

Aboveground biomass and carbon stock of *Rhizophora apiculata* forest in Ca Mau, Vietnam

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Abstract. Bao TQ, Ha NT, Nguyet BTM, Hoan VM, Viet LH, Hung DV. 2021. Aboveground biomass and carbon stock of *Rhizophora apiculata* forest in Ca Mau, Vietnam. *Biodiversitas* 23: 403-414. Despite the small proportion of mangrove forests globally, they contribute significantly in carbon storage. Yet, biomass and carbon stock in mangrove forests might vary depending on various factors including the dominant species that occurred. This study was conducted to determine the biomass and carbon stock of a mangrove forest dominated by *Rhizophora apiculata* Blume in Ca Mau, Vietnam. Data were collected from 56 representative sample plots (50m x 50m), and 46 sample trees with different age classes and diameter sizes were cut down to measure the fresh biomass. The dry biomass and carbon content were analyzed in the laboratory. The average aboveground biomass and carbon stock of the individual tree and the *R. apiculata* forest at different diameter sizes had a significant difference and were mostly found in the stem (74.5%-79.5%). The conversion factor from fresh biomass to dry biomass was 0.56; the conversion factor from dry biomass to carbon was 0.46. The total biomass of the individual trees had a close relationship with two variables diameter at breast height (DBH) and height (Hvn) in the form of the logarithmic function: $\ln(Wtk) = -1,86412 - 1,95419 \cdot \ln(Hvn) + 2,26798 \cdot \ln(DBH \cdot Hvn)$. The total biomass and carbon stock of the entire forest stand increased in accordance with the diameter size and age classes. The *R. apiculata* stand had a density of 1,040-15,800 trees/ha and a timber volume of 27.2 to 365.6 m³/ha. The average biomass of the *R. apiculata* stand was 191.1 tons/ha with a range from 49.6 to 357.4 tons/ha. The carbon stock in forest biomass ranged from 23.8 to 188.7 tons C/ha, with an average of 117.4 tons C/ha. The forest's CO₂ absorption ranged from 60.0 to 691.7 tons CO₂/ha, with an average of 415.9 tons/ha. The carbon stocks of trees of age class I to age class VI were 41.6 tons C/ha, 79.4 tons C/ha, 101.4 tons C/ha, 132.9 tons C/ha, 154.0 tons C/ha, and 167.4 tons C/ha, respectively.

Keywords: biomass, Ca Mau, carbon stock, CO₂ absorption, mangrove, *Rhizophora apiculata*

INTRODUCTION

Forests play an important role in the global carbon cycle. Each year, forests absorb about 1/12 of the CO₂ in the earth's atmosphere and forest ecosystems accumulate about 72% of the earth's carbon stocks (Malhi, Meir, and Brown 2002). The Global Forest Resources Assessment 2020 showed that forests all over the world stored an estimated 295 billion tons of carbon in biomass (FAO 2020). On a global scale, forests in tropical zones have much higher aboveground biomass than those in temperate zones (Komiya, Ong, and Pongpan 2008).

Among various forest types in the world, mangrove forests have an immense role in carbon storage. A mangrove is a group of salt-tolerant shrubs and trees that grow in the intertidal zones between the terrestrial and marine realms. Mangrove forests are distributed in tropical and subtropical estuaries and coastal zones, where the tides rise and fall every day (Ngot et al. 2012). Mangrove forests alone store about 20 billion tons of carbon in their ecosystems, equating to almost 10% of total forest carbon (Jones et al. 2014), despite they only account for about 0.7% of the world's forest area (Donato et al. 2011), which

is about 14.8 million ha (FAO 2020). Mangrove forests are among the most carbon-dense forests in tropical zones with average carbon stock of 1023 Mg C ha⁻¹ ± 88 (Donato et al. 2011). Besides their contribution to global carbon stock, mangrove forests also provide other ecosystem services, including protecting shoreland from abrasion and tsunamis, habitat of various biota and providing timber and non-timber forest products (FAO 2020).

Nonetheless, mangrove forests are among the most threatened and vulnerable ecosystems in the world, and have been decreased over the past half-century. Globally, the area of mangrove forests decreased by 1.04 million ha from 1990 to 2020 (FAO 2020). The average annual loss rate of mangrove forests during the period 2000-2005 was alarming (Kuenzer et al. 2011). The loss rate of mangrove forests has not exceeded 21,200 ha/year in recent decades (FAO 2020). Therefore, various international programs, such as the Ramsar Convention on Wetlands and the Kyoto Protocol, have emphasized the importance of mangrove forests and urged immediate conservation activities and measures to prevent further loss of mangrove forests.

The quantification of biomass and carbon stock in mangrove forests is necessary to provide a scientific basis

for assessing the ecosystem services and to support sustainable forest resource management. In addition, information on forest biomass and carbon stock provides a better understanding of the global carbon cycle and helps with building and evaluating initiatives to reduce global warming. However, the quantification of total forest carbon stock is complicated and costly. Because of difficulties in collecting below-ground biomass data, the majority of studies on biomass estimation are all based on aboveground biomass (Lu 2006), which is the largest carbon sink in forest ecosystems. There are a lot of research works on aboveground biomass and carbon stock, including those in mangrove forests such as (Komiyama, Ong, and Pongparn 2008) and (Hoàn et al. 2018). These studies used a lot of different methods to estimate biomass. Many authors confirmed that the aboveground tree biomass was highly dependent on the stem diameter ($D_{1.3}$) and proposed a one-factor correlation function of $\ln(\text{AGB}) = c + a \ln(\text{DBH})$ (Zhang et al. 2013; Zianis and Mencuccini 2004; Suwanto et al. 2021). Some authors affirmed that to obtain better results, the estimate of the aboveground biomass should also take into account the tree height (Hvn). Therefore, the combination (DBH \times Height) was used by many authors (Chave et al. 2005; Cai, Kang, and Zhang 2013; Analuddin et al. 2020). The correlation between biomass and factors such as diameter and height, obtained by regression analysis of the aboveground biomass estimates from sample trees (Návar 2009), was often used to develop biomass estimation models (Mitchard et al. 2011; Sun et al. 2011).

The research results of (Murdiyarsa et al. 2015; Donato et al. 2011; Alimbon and Manseguiao 2021) showed that the carbon stock accumulated in mangrove forests varied depending on the species composition and forest age. For example, the average carbon stock of *Rhizophora apiculata* in Can Gio Mangrove Biosphere Reserve, Ho Chi Minh City, Vietnam was 97.26 tons of carbon/ha (the range was 58.68-138.65 tons of carbon/ha) (Nam 2011). The biomass of a 15-year-old *R. apiculata* forest stand on Phuket Island on the west coast of Thailand was 159 tons/ha (Christensen 1978). The mangrove biomass and carbon stock in Southern Vietnam ranged from 135.4 to 523.6 tons/ha and from 59.7 to 230.9 tons of C/ha, respectively (Van Vinh et al. 2018).

The total extent of mangrove forests in Vietnam is approximately 164,701 ha (MARD 2018). The largest area is located in the southern region, with the main area of mangrove forest being Ca Mau, which has a total area of mangrove forest of 63,017 ha. This study aimed to determine the biomass and carbon stock of mangrove forests in Ca Mau, and build a model to estimate the region's aboveground biomass and carbon stock. The results may be useful for sustainable management, conservation and restoration of mangrove ecosystems. These results can also be used as a basis to calculate the payment for forest environmental services in Vietnam.

MATERIALS AND METHODS

Study area

This study was conducted in Ngoc Hien District, Ca Mau Province, Vietnam (Figure 1) which is in the southern part of the Mekong Delta and has the geographic coordinates of 8°33'-8°45'N and 104°42'45"-105°3'54"E with an area extent of about 735.18 km². Ngoc Hien is the southernmost district of Vietnam. It is a frequently flooded lowland with a sub-equatorial tropical monsoon climate and a relatively high temperature compared to other provinces in the Mekong Delta. It has an annual average temperature of 26.5 °C, average rainfall of 2,360 mm with 165 rainy days/year, and annual average humidity of 85.6%.

The area of *R. apiculata* forests in the research area in 2018 was 41,157.69 ha of which 11,373.0 ha was natural vegetation of *R. apiculata* and 29,784.68 ha was planted *R. apiculata* forest. The ages of the trees ranged from age class I to age class VI (MARD 2018).

Field data collection

Sample plot survey: The field data were collected from 56 sample plots (50m \times 50m each). All trees in the sample plots were surveyed, and their stem diameters (DBH), total heights (Hvn), canopy diameters, and tree qualities were recorded. In each sample plot, 5 survey sub-plots, including 4 sub-plots in the 4 corners and 1 sub-plot in the center, were set up, each with an area of 10m \times 10m, to investigate the growth and biomass parameters. Therefore, there were 280 survey sub-plots, each with an area of 100 m².

Determination of the fresh biomass: The tree truncation method based on the diameter size and age class was applied. The minimum number of sample trees cut down for each age class was 3. A total of 46 sample trees were cut down and weighed to calculate the biomass of parts of *R. apiculata* trees. All sample trees cut down had diameter size (DBH) ranging from 2 cm to 35 cm. After felling the sample trees, a tape measure was used to measure the lengths of the stems (DBH) and the cross-sections between the 1-m sections and the ends of the stems. A chainsaw was used to separate the stems, branches, aboveground roots, and leaves. A balance was used to determine the fresh biomass of each aboveground part; the total mass of the parts would be the total biomass of the stem (Figure 2).

Sample collection to determine the dry biomass: After determining the fresh biomass of the truncated trees, samples of each part were used to analyze the dry biomass and the carbon stock in the forest tree in a laboratory. Twelve samples were taken per tree (4 parts \times 3 samples): about 0.5-1 kg was taken per branch and stem sample, whereas about 0.2-0.5 kg/sample was taken from the leaves. The collected samples were weighed immediately with an electronic balance to determine their initial weights. The samples were stored in nylon bags. The samples were fully marked with symbols and analyzed at the laboratory of the Southern Academy of Forest Sciences.

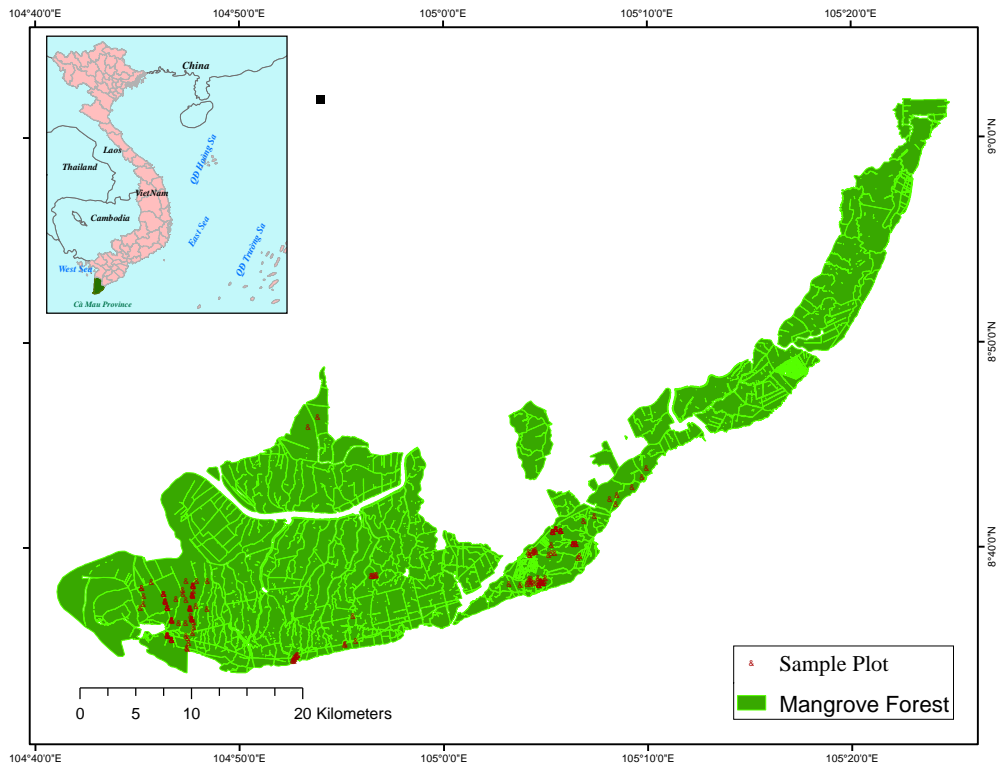


Figure 1. Location of sample plots in mangrove forests of Ca Mau Province, Vietnam



Figure 2. Felling, weighing, and sampling of the fresh biomass of *Rhizophora apiculata*

Biomass analysis in the laboratory

Determination of the dry biomass: Biomass samples were brought to the laboratory and dried at 105 °C for stems, branches and roots and at 80 °C for leaves until their weights became constant. The samples were also dried at room temperature for about 72 hours. A sample whose weight remained constant on three weighing occasions was considered a stable dried sample. After drying, the samples were re-weighed to determine the ratio of the dry biomass to the fresh biomass; the sample withdrawal rate was used to determine the dry biomass weight for each tree part.

Carbon content: The dried samples were used to analyze the carbon content and calculate the percentage of carbon in each part of the tree. The carbon content in the dry biomass was analyzed by direct combustion using the NC Analyzer 2100 in the laboratory of the Southern Academy of Forest Sciences.

Data analysis

Excel and Statgraphics Centurion XVI software were used for data processing with the steps described below.

Determining the conversion factor from the fresh biomass to the dry biomass (P) of the dried samples, and the coefficient C

Determining the conversion factor from the fresh biomass to the dry biomass (P) of the dried samples: Based on the biomass samples analyzed in the laboratory, the conversion factor from the fresh biomass to the dry biomass was calculated according to the following general formula:

$$P_i = \frac{W_{ki}}{W_{ti}} \quad (1)$$

Where: W_{ki} is the dry weight of the sample i dried at 105 °C (for the stem, branch, and root) and at 80°C (for the leaf); and W_{ti} is the fresh weight of the sample i before drying.

Determining the rate of the dry biomass of each part, W_{sk} (stem dry-weight), W_{brk} (branch dry-weight), W_{lk} (leaf dry-weight), W_{rk} (above root dry-weight) using the diameter size: The rate of the dry biomass of each part is equal to the mean of the ratios of the dry biomass to the fresh biomass of the dried samples of this part with the same diameter size.

Determining the total dry biomass of individual trees, W_{tk} (total tree dry-weight): W_{tk} is equal to the total dry biomass of all parts of a given tree.

Determining the general dry biomass conversion factor: The general dry biomass conversion factor is equal to the mean of the ratios of the dry biomass to the diameter size, divided by 100.

Determining the general carbon conversion factor: The general carbon conversion factor is equal to the mean of the ratios of the carbon stock to the diameter size, divided by 100.

Calculating the dry biomass

Dry biomass of individual trees (W_{tk}), the dry biomass of all trees (TAGB - dry biomass of all trees) and tree parts

(BSt, Bbr, Bl and Br), the total aboveground carbon stock (TAGC), and the aboveground carbon stock for tree parts (Cst, Cbr, Cl, Cr) followed the 2006 IPCC Guidelines (IPCC 2006).

The dry biomass of individual trees (W_{tk} - total tree dry-weight): The dry biomass of a given individual tree is calculated by totaling the biomass of all parts of the individual tree (including the dry biomass of stem W_{sk} , branch W_{brk} , leaf W_{lk} , and aboveground root W_{rk}).

Determining the dry biomass of all trees (TAGB): TAGB is calculated by totaling the biomass of all trees in the sample plot based on the model for estimating the dry biomass of individual trees and calculated for 1 ha.

Carbon stock = carbon conversion factor × dry biomass.

Total CO₂ absorbed by an individual tree = Carbon stock of the truncated tree × 3.67

Model for estimating the aboveground dry biomass

The model was set up based on the tree truncation method using some linear functions of one variable or multi-variables, combinations of variables, or non-linear functions converted to linear forms to explore and select the optimal function. The model was processed using the statistical software, Statgraphics Centurion. The dependent variable Y was the biomass of the tree or the biomass of the forest, whereas the independent variable X_i included the forest survey factors such as the diameter at the breast height (DBH, cm) and the tree height (H_{vn}, m). Data to set up the model for individual trees included the diameter at the breast height (DBH, cm), the tree height (H_{vn}, m), and the dry biomass of aboveground parts of 46 truncated trees.

The selection of variables to be used in the model and the most optimal function depended on many statistical criteria. The study used the following criteria for function selection:

Coefficient of determination, R^2 : Generally, the function is best when R^2 has the highest value. However, in some cases, despite the highest R^2 value, the function is not necessarily the most suitable. Therefore, it is necessary to rely on other statistical criteria.

Check the significance of the model and its parameters: It is required that the model and its parameters have a significance level of $p < 0.05$.

Statistical indicators SEE (standard error of estimate), MAE (mean absolute error) and SSR (sum of squared residuals): The function is best when these 3 indicators have their smallest values.

Adjustment Factor (CF) (Kauffman et al.; Chave et al. 2005):

$$CF = \exp(RSE^2/2) \quad (2)$$

Where: CF is always greater than 1. The RSE (residual standard error) is the standard error of the residuals, or the error of the model (SEE). The larger the RSE, the larger the CF, which indicates how less reliable the model is. The model is good as the CF gets closer to 1.

Average deviation S%: To check the applicability of functions and evaluate the degree of deviation, the average deviation of the value is estimated through the model with the observed value.

$$S\% = \frac{100}{n} \sum_{i=1}^n \frac{Y_{lt} - Y_{tn}}{Y_{tn}} \tag{3}$$

Where:

Y_{tn} is the observed empirical value

Y_{lt} is the predictive value through the model

S % is Average deviation

Classification of diameter sizes and age classes of mangrove forests

The diameter sizes and the number of diameter classes were determined based on the largest and smallest diameters, using the Statgraphics Centurion XVI. The age classes were determined based on the year the forest was planted and on the regulations on the age classification of *R. apiculata* trees, i.e. 5 years/age class.

RESULTS AND DISCUSSION

The aboveground biomass and carbon stock of an individual tree

The conversion factor of the biomass and carbon stock of R. apiculata forest

The result of the analysis of fresh biomass samples to determine the percentage of the dry biomass and carbon stock in *R. apiculata* trees is shown in Table 1.

The ratio of the biomass after drying to the biomass before drying was 66.6% for stem, 62.7% for branch, 31.3% for leaf, and 62.6% for root. The conversion factor from fresh biomass to dry biomass was 0.56, and the conversion factor from dry biomass to carbon was 0.46. The dry biomass conversion factor and the carbon conversion factor of each part of the truncated trees are the basis for calculating the dry biomass and carbon stock in the parts of individual trees and in the entire *R. apiculata* forest.

Structure of dry biomass of individual tree

The result of the analysis of the dry biomass of parts of *R. apiculata* trees is shown in Figure 3.

Table 1. Percentage of the dry biomass and carbon in *Rhizophora apiculata* trees and tree parts

DBH (cm)	Hvn (m)	Percentage of dry biomass (%)					Total	Percentage of carbon in biomass (%)					Total
		Stem	Leaf	Branch	Root	Total		Stem	Leaf	Branch	Root	Total	
3	7.5	64.4	31.3	58.1	62.6	54.1	49.0	41.0	48.0	47.0	46.3		
6	10.7	64.4	31.3	58.1	62.6	54.1	49.0	41.0	48.0	47.0	46.3		
9	13.7	64.7	31.3	58.6	62.6	54.3	48.9	41.0	47.8	47.0	46.2		
12	15.0	66.9	31.3	63.9	62.6	56.2	47.1	41.0	46.0	47.0	45.3		
15	17.2	65.9	31.3	63.8	62.6	55.9	47.5	41.0	49.0	47.0	46.1		
18	19.0	65.6	31.3	63.4	62.6	55.7	48.0	41.0	50.0	47.0	46.5		
21	18.0	67.4	31.3	63.3	62.6	56.1	49.0	41.0	46.0	47.0	45.8		
24	22.5	66.3	31.3	62.9	62.6	55.8	49.0	41.0	46.0	47.0	45.8		
27	21.8	70.1	31.3	65.7	62.6	57.4	48.0	41.0	51.0	47.0	46.8		
30	23.0	68.0	31.3	63.6	62.6	56.4	49.0	41.0	49.0	47.0	46.5		
33	24.8	69.2	31.3	68.2	62.6	57.8	50.0	41.0	49.0	47.0	46.8		
Average		66.6	31.3	62.7	62.6	55.8	48.6	41.0	48.2	47.0	46.2		
Dry biomass conversion factor						0.56	Carbon conversion factor					0.46	

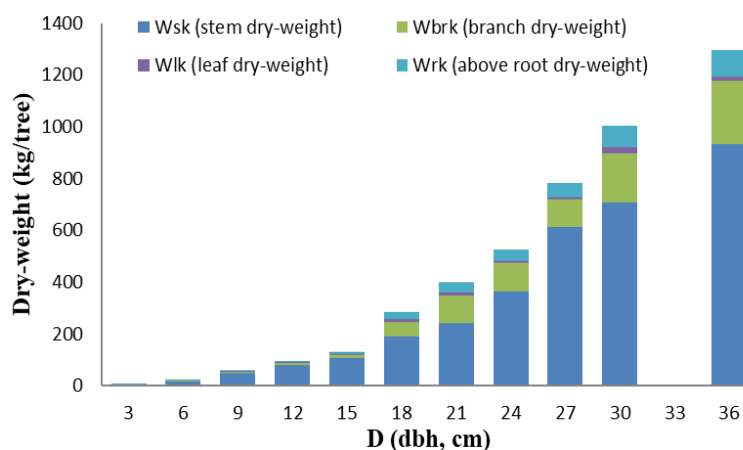


Figure 3. Structure of the dry biomass of individual *Rhizophora apiculata* tree

The dry biomass of *R. apiculata* trees (Figure 3) increased gradually with the diameter sizes (from 4.2 kg to 1300 kg for diameter sizes of 3-36 cm); the stem and branch biomass also increased gradually with diameter size. The dry biomass of tree parts fluctuated greatly. The percentage of the biomass of stem wood, dry branches and above roots was high, accounting for about 97.5% of the total dry biomass of the trees. The percentage of the stem dry biomass of individual *R. apiculata* trees was highest, accounting for 74.5% of the total on average (the range was 60.8-93.4%). This was followed in order by the percentage of the branch dry biomass which accounted for 15.7% (the range was 3.3-26.4%), the root dry biomass which accounted for 7.4%, and the leaf dry biomass which accounted for 2.5% (the range was 0.9-12.4%). The results also showed that when the diameter increased, the percentage of the stem dry biomass increased. The changes in the percentages of other parts (leaf, root) were not obvious; they mostly did not follow any clear rule.

Carbon stock in aboveground parts and individual tree

The carbon stock and the amount of CO₂ absorbed by individual trees gradually increased with the diameter size and the forest biomass. On average, a tree with a diameter of about 12.9 cm accumulated 95.4 kg of carbon in the tree biomass, which also meant that the forest tree absorbed 349.7 kg of CO₂. The amount of CO₂ absorbed ranged from 7.2 to 2,353.3 kg of CO₂/tree.

The greatest amount of carbon, about 71.4 kg C/tree on average, was found mostly in the stem biomass, accounting for 74.9% of the total carbon stock in a given tree (Figure 4). The amount of carbon accumulated in the branch biomass was 15.1 kg C/tree, accounting for 15.8% of the total carbon stock, the amount in the leaf biomass was 2.0 kg C/tree, accounting for 2.1%, and the biomass of the aboveground roots was 6.9 kg C/tree, accounting for 7.2%

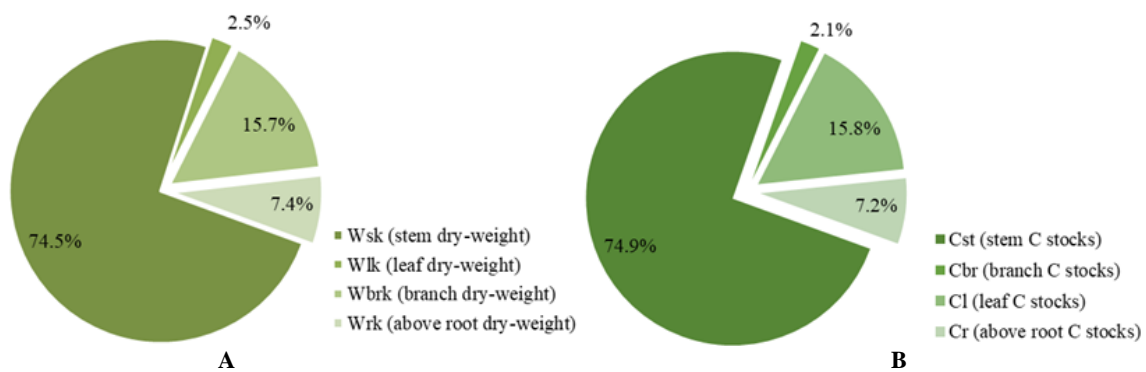


Figure 4. Percentage of the biomass and carbon stock in *Rhizophora apiculata* trees. A. Biomass, B. C stock

Table 2. Summary of the selected models for estimating the dry biomass of *Rhizophora apiculata* trees

Eq.	Established equation	Statistical indicators					
		R ²	SSR	SEE	MAE	S %	CF
(4)	$\ln(W_{tk}) = -1,86412 - 1,95419 \cdot \ln(H_{vn}) + 2,26798 \cdot \ln(DBH \cdot H_{vn})$	99.17	0.79	0.12	0.10	9.91	1.01
(5)	$\ln(W_{sk}) = -2,82608 + 0,939499 \cdot \ln(DBH^2 \cdot H_{vn})$	99.06	0.69	0.13	0.10	9.94	1.01
(6)	$W_{brk} = \exp(-4,75003 + 2,85125 \cdot \ln(DBH))$	91.10	10.46	0.49	0.40	43.64	1.13
(7)	$W_{lk} = \exp(-3,90518 + 2,02418 \cdot \ln(DBH))$	84.62	9.81	0.47	0.34	37.97	1.12
(8)	$W_{rk} = \exp(-5,08821 + 2,72631 \cdot \ln(DBH))$	88.16	13.15	0.55	0.40	45.41	1.16

of the total carbon stock.

Dry biomass estimation models of individual tree

The result of the selection of dry biomass models of stems, branches, leaves, and full *R. apiculata* trees is summarized in Table 2.

All the equations had very statistically significant levels and high correlation coefficients. The 2-way, 2-factor logarithmic model (Eq. 4) had the highest R² (99.17%), the smallest standard error of estimate, mean absolute error, and CF. It also had the smallest average deviation S% (9.91%) and was suitable for estimating the total dry biomass of a given tree, with a confidence level of 99%.

Biomass and carbon stock of *R. apiculata* forest

The biomass structure of *R. apiculata* forest (Figure 5) showed that the percentage of the dry biomass of the stem of all trees was highest, accounting for an average of 79.5% (the range was 74.2-84.2%). The branch biomass accounted for 10.5%, with a range of 7.5-12.4%, the leaf biomass accounted for 4.6%, with a range of 3.6-6.1%, and the root biomass accounted for 5.4%, with a range of 4.4-6.4%.

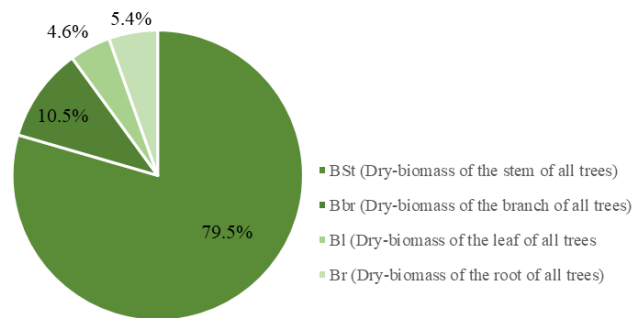


Figure 5. Biomass percentage of parts of the *R. apiculata* stand

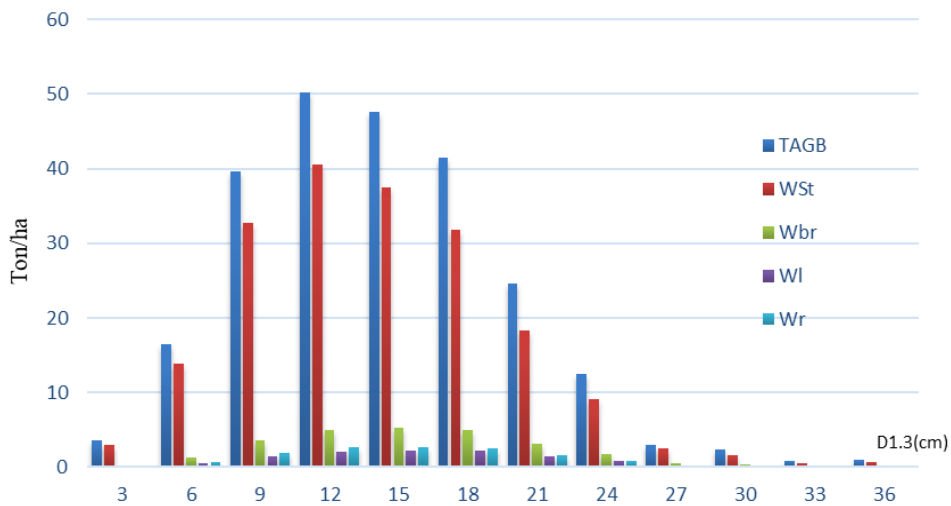


Figure 6. Biomass distribution of the *Rhizophora apiculata* stand by diameter sizes

The dry biomass of *R. apiculata* forest grouped by diameter sizes in Figure 6 shows that the biomass structure of *R. apiculata* forest was in the form of a left-skewed peak, with the highest distribution of biomass found for a diameter size of 12 cm. The distribution of the diameter sizes of the dry biomass of *R. apiculata* forest in the study area was 3 cm-36 cm. The tree density decreased gradually with an increase in the diameter class, with the biomass mostly distributed at diameter sizes of 9 to 18 cm. The biomass of 50.2 tons/ha, which corresponded to a diameter size of 12 cm, was the highest. Although there were not many trees with a diameter size of 18 cm (63/3,539 trees), their biomass was quite high (24.5 tons/ha). Meanwhile, there were a lot of trees with diameter sizes between 3 cm

and 6 cm, but their biomass was very small (3.5-16.4 tons/ha).

The exploration results of the equation for the relationship between the biomass and age of *R. apiculata* forests showed a close relationship between the biomass and age of forest stands (A, years), according to the model $\ln(D) = \ln(m) + b/A^{-2}$. The relationship model is as follow:

$$\ln(\text{AGB}) = 1/(0.166724 + 4.41442 \cdot A^{-2}), \text{ with } R^2 = 87.18, \text{ RSS} = 0.0005, \text{ SEE} = 0.009, \text{ MAE} = 0.007$$

The result of the biomass by age and biomass growth of *R. apiculata* forests by age is shown in Figure 7.

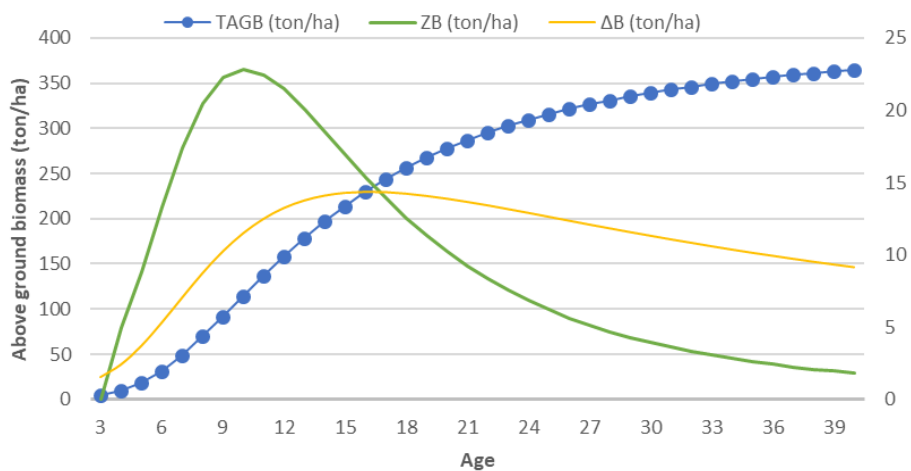


Figure 7. Relationship between biomass and biomass growth by age. Note: TAGB: Total aboveground biomass (ton/ha); ΔB: Average biomass by age (ton/ha); ZB: Annual biomass growth (ton/ha)

The total biomass of *R. apiculata* stands (TAGB) increased quite rapidly in the first 16 years. The annual biomass growth (ZB) peaked at 22.83 tons/year at the age of 10 and then began to decrease gradually. The curve simulating the relationship between the biomass and forest age in Figure 7 shows that the biomass gradually increased with age; the older the forest, the higher the total biomass. At the age of 35, the biomass was 350 tons/ha, and from this age onwards, the curve gradually began to flatten out and became more or less parallel to the forest age axis. Therefore, for *R. apiculata* forests in the study area, after the age of 35, the biomass growth was not significant. The average annual growth (ΔB) curve was in the form of a left-skewed peak. This curve gradually increased at younger ages of the forests, reaching the highest growth at the age of 10 with biomass of 22.83 tons/ha, and then gradually began to decrease. The older the forestage, the lower the annual growth, with almost no increase; after the age of 35, the growth rate was not significant, which was completely in accordance with the growth rule of forest trees.

The carbon stock of *R. apiculata* forest

The results showed that the *R. apiculata* forest had a density of 1,040-15,800 trees/ha and a timber volume of 27.2-365.6 m³/ha. The carbon stock in the forest biomass ranged from 23.8 to 188.7 tons C/ha, with an average of 117.4 tons C/ha. Carbon was mainly distributed in the stem biomass (84.5 tons C/ha), which accounted for about 74.5% of the total carbon stock (Figure 8). This was followed by the branched carbon (17.7 tons C/ha), which accounted for 15.6% of the total. The aboveground root carbon (8.5 tons/ha) accounted for 7.6% of the total carbon stock and the leaf carbon (2.6 tons C/ha) for 2.3%. The forest CO₂ absorption ability ranged from 60.0 to 691.7 tons CO₂/ha. Trees with a diameter of 11.7 cm, the average diameter of all trees in the forest, and growing in an area with a density of 2,580 trees/ha showed the highest CO₂ absorption ability.

The calculation result showed that the carbon stock of *R. apiculata* forest fluctuated according to the age classes of the forest. The carbon stock increased rapidly at young age classes. The rate of increase in older age classes was low. Total carbon stock in the age class I was 41.6 tons C/ha, which was equivalent to the absorbed amount of CO₂ of 152.8 tons/ha. The total carbon stock in age class II was 79.4 tons C/ha, with 291.6 tons of CO₂ absorbed per ha. The carbon stock in the age class III was 101.4 tons C/ha, with 372.1 tons of CO₂ absorbed per ha. The carbon stock in the age class IV was 132.9 tons C/ha, with 487.8 tons of CO₂ absorbed per ha. The carbon stock in the age class V was 154.0 tons C/ha, with 562.2 tons of CO₂ absorbed per ha. The carbon stock was 167.4 tons C/ha in the age class VI, with 614.5 tons of CO₂ absorbed.

Figure 9 showed that in the age class I, the *R. apiculata* forest had not shown a strong differentiation in diameter, meaning there was no or little competition for nutrition in the *R. apiculata* forest. The carbon stock was distributed at

diameter sizes of 3-15 cm, with the highest distributions observed at diameter sizes of 3-6 cm, the value peaking at 18.7 tons/ha at a diameter size of 6 cm, although the highest density of 8395 trees/ha was observed at a diameter size of 3 cm. In age class II, the highest carbon stock of 37.3 tons/ha was distributed at a diameter size of 9 cm, while the highest density of 2491 trees/ha was observed at a diameter size of 2 cm. In age class III, the highest carbon stock of 33.92 tons/ha was distributed at a diameter size of 12 cm, while the highest density of 1273 trees/ha was observed at a diameter size of 9 cm. In the age classes of I, II and III, the distribution of carbon stocks at the available diameter sizes had the form of a left-skewed peak that tended towards the trees with small diameters.

In the age class IV, the carbon stock of the *R. apiculata* forest was more widely differing diameter sizes (from diameter classes of 3 cm to 27 cm) than the carbon stocks in the age classes I, II, and III. The density of trees at small diameter sizes in the age class IV was low. The forest structure was a single peak form meeting the standard distribution. The carbon stock was mainly distributed at diameter sizes of 12 cm to 18 cm. The highest carbon stock of 35.2 tons/ha was observed at a diameter size of 15 cm in the age class IV, with a density of 414 trees/ha. In the age class V, the trees had diameter sizes of 3 to 30 cm, and the forest structure had a right-skewed peak. The carbon stock was mainly distributed at diameter sizes of 15 cm and 18 cm, with respective values of 33.9 tons C/ha and 41.3 tons C/ha for these two diameters. Compared to the results of the age class V, the biomass structure of *R. apiculata* forest in the age class VI had more varied diameters (3-36 cm), with the carbon stock mainly distributed at diameter sizes of 18-24 cm and the highest carbon stock of 29.3 tons C/ha was observed for the diameter size of 21 cm. The structure of the carbon stock in this age class had many peaks, meaning that the forest was mature and had an unsustainable structure that needed adjustment in order to promote the growth of adjacent tree layers and increase the carbon stock of the forest, which would then improve the ecological value of the forest.

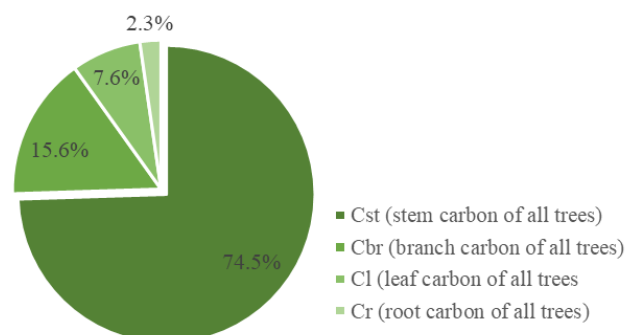


Figure 8. Average percentages of the carbon stocks in four plant parts of the *Rhizophora apiculata* forest

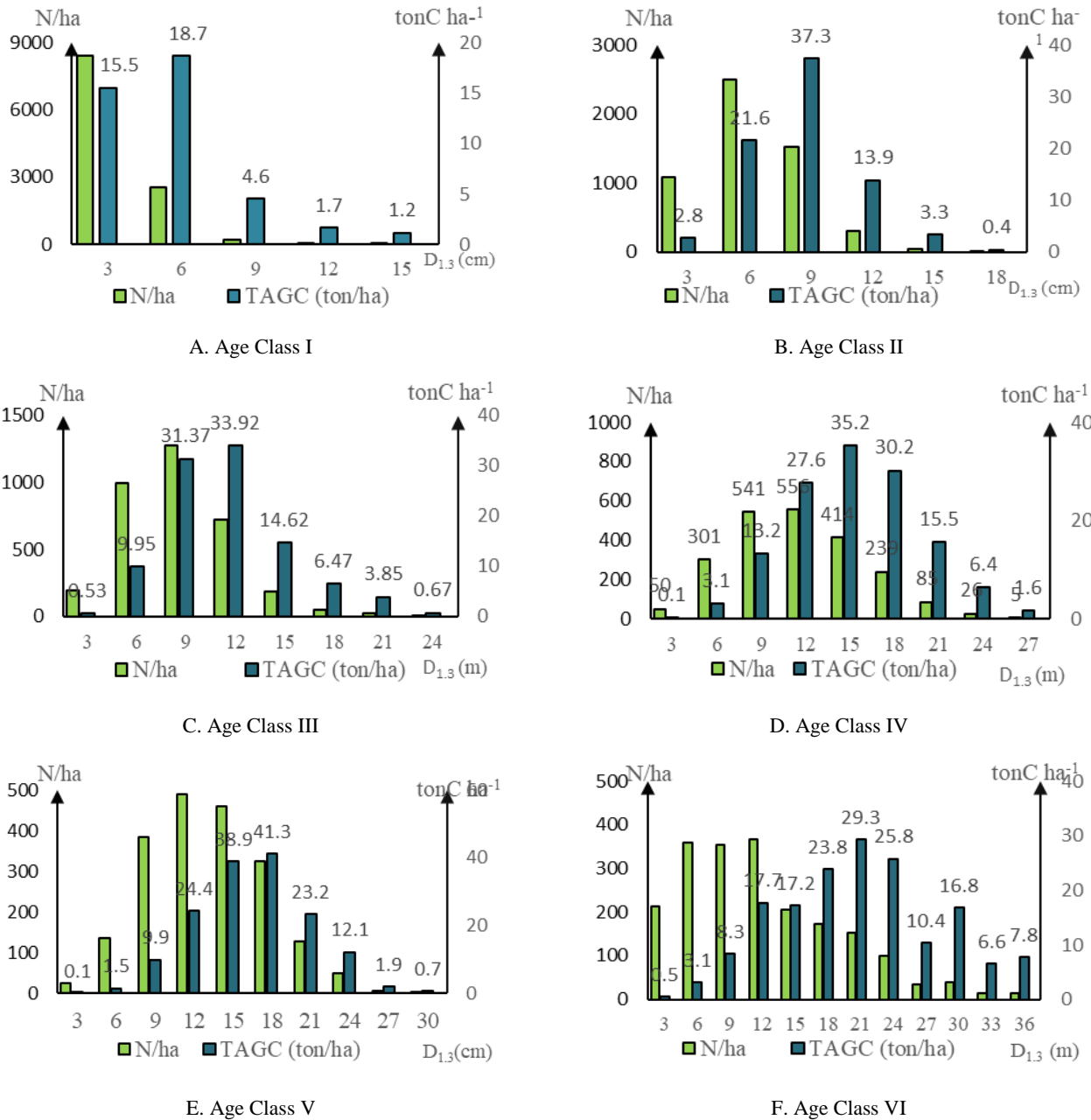


Figure 9. Carbon stocks of *Rhizophora apiculata* forest by diameter sizes at age classes of I-VI

Discussion

The structure of the aboveground dry biomass of individual trees was as follows: the stem dry biomass was 74.5% of the total, the branch dry biomass was 15.7%, the root dry biomass was 7.4%, and the leaf dry biomass was 2.5%. This finding is similar to Lupembe and Munishi (2019) study in Tanzania; the most significant biomass was reported in the stem (74.5%), followed by branch and leaf for 15.7% and 2.5% respectively. Compared to the wood biomass of *Pinus kesiya* accounting for 74.4 % (Le Hong 1996), 72.46% (Phuong 2012), the wood biomass of *Acacia auriculiformis* accounting for 78 % (Thong 1998) and the wood biomass of *Avicennia alba* accounting for 91.32 % (Nam 2003), *R. apiculata* has a percentage of

wood biomass lower than *Acacia auriculiformis*, and *Avicennia alba*, but similar to *Pinus kesiya*.

The regression model for estimating the aboveground dry biomass of individual *R. apiculata* trees showed that total tree biomass and stem biomass were closely related to the stem diameter ($D_{1.3}$) and tree height (H_{vn}). The branch biomass, leaf biomass and root biomass were only correlated with $D_{1.3}$. The models for estimating the total dry biomass and stem biomass had the highest confidence level, with a very low error compared to what is obtainable in reality. Both were 2-factor models, which was very suitable to reality, because the stem biomass and tree biomass depended not only on $D_{1.3}$ but also on H_{vn} . When adding the factor H_{vn} in the models for the branch, leaf, and root biomass, the correlation coefficient did not increase,

and the model error compared to reality was high or did not satisfy some statistical indicators. Thus, the total biomass of any individual tree (Eq. 4, Table 2) had a very close relationship with the growth indicators of the forest trees. Therefore, a correlation model between the total aboveground dry biomass of forest trees and the stem diameter, or a combination of the stem diameter and tree height, to estimate the biomass could be built. The function form that gave the most accurate estimate was the 2-way logarithmic function. This is completely consistent with the results of other authors (Van, Rayachhetry and Center 2000; Zianis and Mencuccini 2004; Khun et al. 2012).

The total biomass of *R. apiculata* forest gradually increased with the diameter size (from 49.6 to 357.4 tons/ha), with the average being 191.1 tons/ha. The results also showed that the forest density varied with the biomass of the forest. Both the smallest density (1,040 trees/ha, equivalent to biomass of 220.8 tons/ha) and the largest density (15,800 trees/ha, equivalent to 96.2 tons/ha) did not correspond to the highest biomass. Due to the arrangement of the nutrition space among the trees and the maximum utilization of the nutrition space, the density that corresponded to the highest biomass (402.8 tons/ha) was 2,580 trees/ha. The thinning method for adjusting the nutrition space among the forest trees was used to improve the productivity of the forest. The following results from other studies on the dry biomass of mangrove forests show that the biomass of *R. apiculata* forest in Ca Mau is higher than those in other areas and of other mangrove species: the dry biomass of mature *R. apiculata* forest was 171.3 tons/ha (Trí 1986), the average dry biomass of *Avicennia alba* forest in Can Gio was 208.62 ton/ha (Nam 2003), and the dry biomass of *R. apiculata* forest in Phuket in Southern Thailand was 159 tons/ha at the age of 15 years (Christensen 1978).

The curve simulating the relationship between the biomass and the age of the forest (Figure 7) shows that the biomass gradually increased with age. The biomass increased rapidly when the forest was young. The older the forest, the higher the total biomass. This result is similar to the research results of a study on *Populus alba* in China (Peng et al. 2019). At the age of 35, the biomass of *R. apiculata* forest was 350 tons/ha, and from this age onwards, the biomass growth was not significant. Comparing the average annual biomass growth in the current study with those obtained in other studies, we see that the average annual biomass growth of the *R. apiculata* forest at the age of 15 in the study area (14.27 tons/ha/year) was higher than that obtained for *R. apiculata* forest in Phuket Island, Thailand (10.5 tons/ha/year) (Christensen 1978), but at the age of 28 (11.82 tons/ha/year), it was lower than that of the *R. apiculata* forest at the age of 20 in Malaysia (5.7 tons/ha/year) (Jin-Eong, Khoo, and Clough 1995). The curve simulating the relationship between age and annual biomass growth has the form of a left-skewed peak, gradually increasing at young ages of forests and reaching the highest growth at the age of 10 with biomass of 22.83 tons/ha, and then gradually decreasing. The older the forest, the lower the annual growth. After the age of 35, the growth rate was not significant, which is completely in

accordance with the growth rules of forest trees. In contrast, in a study on *Populus alba* in Shanxi, China, the highest annual biomass growth was observed at the ages of 15-17 years (Peng et al. 2019).

The results showed that the carbon stock in the biomass of *R. apiculata* forest in the study area ranged from 23.8 to 188.7 tons C/ha, with an average of 117.4 tons C/ha. Compared with the results of the carbon stock of *R. apiculata* forests (59.7 to 230.9 Mg C ha⁻¹) in Southern Vietnam (Van Vinh et al. 2018), the carbon stock in the current study area was lower. However, the carbon stock of *R. apiculata* forest in Ca Mau, Vietnam was higher than the carbon stocks of some mangrove species studied in Indonesia: *R. mucronata* had a carbon stock ranging from 35.7 to 62.7 Mg C ha⁻¹, *Avicennia alba* carbon stock ranged from 1.8 to 23.5 Mg C ha⁻¹, and *Bruguiera gymnorhiza* had a carbon stock ranging from 0.7 to 2.5 Mg C ha⁻¹, with an overall average of 63.7 Mg C ha⁻¹ (Rumengan et al. 2018), but lower than *Rhizophora mangle* and *Avicennia germinans* in Guyana's mangrove forest, accounted for 481 Mg ha⁻¹ (Jaikishun et al. 2017). The results also showed that there was a difference in the forest's CO₂ absorption ability, which was possibly due to the living space or density regulation in the forest. This result is completely different from the results of the mangrove forest in the Philippines, which found that the 15-year-old forest had higher biomass due to its higher density (Camacho et al. 2011). Therefore, to increase the forest's CO₂ absorption ability, it is necessary to have an appropriate regulation of nutrition space for the most optimal growth of trees.

Comparing the carbon stocks at the different age classes (I-VI) in the study area with the carbon stocks in some other areas in Southeast Asia, it was found that the carbon stocks of *R. apiculata* in Peninsular Malaysia at the age classes I (5 years) and IV (18 years) were 87 tons C/ha and 193 tons C/ha, respectively (Alongi 2012), which are higher than the carbon stocks at those age classes in Ca Mau. Compared with the carbon stocks of *R. stylosa* at age classes III, IV and above VI (208.5 ton C/ha, 149.5 ton C/ha, and 370.7 ton C/ha, respectively) in the Philippines (Camacho et al. 2011), the carbon stocks in Ca Mau were also lower. However, the carbon stocks of *R. apiculata* in Ca Mau at age classes I and V (20 ton C/ha and 138 ton C/ha, respectively) were higher than those in Southern Thailand (Alongi 2012) and those in Southern Vietnam at age classes II, IV, and above VI (54 ton C/ha, 72 ton C/ha and 153 ton C/ha, respectively) (Alongi 2012).

The forest in the study area had diameter sizes ranging from 3 to 36 cm. In each age class, the carbon stock was mainly distributed in trees of certain diameter sizes, and when the age class increased, the carbon stock was distributed at larger diameter sizes. This is consistent with the natural rules of forests. In Ca Mau, at the age class I, the highest carbon stock was observed at a diameter size of 6 cm (18.7 tonC/ha); at the age class II, the carbon stock was mainly distributed at a diameter size of 9 cm (37.3 tonC/ha); at the age class III, the carbon stock was mainly distributed at a diameter size of 12 cm (33.9 tonC/ha); at the age class IV, the carbon stock was mainly distributed at a diameter size of 15 cm (35.2 tonC/ha); at the age class V,

the carbon stock was mainly distributed at a diameter size of 18 cm (41.3 tonC/ha); and at the age class VI, the carbon stock was mainly distributed at a diameter size of 21 cm (29.3 tons/ha). The distributions of the biomass and carbon stock of mangrove forest at age classes III, IV and VI in the Philippines were at the smaller diameter sizes compared to those of *R. apiculata* forests in Ca Mau. The degree of variation in diameter sizes at the different age classes in the Philippines was also narrower (only from 2.1 to 15.6 cm). Still, the tree density and carbon stock at the different diameter sizes were higher (Camacho et al. 2011).

In conclusion, the biomass and carbon stock in the aboveground parts of the *R. apiculata* trees and in the entire *R. apiculata* forest were very different. The majority was distributed in the stem biomass, which accounted for 74.5% of the total. The carbon stock in the branch biomass accounted for 15.7% of the total, that in the leaf biomass accounted for 2.5%, and that in the aboveground root biomass accounted for 7.4%. *R. apiculata* in Ca Mau had a percentage of stem biomass lower than those of *Acacia auriculiformis* and *Avicennia alba*, but higher than that of *Pinus kesiya*. The regression model for estimating the aboveground dry biomass of individual trees showed that the total tree biomass and the stem biomass were closely related to the variables diameter at breast height and height, whereas the branch, leaf and root biomass were only correlated with the tree diameter. The function form that gave the most accurate estimate was the 2-way logarithmic function. The *R. apiculata* forest biomass increased gradually with age. The biomass increased rapidly when the forest was young. The older the forest, the higher the total biomass. At the age of 35, the biomass was 350 tons/ha, and after the age of 35, the biomass growth became insignificant. The annual growth was in the form of a left-skewed peak, which gradually increased at younger ages of the forest, reaching the highest growth at the age of 10, with biomass of 22.83 tons/ha, before gradually decreasing. The older the forest, the lower the annual growth. *R. apiculata* in the study area had a diameter at breast height of 3-36 cm and age classes I-VI. The carbon stocks for the age classes I-VI were 41.6 tons of C/ha, 79.4 tons of C/ha, 101.4 tons of C/ha, 132.9 tons of C/ha, 154.0 tons of C/ha and 167.4 tons of C/ha, respectively. The higher the biological productivity, the higher the biomass and carbon stock of the forest trees, and the older the forest trees, the larger the diameter sizes and the higher the biomass and carbon stock. The biomass and carbon stocks in the aboveground parts of *R. apiculata* trees, as well as in the aboveground parts of the entire *R. apiculata* forest, varied greatly, mostly concentrated in the stem biomass. The biomass and carbon stock of the forest depended not only on the density and the maximum average diameter but also on the living space regulation of the forest. The biomass and carbon stock of the *R. apiculata* forest fluctuated with the age classes of the forest trees; the biomass and carbon stock increased rapidly at young age classes, with the level of increase gradually decreasing at older age classes.

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