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Biomass, carbon stock and sequestration in various conditions of mangrove forests in Sungai Apit, Siak, Riau, Indonesia

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Abstract. *Fatonah S, Hamidy R, Mulyadi A, Efriyeldi. 2023. Biomass, carbon stock and sequestration in various conditions of mangrove forests in Sungai Apit, Siak, Riau, Indonesia. Biodiversitas 24: 5837-5846.* The value of aboveground carbon is influenced by differences in conditions of the mangrove. Therefore, this study aimed to estimate biomass, as well as carbon stock and sequestration in various mangrove forests within Sungai Apit Siak, including natural, rehabilitated, and degraded forests. The Line Transect Plot method was used for sampling. Aboveground biomass was determined using an allometric equation based on mangrove stem diameter. Stem diameter measurements were taken from mangrove vegetation in three forest conditions across three villages in Sungai Apit, Siak. The findings revealed that natural forests contained higher values of biomass, carbon stock, and sequestration at 256, 128, and 470 tons/ha, respectively, compared to rehabilitated and degraded forests. The variability in these parameters across different mangrove forests was influenced by stands characteristics, specifically basal area and mean tree diameter, which were associated with the age of mangrove vegetation and recovery duration. Notably, *Rhizophora mucronata, Sonneratia caseolaris*, and *Avicennia alba* exhibited the highest carbon sequestration. These results highlighted that Sungai Apit mangrove forests store a relatively high carbon stock, emphasizing the importance of implementing proper conservation and management measures to ensure sustainability.

Keywords: Aboveground biomass, *Avicennia alba*, Mangrove rehabilitation, REDD, *Rhizophora mucronata*, *Sonneratia caseolaris*

INTRODUCTION

Mangrove forests constitute a unique assemblage of plants typically found in protected coastal areas where land and sea meet. These areas are often characterized by high salinity, extreme tides, strong winds, elevated temperatures, as well as anaerobic soil conditions. The trees exhibit salt tolerance and can absorb water even when the absorption potential is low. As noted in a previous study, certain mangrove plants have developed mechanisms to either absorb or store excess salt, often employing specialized glands in their leaves or bark (Sarhan and Tawfik 2018). The ecosystem plays a pivotal role in providing fisheries and biodiversity, which are essential for ecological and economic functions. Through intricate physical, biochemical, and biological interactions, mangrove forests are linked to adjacent ecosystems, including seagrass, coral reefs, and estuaries. They serve as shelter and nesting sites for fish and shellfish, as well as hatcheries, food sources, and breeding grounds (Hutchison et al. 2014; Lee et al. 2014; Perera-Valderrama et al. 2020).

Mangrove ecosystems play an important role in climate regulation by capturing and storing substantial amounts of carbon, thereby assisting in reducing carbon dioxide levels resulting from the burning of fossil fuels. Approximately 15% of the total carbon accumulation in the ocean is attributed to forests. This capacity to absorb and retain organic carbon from tree biomass and sediments has been well documented (Alongi 2014; Chambers et al. 2014; Kusumaningtyas et al. 2019; Jennerjahn 2020). However, over the past few decades, mangrove ecosystems have experienced a reduction in land area due to overexploitation and land conversion for shrimp farming, aquaculture, and agriculture (Brander et al. 2012; Prawita 2018; Sarhan and Tawfik 2018; Owuor et al. 2019). This degradation has resulted in reduced carbon stock (Kauffman et al. 2014; Eid et al. 2019; Peneva-Reed 2021) and increased emissions (Kauffman et al. 2014), reaching a significant value of 0.12 Pg C/year (Donato et al. 2011). Consequently, there is an urgent need for strategies to reduce the damage to mangrove forests and mitigate climate change.

The differences in the conditions of mangrove forests are directly related to the quantifiable value of aboveground carbon. These differences are linked to stand structure, such as the mean diameter and tree density. Furthermore, various mangrove forests exhibit varying levels of biomass and carbon stock. Undegraded mangrove types display higher values for biomass and carbon stock compared to degraded ones (Kusumaningtyas et al. 2019). Variations in carbon stock were observed in the three sites in Gulf, California (La Paz Bay, Mexico). Mangrove forests in Balandra, which had the lowest anthropogenic impact, exhibited the highest carbon stock (Ochoa-Gómez et al. 2019). Additionally, the values in deforested sites were 100% lower than in natural ones (Sharma et al. 2020).

Sungai Apit, Siak, Riau, Indonesia, has partially natural and degraded mangrove ecosystems. In response, local communities have undertaken rehabilitation efforts in several degraded forests. Differences exist in the floristic structure of the natural, rehabilitated, and degraded forests. The natural type has the highest values for tree density, mean diameter, and basal area. Conversely, rehabilitated and degraded forests exhibit a decrease in these three parameters (Fatonah et al. 2021). The tree density in Mengkapan Village, Sungai Apit, Siak constitutes the sparse to dense category (Efriyeldi et al. 2020), with carbon sequestration measured at 113.18 tons/ha, and the highest contribution coming from *Xylocarpus granatum* (Hamidy 2020). The determination of aboveground carbon relies on biomass measurements derived from tree trunk diameter (Karyati et al. 2019). Consequently, differences in forest conditions significantly impact aboveground carbon content. Hence, this study aimed to estimate biomass, carbon stock, and sequestration in mangrove forests within Sungai Apit, Siak. The results aim to provide insights into the current status of mangrove forests concerning their carbon stock, a key element in climate change mitigation.

MATERIALS AND METHODS

Study site

The research area was located in the mangrove forest of Sungai Apit Sub District, Siak District, Riau Province, Indonesia. The selected locations include the villages of Rawa Mekar Jaya, Sungai Rawa and Mengkapan. Each village was allocated three stations, each station representing one of three types of forests: natural forest (or secondary mangrove forest, undisturbed for several decades), degraded mangrove forest, and rehabilitated forest (undamaged for a dozen to tens of years), degraded mangrove forest and rehabilitated forest (Figure 1).

Sampling was carried out in three villages in Sungai Apit, Siak, Riau Province, Indonesia, namely Rawa Mekar Jaya, Sungai Rawa and Mengkapan. Three mangrove forest conditions were identified in these locations: (1) natural mangrove forest, (2) rehabilitated forest, and (3) degraded forest. Therefore, there were nine observation stations, each of which consisted of three transects. Each line transect measured 1000 m^2, (10 × 100 m). Within each line transect, three plots measuring 10 m × 10 m were established for trees, and 5 m × 5 m for saplings. The number of each tree and sapling species encountered was recorded within each plot. The diameter at breast height (at 1.3 m) was obtained by measuring the circumference of tree and sapling trunks.

The aboveground biomass was measured by the allometric equation, as detailed in Table 1. Biomass measurement encompassed both saplings and trees. The total biomass values were calculated for each transect as replicates at each station, taking into account forest and village conditions. To estimate carbon stocks in the vegetation, 50% of the calculated biomass was converted to carbon (in kg) by applying a conversion factor of 0.50. Carbon stock values were then converted into units of tons/ha. Carbon sequestration was calculated based on the carbon stock value multiplied by 3.67, a constant for converting carbon to CO_2 (Munir 2017; Kusumaningtyas et al. 2019; Hamidy 2020; Slamet et al. 2020).

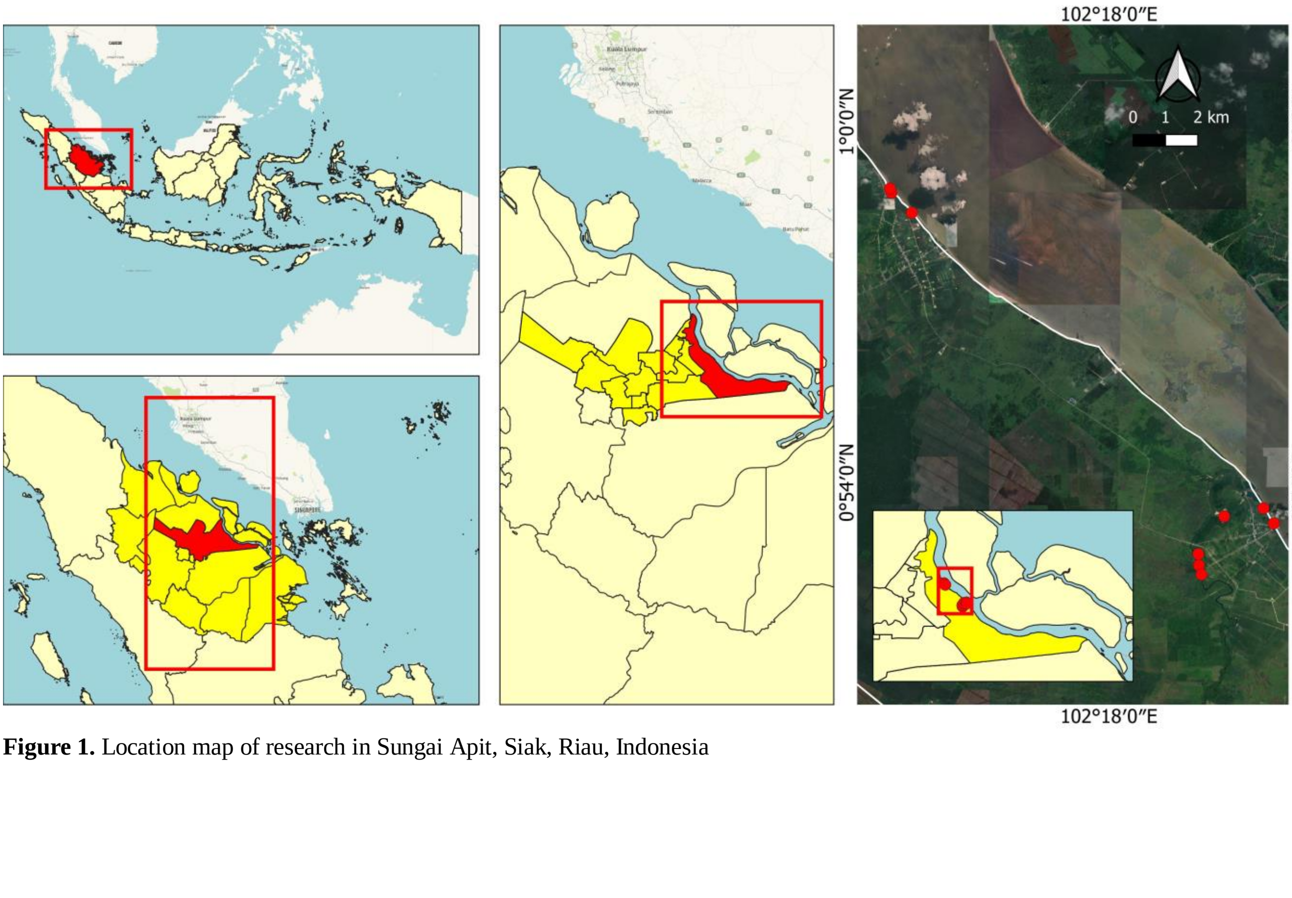

Figure 1. Location map of research in Sungai Apit, Siak, Riau, Indonesia

Table 1. Allometric equation for determining aboveground biomass (D is tree diameter in cm; is wood density (ρ) in g/cm^3)

Species	Equality	Reference	Wood density (g/cm^3)
Avicennia alba	$0.251*\rho*D^{2.46}$	Komiyama et al. (2005)	0.6987
Bruguiera gymnorhiza	$0.0754*\rho*D^{2.505}$	Kauffman and Cole (2010)	0.741
Bruguiera parviflora	$0.0754*\rho*D^{2.505}$	Kauffman and Cole (2010)	0.8427
Ceriops decandra	$0.251*\rho*D^{2.46}$	Komiyama et al. (2005)	0.725
Ceriops tagal	$0.251*\rho*D^{2.46}$	Komiyama et al. (2005)	0.8859
Hibiscus tilliaceus	$0.11*\rho*D^{2,62}$	Ketterings et al. (2001)	0.47
Rhizophora apiculata	$0.043*D^{2.63}$	Amira (2008)	0.8814
Rhizophora mucronata	$0.128*D^{2.60}$	Fromard et al. (1998)	0.8483
Rhizophora stylosa	$0.105*D^{2.68}$	Clough and Scott (1989)	0.94
Scyphiphora hydrophylacea	$0.251*\rho*D^{2.46}$	Komiyama et al. (2005)	0.685
Sonneratia alba	$0.3841*\rho*D^{2.101}$	Kauffman and Cole (2010)	0.6443
Sonneratia caseolaris	$0.251*\rho*D^{2.46}$	Komiyama et al. (2005)	0.5337
Xylocarpus granatum	$0.1832*\rho*D^{2.2}$	Tarlan (2008)	0.6721
Xylocarpus moluccensis	$0.251*\rho*D^{2.46}$	Komiyama et al. (2005)	0.6535

Differences in biomass, carbon stocks, and carbon sequestration values at various mangrove forest sites were analyzed descriptively and presented in tables. Factors of stand characteristics that influence differences in biomass, carbon stocks and carbon sequestration were determined using linear regression analysis. The data were analyzed using SPSS software version 17. The proportion of each mangrove species contributing to carbon sequestration was determined based on the percentage of carbon sequestration values for each species in each condition and location of the mangrove forest.

RESULTS AND DISCUSSION

The biomass and carbon stock values calculated in this study were derived from the aboveground components, specifically trees and saplings. Figure 2 depicts important aspects, namely tree density, average trunk diameter, and basal area. The results of these calculations under various mangrove forest conditions, along with the observed trends, are presented in Table 1 and Figure 3.

Characteristics of tree stands and saplings

The characteristics of tree stands and saplings, as reported by Fatonah et al. (2021), are illustrated in Figures 2 and 3. These figures reveal significant differences in tree density, mean diameter, and basal area across various forest conditions in three villages. In the natural forests, tree density was consistently high, exceeding 1,500 trees per hectare, with Mengkapan recording the highest density of 2,644.18 individuals per ha. In contrast, degraded forests exhibited the lowest tree density. Mean tree diameter (Diameter at Breast Height, DBH) varied from 8.27 to 19.19 cm across different conditions, with natural forests having the largest mean diameter. It's worth noting that in Rawa Mekar Jaya, the mean tree diameter in rehabilitated and degraded forests was quite similar, whereas Sungai Rawa and Mengkapan exhibited higher values for the degraded forest. Natural forests also showed the highest basal area value, while the degraded forests had the lowest.

The sapling density across all observation locations ranged from 533.32 to 2711.04 individuals/ha. Notably, there were minor differences in density, stem diameter, and basal area of the sapling under various forest conditions. Natural forests had the lowest sapling density compared to the other two types. In the case of Rawa Mekar Jaya and Sungai Rawa, rehabilitated forests had the highest densities, while in Mengkapan, the highest density occurred in degraded forests. This variation can be attributed to the greater natural regeneration capacity in degraded forests due to gaps stimulating the germination of mangrove seeds and the growth of undisturbed tillers. Additionally, higher values in rehabilitated forests compared to the natural ones indicate the effectiveness of planting mangrove seedlings in increasing sapling density. In Sungai Apit, substantial rehabilitation efforts involved planting seedlings in Rawa Mekar Jaya, Sungai Rawa, and Mengkapan from 2014 to 2019, 2008 to 2018, and 2002 to 2016 respectively.

The mean diameter of saplings ranged from 2.53-5.04 cm, with the highest and lowest values recorded from degraded and natural forests, respectively. This is mainly due to faster natural regeneration in degraded forests, facilitated by larger gaps (Azad et al. 2020). This was indicated by the lower canopy cover (34-65%) in degraded forests compared to rehabilitated (62-79%) and natural forests (87-92%). The basal area of sapling ranged from 1.10 to 25.27 m^2/ha, with the highest and lowest again observed in degraded and natural forests, respectively. The higher basal area was associated with the larger trunk diameter observed in degraded forests.

Biomass, carbon stock and carbon sequestration

The estimated values for biomass, carbon stock, and sequestration are summarized in Table 2. Differences in these three parameters were evident for both trees and saplings across various forest conditions in Rawa Mekar Jaya, Sungai Rawa, and Mengkapan Village. For trees, biomass, carbon stock, and sequestration values were notably higher (92.58, 46.29, and 166.44 tons/ha) compared to saplings (4.29; 4.28; and 4.17 tons/ha). Furthermore, these parameters exhibited higher values in natural forests than in rehabilitated and degraded ones. The natural mangrove forests of Sungai Rawa had the highest tree biomass (256 tons/ha), while the lowest was observed in the degraded forests of Rawa Mekar Jaya (35 tons/ha). This decrease in biomass was particularly significant in rehabilitated and degraded forests compared to the natural forests, ranging from 51 to 91% (Table 2). This decrease was most pronounced in Sungai Rawa due to the high values of biomass, carbon stock, and sequestration in the natural forests. Carbon stock and sequestration also showed the same decreasing trend as biomass (Table 2).

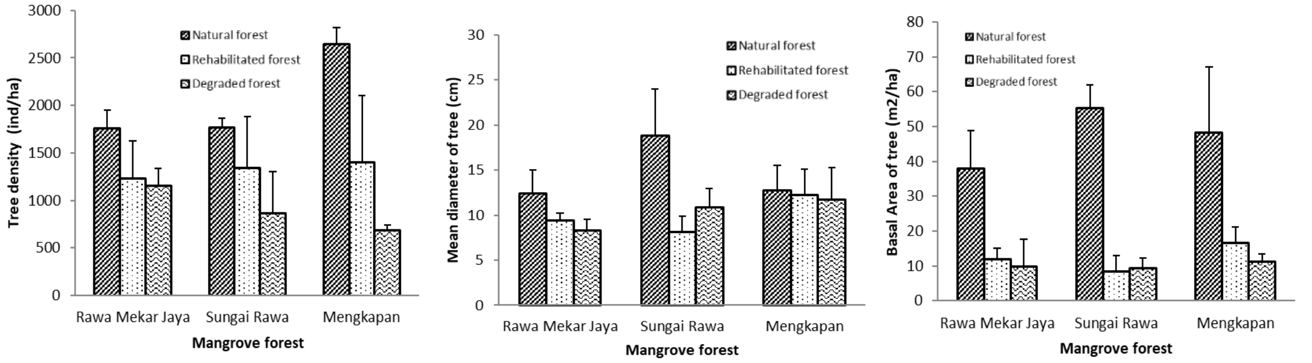

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Figure 2. Tree stand structure in various conditions of mangrove forest in Sungai Apit, Siak District, Indonesia: A. density, B. diameter and C. basal area (Fatonah et al. 2021)

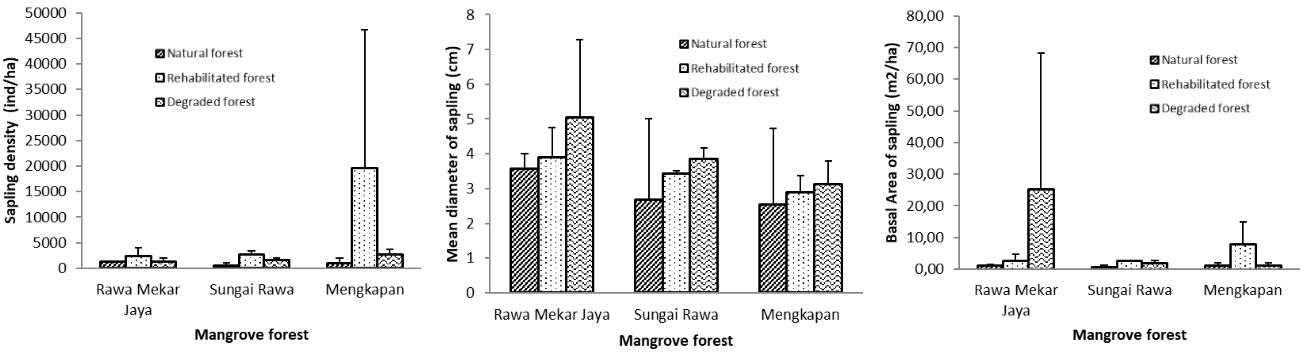

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Figure 3. Sapling stand structure in various conditions of mangrove forest in Sungai Apit, Siak District, Indonesia: A. density, B. diameter, C. basal area

Table 2. Tree and sapling biomass in various conditions of mangrove forests in Sungai Apit, Siak District, Indonesia

Variable		Rawa Mekar Jaya			Sungai Rawa			Mengkapan			Mean	Percentage (%)
		N	R	D	N	R	D	N	R	D		
Biomass (tons/ha)	Tree	139	33 (-76)	35 (-75)	256	24 (-91)	48 (-81)	153	75 (-51)	71 (-54)	92.58	95.71
	Sapling	2	4 (+100)	3 (+50)	1	4 (+300)	7 (+600)	2	10 (+400)	4 (+100)	4.15	4.29
	Total	141	36	38	257	28	55	155	84	75	96.73	100.00
Carbon stock (tons/ha)	Tree	70	16 (-77)	17 (-76)	128	12 (-91)	24 (-81,25)	76	37 (-51)	35 (-54)	46.29	95.72
	Sapling	1	2 (+100)	2 (+100)	0,5	2 (+300)	4 (+700)	1	5 (+400)	2 (+100)	2.07	4.28
	Total	70	18	19	129.5	14	28	77	42	38	48.36	100.00
Carbon sequestration (tons/ha)	Tree	255	60 (-77)	64 (-75)	470	44 (-91)	88 (-81)	280	137 (-51)	100 (-64)	166.44	95.83
	Sapling	3	7 (+133)	3 (+133)	2	8 (+300)	13 (+550)	3	18 (+500)	8 (+167)	7.24	4.17
	Total	258	67	66	471	52	102	284	155	108	173.68	100.00

Note: N: natural forest; R: rehabilitated forest; D: degraded forest. The numbers in brackets indicate the enhancement (+) and reduction values (-) in percent (%) compared to natural forests

Sapling biomass was low, averaging around 4.15 tons/ha, with values ranging from 1 to 10 tons/ha. The lowest and highest values were observed in natural and rehabilitated forests, respectively. In particular, the rehabilitated mangrove forests in Mengkapan showed the most significant sapling biomass. A substantial increase in biomass, carbon stock, and sequestration was observed in degraded (50-600%) and rehabilitated forests (100-400%), with the highest observed in Sungai Rawa (600%). The elevated biomass of saplings within degraded and rehabilitated forests can be attributed to their remarkable regenerating capabilities. Saplings arise from seedlings that mature after a few years, demonstrating notable regrowth potential. The substantial percentage increase in sapling biomass within degraded and rehabilitated forests can be attributed to their enhanced capacity for seedling recruitment. Carbon stock and sequestration also followed this increasing trend as biomass (Table 2). Similar observations have been reported in Segara Anakan, Cilacap, Indonesia, where mangrove forests with lower tree abundance exhibited higher sapling biomass (Widyastuti et al. 2018). Degraded forests, characterized by lower tree densities, generally displayed greater seedling recruitment capabilities compared to natural forests. This phenomenon is associated with higher canopy cover levels and the presence of gaps. These gaps allow light to penetrate the forest floor, promoting seed germination and seedling growth (Amir 2012; Amir and Duke 2019; Chen et al. 2021).

Relationship between stand characteristics and biomass, carbon stock, and sequestration of trees

The influence of stand characteristics on differences in biomass, carbon stock, and sequestration was assessed through linear regression analysis. Figure 4-6 illustrate that tree biomass, carbon stock, and sequestration correlated positively and significantly with the basal area (with r = 0.954, 0.954, and 0.962, respectively) and mean diameter (with r = 0.945, 0.945, and 0.935, respectively). Tree density, on the other hand, showed a non-significant positive correlation with these parameters. There was a strong correlation between biomass, carbon stock, and carbon sequestration with the basal area and mean diameter tree density (r = 0.61 and 0.61), while a moderate correlation was observed between biomass, carbon stock, and carbon sequestration with tree density. These results indicate that the differences in the three parameters across mangrove forests in Rawa Mekar Jaya, Sungai Rawa, and Mengkapan Villages, Sungai Apit, were more strongly influenced by basal area and trunk diameter than by tree density. In other words, greater trunk diameter and basal area were associated with higher biomass, carbon stock, and sequestration, as observed in natural forests.

The results further emphasized the strong correlation between carbon stock and basal area, as well as average tree diameter. Consequently, basal area and mean diameter were identified as key indicators for determining carbon stock in mangrove ecosystems. This aligns with findings in the dominant species within the Sundarbans mangrove forests (Rahman et al. 2015), where basal area was identified as a key indicator of ecosystem carbon stock, along with the mean tree height. Therefore, carbon stock can be predicted using regression equation that emphasizes the basal area, mean diameter, or height of trees.

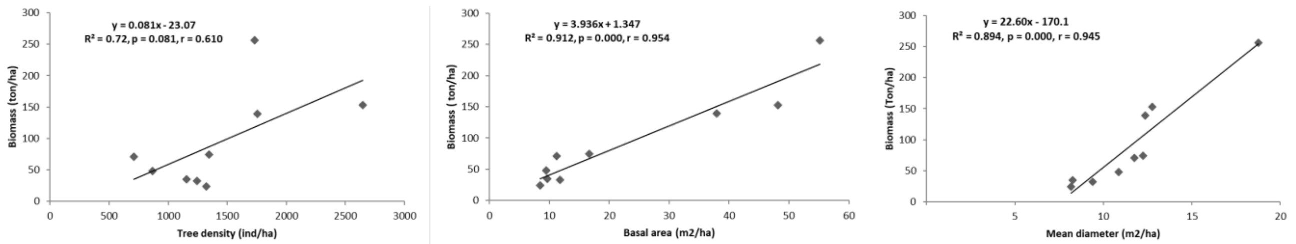

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Figure 4. Relationship between tree biomass with tree density, basal area and mean diameter

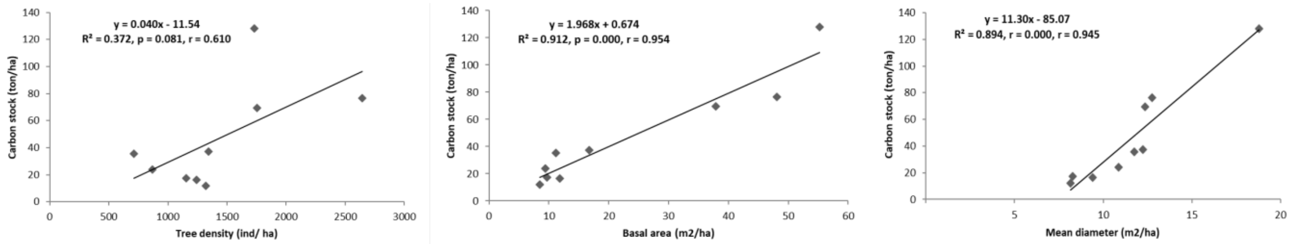

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Figure 5. Relationship between carbon stock with tree density, basal area and mean diameter

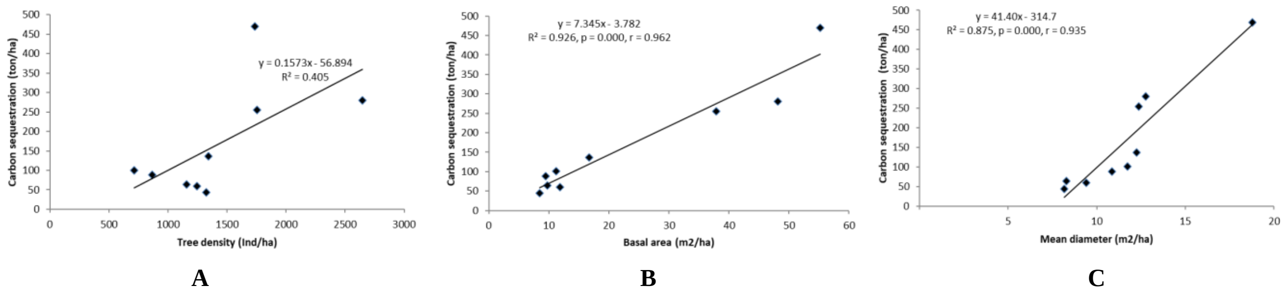

Figure 6. Relationship between carbon sequestration with tree density, basal area and mean diameter

Notable differences in carbon stock were observed across various forest conditions in Sungai Apit. Carbon stock values for trees in natural mangrove forests (ranging from 70-128 tons C/ha) were notably higher than those in degraded and rehabilitated forests (12-37 tons C/ha). These differences were primarily attributed to structural variations within the stand, specifically tree diameter. Trees in natural forests exhibited larger diameters (ranging from 12.37-18.78 cm) compared to those in degraded forests (8.27-11.75 cm). This result was reinforced by the strong correlation between carbon stock and tree diameter ($r = 0.945$). The relationships among biomass, carbon stock, and sequestration were predominantly influenced by tree diameter and density (Camacho et al. 2011). Similar findings have been reported in several other mangrove forests. Carbon stock values can exhibit significant differences between various ecosystems, and these differences are often influenced by factors such as age and environmental conditions. For example, in Berau, East Kalimantan natural mangrove ecosystems were found to have higher carbon stock values at 130.1 tons/ha, while the Kepulauan Seribu Jakarta recorded 74.3 tons/ha. These values were notably higher than those observed in the degraded mangrove forest at Segara Anakan lagoon, Central Java, which had a carbon stock of 15.8 tons/ha (Kusumaningtyas et al. 2019). Furthermore, the age of mangrove stands can have a substantial impact on carbon stock. In Bohol Province, Philippines, mangrove forests aged 40 years showed higher carbon stock values compared to those aged 20 and 15 years (Camacho et al. 2011), which suggests that older mangrove stands tend to store more carbon. Variations in this parameter across different mangrove forest conditions are also evident in the Colombian Pacific. For instance, Málaga Bay station, located within a national marine park, exhibited higher carbon stock values than Buenaventura Bay (main port area) (Peñaranda et al. 2019), which underscores the influence of local conditions and management practices on carbon stock within mangrove ecosystems.

Carbon stock values also exhibited disparities among the three locations (villages) within natural forests. The highest value was recorded at Sungai Rawa (128 tons/ha), followed by Mengkapan (76 tons/ha) and Rawa Mekar Jaya (70 tons/ha). The estimated carbon stock in Mengkapan was lower compared to the value (113.18 tons/ha) obtained in another study by Hamidy (2020). This variation may be attributed to differences in sampling locations, including in age and species compositions. Variations in biomass and carbon stock in mangrove forests have been associated with the age and species of mangroves in Tamil Nadu, India (Sahu and Kathiresan 2019).

Tree biomass in natural forests ranged from 139 to 256 tons/ha, with carbon stock values ranging from 70 to 128 tons/ha. These values are relatively high compared to results obtained in various other mangrove forests. Similar trends in these two parameters were observed in the rehabilitated and degraded forests (Table 3). These differences were related to the conditions of the mangrove forests and the tree age, as evidenced by their relationships with the stand structure. Biomass, carbon stock, and sequestration showed a high correlation ($r = 0.935$-0.962) with basal area and mean tree diameter. A previous study has shown that biomass and carbon stock of mangroves in Bedul, Banyuwangi, East Java were positively correlated with mean diameter, tree height, and density (Purnamasari et al. 2020). Additionally, the greater biomass of some dominant mangrove trees in various locations has been attributed to their height (Duke et al. 2013). Carbon sequestration also increased with advanced mangrove age (Sahu and Kathiresan 2019). Degraded forests typically showed lower carbon stock compared to the natural type (Senger et al. 2021).

Proportion of mangrove species in contributing to carbon sequestration

Mangrove forests contribute significantly to the mitigation of global warming and climate change by helping to reduce CO_2 concentrations in the atmosphere. These ecosystems play a vital role in carbon sequestration. The process involves mangrove vegetation absorbing CO_2 during photosynthesis and storing carbon in the form of biomass in their stems, leaves, twigs, and litter (Mitra and Gatti 2015; Dewiyanti et al. 2019; Inoue 2019). To estimate the carbon potential stored in various mangrove species, the study calculated the percentage of carbon sequestration in each mangrove tree species found in different conditions of Sungai Apit mangrove forest (Table 4).

Table 3. Biomass and carbon stocks of mangrove trees in various mangrove forest locations

Location	**Biomass (ton/ha)**	**Carbon stocks (ton/ha)**	**Reference**
The reclamation land of Serang, Jakarta Bay, Indonesia	8.05-69.56		Slamet et al. (2020)
The Ajuruteua Peninsula on the Brazilian Amazon coast	172.06	72.93	Virgulino-Júnior et al. (2020)
The rehabilitated area of Sinjai, South Sulawesi, Indonesia	125.48	60.23	Malik et al. (2020)
Kuala Sepetang, Perak Malaysia	168.93	84.47	Eusop et al. (2018)
Sulaman Lake Forest Reserve, Sabah, Malaysia		67.30	Suhaili et al. (2020)
Guangdong Province, China		84.61	Liu et al. (2014)
Kerala, southwest coast, India		58.56	Harishma et al. (2020)
Sirik Azini Creek, Ormozgan, Iran		96	Askari et al. (2022)
Kadalundi estuarine wetland, south-west coast, India	236.56	118.28	Vinod et al. (2018)
The Oligohaline Zone of the Sundarbans Protected Forest, Bangladesh	154.8		Kamruzzaman et al. (2017)
Berau, East Kalimantan, Indonesia	130.1		Kusumaningtyas et al. (2019)
Merbok, Kedah, Malaysia	176		Zarawie et al. (2015)
Benoa Bay, Bali, Indonesia	364,241	171,193	Mahasani et al. (2021)
Karimunjawa-Kemujan Islands, Indonesia	8-328	4-164	Wirasatriya et al. (2022)

Table 4. Proportion of mangrove species in contributing to carbon sequestration in various conditions of mangrove forests in Sungai Apit, Siak District, Indonesia

Mangrove species	**Proportion (%)**								
	Rawa Mekar Jaya			**Sungai Rawa**			**Mengkapan**		
	N	**R**	**D**	**N**	**R**	**D**	**N**	**R**	**D**
Avicennia alba Blume						**37**	**39**	9	15
Avicennia marina (Forssk.) Vierh.						20			
Bruguiera gymnorhiza (L.) Lam.				3	4		3	4	
Bruguiera hainesii C.G. Rogers				2	13				
Bruguiera sexangula (Lour.) Poir.	5	17	7	4	6		3		
Ceriops tagal C.B. Rob.					**26**				
Clerodendrum serratum Moon	15								
Flacourtia rukam Zoll. & Moritzi				0					
Heritiera littoralis Aiton.	1								
Hibiscus tilliaceus L.									1
Rhizophora apiculata Blume	26	**27**	30	3	8		2	3	3
Rhizophora mucronata Poir.	**52**	26	**63**	2			18		
Rhizophora stylosa Griff.				1			7		
Scyphiphora hydrophylacea C.F.Gaertn.					19		5	**55**	**70**
Sonneratia alba Sm.		14		20	13	32	11	17	7
Sonneratia caseolaris Engl.				**58**					
Sonneratia ovata Backer						12	5	13	
Cantleya corniculata (Becc.) R.A.Howard		16							
Xylocarpus granatum J.Koenig.				4	9		8		5
Xylocarpus moluccensis M.Roem.				3					

Note: N: natural forest; R: rehabilitated forest; DF: degraded forest

This study revealed the presence of twenty different mangrove species at various observation sites across tree villages (Fatonah et al. 2021). These species made significant contributions to the carbon stored within the mangrove forests under different forest conditions. Notably, *Rhizophora mucronata*, *Sonneratia caseolaris*, and *Avicennia alba* were the leading contributors to carbon sequestration in natural forests in Rawa Mekar Jaya, Sungai Rawa, and Mengkapan, respectively. This outcome diverges from the importance value or the dominantly prevalent species within natural forests in these villages, which is primarily *Rhizophora apiculata* (Fatonah et al. 2021). This deviation can be attributed to the fact that the importance value is determined by tree density and basal area, whereas carbon sequestration is more contingent on basal area and stem diameter rather than tree density (Figure 8). In addition, the coefficient value in the allometric equation for *R. apiculata*, which is used to calculate aboveground biomass, is lower than *R. mucronata*, *S. caseolaris*, and *A. alba* (Table 1). The differences in the species contributing the most carbon to the natural forests in these three villages are linked to the tree age and mangrove forest type. For example, the mangrove forest in Rawa Mekar Jaya, known as a river mangrove, is connected to the river, while the mangrove forest in Sungai Rawa, associated with the estuary, and the mangrove forest in Mengkapan, linked to the strait, exhibit varied species composition (Fatonah et al. 2021). The species contributing the highest carbon sequestration are typically correlated with older tree age, which in turn, results in larger tree diameter. This tree diameter, in a positive correlation, leads to higher aboveground carbon stocks (Purnamasari et al. 2020). Furthermore, there is a positive correlation between tree age and diameter, tree age and height, and tree age and biomass (Cabuy 2015).

There are differences in species contributing the most to carbon sequestration in both rehabilitated and degraded forests in the three villages. In the rehabilitated forests of Rawa Mekar Jaya, *R. apiculata* takes the lead, while in Sungai Rawa, it was *Ceriops tagal*, and in Mengkapan it was *Scyphiphora hydrophylacea* that makes the highest percentage contribution to carbon sequestration. On the other hand, in the degraded forests of Rawa Mekar Jaya, *R. mucronata* holds this position, while in Sungai Rawa, it's *A. alba*, and in Mengkapan, it's *S. hydrophylacea*. These differences stem from the distinctive composition of mangrove species in the forests across the three villages and their varying adaptability to diverse environmental conditions.

The natural forest in Sungai Apit contributes the highest carbon sequestration, so the species that contribute the highest carbon sequestration are the species with the highest proportion of carbon sequestration in the natural forest. It's essential to note that the majority of the mangrove forests in Sungai Apit are classified as natural forests. Here, 'natural forests' refer to secondary forests that have regrown after being initially degraded, spanning over decades. The outcomes of this study pinpoint *Rhizophora mucronata*, *S. caseolaris*, and *A. alba* as the species that contribute most significantly to carbon sequestration. The genera *Rhizophora*, *Sonneratia* and *Avicennia* have the highest carbon sequestration in various mangrove forest sites, for example, mangrove forests at Muara Gembong Bekasi (Rachmawati et al. 2014); Segara Anakan Lagoon and Meranti Island (Hilmi et al. 2017); coastal North Sumatra (Suprayogi et al. 2022); Nusa Lembongan, Bali (Pricillia et al. 2021); Rawa Aopa Watumohai National Park in the coral reef triangle ecoregion, Southeast Sulawesi (Analuddin et al. 2020); and Tanakeke Island, South Sulawesi (Cameron et al. 2019).

The results illustrate disparities in biomass, carbon stocks, and carbon sequestration across various conditions and locations of mangrove forests. These differences are a reflection of variations in mangrove vegetation structure primarily linked to tree age and the length of recovery. This is reinforced by the significant correlation between tree biomass, carbon stocks and carbon sequestration with floristic structure, specifically the mean stem diameter and basal area. Those mangrove forests with high biomass, carbon stocks and carbon sequestration generally correspond to higher values of mean diameter and basal area. Differences in carbon stocks between plantation and natural mangrove forests, as observed in Bohol, Philippines, were related to tree age. The 40-year-old mangrove plantation forests exhibit the highest carbon stock (370.7 tons), followed by the 15-year-old plantation forests with 208.5 tons/ha, and the 20-year-old plantation forests with 149.5 tons/ha (Camacho et al. 2011).

Accurate determination of tree carbon stocks is essential for estimating carbon stocks in mangrove sediments. Mangrove trees significantly contribute to carbon accumulation in these sediments. This relationship is substantial by the positive correlation between organic carbon content in the soil within mangrove forests and the biomass of mangrove trees (Wang et al. 2013; Savari et al. 2020). Additionally, calculations of mangrove forest carbon stocks along the southeast coast of China reveal a positive association between carbon stocks derived from mangrove tree biomass and those from below-ground carbon stocks, encompassing roots, dead trees, leaf litter, and mangrove sediments (Meng et al. 2021). In comparison to the carbon stock in mangrove sediments, mangrove forests in the Gulf of California showed lower values (Ochoa-Gómez et al. 2019).

Notably, carbon stock values in rehabilitated forests were lower than those in degraded forests in Rawa Mekar Jaya and Sungai Rawa, while carbon stock values in both forest conditions in Mengkapan appear to be quite similar. This is because the rehabilitated forest in Sunga Apit was previously more severely damaged than the degraded forest. Tree density in the rehabilitated forest was higher, but tree diameter and basal area were lower than in the degraded forest (Figure 2). However, the rehabilitation of these mangrove forests assumes paramount importance due to their deforested areas. Mangrove rehabilitation is crucial not only for environmental reasons but also due to its significant impact on carbon stocks. An illustrative example is observed in the mangrove forests of Bohol Province, Philippines. Notably, 15-year-old mangrove forests exhibit higher carbon stocks in comparison to their 20-year-old counterparts, predominantly due to the more intensive management practices applied in the younger forests (Camacho et al. 2011). Additionally, mangrove rehabilitation and the restoration of hydrological conditions, particularly in abandoned shrimp ponds, have demonstrated the potential to enhance the survival of mangrove species and, by extension, boost carbon stocks (Matsui et al. 2012). Mangrove rehabilitation is of vital importance in many tropical countries, as it plays a central role in addressing issues related to climate change. The success rate of these rehabilitation efforts carries far-reaching implications for the welfare of local communities. Effective mangrove rehabilitation can significantly increase the value of carbon stocks, consequently amplifying the effectiveness of climate regulation services through carbon sequestration services. Mangrove rehabilitation stands a dedicated endeavor aimed at the protection and sustainable management of these vital ecosystems. These efforts can be further augmented through the implementation of payment for environmental services programs, ultimately leading to the increase in various values attributed to mangrove ecosystem services, including carbon sequestration, biodiversity conservation, cultural significance, and provisioning services (Camacho et al. 2011). Furthermore, the practice of mangrove carbon stock accounting has emerged as an invaluable tool, enabling the assessment of ecosystem services and proving essential for ecosystem service payments and initiatives such as REDD (Reducing Emissions from Deforestation and Forest Degradation Project) (Kusumaningtyas et al. 2019). Recognizing the critical role of mangrove vegetation in providing soil organic carbon, it becomes imperative to focus on the conservation and sustainable management of mangrove forests, thereby ensuring the preservation and augmentation of carbon stocks (Savari et al. 2020).

In conclusion, biomass, carbon stock, and carbon sequestration values in natural forests are higher than in rehabilitated and degraded forests, with the highest values in natural mangrove forests in Sungai Rawa (256, 128 and 470 tons/ha, respectively). The difference in biomass value, carbon stock and carbon sequestration in various mangrove forests in Sungai Apit, Siak, Riau is found to be influenced by the stand characteristics like basal area and average tree diameter. The characteristics of these stands are related to the age of mangrove vegetation and the duration of recovery. *R. mucronata, S. caseolaris,* and *A. alba* were the mangrove species showing the greatest levels of carbon sequestration.

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