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Carbon Stock Estimation in the Mangrove Area of the Marine Station of Universitas Riau, Dumai

Estimasi Stok Karbon di Kawasan Mangrove Stasiun Laut Universitas Riau, Dumai

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Abstract

Mangrove forests can store more carbon than most terrestrial forest ecosystems, making them important for climate change mitigation. Their carbon sequestration potential depends on the trees' ability to absorb atmospheric CO_2 through photosynthesis. This study aimed to estimate biomass, carbon stock, and CO_2 sequestration in the mangrove area of the Marine Station of Universitas Riau, Dumai, Indonesia. The research was conducted from September to November 2025 at three stations representing terrestrial, riverine, and marine zones. Data were collected through DBH measurements of mangrove vegetation and sediment coring, supported by environmental parameters such as temperature, pH, and salinity. Mangrove density ranged from 1,200 to 2,388.33 individuals ha^{-1}, with the highest value at Station 2 and the lowest at Station 3. This pattern was positively related to biomass, vegetation carbon stock, and CO_2 sequestration. Estimated biomass reached 897.73 tons ha^{-1}, while vegetation carbon stock was 421.93 tons ha^{-1}. Sediment was the largest carbon pool, ranging from 1,896.10 to 2,202.97 tons ha^{-1}, with the highest value at Station 1. Total carbon stock reached 2,462.12 tons ha^{-1}. Statistical analysis showed a strong positive correlation among stand density, biomass, carbon stock, and CO_2 sequestration. Regression analysis indicated a significant relationship ($R^2 = 0.502$), meaning 50.2% of the variability in these parameters was explained by stand density. At the same time, the remainder was influenced by other factors such as stand age, substrate fertility, and planting distance.

Keywords: Mangrove, Carbon Stock, Density, Sediment

Abstrak

Hutan mangrove dapat menyimpan lebih banyak karbon daripada kebanyakan ekosistem hutan darat, menjadikannya penting untuk mitigasi perubahan iklim. Potensi penyerapan karbon mereka tergantung pada kemampuan pohon untuk menyerap CO_2 atmosfer melalui fotosintesis. Penelitian ini bertujuan untuk memperkirakan biomassa, stok karbon, dan penyerapan CO_2 di kawasan mangrove Stasiun Laut Universitas Riau, Dumai, Indonesia. Penelitian dilakukan pada September hingga November 2025 di tiga stasiun yang mewakili zona darat, sungai, dan laut. Data dikumpulkan melalui pengukuran DBH vegetasi mangrove dan inti sedimen, didukung oleh parameter lingkungan seperti suhu, pH, dan salinitas. Kepadatan mangrove berkisar antara 1.200 hingga 2.388,33 individu ha^{-1}, dengan nilai tertinggi di Stasiun 2 dan terendah di Stasiun 3. Pola ini berhubungan positif dengan biomassa, stok karbon vegetasi, dan penyerapan CO_2. Perkiraan biomassa mencapai 897,73 ton ha^{-1}, sedangkan stok karbon vegetasi

adalah 421,93 ton ha^{-1}. Sedimen merupakan kolam karbon terbesar, berkisar antara 1.896,10 hingga 2.202,97 ton ha^{-1}, dengan nilai tertinggi di Stasiun 1. Total stok karbon mencapai 2.462,12 ton ha^{-1}. Analisis statistik menunjukkan korelasi positif yang kuat antara kepadatan tegakan dan biomassa, stok karbon, dan penyerapan CO_2. Analisis regresi menunjukkan hubungan yang signifikan (R^2 = 0,502), yang berarti 50,2% variabilitas parameter ini dijelaskan oleh kepadatan tegakan yang dipengaruhi oleh faktor lain seperti usia tegakan substrat, kesuburan substrat, dan jarak tanam.

Kata kunci: Mangrove, Stok Karbon, Kepadatan, Sedimen

1. Introduction

Global warming is an indication of ecosystem imbalance characterized by an increase in the average temperature of the atmosphere, oceans, and terrestrial environments. The issue of global warming has now become a major concern in the field of environmental studies, as evidenced by the rising global temperature in line with the increasing emissions of greenhouse gases (Syahadat & Putra, 2022). The Intergovernmental Panel on Climate Change (IPCC) reported that since 2010, greenhouse gas emissions resulting from human activities have continued to increase across major sectors globally. Therefore, reducing carbon emissions has become an important step in addressing climate change.

One of the media for buying and selling carbon units is the use of mangrove forests, which absorb carbon at a higher rate than other tropical forests (Hidayah & Santoso, 2023). One of the mangrove ecosystems in Riau Province, particularly in Dumai City, is located in Purnama Village, which is an administrative area of West Dumai District. This district is located at coordinates 101°20'06"–101°24'10" E and 1°35'25"–1°37'30" N, with an area of approximately 120 km^2 (Saputra et al., 2016). The research site is located at the Marine Station in Purnama Village, West Dumai District, Dumai City, Riau Province.

The waves in these waters are relatively small because the winds are obstructed by surrounding islands, resulting in relatively calm water conditions. The surrounding waters are covered by mangrove vegetation, with an area of approximately 23 ha of the total area, and the condition is still considered relatively good. A total of 22 mangrove species have been identified in this area, most of which are common in Indonesia (Rozanda et al., 2020). Data on biomass, carbon stocks, and CO_2 sequestration capacity in this region are still scarce. Research exploring the relationship between mangrove density and carbon storage remains limited. Consequently, these information gaps challenge the effective management of mangrove ecosystems.

2. Material and Method

2.1. Time and Place

The research was conducted from September to November 2025 in the mangrove forest area located at the Marine Station of Universitas Riau, Purnama Village, Dumai City, Riau Province. The samples obtained were analyzed at the Marine Chemistry and Physical Oceanography Laboratory, Faculty of Fisheries and Marine Science, Universitas Riau.

2.2. Methods

The method used in this research was a survey, conducted through direct observation and field sampling. This approach was chosen because it provides a realistic representation of mangrove ecosystem conditions, including vegetation structure, water quality parameters, and potential carbon storage. Furthermore, the data obtained were processed and presented as tables and graphs showing carbon stocks in mangrove vegetation and sediments, as well as CO_2 sequestration

2.3. Procedures

2.3.1. Station Location Determination

Research stations were determined using purposive sampling based on location characteristics. Three research stations were established as follows: Station I: A high-density of mangrove vegetation area located on land that represents mangrove conditions; Station II: An area with low stand density of mangrove vegetation located near the riverbank, representing a transitional zone between terrestrial and aquatic environments; Station III: An area with sparse stands of mangrove vegetation, characterized by coastal marine conditions, representing mangrove ecosystems that directly interact with seawater.

Figure 1. Research location map

2.3.2. Sampling Plot

The sample plot design was adjusted to field conditions and may take the form of circular, rectangular, or square plots (Sandhyavitri et al., 2013). In this study, rectangular strip plots (transects) were employed, with three transects established at each station, each extending 100 meters in length. Within each transect, three plots were arranged using a nested sampling method, in which sample subunits were adjusted according to vegetation class. Seedling plots measuring 2 × 2 m were used to observe seedling or sapling-stage vegetation, sapling plots measuring 5 × 5 m were used for vegetation taller than 1.5 m with a diameter of less than 10 cm, and tree plots measuring 10 × 10 m were used for vegetation with a diameter of at least 10 cm.

2.3.3. Mangrove Density and Biomass

In this study, mangrove ecosystem biomass and carbon stocks were estimated using a non-destructive approach, meaning no trees were felled or harvested. This method began with the identification of all mangrove species at the study site based on morphological characteristics, including leaf shape, roots, fruits, and flowers. Biomass measurements were conducted on trees with a diameter ≥10 cm, obtained by converting stem circumference values using the appropriate equation. Diameter measurements were taken at approximately 130 cm above ground level, accounting for mangrove tree growth form, in accordance with the guidelines in Appendix 6. Each measured tree was marked to avoid duplicate recording, and all stem circumference data were documented on data sheets for the identified mangrove species. Subsequently, species density was calculated as the number of individuals of a given species per unit area using the prescribed formula.

$$K = \frac{Ni}{A} \times 10{,}000$$

Description:
K = density by species (trees/ha); Ni = number of individuals of given species; A= sampling area (m^2); 10,000= conversion factor to ha.

Tree stem diameter data obtained from measurements of mangrove community structure were utilized as the primary independent variable for estimating biomass, as stem diameter is widely recognized as a reliable predictor of tree growth and biomass accumulation. These data were subsequently incorporated into species-specific allometric equations for both aboveground and belowground components, enabling more accurate and representative biomass estimates for each mangrove species. The use of species-specific models was essential to account for differences in morphological characteristics, growth patterns, and root development among mangrove taxa, thereby improving the precision of the overall biomass assessment.

Table 1. Allometric model for aboveground mangrove biomass

Species	Above-ground biomass allometric equations
Avicennia alba	$B = 0.308*D^{2.11}$ (Komiyama et al., 2005)
Avicennia marina	$B = 0.1848*\rho*D^{2.3624}$ (Komiyama et al., 2005)
Bruguiera gymnorrhiza	$B = 0.0754*D^{2.505}*\rho$ (Kauffman & Donato, 2012)
Ceriops tagal	$B = 0.251*\rho*D^{2.46}$ (Komiyama et al., 2005)
Excoecaria agallocha	$B = 0.251*\rho*D^{2.46}$ (Komiyama et al., 2005)
Lumnitzera littorea	$B = 0.251*\rho*D^{2.46}$ (Komiyama et al., 2005)
Rhizophora apiculata	$B = 0.043*D^{2.63}$ (Amira, 2008)
Rhizophora mucronata	$B = 0.128*D^{2.6}$ (Fromand et al., 1998)
Sonneratia alba	$B = 0.3841*D^{2.101}*\rho$ (Kauffman & Donato, 2012)
Xylocarpus granatum	$B = 0.1832*D^{2.21}$ (Tarlan, 2008)

Table 2. Allometric model for belowground mangrove biomass

Species	Below-ground biomass allometric equations
Avicennia alba	$B = 0.199*\rho^{0.899}*D^{2.22}$ (Tue et al., 2014)
Avicennia marina	$B = 1.28*D^{1.17}$ (Komiyama et al., 2005)
Bruguiera gymnorrhiza	$B = 0.199*D^{0.22}*\rho^{0.899}$ (Komiyama et al., 2005)
Ceriops tagal	$B = 0.158*D^{1.95}$ (Comley & McGuiness, 2005)
Excoecaria agallocha	$B = 0.251*\rho*D^{2.46}$ (Komiyama et al., 2005)
Lumnitzera littorea	$B = 0.251*\rho*D^{2.46}$ (Komiyama et al., 2005)
Rhizophora apiculata	$B = 0.00698*D^{2.61}$ (Ong et al., 2004)
Rhizophora mucronata	$B = 0.00974*D^{2.6}$ (Komiyama et al., 2005)
Sonneratia alba	$B = 0.199*D^{0.24}*\rho^{0.899}$ (Komiyama et al., 2005)
Xylocarpus granatum	$B = 0.145*D^{2.55}$ (Komiyama et al., 2005)

Mangrove wood density varies among species. The stem wood density values used in this study were based on the findings of Ardhana et al. (2018); Purwiyanto & Agustriani (2017).

Table 3. Wood density of mangrove species

Species	Wood density values (g/cm^3)
Avicennia alba	0.6987
Avicennia marina	0.69
Bruguiera gymnorrhiza	0.741
Ceriops tagal	0.88
Excoecaria agallocha	0.45
Lumnitzera littorea	0.88
Rhizophora apiculata	1.065
Rhizophora mucronata	0.77
Sonneratia alba	0.78
Xylocarpus granatum	0.7

2.3.4. Vegetation Carbon Stock

The calculation of carbon stored in mangrove vegetation was conducted using the formula proposed by the BSN (2011), as follows:

$$C_b = B \times C_{\text{organic}}$$

Description:

C_b= mangrove carbon stock (kg); B = total biomass (kg); C_{organic}= organic carbon fraction (0.47)

2.3.5. Sediment Organic Carbon Stock

The data required to calculate the percentage of sediment organic carbon included sample depth, sub-sample interval, and bulk density. Sediment samples were collected using the coring method (Mahasani et al., 2015). Prior to sampling, the sediment surface was first cleared of organic debris and live leaves. The sediment corer was then inserted vertically until it reached the predetermined sampling point at the core base; if the instrument could not reach the full depth, sampling was conducted at an alternative location. The intact sediment samples obtained were subsequently divided horizontally into three depth layers: upper (0–5 cm), middle (5–10 cm), and lower (15–20 cm). Each sub-sample was placed in a plastic bag and stored in a cooler box for subsequent laboratory analysis.

Sediment organic carbon analysis was performed using the Loss on Ignition (LOI) method based on Howard et al. (2014). Sediment samples were first oven-dried in aluminium dishes at 60°C for 48 hours, then ground with a mortar until homogeneous. Approximately 2 g of each sample was then weighed, placed on aluminium foil, and combusted in a muffle furnace at 550°C for 4 hours. The combusted samples were subsequently reweighed to determine the percentage of organic carbon. To determine the carbon content in mangrove sediment, calculations were performed using the following equation based on BSN Standard 7724:2011:

$$C_t = K_d \times \rho \times \%C_{\text{organic}} (\text{g/cm}^2)$$

Description:

C_t = sediment carbon content (g/cm^3); K_d = sediment sample depth (cm); ρ = soil bulk density (gr/cm^3) $\%C_{\text{organic}}$= percentage of organic carbon

2.3.6. CO_2 sequestration

CO_2 sequestration can be calculated using a formula referring to Bismark et al. (2008), as follows:

$$SCO_2 = \frac{Mr.CO_2}{ArC} \times Kc$$

Description:

SCO_2= Carbon dioxide (CO_2) sequestration; $MrCO_2$ = Relative molecular weight of CO_2; equal to 44; Kc = Carbon content (kg); ArC = Relative atomic weight of carbon equal to 12

3. Result and Discussion

3.1. Water Quality

The measured water quality parameters at each station showed relatively similar values with no substantial differences. Temperature measurements at the Marine Station of Universitas Riau, Dumai, ranged from 30 to 31.4°C, with an average value of 30.6°C. This temperature range is considered suitable for supporting optimal mangrove growth (Table 4).

Table 4. Water quality parameters

Parameters	Station			Avg.
	1	2	3	
Temperature (℃)	30	31.4	30.6	30.6
pH	7.41	7.52	7.29	7.4
Salinity (‰)	16.6	21	24.6	20.7

3.2. Mangrove Species and Density

Mangrove species recorded across the three stations included *A. alba*, *A. marina*, *B. gymnorrhiza*, *C. tagal*, *E. agallocha*, *L. littorea*, *R. apiculata*, *R. mucronata*, *S. alba*, and *X. granatum*. The detailed distribution of these species is presented in Table 5.

Table 5. Distribution of mangrove vegetation

Species	Station		
	1	2	3
Avicennia alba	+	+	-
Avicennia marina	+	-	+
Bruguiera gymnorrhiza	+	+	-
Ceriops tagal	-	+	+
Excoecaria agallocha	-	+	+
Lumnitzera littorea	-	-	+
Rhizophora apiculata	+	+	+
Rhizophora mucronata	-	-	+
Sonneratia alba	+	+	-
Xylocarpus granatum	+	+	+

Description: + = Types of mangroves found; - = Types of mangroves that are not found

The highest mangrove density was recorded at Station 2, with 2,388.88 individuals/ha, which was higher than Station 1 (1,733.33 ind. ha^{-1}) and Station 3 (1,200 ind. ha^{-1}). The ecological characteristics of each site likely influenced this variation. Station 2, located along the riverbank, represents a transitional zone between terrestrial and aquatic environments and generally receives higher nutrient inputs that support optimal vegetation growth. Station 1, the area closest to the mainland, was relatively stable due to minimal tidal influence, resulting in the dominance of larger trees and a relatively high stand density. Meanwhile, Station 3 was located in the coastal zone, directly exposed to marine waters and thus experiencing more complex environmental pressures, including wave action, high salinity, tidal currents, and shipping activity. These conditions make Station 3 more vulnerable to degradation, which likely contributed to its lower mangrove density. This finding is in line with Susanto & Purnobasuki (2018), who stated that low mangrove density may indicate less favorable habitat conditions or ecosystem dynamics that limit population density.

Table 6. Mangrove density (Ind. ha^{-1})

Station	Mangrove density	Criteria	Condition
1	1,733.33	good	Very high
2	2,388.88	good	Very high
3	1,200	good	Middle
Average	1,774.07		

3.3. Mangrove Biomass

Biomass was recorded at Station 2, reaching 1,144.26 tons ha^{-1}, while the lowest biomass was found at Station 3, with 599.30 ton/ha. Differences likely influence the variation in biomass values among stations in stand density, where Station 2 exhibited the highest density, followed by Station 1 and Station 3. This condition is consistent with Irsadi et al. (2017), who stated that mangrove density is positively correlated with biomass content. Thus, higher stand density within a mangrove ecosystem corresponds to greater biomass storage, and vice versa. Overall, the total estimated mangrove biomass in the mangrove forest of the Universitas Riau Marine Station was 811.47 tons ha^{-1}.

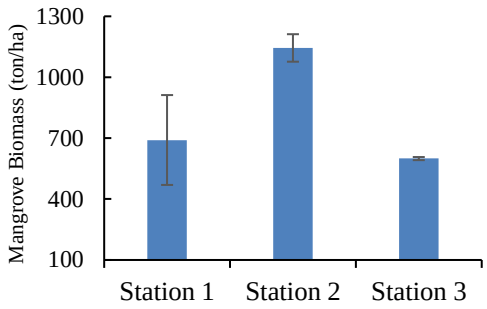

Figure 2. Mangrove biomass

3.4. Vegetation Carbon Stock

The highest mangrove vegetation carbon stock was recorded at Station 2, amounting to 537.80 tons ha^{-1}, while the lowest value was observed at Station 3, at 281.39 tons ha^{-1}. Differences primarily influenced this variation in stand density and total biomass among stations. Station 2 had the highest stand density and biomass, resulting in a greater carbon stock. This finding is consistent with Chanan (2012), who stated that forest biomass and carbon content are positively related, such that an increase in biomass follows any increase in carbon content. This result is also supported by Azzahra et al. (2020), who explained that mangrove vegetation carbon stock is strongly influenced by tree biomass, with higher biomass leading to greater carbon conversion. This indicates that the CO_2 sequestration capacity of mangrove stands is closely related to the amount of biomass stored. Efriyeldi et al. (2025) also state that the relationships among diameter, biomass, and carbon sequestration are directly proportional.

Station 2 exhibited the highest vegetation carbon stock because it was located near the river channel. This area represents a transitional zone influenced by both tidal processes and riverine input, making it relatively nutrient-rich compared in open coastal areas or locations closer to the mainland. As an estuarine zone, Station 2 receives inputs of organic matter, fine sediments, and nutrients from terrestrial runoff and river flow, which support optimal mangrove growth. This condition is consistent with the findings of Hickmah et al. (2021), who reported that the horizontal distribution of organic carbon is generally higher in locations near river channels. The percentage of organic carbon in stations located near river flow can even be up to five times greater than in locations farther from water flow. These findings underscore the important role of water sources and hydrological dynamics in supporting mangrove growth, biomass accumulation, and increased vegetation carbon stock.

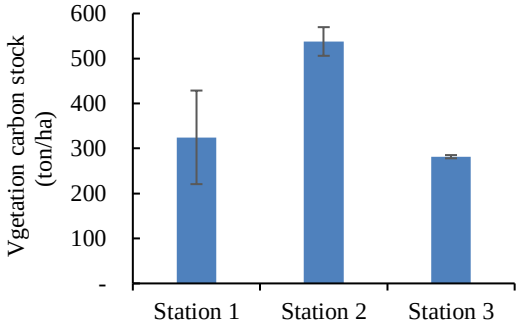

Figure 3. Vegetation carbon stock

3.5. Density and Carbon Stock Distribution by Species

R. apiculata was identified as the dominant species within the mangrove ecosystem of the Marine Station. This dominance may be attributed to its high adaptability to tidal environments, particularly in muddy, fine-textured, and permanently inundated soils. Such ecological tolerance enables the species to grow successfully under a wide range of hydrological and substrate conditions commonly found in mangrove habitats. This is consistent with the present findings, which recorded the occurrence of *R. apiculata* at all research stations despite differences in environmental characteristics among sites. Hidayatullah & Pujiono (2014) also reported that *R. apiculata* dominates across all growth stages due to its superior ability to adapt to environmental factors compared with other mangrove species.

The results indicate that *R. apiculata* had the highest density and the greatest carbon storage. This suggests that the species plays a dominant role in carbon sequestration at the study site. Its high values may be associated with the morphological characteristics of *R. apiculata*, which include a relatively large stem diameter and a complex root system. In contrast, *E. agallocha* and *L. littorea* exhibited relatively low density and carbon storage values. This indicates that the contribution of these two species to the total ecosystem carbon stock is smaller. Their lower carbon storage may be attributed to smaller tree size or slower growth rates compared with those of the dominant species. Although the overall results showed a nearly linear pattern, several species, such as *X.*

granatum and *C. tagal*, with moderate to high densities also demonstrated considerable carbon storage. This confirms that, in addition to density, stem diameter (DBH), tree height, and wood type (wood density) strongly influence biomass and stored carbon.

Table 7. Distribution of density and carbon stock

Species	Station 1		Station 2		Station 3	
	Density (Ind. ha^{-1})	Carbon stock (tons ha^{-1})	Density (Ind. ha^{-1})	Carbon stock (tons ha^{-1})	Density (Ind. ha^{-1})	Carbon stock (tons ha^{-1})
A. alba	-	-	266.67	40.60	-	-
A. marina	233.33	34.63	-	-	100	17.49
B.gymnorrhiza	44.44	2.04	300.00	61.32	-	-
C. tagal	-	-	222.22	71.26	166.67	35.86
E. agallocha	-	-	33.33	4.80	44.44	3.61
L. littorea	-	-	-	-	133.33	47.89
R. apiculata	1,222.22	222.56	1,055.56	104.81	522.22	29.29
R. mucronata	-	-	-	-	88.89	39.32
S. alba	77.78	10.43	133.33	28.71	-	-
X. granatum	155.56	55.04	377.78	226.30	144.44	108.21
Total	1,733.33	324.70	2,388.89	537.80	1200.00	281.67

3.6. Sediment Organic Carbon Stock

Sediment carbon stock at each station was recorded at 2,202.97 tons ha^{-1} for Station 1, 2,021.48 tons ha^{-1} for Station 2, and 1,896.10-tons ha^{-1} for Station 3. This pattern differs from stand density, biomass, and vegetation carbon stock, which consistently showed the highest values at Station 2. The higher sediment carbon stock at Station 1 is likely influenced by its finer sediment texture compared to the other stations. According to Wahyuningsih et al. (2020), sediment grain size plays an important role in the ability of sediment to bind organic matter, with finer-textured sediments tending to be more effective in absorbing and storing organic carbon.

The results of sediment fraction analysis using the Shepard triangle showed that Station 1 was classified as sandy mud, Station 2 as gravelly mud, and Station 3 as mixed sediment (gravel, sand, and mud). Thus, Station 1, which had the finest sediment texture, exhibited a greater capacity for organic carbon storage. These findings are also consistent with Hickmah et al. (2021), who stated that mangrove vegetation productivity generates organic matter from leaf litter, twigs, and other fallen plant parts, which subsequently decompose and become a source of organic carbon in sediment. Litter that falls onto the soil surface accumulates and becomes part of the sediment layer, thereby increasing organic carbon content. The magnitude of sediment organic carbon storage is influenced not only by organic matter input from vegetation but also by sediment grain size, which determines the sediment's capacity to retain organic material. In this context, Station 1 had more favorable conditions for organic carbon accumulation due to its finer sediment texture.

Sediment organic carbon storage is an important component of mangrove ecosystems because the majority of mangrove carbon reserves are stored below ground. This is in line with Sulistyorini et al. (2020), who stated that mangrove forests store carbon both above and below the soil surface, with the largest proportion generally occurring as soil organic carbon (SOC). The high sediment carbon stock observed in this study underscores the important role of mangrove ecosystems in absorbing and storing atmospheric carbon, thereby mitigating global warming and climate change.

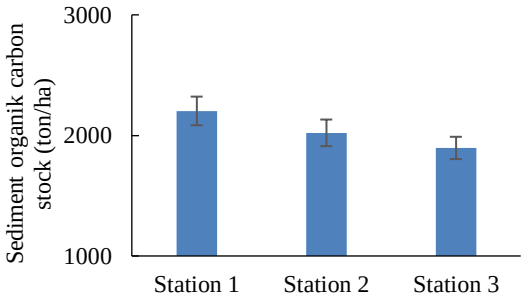

Figure 5. Sediment organic carbon stock

3.7. Total Carbon Stock

The distribution of carbon stocks at the Marine Station of Universitas Riau, Dumai, is considered significant, with an average total of 2,421.64 tons/ha. This value indicates a very high carbon storage potential, suggesting that the mangrove ecosystem is in an optimal condition with a substrate rich in organic matter. The high carbon accumulation in the sediment (1,896.10–2,202.97 tons/ha) confirms that mangroves function as highly efficient blue carbon ecosystems. Sediments act as long-term carbon storage due to waterlogged (anaerobic) conditions that inhibit litter decomposition, allowing carbon to be trapped in the soil rather than released into the atmosphere.

In addition, a pH range of 7.29–7.41 supports the growth of decomposer microorganisms (Destiana & Darwati, 2021), thereby enabling optimal decomposition processes.

Variations in vegetation carbon among stations, particularly at Station 2 (537.80 tons/ha), are influenced by community structure, density, and stem diameter. This indicates that vegetation density is directly proportional to the capacity for CO_2 absorption through photosynthesis, which is subsequently converted into biomass. Overall, the high carbon stock highlights the importance of conserving this area. Ecosystem degradation would not only reduce carbon sequestration capacity but also has the potential to release stored sediment carbon into the atmosphere, thereby accelerating global warming.

Table 8. Total carbon stock

Station	Carbon stock (tons ha^{-1})		Total
	vegetation	sediment	
1	324.70	2.202.97	2.527.67
2	537.80	2.021.48	2.559.28
3	281.87	1.896.10	2.177.97
Average			2.421.64

3.8. CO_2 sequestration

Based on the research findings, the highest CO_2 sequestration was recorded at Station 2, with 1,971.94 tons ha^{-1}, while the lowest was observed at Station 3, with 1,032.79 tons ha^{-1}. This difference indicates that CO_2 sequestration is influenced by stand density at each sampling transect. However, other factors such as tree age and diameter at breast height (DBH) also play important roles. Vegetation at Station 1 had an average diameter of 10.25 cm, whereas Station 3 had an average diameter of 9.7 cm. This suggests that Station 3 was dominated by younger stands, which generally have higher carbon uptake capacity. Species composition also contributed to the CO_2 sequestration pattern observed at Station 3. Compared with Station 1, Station 3 contained species with relatively higher sequestration capacity, such as *C. tagal* and *L. littorea*, whose estimated CO_2 uptake was nearly four times greater than that of *R. apiculata*. Such differences are largely influenced by species-specific allometric equations, growth characteristics, and wood density values, which determine the amount of biomass and carbon that can be stored.

Utami et al. (2023) stated that stem carbon content increases significantly with increasing DBH and tree age, emphasizing the importance of stand maturity in long-term carbon accumulation. Furthermore, carbon stocks in mangrove ecosystems are influenced by multiple environmental factors, including stand density, climatic conditions, topography, soil characteristics, nutrient availability, and vegetation age. Therefore, although Station 3 had lower stand density than Station 1, its estimated CO_2 sequestration remained relatively comparable. Overall, the average CO_2 sequestration at the Marine Station of Universitas Riau, Dumai City, was 1,398.44 tons ha^{-1}.

3.9. Relationship between Vegetation Density, Mangrove Biomass, Carbon Stock, and CO_2 Sequestration

Based on the statistical analysis, the correlation coefficients (r) for the relationships between mangrove density and biomass, carbon stock, and CO_2 sequestration were 0.799, 0.799, and 0.799, respectively. According to the correlation interpretation criteria, these values indicate a strong positive relationship. This suggests that increases in mangrove stand density are significantly associated with corresponding increases in biomass, carbon stock, and CO_2 sequestration at the study site. Higher stand density generally reflects a greater number of trees per unit area, contributing to greater biomass accumulation and enhanced carbon storage capacity. As biomass increases, the amount of carbon retained within vegetation tissues also rises, thereby improving the ecosystem's ability to absorb and sequester atmospheric CO_2 through photosynthesis.

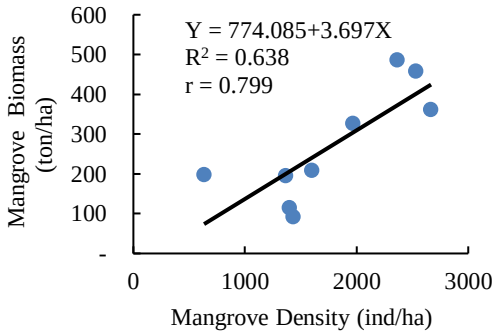

Figure 6. Relationship between mangrove density and biomass

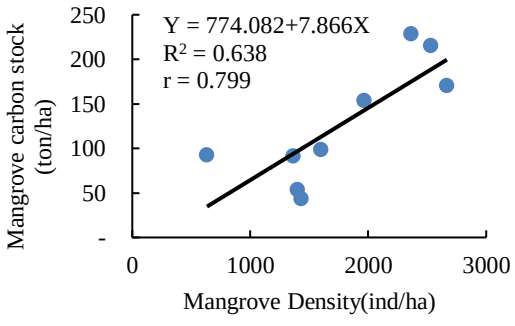

Figure 7. Relationship between mangrove density and carbon stock

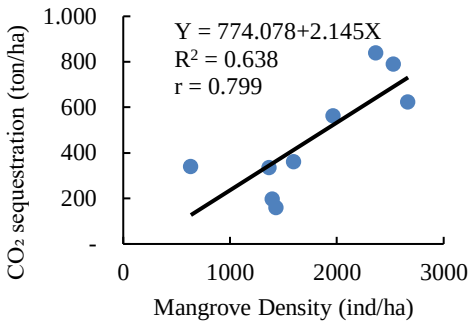

Figure 8. Relationship between mangrove density and CO_2 sequestration

The coefficient of determination analysis shows that stand density accounts for 63.8% of the variability in biomass, carbon stock, and CO_2 sequestration. In comparison, other external factors beyond the scope of density influence the remaining 36.2%. This finding is consistent with Salsabilla et al. (2025), who reported that carbon accumulation in forest ecosystems is also affected by additional parameters, including stand age, substrate or sediment fertility, and planting distance. These results confirm that mangrove density is a primary factor influencing biomass, carbon stocks, and CO_2 sequestration in the mangrove ecosystem at the study site. Higher stand density enhances the vegetation's capacity to accumulate biomass through growth and tissue formation. This increase in biomass directly contributes to greater carbon storage in plant tissues, as carbon is a primary product of photosynthesis and is stored in stems, branches, leaves, and roots. Consequently, increases in carbon stock are directly proportional to CO_2 sequestration capacity, since the stored carbon originates from the uptake of atmospheric carbon dioxide during photosynthesis.

4. Conclusions

Based on the research findings, the estimated mangrove biomass, mangrove carbon stock, sediment organic carbon stock, and CO_2 sequestration were 811.47 tons ha^{-1}, 381.39 tons ha^{-1}, 1,398.44 tons ha^{-1}, and 2,040.18 tons ha^{-1}, respectively. The total carbon stock reached 2,421.64 tons ha^{-1}, with the highest value recorded at Station 2 (2,559.28 tons ha^{-1}). These results indicate that the study area has high carbon storage potential in both vegetation and sediment, highlighting its important role in climate change mitigation through blue carbon storage. A positive relationship was also found between mangrove stand density and total carbon stock, biomass, and CO_2 sequestration. The correlation coefficient (r) was 0.708, indicating a strong association. Vegetation density accounted for 50% of the variability in biomass, vegetation carbon stock, and CO_2 sequestration, confirming its importance as a key factor influencing carbon storage capacity in mangrove ecosystems.

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