

Carbon stock and biomass of Baluno Mangrove Forest ecosystems in West Sulawesi, Indonesia

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Manuscript received: 1 July 2024. Revision accepted: 16 September 2024.

Abstract. Carong SR, Anwar A, Ahmed Y, Arbit NIS, Mannan A, Rusmidin, Anwar T, Rimbawan F. 2024. Carbon stock and biomass of Baluno Mangrove Forest ecosystems in West Sulawesi, Indonesia. *Biodiversitas* 25: 3067-3074. Global warming, fueled by rising CO₂ levels, threatens life on earth. Mangrove ecosystems, with their high CO₂ absorption capacity, are crucial in climate mitigation efforts. This study aims to identify the attributes of mangrove biomass, quantify carbon stock, and assess the capacity of above-ground biomass (including trees, saplings, and seedlings) and soil to sequester carbon. Carbon stock measurements were conducted in the Baluno Mangrove Forest conservation area which is under the management of the *Yayasan Peduli Pengembangan Masyarakat Desa* (YPPMD). The sampling strategy employed was stratified proportionate random sampling. The research area is partitioned into multiple strata of mangrove forest vegetation density. The study area consists of 25 plots, each measuring 20x20 (400 m² soil samples are collected using a soil core to a certain depth, typically up to 30 cm or more. The samples are then analyzed in a laboratory to determine the organic carbon content. Therefore, the total area covered by the plots is 10,000 m², which is equivalent to 1 hectare. The Baluno Mangroves have a total biomass of 1,558.15 tons/ha. The species with the highest biomass was *Sonneratia* sp., with a value of 30.81 tons. Conversely, the species having the lowest biomass was *Bruguiera gymnorrhiza*, with a value of 0.0625 tons. The Baluno Mangrove area has an average carbon stock of 989.04 tons per hectare, with the potential to absorb 3,629.79 tons of CO₂ per hectare. In conclusion, Baluno Mangroves store 58,719.57 metric tons of carbon, with *Sonneratia* sp. as the largest contributor, emphasizing the vital role of Indonesia's mangroves in global carbon sequestration and climate mitigation.

Keywords: Baluno mangrove, global warming, mangrove biomass, soil carbon stock, West Sulawesi

INTRODUCTION

Global warming is a critical environmental issue that has gained global attention due to its impacts on life on earth. The primary drivers of global warming are increasing concentrations of greenhouse gases like carbon dioxide (CO₂), methane (CH₄), and chlorofluorocarbons (CFCs) (Gadagbui and Onyema, 2023; Dilmore and Zhang, 2018). CO₂ emissions have the greatest impact on temperature rise compared to other greenhouse gases. The level of CO₂ in the atmosphere has been increasing at an average rate of approximately 2.5 parts per million (ppm) annually in the past decade, and this pace is anticipated to accelerate in the future (NOAA 2023).

The rise in CO₂ emissions is directly correlated with the increase in temperature. Under the United Nations Framework Convention on Climate Change (UNFCCC), the COP 21 agreement requires 195 countries to adhere to legally binding climate agreements. These agreements aim

to limit the global temperature increase to around 2°C, with a preference for keeping it below 1.5°C by the year 2100 (UNFCCC 2020). However, recent data highlights the urgency of this goal. According to research from the International Monetary Fund (IMF), CO₂ concentrations in the global atmosphere reached 420.99 parts per million (ppm) by May 2022, marking an 11.95% increase since 2015 (IMF 2022). This significant rise underscores the critical need for research focused on carbon sequestration and mitigation strategies, such as the study of mangrove ecosystems, to meet global climate targets. One solution to global warming is to reduce CO₂ using plants. Plants have the ability to perform photosynthesis, assimilating CO₂ into energy-rich compounds (carbohydrates) (O'Brien et al. 2022). The methods used to control excess CO₂ include carbon capture (Ngu 2024) and carbon sinks (Li et al. 2018). Mangrove is a plant with a significant capacity for carbon dioxide (CO₂) storage and absorption (Rudianto et al. 2019; Dinilhuda et al. 2020; Banerjee et al. 2021).

According to Cusack et al. (2018), mangrove ecosystems possess the capacity to absorb carbon at a rate that is four times higher than terrestrial, swamp, and seagrass environments. Mangroves store carbon in their biomass, specifically in stands (Nuraini et al. 2021), sediments (Rudianto et al. 2019), stems, and leaves (Bachmid et al. 2018). Consistent with prior studies, it was shown that Indonesian mangroves absorb an average of 313.52 tons of carbon per hectare. The mean soil carbon stocks were recorded at 1819.31 tons/ha, while the average amount of CO₂ absorbed by the soil was 1074.99 tons/ha. (Handoyo et al. 2020).

Our research on the carbon absorption capacities of different mangrove species has significant implications for climate change and conservation efforts. For instance, the *Nypa fruticans* species, thriving in various Southeast Asian mangrove ecosystems, has a carbon sequestration capacity of 21.82 tons of carbon per hectare and can absorb up to 80.02 tons of CO₂ per hectare. The species *Rhizophora mucronata*, commonly found in Indonesian mangroves, has a carbon saving of 19.94 tons C/ha and can absorb 73.13 tons of CO₂/ha. The species *Avicennia alba*, typically found in the Indo-West Pacific region, has a carbon saving of 53.96 tons C/ha and can absorb 197.87 tons of CO₂/ha (Rahman et al. 2017). Azzahra et al. (2020) further support these findings, reporting that *Avicennia marina* (Forssk.) Vierh. and *Rhizophora mucronata* Lam. in Indonesian mangroves hold a carbon content of 190.257 tons carbon per hectare in their stands, 480.608 tons carbon per hectare in the sediments, and 0.00165 tons carbon per hectare per day in the mangrove leaf litter.

The Baluno Mangrove area is 59.37 hectares and extends from Binanga Village, Totolisi Village, to Palipi Village in Majene District, West Sulawesi Province (Baluno Mangrove). The Baluno Mangroves exhibit a wide

range of mangrove species and are currently under the supervision of the Mangrove Learning Center. Studying the carbon storage and uptake of mangroves in this area is crucial for determining the amount of biomass and carbon absorbed by the mangrove forest. This information is essential for supporting sustainable management efforts in the region, particularly in reducing CO₂ levels within the atmosphere. The study aimed to analyze the attributes of mangrove biomass and assess the capacity for carbon sequestration in mangrove stands and substrates.

MATERIALS AND METHODS

Study area

This research will use data on biomass, tree density, stands, sediment, and mangrove leaf litter. Stationery, calipers, clinometers, GPS, roll meters, sample bags, and work maps will also be used. In the laboratory, ovens, analytical balances, crucibles, and porcelain were used for testing. The research location is a conservation area in the form of a mangrove forest under the management of the Mangrove Learning Center. Geographically, the area is located at 3° 20' 20.451" S, 118° 50' 39.412" E. Data collection covers the area from Binanga, Totolisi, and Palipi Villages, West Sulawesi Province (Figure 1).

Procedures

Vegetation data collection method

Data gathering approaches were conducted using primary and secondary surveys. The primary survey involved observation and field measurements. Simultaneously, the secondary survey involved a thorough examination of documents acquired from relevant agencies.

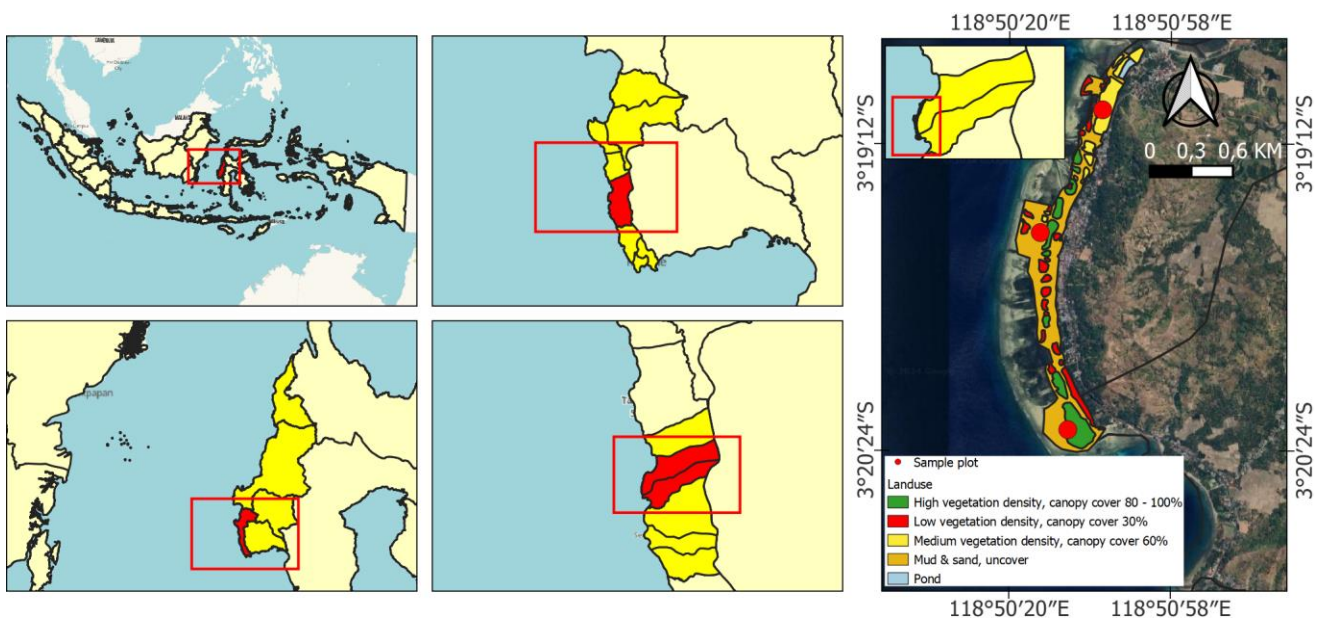


Figure 1. Location of research data collection of Binanga, Totolisi, and Palipi Villages, West Sulawesi Province, Indonesian

Data was collected by conducting a primary survey, namely through field observations, by capturing the existing conditions in the field. Observations were made about the biomass and potential carbon sequestration of species in the Baluno Mangrove Forest area. Field measurements were conducted to gather diameter and height data for both tree and sapling categories. In addition, data were collected regarding the number of seedlings, the cumulative weight of the seedlings when wet, and the soil where the mangroves grow. The data were examined to determine the biomass and carbon sequestration capacity in the research region.

Plants are classified based on their size and type. There are four categories: (i) seedlings, which are tillers that are sprouts or less than 1.5 m tall; (ii) saplings, which are tillers with a height between 1.5 m and a diameter less than 5 cm; (iii) trees, which are plants with a diameter of 5 cm or more; and (iv) understorey, which includes plants like grass, herbs, and shrubs, excluding mangrove seedlings. Each meeting was subject to observations.

Biomass measurement

Above surface biomass measurement

The determination of above-ground biomass was conducted using a non-destructive sampling method to measure trees and saplings, employing the appropriate allometric equations. The first step involved measuring parameters that can be used to estimate biomass, such as diameter, total height, and wet weight in the field. These parameters were essential for applying the allometric equations accurately. Table 1 shows the plot and sub-plot dimensions used for plant categorization, which provided the framework for the categorization of different plant sizes during the biomass assessment. Table 2 provides the specific

allometric equations used for various types of mangrove trees.

Measurement of seedlings and undergrowth

Estimation of seedling and understorey biomass using the total wet weight parameter. The measurement method is to cut all the seedlings (saplings <2.5 cm in diameter) without including the roots found in the 2×2 m plot. Furthermore, the wet weight was weighed, and samples weighing 250-300 grams were taken. The samples were brought to the laboratory, and the samples were dried in an oven at a temperature of 75°C for 3×24 hours (Kauffman and Donato 2012)

$$\text{Total dry weight (g)} = \frac{\text{Sample dry weight (g)}}{\text{Sample wet weight (g)}} \times \text{Total wet weight (g)}$$

Soil biomass calculation

The Walkley-Black method is used to measure the organic carbon content in soil. The process begins by adding a potassium dichromate solution and concentrated sulfuric acid to a weighed soil sample. This reaction oxidizes the organic material in the soil. After a 30-minute incubation, the mixture is titrated using a ferrous ammonium sulfate solution until the color changes to pink or light orange, indicating the titration endpoint. The organic carbon content is then calculated based on the difference in titrant volume between the sample and blank control. The calculation of soil carbon (Ct) is as follows:

$$\text{SOC (\%)} = [(B-S) \times N \times 0.003 \times f \times 100] / \text{sample weight (g)}$$

Where: B: volume of ferrous ammonium sulfate used for the blank titration (mL); S: volume of ferrous ammonium sulfate used for the sample titration (mL); N: normality of ferrous ammonium sulfate; f: correction factor (usually around 1.3).

Table 1. Plot and sub-plot dimensions for plant categorization

Plant categorization	Plot size (m)	Sub-plot size (m)	Number of plots	Total area (m ²)
Seedlings and Understorey	2×2	2×2	25	100 (25×4)
Saplings	5×5	5×5	25	625 (25×25)
Trees	20×20	20×20	25	10,000 (25×400)

Note: The total area covered by plots was 10,000 m² (equivalent to 1 hectare)

Table 2. Allometric equations of several types of mangroves

Species	Biomass allometric method	Specific gravity (ρ)
Tree		
<i>Aegiceras corniculatum</i> (L.) Blanco	AGB = 0.199 x ρ ^{0.899} x DBH ^{2.22} (Komiyama et al. 2008)	ρ = 0.51
<i>Ceriops tagal</i> (Perr.) C.B.Rob.	AGB = 0.251 x ρ x DBH ^{2.46} (Komiyama et al. 2005)	ρ = 0.97
	AGB = 0.199 x ρ ^{0.899} x D ^{2.22} (Komiyama, Ong and Pongpam, 2008)	ρ = 0.746
<i>Sonneratia</i> sp.	AGB = 0.3841x DBH ^{2.101} x ρ (Kauffman and Donato 2012)	ρ = 0.078
	AGB = 0.184 x DBH ^{2.3524} x ρ (Indrayani et al.2021)	
	AGB = 0.258*DBH ^{2.287} (Kusmana and Sukristijiono. 2016)	
<i>Rhizophora mucronata</i> Lam.	AGB = 0.043 x DBH ^{2.63} (Santos et al. 2009)	ρ = 0.792
	AGB = 0.199 x ρ ^{0.899} DBH ^{2.22} (Komiyama et al. 2008)	ρ = 0.701
<i>Rhizophora stylosa</i> Griffith	AGB = 0.235 x DBH ^{2.42} (Gevana and Im et al. 2016)	
	AGB = 0.261 x DBH ^{1.86} (Komiyama 2008)	
<i>Rhizophora apiculate</i> Blume	AGB = 0.043 x DBH ^{2.63} (Kauffman and Donato 2012)	ρ = 1.050
<i>Avicennia marina</i> (Forssk.) Vierh.	AGB = 0.1848 x DBH ^{2.3524} (Dharmawan and Siregar 2008 in Kauffman and Donato 2012)	ρ = 0.650
	AGB = 1.28 x DBH ^{1.17} (Komiyama et al. 2008)	
<i>Bruguiera gymnorrhiza</i> (L.) Lam.	AGB = 0.0754 x DBH ^{2.505} x ρ (Komiyama et al. 2005)	ρ = 1.052
Sapling	AGBs = exp (-3.068 + 0957 ln (DBH ² x H) (Honzak et al. 1996 in Sutaryo 2009)	

Calculation of carbon storage and carbon capture

The carbon content in organic materials is 47%. The calculation of carbon stored in the biomass of trees, saplings, and seedlings can be determined by multiplying the biomass value (B) by 0.47, as shown in the following equation (Martin and Thomas 2011; Thomas and Martin 2012):

$$C = B \times 0.47$$

Where:

C: total carbon stock (tons)

B: biomass

The total carbon stock in the research plot area is determined by summing the carbon content of all trees, saplings, seedlings, and soil substrate. This can be determined using the following formula:

C plot = C tree (vegetal carbon) + C sapling (vegetal carbon) + C seedling (vegetal carbon) + C substrate (soil carbon)

The absorption potential of carbon dioxide gas (CO₂) is determined by multiplying the carbon content by the amount of carbon dioxide (CO₂) absorption using the specified formula:

$$WCO_2 = C \times FKCO_2$$

Where:

WCO₂: The amount of CO₂ absorbed (ton)

C: Carbon in vegetal biomass and soil (ton)

FKCO₂: Conversion factor of element carbon (C) to CO₂ = 3.67

RESULTS AND DISCUSSION

Mangrove species biomass at the research site

The computation results indicated that the highest overall tree biomass value identified in the *Sonneratia* sp. is 30,811.06 kg. The biomass of *R. mucronata* is 14,444.27 kg, *Rhizophora stylosa* Griffith is 10,152.54 kg, *Aegiceras corniculatum* (L.) Blanco is 5,422.61 kg, *Rhizophora apiculata* Blume is 1,132.21 kg, *A. marina* is 215.39 kg, *Ceriops tagal* (Perr.) C.B.Rob. is 85.40 kg, and *Bruguiera*

gymnorhiza (L.) Lam. is 62.50 kg. The Mangrove Baluno stands biomass map is presented in Figure 2.

The carbon stock calculated in this study is relatively high (62.33 tons/ha) in comparison to the results of Suryono et al. (2018) in the Perancak-Jembrana Mangrove, Bali. However, it is lower than the results reported by Murdiyarso et al. (2015), Kusumaningtyas et al. (2019), Suryono et al. (2018), and Dewi (2020) (Table 3). The value of 62.33 tons/ha represents the mean carbon stock in the vegetal biomass alone. This is considered a high value for vegetation, as general carbon stock values that include all compartments (vegetal biomass, soil, and other substrates) are typically higher. In Bintuni Bay, the high carbon stock is attributed to the relatively undisturbed condition of the mangroves, which is relatively undisturbed and has experienced little human interference, such as the use of mangrove wood (Murdiyarso et al. 2015). The lower average carbon stock observed at the study site indicates a decline in mangrove health, serving as a stark reminder of the potential impact of human activities such as encroachment and land conversion around Totolisi, a densely populated area. However, it's crucial to acknowledge that carbon stock is also positively correlated with both the quantity and density of vegetation. Therefore, the lower carbon stock in this study could also be influenced by the lower vegetation density compared to other sites. Further comparison with recent studies that consider vegetation density, such as Andini et al. (2024), Chaudhary and Aryal (2024) revealed that edaphic, physical and topographic factors affect tree and soil carbon stocks, improving understanding of carbon storage dynamics.

Carbon content, total carbon, and carbon sequestration

The biomass calculation reveals that trees have an average carbon content of 29.29 tons/ha, saplings have a carbon content of 1.61 tons/ha, seedlings have a carbon content of 0.05 tons/ha, and the soil has a carbon content of 958.50 tons/ha. The carbon yield obtained is 989.04 tons/ha, while the estimated carbon absorption by mangroves in Baluno is 3629.79 tons/ha. The study presents a comparison of the carbon stock of trees, saplings, seedlings, soil, total carbon, and carbon uptake observed at the study site in Table 4. Figure 3 shows a map of carbon stocks in the Baluno Mangrove area, Majene District, West Sulawesi Province.

Table 3. Comparison of carbon stock in mangrove biomass

Reference	DBH range (cm)	Average carbon stock biomass (tons/ha)	Location
(Murdiyarso et al. 2015)	Tall tree	367.2	Bintuni
(Suryono et al. 2018)	Highest 15	47.93	Jembrana, Perancak Bali
(Kusumaningtyas et al. 2019)	>50	615	Berau, East Kalimantan
(Dewi 2020)	5-12	127.94	Tanjung Batu, Derawan Islands
Study results (2021)	5-26	62.33	Baluno, Sendana, Majene District



Figure 2. Mangrove Baluno stands for biomass map

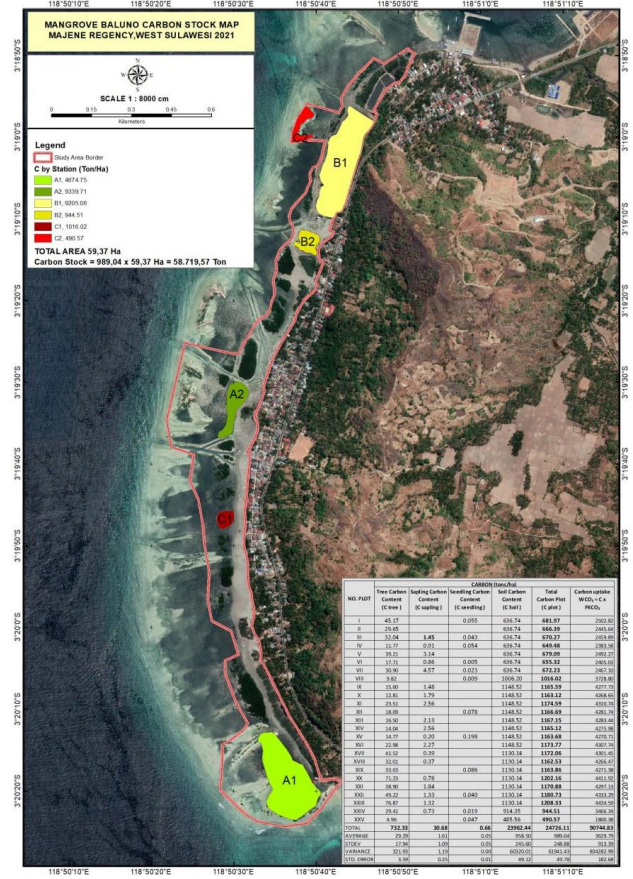


Figure 3. Mangrove Baluno carbon stock map

Table 4. Carbon content, total carbon, and carbon sequestration

No. plot	Carbon (tons/ha) C plot					Carbon uptake WCO ₂ = C x FKCO ₂
	Tree carbon content (C tree)	Sapling carbon content (C sapling)	Seedling carbon content (C seedling)	Soil carbon content (C soil)	Total carbon plot (C plot)	
1	45.17	-	0.055	636.74	681.97	2502.82
2	29.65	-	-	636.74	666.39	2445.64
3	32.04	1.45	0.043	636.74	670.27	2459.89
4	11.77	0.91	0.054	636.74	649.48	2383.58
5	39.21	3.14	-	636.74	679.09	2492.27
6	17.71	0.86	0.005	636.74	655.32	2405.03
7	30.90	4.57	0.023	636.74	672.23	2467.10
8	9.82	-	0.009	1006.20	1016.02	3728.80
9	15.60	1.48	-	1148.52	1165.59	4277.73
10	12.81	1.79	-	1148.52	1163.12	4268.65
11	23.51	2.56	-	1148.52	1174.59	4310.74
12	18.09	-	0.078	1148.52	1166.69	4281.74
13	16.50	2.13	-	1148.52	1167.15	4283.44
14	14.04	2.56	-	1148.52	1165.12	4275.98
15	14.77	0.20	0.198	1148.52	1163.68	4270.71
16	22.98	2.27	-	1148.52	1173.77	4307.74
17	41.52	0.39	-	1130.14	1172.06	4301.45
18	32.01	0.37	-	1130.14	1162.53	4266.47
19	33.63	-	0.086	1130.14	1163.86	4271.38
20	71.23	0.78	-	1130.14	1202.16	4411.92
21	38.90	1.84	-	1130.14	1170.88	4297.13
22	49.22	1.33	0.040	1130.14	1180.73	4333.29
23	76.87	1.32	-	1130.14	1208.33	4434.59
24	29.41	0.73	0.019	914.35	944.51	3466.34
25	4.96	-	0.047	485.56	490.57	1800.38

Discussion

The research findings indicating that each hectare of land in Baluno, Sendana, Majene District can store approximately 62.33 tons of carbon per hectare in the form of living biomass represents a highly significant discovery, as shown in Table 3. Biomass refers to the collective organic matter produced during the process of photosynthesis, which plants utilize for both horizontal and vertical growth. According to Azzahra et al. (2020), as the diameter of trees increases due to the conversion of biomass, the amount of CO₂ stored by the trees and the number of CO₂ molecules absorbed from the atmosphere both increase. Secondary growth occurs as a result of the activity of the cambium, leading to an increase in stem diameter and, consequently, an increase in stem biomass. Additionally, research on long-term CO₂ enrichment in Duke Forest revealed a 21% increase in above-ground biomass, with further increases when considering changes in tree allometry, indicating that trees grew taller at a given diameter under elevated CO₂ conditions (Kim et al. 2020). These findings underscore the critical role of trees in absorbing CO₂ from the atmosphere, thereby promoting the removal of this greenhouse gas. This process enhances biomass accumulation and carbon sequestration capabilities, highlighting the importance of tree growth in mitigating elevated CO₂ levels.

The biomass content within a given region is directly correlated with tree density, where a higher number of trees results in increased biomass. The quantity of trees influences the variation in biomass across different diameter classes in each diameter category. The value of biomass is influenced not only by the number of trees but also by the diameter of each tree; specifically, the biomass grows as the tree's diameter expands. Typically, the tree with the greatest diameter has the most biomass for each area of the tree (Dutcă and Mcroberts 2024). This pertains to the process of photosynthesis, in which plants assimilate carbon dioxide (CO₂) and transform it into organic compounds. The products of photosynthesis are stored in various components of trees and utilized for both radial and vertical growth. The tree trunk, being the woody portion, serves as the primary storage site for photosynthetic reserves.

The total value of tree biomass is 62,325.98 kg, with the highest biomass potential in *Sonneratia* sp., i.e., 30,811.06 kg. The species *Sonneratia* sp. has the largest average tree diameter in Figure 2. The biomass amount was determined by the tree's diameter, height, and density of the tree/wood (Lembang et al. 2019; Billard et al. 2020; Song et al. 2023), and the lowest was on the *B. gymnorhiza* tree, which was 62.50 kg. This is because the average diameter of *B. gymnorhiza* trees is small, and very few of them are found at the study site. Total carbon (C) stored in the Baluno Mangrove Forest area amounted to 989.04 tons/ha, with an estimated potential for absorption of carbon dioxide (CO₂) in the mangrove trees amounted to 3,629.79 tons/ha. Based on the result known in the mangrove ecosystem, carbon storage and capture potential, Baluno CO₂ is still relatively large. This is because the density of mangrove species is relatively high, and the mangroves' diameter directly

influences biomass and carbon sequestration. Other factors also contribute to these high values. Among them, the soil plays a significant role in carbon storage. Therefore, it would be worthwhile to investigate further what unique features of the mangrove ecosystem make it so efficient at storing carbon in the soil. However, it's important to note that this potential remains significant even when considering different landscapes. Some plots were established in areas with low vegetational coverage, and the value presented here is an average across all surveyed areas. Therefore, variations in vegetational coverage should be considered when interpreting the carbon sequestration potential measured in this region.

Sonneratia sp. is a species of mangrove that exhibits the highest carbon absorption among other species in this research area due to its superior biomass content. There is a direct correlation between carbon and biomass, and the amount of biomass in trees has a significant impact on the capacity to store carbon. It's important to highlight that the higher biomass presented by *Sonneratia* sp. is not only due to its high carbon absorption ability but also potentially related to its massive presence in the area. Mangroves, including *Sonneratia* sp., can hold up to four times more carbon per hectare than tropical forests, underscoring their critical role in carbon capture and climate change mitigation (Indriyani et al. 2020). The detail is that the high biomass of *Sonneratia alba*, supported by tree density and diameter, results in substantial carbon and CO₂ storage (Tupan and Lailossa 2019). This aligns with findings from (Harefa et al. 2024), who reported significant carbon storage in *S. alba* restoration areas. Amalia et al. (2021) further demonstrate the high CO₂ absorption capacity of mangrove stands in specific reserves, while Hadi et al. (2019) emphasize the high carbon storage contribution of *S. alba* compared to other mangrove species. All factors that influence biomass will also have an impact on carbon storage in a stand, albeit indirectly. Several factors, including stem diameter, individual density, tree species variety, and soil type, influence the biomass of an ecosystem. Additionally, solar incidence and rainfall patterns also play a crucial role in determining biomass, as they directly impact the growth and health of vegetation. These factors combined contribute to the overall biomass and, consequently, the carbon sequestration potential of the ecosystem. The density of trees in a given area has a direct impact on the rate at which carbon stocks rise, primarily due to the corresponding increase in biomass (Lembang et al. 2019).

The Baluno Mangrove vegetation shows a fairly healthy and dynamic population structure. This is characterized by various growth rates for each type of mangrove tree found, such as trees, seedlings, and saplings (Djamiluddin 2019). This statement is in line with the results of observations in this study, which found various levels of categories of seedlings (saplings), saplings, and trees in 1 observation plot and the surrounding area. In this study, the seedlings and saplings were categorized as DBH <5 cm, and the tree category was classified as DBH >5 cm. This can be used as an indication that the process of mangrove regeneration ability in Baluno is still going quite well.

The laboratory study results indicate a positive correlation between the organic carbon value and the carbon content of the soil substrate. The significant presence of organic carbon at the research site is closely linked to the role of soil organic matter. The dynamic nature of Soil Organic Carbon (SOC) plays a vital role in contributing to ecosystem services. Organic matter and carbon have a proportional relationship in soils, and their presence often indicates ongoing burial processes. Environmental conditions, such as salt levels and flooding in mangrove ecosystems, are particularly conducive to burying carbon in the soil, leading to the formation of long-term carbon deposits. These conditions make mangrove soils highly efficient in storing carbon. It is worth noting that Indonesia's soil carbon stock is among the highest in the world, further emphasizing the significance of understanding and preserving these critical ecosystems. A more detailed discussion on the soil carbon stock in mangroves, particularly in the Indonesian context, would provide valuable insights into their global importance for carbon sequestration (Donato et al. 2011; Murdiyarso et al. 2015; Pouyat et al. 2020).

Carbon stock refers to the process of carbon (C) accumulation in living plants, known as carbon sequestration (C sequestration). This process involves the storage of CO₂ from the atmosphere in the bodies of plants on land, as described by Rudianto et al. (2019). The carbon stock will experience an increase as the quantity of biomass present directly influences it. As the amount of biomass increases, so does the amount of carbon stored.

In theory, the carbon stock is comprised of biomass. Therefore, in practice, the carbon stock increases as the tree biomass increases. The analysis of carbon stock in mangrove biomass (Table 2) in this study reveals a strong correlation between carbon stock and biomass. Mangrove tree biomass exhibits the highest carbon composition, mostly due to its substantial Diameter at Breast Height (DBH) (Dinilhuda et al. 2020). In summary, this study demonstrates a positive correlation between biomass and carbon stock, indicating that an increase in biomass leads to a corresponding increase in carbon storage. However, it is important to note that biomass is not the sole contributor to carbon stock. The soil also plays a crucial role, often accounting for a substantial share of the overall carbon stored in the ecosystem. In mangrove ecosystems, the soil is particularly effective at sequestering carbon, making it a critical component of the overall carbon storage capacity.

In conclusion, the Baluno Mangrove region demonstrates significant biomass and carbon storage, with a total biomass of 1,558.15 tons/ha and a carbon stock of 989.04 tons/ha, including a substantial contribution from soil carbon. *Sonneratia* sp. leads in biomass value, while *B. gymnorrhiza* has the lowest. The Baluno Mangroves, covering 59.37 hectares, store approximately 58,719.57 metric tons of carbon, highlighting their critical role in global carbon sequestration. This underscores the exceptional importance of Indonesia's mangroves, which are among the most significant in the world for carbon storage, reinforcing the need for their conservation as a key strategy in climate change mitigation.

ACKNOWLEDGEMENTS

The author expresses his deepest gratitude to *Yayasan Keanekaragaman Hayati Indonesia (KEHATI)* for the support that has received. We also thank who conveyed to the technical team from *Yayasan Pemuda Masyarakat Desa (YPMMD)* Mangrove Learning Center Baluno and Universitas Sulawesi Barat, who assisted during research activities, both at the Baluno mangrove area and during analysis in the laboratory.

REFERENCES

- Amalia L, Juniarti Y, Ardiana C, Saputra ID. 2021. Estimation of carbon stock in true mangrove stands in the Cipalawah Block of Sancang Sea Nature Reserve Garut West Java. *IOP Conf Ser Mater Sci Eng* 1098 (6): 062059. DOI: 10.1088/1757-899X/1098/6/062059.
- Andini WT, Nurlina N, Ridwan I. 2024. Monitoring vegetation change using forest cover density model. *Ecol Eng Environ Technol* 25 (9): 369-378. DOI: 10.12912/27197050/190928.
- Azzahra FS, Suryanti S, Febrianto S. 2020. Estimation of carbon sequestration in mangrove forest of Bedono Village, Demak, Central Java. *J Fish Mar Res* 4 (2): 308-315. DOI: 10.21776/ub.jfmr.2020.004.02.15. [Indonesian]
- Bachmid F, Sondak C, Kusen J. 2018. Estimation of carbon absorption at Bawoho Mangrove Forest, Tongkaina Urban Village, Bunaken Sub-district. *Jurnal Pesisir dan Laut Tropis* 6 (1): 8-13. DOI: 10.35800/jplt.6.1.2018.19463. [Indonesian]
- Banerjee K, Mitra A, Villasante S. 2021. Carbon cycling in mangrove ecosystem of western bay of Bengal (India). *Sustainability* 13 (12): 6740. DOI: 10.3390/su13126740.
- Billard A, Bauer R, Mothe F, Jonard M, Colin F, Longuetaud F. 2020. Improving above-ground biomass estimates by taking into account density variations between tree components. *Ann For Sci* 77: 103. DOI: 10.1007/s13595-020-00999-1.
- Chaudhary S, Aryal B. 2024. Factors affecting the tree and soil carbon stock in Shorea robusta Gaertn. forests along the elevational gradient in Eastern Nepal. *Ecol Front* 44 (3): 517-528. DOI: 10.1016/j.chnaes.2023.09.001.
- Cusack M, Sademe V, Arias-Ortiz A, Masque P, Krishnakumar PK, Rabaoui L, Qurban MA, Qasem AM, Prihartato P, Loughland RA, Elyas AA, Duarte CM. 2018. Organic carbon sequestration and storage in vegetated coastal habitats along the western coast of the Arabian Gulf. *Environ Res Lett* 13 (7): 074007. DOI: 10.1088/1748-9326/aac899.
- Dewi IS. 2020. Study of organic carbon stock in mangroves at Tanjung Batu, Kepulauan Derawan District, Berau, East Kalimantan. [Dissertation]. Institut Pertanian Bogor, Bogor. [Indonesian]
- Dinilhuda A, Akbar AA, Herawaty H. 2020. Potentials of mangrove ecosystem as storage of carbon for global warming mitigation. *Biodiversitas* 21 (11): 5353-5362. DOI: 10.13057/biodiv/d211141.
- Dilmore R, Zhang L. 2018. Greenhouse Gases and Their Role in Climate Change. *Greenhouse Gases and Clay Minerals: Enlightening Down-to-Earth Road Map to Basic Science of Clay-Greenhouse Gas Interfaces*: 15-32. DOI: 10.1007/978-3-319-12661-6_2.
- Djamiluddin R. 2019. Growth pattern in tropical mangrove trees of Bunaken National Park, North Sulawesi, Indonesia. *Biodiversitas* 20 (6): 1713-1720. DOI: 10.13057/biodiv/d200630.
- Donato DC, Kauffman JB, Murdiyarso D, Kurnianto S, Stidham M, Kanninen M. 2011. Mangroves among the most carbon-rich forests in the tropics. *Nat Geosci* 4 (5): 293-297. DOI: 10.1038/ngeo1123.
- Dutca I, McRoberts RE. 2024. Optimal sample trees diameter distribution in developing allometric biomass models. *Research Square*. DOI: 10.21203/rs.3.rs-4222725/v1.
- Gadagbui BK, Onyema C. 2023. Organic Chlorofluoro Hydrocarbons. In *Patty's Toxicology* (pp. 1-76). John Wiley & Sons, Inc. DOI: 10.1002/0471125474.tox068.pub3.
- Gevana DT, Im S. 2016. Allometric models for *Rhizophora stylosa* griff. in dense monoculture plantation in the Philippines. *Malays For* 79 (1-2): 39-53.

- Hadi S, Budiastuti S, Fajarningsih RU. 2019. Biomass and carbon storage of Jor Bay mangrove forest in East Lombok. AIP Conf Proc 2120 (1): 040023. DOI: 10.1063/1.5115661.
- Handoyo E, Amin B, Elizal E. 2020. Estimation of carbon reserved in Mangrove Forest of Sungai Sembilan Sub-District, Dumai City, Riau Province. Asian J Aquat Sci 3 (2): 123-134. DOI: 10.31258/ajoaas.3.2.123-134.
- Harefa MS, Nasution Z, Tuhono E, Susilowati A, Wulandari W. 2024. Carbon stock estimation of *Sonneratia alba* in mangrove restoration area in Pasar Rawa, Langkat North Sumatera. IOP Conf Ser: Earth Environ Sci 1302: 012007. DOI: 10.1088/1755-1315/1302/1/012007.
- Indrayani E, Kalor JD, Warpur M, Hamuna B. 2021. Using allometric equations to estimate mangrove biomass and carbon stock in Demta Bay, Papua Province, Indonesia. J Ecol Eng 22 (5): 263-271. DOI: 10.12911/22998993/135945.
- Indriyani L, Bana S, Yasin A, Sudia LB, Kahirun, Midia LO, Hardina. 2020. The potential of blue carbon stocks and carbon dioxide absorption in mangrove forests to support low carbon emission development in Southeast Sulawesi Province, Indonesia. Intl J Adv Sci Eng Inf Technol 10 (6): 2526-2535. DOI: 10.18517/ijaseit.10.6.13332.
- International Monetary Fund (IMF). 2022. World Economic Outlook: Countering the Cost-of-Living Crisis. <https://www.imf.org/en/Publications/WEO/Issues/2022/10/11/world-economic-outlook-october-2022>.
- Kauffman JB, Donato DC. 2012. Protocols for the measurement, monitoring and reporting of structure, biomass and carbon stocks in mangrove forests. CIFOR, Bogor. [Indonesian]
- Kim D, Medvigy D, Maier CA, Johnsen K, Palmroth S. 2020. Biomass increases attributed to both faster tree growth and altered allometric relationships under long-term carbon dioxide enrichment at a temperate forest. Glob Chang Biol 26 (4): 2519-2533. DOI: 10.1111/gcb.14971.
- Komiyama A, Ong JE, Pongpan S. 2008. Allometry, biomass, and productivity of mangrove forests: A review. Aquat Bot 89 (2): 128-137. DOI: 10.1016/j.aquabot.2007.12.006.
- Komiyama A, Pongpan S, Kato S. 2005. Common allometric equations for estimating the tree weight of mangroves. J Trop Ecol 21 (4): 471-477. DOI: 10.1017/S0266467405002476.
- Kusmana C, Sukristijono S. 2016. Mangrove resource uses by local community in Indonesia. J Nat Resour Environ Manag 6 (2): 217-224. DOI: 10.19081/jpsl.2016.6.2.217.
- Kusumaningtyas MA, Hutahaean AA, Fischer HW, Pérez-Mayo M, Ransby D, Jennerjahn TC. 2019. Variability in the organic carbon stocks, sources, and accumulation rates of Indonesian mangrove ecosystems. Estuar Coast Shelf Sci 218: 310-323. DOI: 10.1016/j.ecss.2018.12.007.
- Lembang RK, Huliselan S, Adji F. 2019. Estimation of biomass and carbon saved on mangrove *Rhizophora apiculata* and *Sonneratia alba* in Simau Village. Jurnal Hutan Pulau-Pulau Kecil 3 (1): 68-72. DOI: 10.30598/jhpk.2019.3.1.68. [Indonesian]
- Li S, Chen P, Huang J, Hsueh M, Hsieh L, Lee C, Lin H. 2018. Factors regulating carbon sinks in mangrove ecosystems. Global Change Biol 24 (9): 4195-4210. DOI: 10.1111/gcb.14322.
- Martin AR, Thomas SC. 2011. A reassessment of carbon content in tropical trees. Plose One 6 (8): e23533. DOI: 10.1371/journal.pone.0023533.
- Murdiyarsa D, Purbopuspito J, Kauffman JB, Warren MW, Sasmito SD, Donato DC, Manuri S, Krisnawati H, Taberima S, Kurnianto S. 2015. The potential of Indonesian mangrove forests for global climate change mitigation. Nat Clim Change 5: 1089-1092. DOI: 10.1038/nclimate2734.
- National Oceanic and Atmospheric Administration (NOAA). 2023. Global Monitoring Laboratory - Trends in Atmospheric Carbon Dioxide. <https://gml.noaa.gov/ccgg/trends/>.
- Ngu LH. 2024. Carbon Capture Technologies. In Encyclopedia of Sustainable Technologies (pp. 358-377). Elsevier. DOI: 10.1016/B978-0-323-90386-8.00028-0.
- Nuraini RAT, Pringgencies D, Suryono CA, Adhari VH. 2021. Carbon stocks in mangrove vegetation stands on Karimunjawa Island. Buletin Oseanografi Marina 10 (2): 180-188. DOI: 10.14710/buloma.v10i2.31616. [Indonesian]
- O'Brien CP, Watson MJ, Dowling AW. 2022. Challenges and opportunities in converting CO₂ to carbohydrates. ACS Energy Lett 7 (10): 3509-3523. DOI: 10.1021/acseenergylett.2c01550.
- Pouyat RV, Day SD, Brown S, Schwarz K, Shaw RE, Szlavecz K, Trammell TLE, Yesilonis ID. 2020. Urban Soils. In Forest and Rangeland Soils of the United States under Changing Conditions: A Comprehensive Science Synthesis 127-144. DOI: 10.1007/978-3-030-45216-2_7.
- Putra AA, Rudianto, Dewi CSU. 2019. Analysis of the ability of mangrove sequestration and carbon stock in Pejarakan Village, Buleleng Regency, Bali. Jurnal Ilmu aan Teknologi Kelautan Tropis 11 (3): 511-526. DOI: 10.29244/jikt.v11i3.24049. [Indonesian]
- Rahman, Effendi H, Rusmana I. 2017. Stock estimation and carbon absorption of mangrove in Tallo River, Makassar. Jurnal Ilmu Kehutanan 11 (1): 19-28. DOI: 10.22146/jik.24867. [Indonesian]
- Santos HVS, Hollanda FSR, Santos T de O, Andrade KVS de, Santana MBS, Estrada GCD, Soares MLG. 2009. Allometric models for estimating the aboveground biomass of the mangrove *Rhizophora mangle*. BJOE XV (2): 116-120. DOI: 10.1590/S1679-87592017127006501.
- Song Q, Albrecht CM, Xiong Z, Zhu XX. 2023. Biomass estimation and uncertainty quantification from tree height. IEEE J Sel Top Appl Earth Observations Remote Sens 16: 4833-4845. DOI: 10.1109/JSTARS.2023.3271186.
- Suryono, Soenardjo N, Wibowo E, Ario R, Rozy EF. 2018. Estimation of biomass and carbon content in Perancak Mangrove Forest, Jembrana District, Bali Province. Buletin Oseanografi Marina 7 (1): 1-8. DOI: 10.14710/buloma.v7i1.19036. [Indonesian]
- Sutaryo D. 2009. Biomass calculation: An introduction to carbon studies and carbon trading. Wetlands International Indonesia Programme, Bogor. [Indonesian]
- Thomas SC, Martin AR. 2012. Carbon content of tree tissues: A synthesis. Forests 3 (2): 332-352. DOI: 10.1093/forestry/cpr053.
- Tupan CI, Lailossa GW. 2019. Potential of stock carbon in mangrove *Sonneratia alba* in Passo coastal waters, Inner Ambon Bay. IOP Conf Ser: Earth Environ Sci 339 (1): 012009. DOI: 10.1088/1755-1315/339/1/012009.
- UNFCCC. 2020. The Paris Agreement: Key Aspects. <https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement/key-aspects-of-the-paris-agreement>.