrove ecosystem and potential for environmental services. Mangrove forests are formed on alluvial lands with two main tree species *Avicennia alba* and *Sonneratia alba*, which develop into populations and communities depending on the distribution area. Compared to the *A. alba* species, *S. alba* in the Can Gio mangrove forest has only been generalised regarding distribution and morphological description. Also, there is modest research on forest environmental services in this area. Cao and Vien (2016) investigated carbon sequestration of *Ceriops zippeliana*. Regarding *S. alba*, Bui and Vien (2016) examined the relationship between above-ground biomass and diameter, and above-ground carbon stock and diameter in a standard log-linear regression. A recent study by Bajaj et al. (2024) has provided regional-scale carbon stock assessments using satellite data, including for the Can Gio area. However, detailed field-based quantification, especially linked to economic valuation at the species level, remains scarce. This study extended the study of Bui and Vien (2016) by taking more sample plots and collecting data at various levels of diameters to improve the estimated equations for biomass and carbon stock. We investigated the relationships in different regressions for comparisons and evaluated how well the estimated equations performed. Generalisation errors were used to validate the chosen equations. We also calculated the below-ground biomass and carbon stock, used summed values of above-ground and below-ground accumulations to evaluate carbon uptake and oxygen production, enhancing the necessary information to consider environmental services.

Biomass, carbon stock, carbon uptake, and oxygen production: relationships and estimations

Carbon uptake is the process by which plants absorb CO_2 from the atmosphere during photosynthesis. This helps reduce the amount of CO_2 in the air and produces oxygen, which is essential for people and animals. Carbon is stored in the plant over time, forming what we call carbon stock. This plays a key role in reducing greenhouse gases and controlling the climate (Hairiah et al. 2011). The carbon stock of a forest depends on the total biomass it accumulates (Shafiiq 2012).

To estimate biomass, many studies use a model that links tree diameter with biomass. A common form is the log-linear equation $\ln Y = \ln a + b \ln X$ (Komiyama et al. 2005, Cao & Vien 2016). This can be converted to $Y = aX^b$, which makes it easier to apply. However, this transformation can introduce some bias. To adjust for this, a correction factor $CF = \exp(SEE^2/2)$ was used by Sprugel (1983) and Ong et al. (2004). McArdle (1988) argued that this correction might not be needed if R^2 is greater than 0.9.

Most studies on *S. alba* have been carried out in Southeast Asia, especially Indonesia. Komiyama et al. (1988) reported above-ground biomass of 169.10 metric tons per hectare (t ha^{-1}) in Halmahera Island. In Inner Ambon Bay, the total biomass reached 327.26 t ha^{-1}, including 237.24 t ha^{-1} above-ground and 90.02 t ha^{-1} below-ground (Tupan & Lailossa 2019). Komiyama et al. (2008) also noted that most secondary mangrove forests have less than 100 t ha^{-1} of above-ground biomass, which fits with areas beyond 24° 23' N or S latitude.

In terms of carbon stock, Juwari et al. (2020) reported values ranging from 18.12 to 28.13 t ha^{-1} in Ngurah Rai Forest Park, Bali. Higher values were found by Harefa et al. (2024) in Pasar Rawa, Langkat, Indonesia, with 60.89 t ha^{-1} of carbon stock and a carbon uptake potential of 192.13 t ha^{-1}. Arsad et al. (2022) provided more detailed measurements: 0.008 t ha^{-1} in leaves, 0.27 t ha^{-1} in roots, and 0.016 t ha^{-1} in sediments. For carbon uptake, they found 1.00, 0.85, and 0.06 t ha^{-1} for those same parts. In Can Gio, Bui and Vien estimated an above-ground carbon stock of around 30 t ha^{-1}.

More recently, Bajaj et al. (2024) assessed changes in carbon stocks in Vietnam's mangrove forests between 1989 and 2020 using satellite data. They reported a total estimated carbon stock ranging from 269 to 254 teragrams of carbon (TgC) over this period. These regional-scale findings help place our study in a broader national and temporal context. While many studies focus on carbon, we found no research specifically estimating oxygen production for *S. alba*, which is one of the key aims of this study.

Estimations for forest environmental service payment

Estimating biomass, carbon stock, carbon uptake, and oxygen production helps to understand the benefits forests provide. These values are important for putting an economic value on ecosystem services and can be used in planning conservation and climate policies. For example, carbon uptake is often linked to carbon credit prices in emissions trading systems. In Vietnam, carbon from forests has been sold at around 5 USD per ton (USD t^{-1}) (World Bank 2024).

Although oxygen does not have a direct market, its value can still be estimated based on industrial oxygen prices (Chen et al. 2022). In Takalar Regency, Indonesia, Sribianti et al. (2021) estimated the value of carbon uptake at 198.3 IDR ha^{-1} $year^{-1}$ and oxygen production at about 2 million IDR ha^{-1} $year^{-1}$. These numbers show how forest services can be valued in a green economy.

Vietnam has considered forest environmental services through Decree No. 156/2018/ND-CP (Government of Vietnam 2018), which supports carbon-related services under national programs. Bajaj et al. (2024) emphasised the importance of linking carbon stock monitoring to policy tools like Payment for Environmental Services (PES), especially as mangrove areas fluctuate. Financial mechanisms such as forest protection funds and Reducing Emissions from Deforestation and Forest Degradation (REDD+) also support these efforts (Lu et al. 2012). A case study on blue carbon and REDD+ in the Matang Mangrove Forest Reserve, Malaysia, showed how these mechanisms can be applied (Ammar et al. 2014).

Some studies also highlight the role of willingness to pay for ecosystem services (Zhang et al. 2024). Still, studies that estimate payment-worthy values like carbon uptake and oxygen production for dominant mangrove species are limited. This research addresses that gap by focusing on *S. alba* in Can Gio.

MATERIALS AND METHODS

We first sampled forestry compartments (FCs) in the protective forest area of the Can Gio Mangrove Biosphere Reserve with natural *S. alba* populations to investigate the forest structure with *S. alba* and obtain data on tree diameter at 1.3 m height (DBH), biomass, and organic carbon content. The data was then used to estimate relationships among factors to evaluate biomass, carbon stock, carbon uptake, and oxygen production in the Can Gio mangrove forest. Specifically, we made two estimations for the relationship between biomass and DBH, as well as between carbon stock and DBH, to evaluate above-ground biomass and carbon stock. Additionally, conversion factors between carbon stock and biomass were addressed through the ratio of carbon stock and biomass in the data to evaluate below-ground carbon stock. Finally, we assessed the values of biomass, carbon stock, carbon uptake, and oxygen production in environmental services. Stagraphics version 5.1 was used in estimations and calculations.

Sampling

Sample plots were taken at eight FCs, including FCs 02, 11, 16, 17, 19, 20, 21, and 22 (Figure 1). Fifty sample plots were distributed in the FCs proportional to their area. The plot size is 500 m^2 (i.e., 25 m × 20 m) and was surveyed for DBH and density in each plot. Due to strict legal restrictions on cutting trees in the protected forests of Can Gio Biosphere Reserve, all destructive sampling activities require formal approval from the local forest management authority. The number of 50 trees was approved to ensure statistical validity across diameter classes and minimal disturbance to the natural forest structure. The forest structure explored from the sample plots would help address appropriate diameter classes. The selected trees were evenly distributed across a DBH range from 4–33 cm. They are healthy, straight-boled, and have stable canopies. Each tree was cut into 1-meter segments to measure the fresh weight of the stems, branches, and leaves.

The tree stem and branch length were divided into three equal parts for each. We got 0.5 kg of wood in each part and 0.5 kg of tree leaves. We dried them at 105 °C until the weights did not change. The dried samples were used to calculate the amount of carbon stock using the Walkey-Black method (van Reeuwijk 2002). We oxidised organic carbon with excess potassium dichromate solution in a sulfuric acid medium, using the heat from dissolving concentrated sulfuric acid into the dichromate solution. The excess dichromate was titrated with a ferric solution, and the organic carbon content or above-ground carbon stock was deduced.

The biomass of individual trees was determined through direct weighing in the field and drying in the laboratory from the trees' stems, branches, and leaves. A biomass and

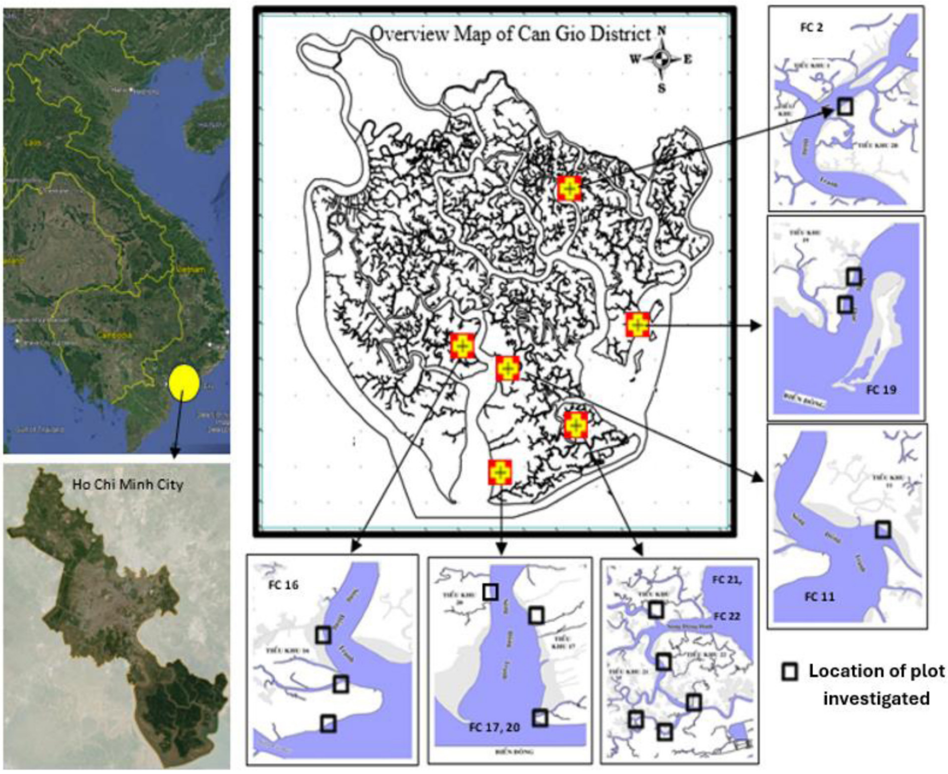

Figure 1 Sampling location

Table 1 Distribution and characteristics of *Sonneratia alba* in forestry compartments (FCs)

FC	No. of sample plots	Area (ha)	Density (N ha^{-1})	DBH (cm)			
				Mean	SD	Min	Max
2	8	68.2	1323	11.6	5.94	4.2	27.5
11	2	23.1	1500	10.5	4.78	4.0	26.8
16	9	78.4	1340	12.4	4.35	4.2	20.3
17	5	41.2	985	12.1	4.21	4.5	26.1
18	1	9.30	1260	13.4	3.18	4.2	36.8
19	8	74.3	1215	12.3	4.67	4.0	32.4
20	6	51.2	1180	10.3	5.54	4.4	28.2
21	5	33.1	944	12.1	4.89	4.1	29.4
22	6	47.2	1347	11.2	5.39	4.1	26.7

carbon stock ratio or conversion factor between biomass and carbon stock R was evaluated.

Data analysis

Biomass and carbon accumulations include above-ground (i.e., in separate tree components) and below-ground accumulations. For the above-ground accumulation, the relationship between biomass and DBH and carbon stock and DBH will be estimated based on the sampling data. Besides the log-linear relationship between biomass and DBH and between carbon stock and DBH, addressed by Bui and Vien (2016), we tried estimating other terms of regression models in terms of square root and exponential functions for comparisons. The criteria for selecting an optimal allometric equation included a significant coefficient of determination (R-squared), a minor standard error of estimation (SEE), a minor mean absolute error (MAE), and a minor sum of square residuals (SSR). Also, parameters must be significant at 5% level.

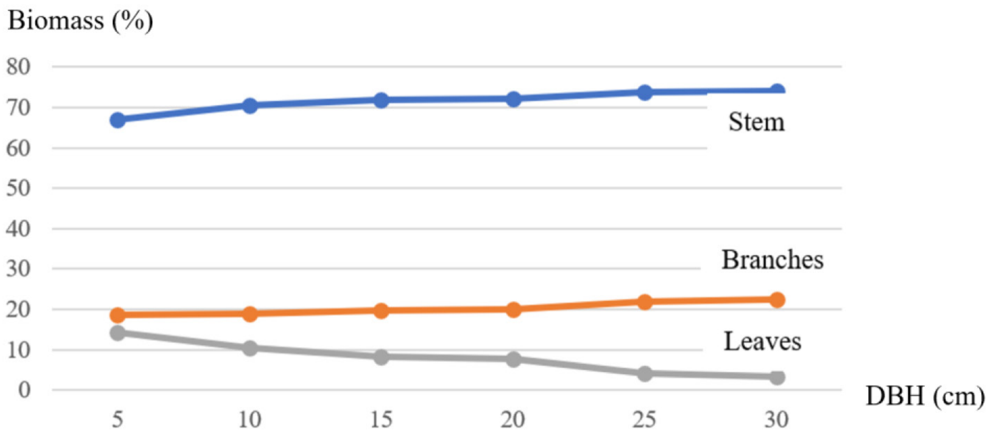

Figure 2 The percentage biomass of tree parts varied in different diameter at breast heights (DBHs)

For data usage, the dataset of 50 trees was split into 42 for training and 8 for testing the allometric models. Their difference measures how well-estimated models can generalise unseen data in a test dataset. The generalisation error was determined by equation (1) to validate the chosen estimated model.

$$\Delta = \left|\frac{Y_{test} - Y_{training}}{Y_{test}}\right| \times 100\% \qquad (1)$$

where Y_{test} are true values of the tested trees, $Y_{training}$ are estimated values of tested trees and Δ is a generalisation error.

According to Komiyama et al. (2005), below-ground biomass for the species *S. alba* is calculated as in equation (2). The below-ground carbon stock was then evaluated based on the conversion factor between biomass and carbon stock.

$$B_{below} = 0.199\rho^{0.899} DBH^{2.22} \qquad (2)$$

$$C_{below} = B_{below} \times R \qquad (3)$$

where B_{below} is below-ground biomass, ρ is 0.475, and R is the conversion factor between biomass and carbon stock evaluated in the measured data.

According to Murdiyarso (1999), the potential of CO_2 uptake is obtained by multiplying carbon stock with a conversion factor F as equation (4). Oxygen production is calculated as equation (5), according to Nowak et al. (2019).

$$CO_2 = C \times F \qquad (4)$$

$$O_2 = C \times K \qquad (5)$$

where C is the total carbon stock, F is 3.67, the conversion factor of C to CO_2, and K is 2.67, the conversion factor of C to O_2.

RESULTS AND DISCUSSION

Distribution and characteristics of *Sonneratia alba*

The tree density of *S. alba* in the study area is from 944 to 1500 trees per hectare. Above 70% of sample plots are distributed in FCs 2, 16, 19, 20, and 22. These are sub-areas adjacent to large rivers connecting to the East Sea. Alluvial soil formation is stronger in the areas than in the remaining regions. The high density of the trees in these areas has shown favorable conditions for the development of *S. alba*. The tree's DBH has great dispersion, ranging from 4.0–36.8 cm. Their distributions are from 10.3 (5.54) cm to 13.4 (3.18) cm among FCs (Table 1).

Biomass and its relationship with DBH

Compared to the total biomass of individual trees, the biomass of the stem accounted for the highest average proportion, with 71.53 ± 2.15%, the biomass of the branches accounted for a lower proportion, 24.13 ± 2.02%, and the biomass of the leaves accounted for the lowest proportion, 4.34 ± 1.85% (Figure 2). Intrinsically, as the diameter level increased, the biomass proportion of the trunks and branches increased while the biomass of the leaves decreased.

Table 2 The relationship between above-ground biomass and diameter at breast height (DBH) in different regressions

Allometric equation	R^2	SEE	MAE	SSR	P_a	P_b
Above-ground						
$\ln(B_{above}) = -1.603 + 2.291\ln(DBH)$	0.99	0.08	0.05	0.18	0.00	0.00
$B_{above} = (-12.412 + 5.994\sqrt{DBH})^2$	0.96	1.06	0.88	36.5	0.00	0.00
$B_{above} = \exp(1.990 + 0.151DBH)$	0.93	0.32	0.27	3.46	0.00	0.00
Stem						
$\ln(B_{stem}) = -2.073 + 2.310\ln(DBH)$	0.99	0.10	0.08	0.29	0.00	0.00
$B_{stem} = \exp(-10.537 + 5.084\sqrt{DBH})^2$	0.97	0.92	0.73	27.1	0.00	0.00
$B_{stem} = \exp(-1.634 + 0.152 \times \sqrt{DBH})$	0.92	0.35	0.29	3.92	0.00	0.00
Branches						
$\ln(B_{branches}) = -3.315 + 2.354\ln(DBH)$	0.99	0.08	0.06	0.21	0.00	0.00
$B_{branches} = (-6.606 + 3.067\sqrt{DBH})^2$	0.95	0.66	0.54	13.97	0.00	0.00
$B_{branches} = \exp(0.421 + 0.158DBH)$	0.94	0.32	0.28	3.27	0.00	0.04
Leaves						
$\ln(B_{leaves}) = -2.767 + 1.578\ln(DBH)$	0.98	0.09	0.09	0.31	0.00	0.00
$B_{leaves} = (-1.240 + 0.888\sqrt{DBH})^2$	0.97	0.15	0.12	0.68	0.00	0.00
$B_{leaves} = \exp(-0.276 + 0.105DBH)$	0.93	0.22	0.17	1.67	0.05	0.00

Table 2 shows the estimated models of the biomass of tree trunk parts with DBH. The log-linear regression models show the best fit, with a coefficient of determinant R^2 higher than 99% at a significant level of 1% and smaller SEE, MAE, and SSR compared to other terms. The models can explain 99% of the variation in biomass based on DBH, and they were chosen to represent the relationship between the biomass of tree trunk parts and DBH.

Because of the log-linear equations having a coefficient of determination R^2 larger than 0.9, the equations could be directly transformed to the form $Y = aX^b$ (McArdle 1988). Table 3 shows the transformed equations between biomass components and growth indicators of DBH. The average generalisation error of all equations is within an error limit of 10%. The total biomass equation has the lowest error, and it could be used for calculating the biomass of the population. Figure 3 shows changes in the biomass of tree parts with DBH as a result of the transformed equations.

Table 4 compares the error level of these equations to other studies' results. Results showed differences between 7.03–13.77%. The smallest difference of 7.03% was found in Thailand and Indonesia, which are in a similar context in Southeast Asia. Figure 4 shows the difference in calculation results for the biomass of *S. alba* among studies.

Carbon stock and its relationship with DBH

The ratio of carbon stock in biomass in stems, branches, and leaves is 0.43 ± 0.03, 0.42 ± 0.02, and 0.43 ± 0.01, respectively. The overall carbon coefficient is 0.43 ± 0.01. The carbon conversion coefficients from biomass in the Can Gio mangrove forest are lower than a coefficient of 0.47 in mangrove forests across a broad area of the Indo-Pacific region (Kauffman et al. 2011).

The estimated models of the organic carbon content or carbon stock of tree trunk parts with the growth indicators of DBH are shown in

Table 3 Transformed allometric equation of above-ground biomass with diameter at breast height (DBH)

Components	Allometric equation	Generalisation error (%)		
		Min	Max	Mean
Above-ground	$B_{above} = 0.2019\ DBH^{2.291}$	1.38	7.53	3.13
Stem	$B_{stem} = 0.1258\ DBH^{2.310}$	0.18	8.69	3.69
Branches	$B_{branches} = 0.0363\ DBH^{2.354}$	0.44	7.98	4.55
Leaves	$B_{leaves} = 0.0628\ DBH^{1.578}$	0.22	9.01	6.57

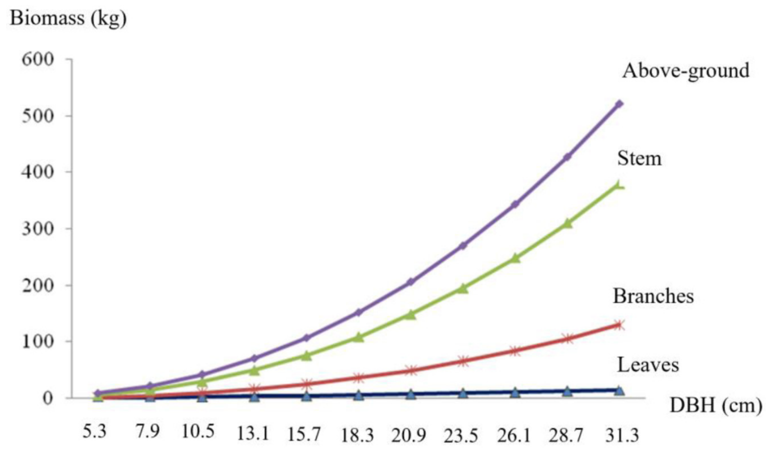

Figure 3 Changes in biomass of tree parts in different diameter at breast heights (DBHs)

Table 4 Comparison with above-ground biomass equations of *Sonneratia alba* in different studies

Allometric equation	Source	Location Study	Difference comparison to this study (%)	Note
$B_{above} = 0.251\rho DBH^{2.46}$	Komiyama et al. (2005)	Thailand, Indonesia	7.03	$\rho = 0.475$ (g cm^{-3}) $DBH_{max} = 49$ cm
$B_{above} = V\ \rho 1000$ $V = 0.0003841 DBH^{2.10}$	Kauffman et al. (2010)	Micronesia	12.02	$\rho = 0.78$ (g cm^{-3}) $DBH_{max} = 32.3$ cm
$B_{above} = 0.1688\rho DBH^{2.471}$	Chave et al. (2005) Komiyama et al. (2008)	America	13.77	$\rho = 0.78$ (g cm^{-3}) $DBH_{max} = 42$ cm

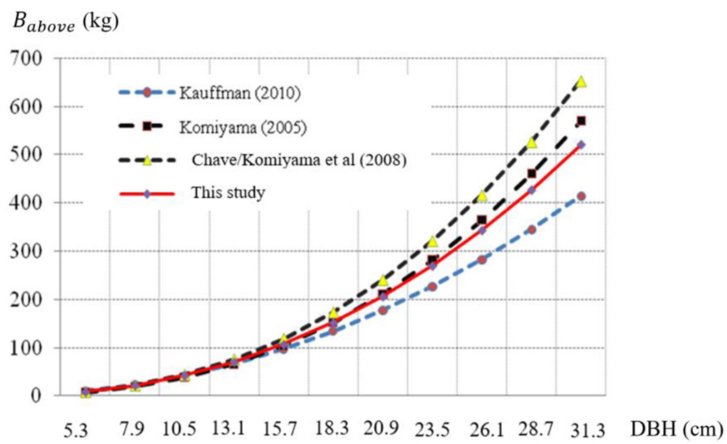

Figure 4 Comparison with above-ground biomass of *Sonneratia alba* calculated based on other studies' equations

Table 5. The log-linear regression models have the best fit with a factor of determinant R^2 higher than 99% at a significant level of 1% and smaller SEE, MAE, and SSR compared to other terms. The models can explain more than 99% of the variation in carbon stock based on DBH, and they were chosen to represent the relationship between the organic carbon content of tree trunk parts and DBH.

Because of the log-linear equations having a coefficient of determination R^2 larger than 0.9, they could be directly transformed to the form $Y = aX^b$ (McArdle 1988), as shown in Table 6. The average generalisation error of all equations is within an error limit of 10%. The total carbon stock equation has the lowest error and could be used to calculate the population's carbon stock.

Table 5 The relationship between organic carbon content and diameter at breast height (DBH)

Allometric equation	R^2	SEE	MAE	SSR	P_a	P_b
Above-ground						
$\ln(C_{above}) = -2.516 + 2.305\ln(DBH)$	99.24	0.07	0.07	0.20	0.00	0.00
$C_{above} = \exp(-1.259 + 1.246\sqrt{DBH})$	98.23	0.17	0.13	0.95	0.00	0.00
$C_{above} = (2.716 + 0.014DBH^2)^2$	96.36	0.81	0.65	20.97	0.00	0.00
Stem						
$\ln(C_{stem}) = -2.954 + 2.3110\ln(DBH)$	99.05	0.10	0.09	0.22	0.00	0.00
$C_{stem} = \exp(-1.636 + 1.256\sqrt{DBH})$	97.61	0.20	0.16	1.31	0.00	0.00
$C_{stem} = \exp(-7.237 + 3.432\sqrt{DBH})^2$	96.51	0.67	0.53	14.5	0.00	0.00
Branches						
$\ln(C_{branches}) = -4.154 + 2.311\ln(DBH)$	99.04	0.12	0.15	0.18	0.00	0.00
$C_{branches} = \exp(-2.9475 + 1.304\sqrt{DBH})$	98.43	0,17	0.12	0.92	0.00	0.00
$C_{branches} = (-0.7845 + 0.267DBH)^2$	98.31	0.29	0.21	2.62	0.00	0.00
Leaves						
$\ln(C_{leaves}) = -3.612 + 1.723\ln(DBH)$	98.12	0.10	0.11	0.35	0.00	0.00
$C_{leaves} = (0.235 + 0.894DBH)^2$	97.83	0.09	0.67	0.36	0.03	0.00
$C_{leaves} = 0.562 + 0.012DBH^2$	96.93	0.36	0.39	1.78	0.02	0.00

Table 6 Transformed allometric equation of organic carbon content with diameter at breast height (DBH)

Components	Allometric equation	Generalisation error (10%)		
		Min	Max	Mean
Above-ground	$C_{above} = 0.0807DBH^{2.305}$	0.17	5.01	2.31
Stem	$C_{stem} = 0.0520DBH^{2.311}$	0.98	8.12	4.47
Branches	$C_{branches} = 0.0157DBH^{2.311}$	1.03	7.91	5.38
Leaves	$C_{leaves} = 0.0269DBH^{1.723}$	0.98	7.11	3.43

Values for mangrove forest ecosystem services

Table 7 summarises the density, biomass, carbon stock, carbon uptake, and oxygen production of *S. alba* in various diameter classes at Can Gio. Table 8 presents values for the forest environmental service of *S. alba* following the FC distribution. The density changes in a decreasing direction as the diameter increases. Both density and diameter contribute to the total biomass, carbon stock, carbon uptake, and oxygen production per hectare. The diameter class 11.8–14.4 has the highest total biomass of 14.12 t ha^{-1}. The diameter class 4.0–6.6 has the smallest total biomass of 5.12 t ha^{-1}. The carbon stock calculation findings showed that as the diameter increased, so did the carbon stock, but slightly reduced in a higher diameter class with low density. The average above-ground carbon

Table 7 Biomass, carbon stock, carbon uptake, and oxygen production of mangrove *Sonneratia alba* in various diameter classes

Diameter class (cm)	Density (N ha^{-1})	Above-ground biomass (t ha^{-1})	Below-ground biomass (t ha^{-1})	Total biomass (t ha^{-1})	Above-ground carbon stock (t ha^{-1})	Below-ground carbon stock (t ha^{-1})	Total carbon stock (t ha^{-1})	Carbon uptake (t ha^{-1})	Oxygen production (t ha^{-1})
4.0–6.6	322	3.62	1.50	5.12	1.56	0.65	2.20	8.08	5.88
6.6–9.2	289	7.85	2.28	10.13	3.38	0.98	4.36	15.99	11.63
9.2–11.8	224	8.96	2.76	11.72	3.85	1.19	5.04	18.50	13.46
11.8–14.4	149	9.94	4.18	14.12	4.27	1.80	6.07	22.28	16.21
14.4–17.0	101	8.95	3.45	12.40	3.85	1.48	5.33	19.57	14.24
17.0–19.6	63	7.97	3.43	11.40	3.43	1.47	4.90	17.99	13.09
19.6–22.2	31	6.78	2.76	9.54	2.92	1.19	4.10	15.06	10.95
≥ 22.2	44	9.84	3.98	13.82	4.23	1.71	5.94	21.81	15.87
Total	1223	63.91	24.34	88.25	27.48	10.47	37.95	139.27	101.32

Table 8 Values for mangrove forest environmental services of *Sonneratia alba*

FC	Total biomass (t ha^{-1})	Total carbon stock (t ha^{-1})	Carbon uptake (t ha^{-1})	Oxygen production (t ha^{-1})
2	87.12	37.46	137.48	100.02
11	95.54	41.08	150.77	109.69
16	134.91	58.01	212.90	154.89
17	89.85	38.64	141.79	103.16
18	95.26	40.96	150.33	109.37
19	100.13	43.06	158.02	114.96
20	48.64	20.92	76.76	55.84
21	71.70	30.83	113.15	82.32
22	71.09	30.57	112.19	81.62
Mean	88.25	37.95	139.27	101.32

stock is 27.48 t ha^{-1}, somewhat lower than the 30 t ha^{-1} found in the study by Bui and Vien (2016).

For the carbon uptake and oxygen production capacities, the diameter class 11.8–14.4 has the highest carbon uptake of 22.28 t ha^{-1} and oxygen production capacity of 16.21 t ha^{-1}. Despite the large number of trees, the ability to absorb carbon and produce oxygen at diameter class 4.0–6.6 is the lowest because of its small diameter class.

The average total biomass of the *S. alba* population found in this study is 88.25 t ha^{-1}, including 63.91 t ha^{-1} above-ground biomass. The result is consistent with the findings of Komiyama et al. (2008), who found that secondary mangrove forest areas have a total above-ground biomass of less than 100 t ha^{-1}. The population at FC 16 has a high density in the largest region and has the largest average total biomass of 134.91 t ha^{-1}. For the *S. alba* carbon stock, the average value of 37.95 t ha^{-1} in Can Gio Mangrove Biosphere Reserve is larger than the value of 28.13 t ha^{-1} found in Ngurah Rai Forest Park, Bali, Indonesia (Juwari et al. 2020), but smaller than the value of 60.89 t ha^{-1} found in Pasar Rawa, Langkat North Sumatera, Indonesia (Harefa et al. 2024) and the value of 153.81 t ha^{-1} found in Inner Ambon Bay (Tupan & Lailossa 2019). These differences are primarily related to variations in stand age and structure. In Ngurah Rai Forest Park, Juwari et al. (2020) reported an average basal area of *S. alba* ranging from 0.006–0.009 m^2 $tree^{-1}$, implying a DBH of approximately 8.76–10.71 cm, assuming a circular cross-section. These relatively small average values suggest a younger or less structurally developed mangrove stand. By contrast, the higher value observed in Pasar Rawa reflects a more advanced restoration stage. Although individual tree diameter values were not provided, the reported total basal area of 352.15 m^2 ha^{-1} (Harefa et al. 2024) indicates a dense and well-developed forest structure. Notably, the very high values recorded in Inner Ambon Bay are associated with a greater proportion of large-diameter trees (up to 49 cm DBH) (Tupan & Lailossa 2019), which is indicative of mature forest conditions.

In line with these structural patterns, the estimated carbon uptake in Can Gio was 139.27 t ha^{-1}, lower than the 192.13 t ha^{-1} reported for Langkat (Harefa et al. 2024). The oxygen production potential was estimated at 101.32 t ha^{-1}. To our knowledge, species-specific estimates of oxygen production for *S. alba* have not been previously reported.

Using a reference price of 5 USD per ton of carbon uptake from forest carbon credit transactions in Vietnam (World Bank 2024), and a general ecosystem-level oxygen value of 927,000 IDR t^{-1} (approx. 60 USD t^{-1}) from mangrove studies (Sribianti et al. 2021), the average economic value of *S. alba* in Can Gio is estimated at 696.3 USD ha^{-1} for carbon uptake and 6079.20 USD ha^{-1} for oxygen production. These values represent the contribution of *S. alba* to environmental services in the Can Gio mangrove forest.

CONCLUSIONS

This study attempts to evaluate the value of the natural *S. alba* population for mangrove forest environmental service through biomass, carbon stock, carbon uptake, and oxygen production in the Can Gio Mangrove Biosphere Reserve, Vietnam. Our findings have confirmed that the allometric equation $Y = aX^b$ can quickly evaluate above-ground biomass and carbon stock using DBH with acceptable generalisation errors. Addressed specific equations will increase accuracy and convenience in calculating biomass, carbon stock, carbon uptake, and oxygen production. We evaluated 88.25 tons of biomass, 37.95 tons of carbon stock, 139.27 tons of carbon uptake, and 101.32 tons of oxygen per hectare *S. alba* at the Can Gio Mangrove Biosphere Reserve. *Sonneratia alba* could bring specific economic values to the area, including 696.3 USD ha^{-1} for carbon uptake and 6079.2 USD ha^{-1} for oxygen production.

A limitation of this study is that the below-ground biomass and carbon stock of *S. alba* has not been investigated or calculated directly. Still, conversion factors referred to from other studies have been used. Additionally, this study investigated current values of biomass, carbon stock, carbon uptake, and oxygen production rather than timely accumulations. Further research could clarify the components to enhance the accuracy and details of ecosystem services. Despite this limitation, the calculations presented in this study could serve as a baseline for designing payment for ecosystem services schemes. These findings are useful for informing future policy discussions. Also, the findings enhance knowledge of the values of *S. alba* in Southeast Asia countries, especially in oxygen production.

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