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# Harnessing Biomass and Blue Carbon Potential: Estimating Carbon Stocks in the Vital Wetlands of Eastern Sumatra, Indonesia

**Mohammad Basyuni [1,2,*], Andi Aznan Aznawi [1,3], Muhammad Rafli [2], Jeli Manogu Tua Tinumbunan [2], Erika Trinita Gultom [2], Revani Dwi Arisindy Lubis [2], Hegi Alfarado Sianturi [2], Elham Sumarga [4], Erizal Mukhtar [5], Bejo Slamet [1,2], Erni Jumilawaty [1,6], Rudhi Pribadi [7], Rama Riana Sitinjak [8] and Shigeyuki Baba [9]**

1 Center of Excellence for Mangrove, Universitas Sumatera Utara, Medan 20155, Indonesia; aznanaznawi@students.usu.ac.id (A.A.A.); bejo@usu.ac.id (B.S.); erni1@usu.ac.id (E.J.)
2 Department of Forestry, Faculty of Forestry, Universitas Sumatera Utara, Medan 20155, Indonesia; mrafli@students.usu.ac.id (M.R.); jelimanogu@students.usu.ac.id (J.M.T.T.); erikatrinita@students.usu.ac.id (E.T.G.); revanicindyy@gmail.com (R.D.A.L.); hegialfarado@students.usu.ac.id (H.A.S.)
3 Graduate School of Agriculture, Faculty of Agriculture, Universitas Sumatera Utara, Medan 20155, Indonesia
4 School of Life Sciences and Technology, Institut Teknologi Bandung, Bandung 40132, Indonesia; elham@sith.itb.ac.id
5 Department of Biology, Faculty of Mathematics and Sciences, Universitas Andalas, Padang 25163, Indonesia; erizalmukhtar@sci.unand.ac.id
6 Department of Biology, Faculty of Mathematics and Sciences, Universitas Sumatera Utara, Medan 20155, Indonesia
7 Center for Coastal Rehabilitation and Disaster Mitigation Studies, Universitas Diponegoro, Semarang 50275, Indonesia; rudhipribadi@lecturer.undip.ac.id
8 Agro Sustainable Centre, Universitas Prima Indonesia, Medan 20117, Indonesia; ramarianasitinjak@unprimdn.ac.id
9 International Society for Mangrove Ecosystems, University of the Ryukyus, Senbaru 1, Nishihara, Okinawa 903-0129, Japan; babasan@mangrove.or.jp
* Correspondence: m.basyuni@usu.ac.id; Tel./Fax: +62-61-8201920

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**Abstract:** Global warming is a critical factor driving climate change, impacting every aspect of life on Earth. The escalating concentration of greenhouse gasses in the atmosphere, the primary contributor to global warming, necessitates immediate action through effective climate mitigation strategies. This study aimed to quantify the biomass and blue carbon stocks in the eastern coastal mangrove forests of North Sumatra and Aceh Provinces in Indonesia, focusing on key sites in Langkat, Deli Serdang, Batu Bara, Tanjung Balai, and Aceh Tamiang Regencies. We measured carbon stock in three carbon pools: biomass (above and below ground), necromass, and soil. By analyzing tree stands using parameters such as tree height and diameter at breast height within circular plots (7 m in radius, 125 m apart), we gathered fundamental data on forest structure, species composition, and above- and below-ground biomass. Additionally, we collected soil samples at various points and depths, measuring the amount of wood, stems, or branches (necromass) that fell to or died on the forest floor. Data were collected in plots along a line transect, comprising three transects and six circular plots each. Sixteen diverse mangrove species were found, demonstrating rich mangrove biodiversity. The mangrove forests in the five regencies exhibited significant carbon storage potential, with estimated average above-ground carbon ranging from 96 to 356 MgC/ha and average below-ground carbon from 28 to 153 MgC/ha. The estimated average deadwood carbon varied between 50 and 91 MgC/ha, while soil carbon ranged from 1200 to 2500 MgC/ha. These findings underscore the significant carbon storage potential of these mangrove forests, highlighting their importance to global carbon cycling and climate change mitigation. This research contributes to a broader understanding of mangroves as vital blue carbon ecosystems, emphasizing the necessity of conservation efforts such as forest restoration and rehabilitation to enhance their role in stabilizing coastal areas and improving global climate resilience.

**Keywords:** carbon stock; mangrove; global warming; $CO_2$; restoration; carbon sequestration

## 1. Introduction

Mangroves are typical coastal environments in tropical and subtropical regions, thriving in areas such as protected beaches, deltas, and river estuaries. They offer numerous benefits from ecological, biological, and economic perspectives. Mangroves serve as habitats for birds and act as ecological guardians of coastal stability. Biologically, they function as breeding and hatchery grounds for fish, shrimp, and other marine life. Economically, mangroves are used for recreation and timber. Like other forests, mangroves play a crucial role in absorbing carbon dioxide from the air. This function relates to their role as carbon sinks, where some carbon dioxide is used in photosynthesis while a portion remains in the atmosphere. Over the past decade, carbon dioxide emissions have surged from 1400 million metric tons to 2900 million metric tons per year, contributing to global climate change [1]. Global warming has emerged as a significant environmental issue due to its substantial impacts on life around the world, such as through rising global temperatures and increasing sea levels. This phenomenon occurs due to higher temperatures in the atmosphere, oceans, and land. It can cause flooding, erosion, changes in water quality, and shifting wetlands. Scientists attribute this phenomenon to human activities, particularly the burning of fossil fuels such as petroleum, coal, and natural gas, which release carbon dioxide and other greenhouse gasses into the atmosphere [2]. Changes in land cover and land use, too, and particularly the conversion of forests to artificial surfaces, significantly contribute to atmospheric $CO_2$ due to the loss of stored carbon [3].

Carbon sequestration efforts are among the strategies that can be employed in mangrove forests to reduce global warming. These forests can store four times more carbon than tropical forests. Mangroves sequester elemental carbon from the atmosphere at a rate five times greater than other terrestrial forests, absorbing 42 million metric tons of carbon annually—equivalent to the carbon emissions of 25 million cars [4]! The carbon storage capacity of mangroves is more than three times greater than the average carbon storage per hectare of tropical forests. According to [2], the optimal function of mangrove forests in absorbing carbon can reach 77.9%, which is then stored in the biomass of mangrove trees, including trunks, roots, and leaves. Mangroves' carbon storage is double that of other forests. Biomass is the primary source of carbon storage; it decomposes and is subsequently stored by the soil layer. Estimating carbon storage in mangrove forests is crucial for assessing their capacity to absorb atmospheric carbon dioxide and sequester carbon in organic compounds [5].

Mangrove forests are critical for blue carbon sequestration, as they hold substantial carbon stocks in both biomass and soil. According to [6], mangrove forests have an estimated 68,000 tons of dry biomass and 34,000 tons of stored carbon. Research in Malaysia has demonstrated the potential of satellite-based approaches for mapping blue carbon stocks [7]. In Indonesia, mean carbon stocks were found to be 100.66 MgC/ha for above-ground biomass, 2.81 MgC/ha for roots, and 570.76 MgC/ha for soil organic carbon [8]. A Vietnamese study estimated the total $CO_2$ absorption by mangroves at 1,631,834 tons, with 170,462 tons in tree biomass and 1,461,372 tons in soil [9]. These findings underscore the importance of mangrove conservation and restoration for climate change mitigation and supporting the development of carbon credit schemes in coastal areas.

Estimating biomass in mangrove ecosystems involves assessing both above-ground (AGB) and below-round (BGB) components. AGB includes living vegetation, including trunks, branches, and leaves of mangrove trees, while BGB comprises roots and other subterranean structures. These measurements are essential for applying allometric equations, which are mathematical models linking measurable tree characteristics to biomass [10]. In addition to estimating living biomass, assessing soil carbon stocks in mangrove ecosystems is critical. Mangrove soils exhibit high organic material content due to waterlogged, anaerobic conditions that impede the decomposition of plant matter, facilitating the accumulation of organic carbon. Consequently, the destruction or degradation of mangroves can result in considerable carbon emissions [11].

However, challenges exist in estimating biomass and blue carbon in mangrove ecosystems. Site-specific studies are essential for developing precise allometric equations and soil carbon models, as a single model or equation is not universally applicable to all mangrove forests [12]. Estimating biomass and blue carbon stocks in mangrove forests serves as both a scientific endeavor and an essential element of global climate change mitigation strategies [11]. Accurate assessments of biomass and carbon stocks are vital for integration into initiatives such as REDD+ (Reducing Emissions from Deforestation and Forest Degradation), which encourages developing countries to preserve forests in line with their national climate change mitigation obligations.

This study aimed to quantify the biomass and blue carbon stocks in mangrove forests in coastal wetlands, which is vital for understanding their role in the global carbon cycle and guiding conservation efforts. We blended field observations and allometric modeling. These estimations are important not only for scientific study but also for shaping policy and conservation efforts aimed at maintaining mangroves as essential carbon sinks in the battle against climate change.

## 2. Materials and Methods

### *2.1. Study Site*

This research was conducted from October to December 2023 on the east coast of Aceh and Sumatra, directly adjacent to the Malacca Strait. We investigated forest inventory, AGB, BGB, necromass, and soil carbon in the regencies of Aceh Tamiang (Pusong Kapal), Langkat (Besitang), Serdang Bedagai (Sei Nagalawan), Batubara (Lima Puluh), and Asahan (Bagan Asahan) as shown in Figure 1.

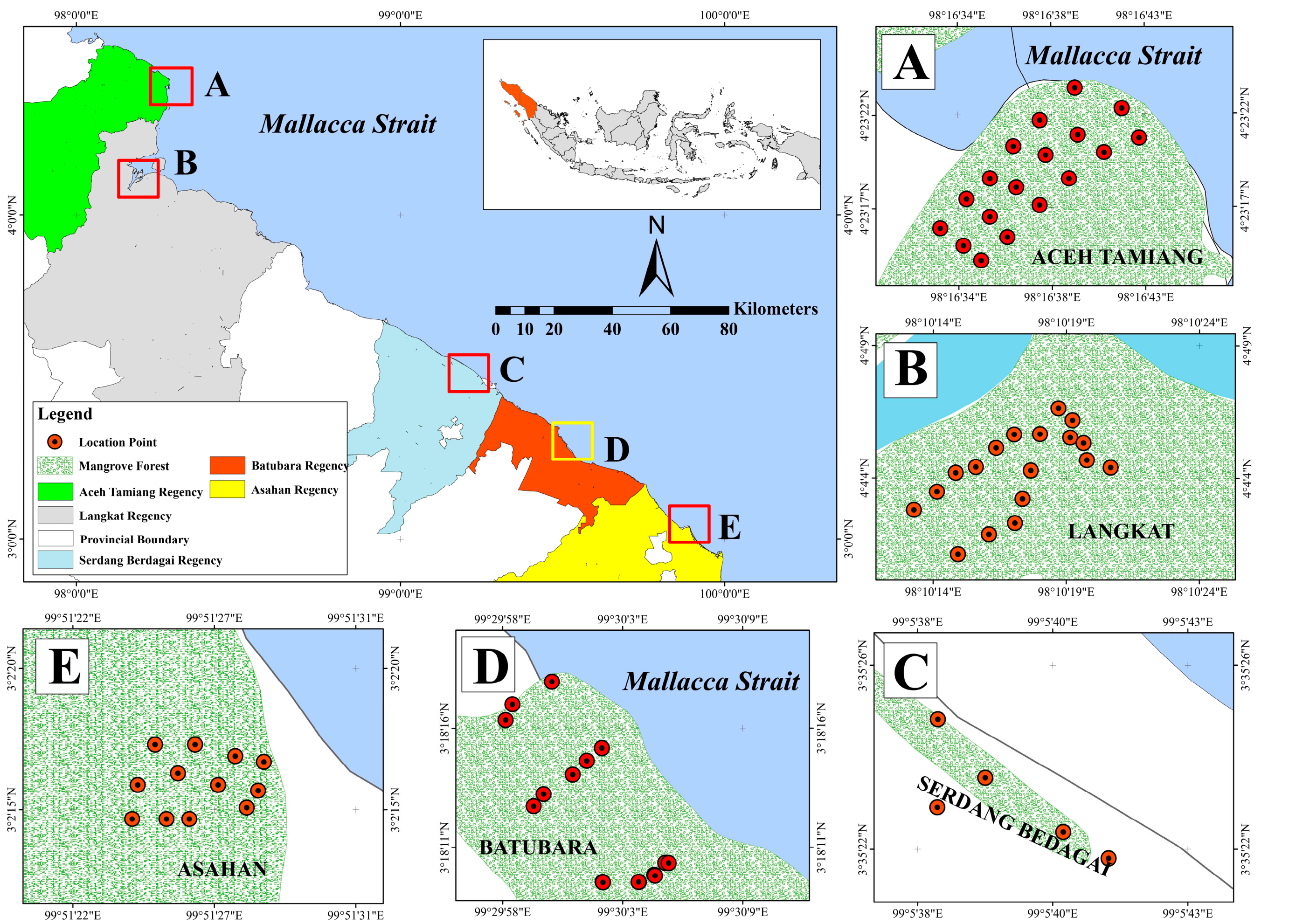


**Figure 1.** Research sites in Aceh Tamiang (**A**) of Aceh Province, and Langkat (**B**), Serdang Bedagai (**C**), Batubara (**D**), and Asahan Regency (**E**) of North Sumatra Province, Indonesia.

## 2.2. Measurement of Tree and Diameter Data

This study employed non-destructive techniques, which do not involve harvesting. We collected data on mangrove vegetation, soil samples, and dead wood. Data were collected in plots along a line transect, comprising three transects and six circular plots each. We investigated extensive circular plots with a radius of 7 m, designated for trees with a diameter above 5 cm. We used smaller circular plots with a radius of 2 m for young trees with a diameter of less than 5 cm. The mangrove height and species names were also measured and recorded. Measurements of the plot for calculating mangrove vegetation diameter and height are illustrated in Figure 2.

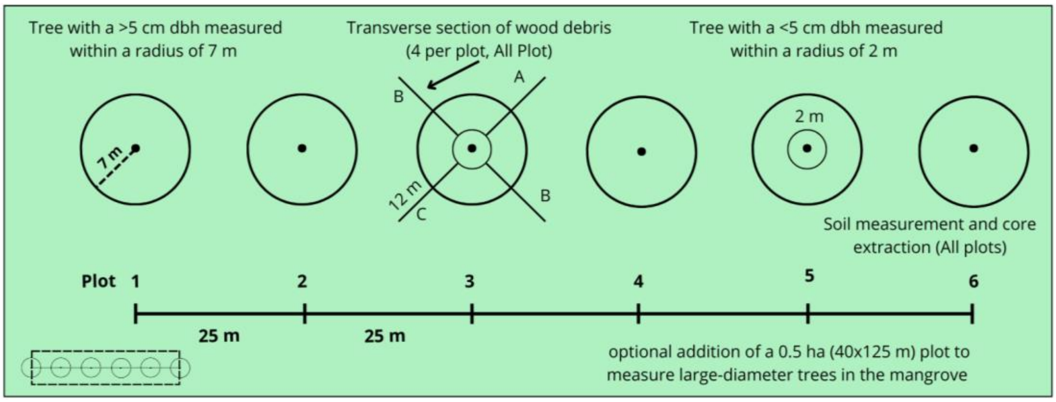


**Figure 2.** Standard plot design and size for measuring mangrove forest carbon stocks [13].

## 2.3. Soil Sampling

Deadwood located above ground level was measured using a non-destructive line intersection technique (intersecting on four sides of a circular plot), as shown in Figure 3.

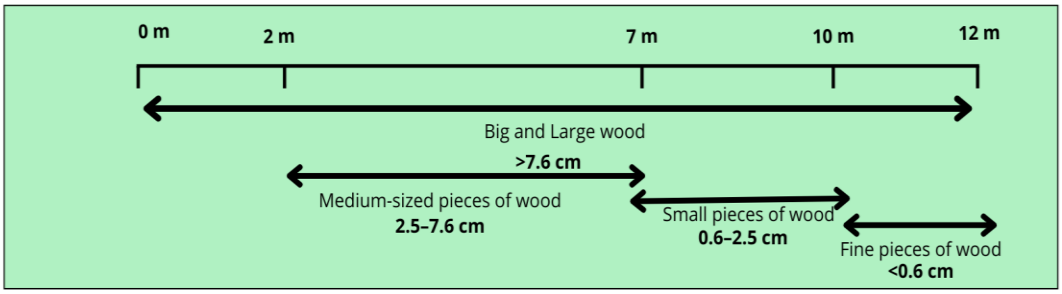


**Figure 3.** Data collection field for dead wood using non-destructive line intersection technique.

Woody debris (necromass) was classified into four categories size-wise: fine (0–0.6 cm), small (0.6–2.5 cm), medium (2.5–7.6 cm), and large (>7.6 cm). Fine, small, and medium-sized deadwoods were enumerated based on their intersection with the transect tape. When substantial dead wood intersected the transect tape, its diameter was measured and documented [13].

## 2.4. Deadwood Data Collection

Soil samples were collected from a single transect in natural mangrove woods, representing one location. Soil samples were obtained from four depths: 0–15 cm, 15–30 cm, 30–50 cm, and 50–100 cm. The subsamples collected were approximately 5 cm from the four soil depths obtained [13].

*2.5. Data Analysis*

2.5.1. Calculating Biomass and Carbon of Mangrove Vegetation

To determine mangrove biomass, allometric equations were used for each species (Table 1). We obtained diameter data, DHH (diameter at breast height) from each mangrove stand in the field, and estimated the biomass content through the allometric equation.

**Table 1.** Allometric equations for calculating mangrove tree biomass.

| Above-Ground Biomass (W kg) | Below-Ground Biomass (WR kg) |
|---|---|
| *A. marina* | *A. marina* |
| W = 0.308 DBH 2.11, D max = 35 cm [14] | WR = 1.28 DBH 1.17, D max = 35 cm [14] |
| *B. gymnorrhiza* | *B. gymnorrhiza* |
| W = 0.186 DBH 2.31, D max = 25 cm [15] | WR = 0.0188 ($D^2$H) 0.909, D max = 33 cm [16] |
| *E. agallocha* | *E. agallocha* |
| W = 0.251 (0.45) D 2.46 [17] | WR = 0.199 (0.45) 0.899 D 2.22 [17] |
| *L. racemosa* | *L. racemosa* |
| W = 0.251 (0.727) D max = 49 cm [18] | WR = 0.199 (0.727) 0.899 D max = 45 cm [18] |
| *R. apiculata* | *R. apiculata* |
| W = 0.235 DBH 2.42, D max = 28 cm [19] | WR = 0.00698 0.00698DBH 2.61, D max = 28 cm [19] |
| *R. mucronata* | *R. mucronata* |
| W = 0.128 DBH 2.60, D max = 32 cm [20,21] | WR = 0.00974 (DBH) 1.05 D max = 40 cm [16] |
| *R. stylosa* | *R. stylosa* |
| W = 0.128 DBH 2.60 [20,21] | WR = 0.261 DBH 1.86 [14] |
| *S. alba* | *S. alba* |
| W = 0.251 (0.6443) D 2.46 [17] | WR = 0.168 (0.6443) 0.899 D 2.22 [17] |

The biomass value was calculated in kilograms and converted into megagrams per hectare (Mg/ha). Additionally, the carbon stock estimation relies on the biomass value generated, as 50% of the biomass constitutes carbon. Consequently, to calculate carbon storage, the biomass value is multiplied by 0.5.

2.5.2. Deadwood Carbon Stock Analysis

In mangrove forests, biomass values are computed through allometric equations to ascertain the carbon stock above ground. According to [18], the allometric equation used in this study refers to that for each species [13], as follows:

- Volume of wood size grade:

$$Volume\ (\mathrm{m^3h^{-1}}) = \pi^2 \frac{Ni \times QMDi^2}{8 \times L} \tag{1}$$

In this context, $V$ represents the quantity of wood chips in size class $i$, $QMD$ the quadratic mean diameter of class $i$ (cm), and $L$ the length of the transect (m).

Specific gravity of wood:

$$Specific\ gravity(\mathrm{g/cm^3}) = \frac{Weight\ (\mathrm{g})}{Volume\ (\mathrm{cm^3})} \tag{2}$$

Deadwood biomass:

$$\text{Deadwood Biomass (Mg/ha)} = \text{Deadwood Volume} \times \text{Average Specific Gravity} \tag{3}$$

Deadwood carbon:

$$\text{Deadwood Carbon} = \text{Deadwood Biomass} \times 0.5 \tag{4}$$

Soil bulk density:

$$Bulk\ Density\ \left(\mathrm{g/cm^3}\right) = \frac{Dry\ Soil\ Weight\ (\mathrm{g})}{Sample\ Volume\ (\mathrm{cm^3})} \tag{5}$$

where the sample volume is 71.47 $cm^3$.

Calculating $\%C$,

$$\%C = \frac{1}{1.724} \times \%BO \tag{6}$$

Thus, $\%C$ denotes the percentage of carbon content in the sediment. The constant used to convert the percentage of organic matter into the percentage of organic carbon is 1.724, while $\%BO$ is the percentage of sediment organic matter lost during burning.

Carbon content is

$$Soil\ C\ (\mathrm{MgC/ha}) = Bulk\ Density \times Soil\ Depth\ Interval\ (SDI) \times \%C \tag{7}$$

where *Soil C* represents the estimated carbon storage, *SDI* denotes the sample depth interval, and $\%C$ indicates the percentage of sediment carbon content.

## 3. Results

### 3.1. Forest Inventory

The higher number of species observed can be attributed to the well-preserved nature of the mangrove forests in the five research locations. Bruguiera gymnorrhiza, Rhizophora apiculata, and Sonneratia alba were consistently observed at all sites. The most prevalent species (16) were recorded in Besitang, Langkat, North Sumatra Province, followed by Aceh Tamiang (Pusong Kapal) and Batu Bara (Lima Puluh) with 9 species each, and Deli Serdang (Sei Nagalawan) and Asahan (Bagan Asahan) with 8 species each (Table 2). *R. apiculata* and *S. alba* served as pioneer species at each site due to their considerable resilience to salinity and tidal fluctuations, as well as their adaptability and rapid growth as mangrove species [22–24]. Details of the tree species that comprise the mangrove forest at the research site are furnished in Table 2.

**Table 2.** Mangrove species composition in five study sites.

| No. | Species | Aceh Tamiang | Langkat | Serdang Bedagai | Batu Bara | Asahan |
|---|---|---|---|---|---|---|
| 1. | *A. marina* | ✔ | | ✔ | ✔ | |
| 2. | *A. alba* | ✔ | | | | ✔ |
| 3. | *A. officinalis* | | ✔ | | | ✔ |
| 4. | *B. gymnorhiza* | ✔ | ✔ | ✔ | ✔ | ✔ |
| 5. | *B. sexangular* | | ✔ | | | |
| 6. | *B. cylindrical* | | ✔ | | | |
| 7. | *E. agallocha* | ✔ | ✔ | | ✔ | ✔ |
| 8. | *Ceriops tagal* | | ✔ | | | |
| 9. | *L. racemose* | | ✔ | | ✔ | |
| 10. | *L. littorea* | | ✔ | | ✔ | |
| 11. | *Nypa fruticans* | | ✔ | ✔ | | |
| 12. | *R. apiculata* | ✔ | ✔ | ✔ | ✔ | ✔ |
| 13. | *R. mucronata* | | ✔ | ✔ | ✔ | |
| 14. | *R. stylosa* | ✔ | ✔ | | ✔ | |
| 15. | *S. hydrophylacea* | | ✔ | ✔ | | |
| 16. | *Sonneratia alba* | ✔ | ✔ | ✔ | ✔ | ✔ |
| 17. | *S. caseolaris* | | ✔ | ✔ | | ✔ |
| 18. | *X. granatum* | ✔ | ✔ | | | ✔ |

Species composition denotes the configuration and quantity of species within a specific plant community, highlighting the three key terms of species, configuration, and quantity. Significant mangroves can establish monospecific stands and excrete saline water, enabling their survival in sluggish aquatic environments. Conversely, minor mangroves proliferate along the periphery of mangrove ecosystems and do not establish stands [25]. The above- and below-ground biomass was depicted in Table 3.

**Table 3.** Above- and below-ground biomass (data are mean ± SD (*n* = 15)).

| Location | Above-Ground Biomass (MgC/ha) | Below-Ground Carbon (MgC/ha) | Total (MgC/ha) |
|---|---|---|---|
| Aceh Tamiang | 191.28 ± 4.07 | 56.81 ± 1.30 | 248.09 ± 5.28 |
| Langkat | 503.09 ± 5.95 | 249.69 ± 2.50 | 752.78 ± 8.09 |
| Serdang Bedagai | 365.96 ± 2.72 | 79.37 ± 0.34 | 445.33 ± 2.92 |
| Batu Bara | 391.72 ± 1.90 | 167.94 ± 0.91 | 559.65 ± 2.73 |
| Asahan | 711.97 ± 3.62 | 306.63 ± 1.34 | 1018.60 ± 4.97 |

According to the allometric equation calculations, the total AGB and BGB were 248.09 MgC/ha in Aceh Tamiang Regency, 752.78 MgC/ha in Langkat Regency, 445.33 MgC/ha in Serdang Bedagai Regency, 559.65 MgC/ha in Batu Bara Regency, and 1018.60 MgC/ha in Asahan Regency (Table 3). The total biomass across the five districts was 3024.45 MgC/ha. The variation in biomass values in the five districts can be attributed to differences in vegetation density, leading to variations in tree diameter and height, which are crucial factors in calculating biomass values. According to [26], tree dimensions, specifically tree height, and diameter, significantly influence biomass value. This finding implies that tree height and diameter directly correlate with a stand's biomass value.

### 3.2. Above- and Below-Ground Carbon

The carbon value is derived from half the biomass value and is presented in Table 4.

**Table 4.** Above- and below-ground carbon (data are mean ± SD (*n* = 15)).

| Location | Above-Ground Carbon (MgC/ha) | Below-Ground Biomass (MgC/ha) | Total (MgC/ha) |
|---|---|---|---|
| Aceh Tamiang | 95.64 ± 2.03 | 28.41 ± 0.65 | 124.05 ± 2.64 |
| Langkat | 251.54 ± 2.97 | 124.85 ± 1.25 | 376.39 ± 4.05 |
| Serdang Bedagai | 182.98 ± 1.36 | 39.69 ± 0.17 | 222.67 ± 1.46 |
| Batu Bara | 195.86 ± 0.95 | 83.97 ± 0.45 | 279.83 ± 1.36 |
| Asahan | 355.99 ± 1.81 | 153.32 ± 0.67 | 509.31 ± 2.48 |

The carbon values obtained are as follows: Aceh Tamiang Regency 124.04 MgC/ha, Langkat Regency 376.39 MgC/ha, Serdang Bedagai Regency 222.67 MgC/ha, Batu Bara Regency 279.83 MgC/ha, and Asahan Regency 509.31 MgC/ha. The total quantity of carbon obtained was 1512.22 MgC/ha. Carbon values fluctuate due to variations in biomass values, which are influenced by vegetation density, species composition, and tree size in the forested region. According to [27], the amount of biomass and carbon in a forest area is strongly influenced by several factors, including tree diameter and height, individual density, and species diversity.

### 3.3. Soil Carbon

The soil carbon values varied across forest locations in each district. The highest soil carbon value was in Aceh Tamiang Regency at 2505.86 MgC/ha, followed by Asahan Regency at 2437.31 MgC/ha, Langkat Regency at 1981.78 MgC/ha, Serdang Bedagai Regency at 1601.45 MgC/ha, and Batubara Regency at 1175.72 MgC/ha. Several factors, including topographic conditions, climate, and soil type, influence the size of the carbon value in each district [28]. Other factors affecting the differences in soil carbon values include soil types, rainfall, vegetation types, soil composition, tillage practices, and soil depth [29]. Figure 4, below, illustrates the soil carbon values obtained.

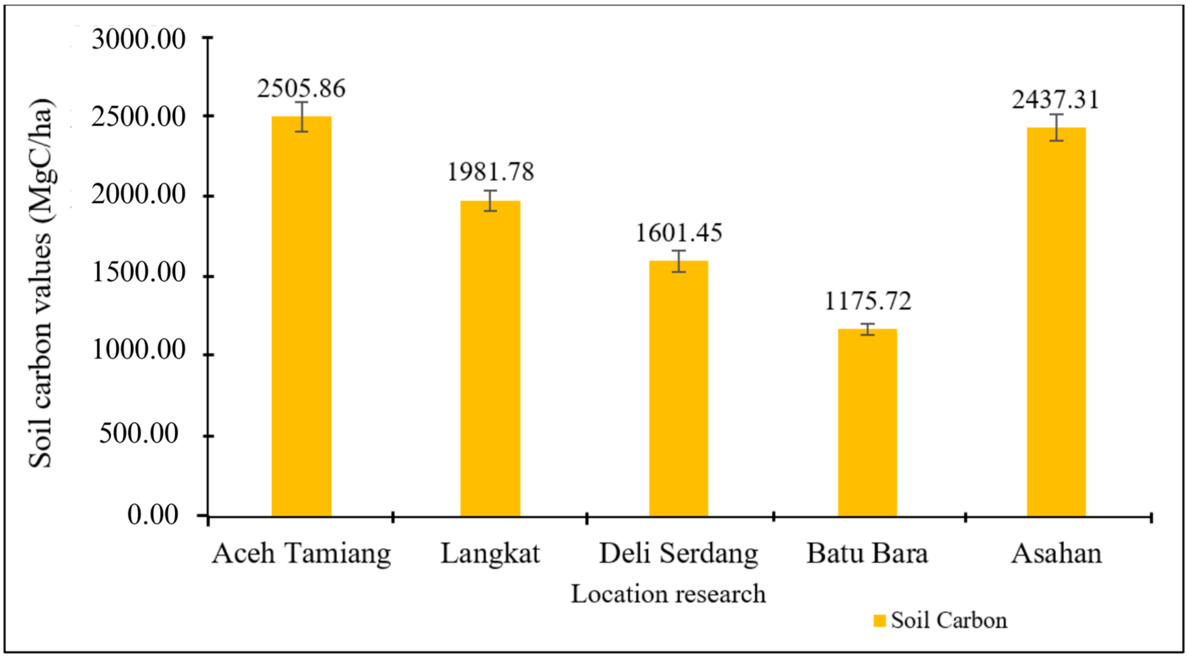


**Figure 4.** Soil carbon levels of mangrove forest in each location (data are mean ± SD ($n$ = 15)).

The soil carbon levels in Figure 4 indicate that Aceh Tamiang and Asahan locations have high carbon levels of approximately 2500 MgC/ha, while Batubara has a low carbon level of approximately 1200 MgC/ha. This finding facilitated the determination of both the total BGB and the overall ecosystem carbon stock within the upper meter of soil. When soil carbonates were elevated, both organic and inorganic carbon were quantified using specified procedures [30].

### 3.4. Deadwood Carbon

The highest value of deadwood carbon was recorded in Aceh Tamiang District at 91.08 MgC/ha, followed by Asahan District at 64.77 MgC/ha, Batu Bara District at 58.89 MgC/ha, and Serdang Bedagai District at 51.85 MgC/ha, and the lowest in Langkat District at 49.94 MgC/ha (Figure 5). The carbon value of deadwood is influenced by the number of twigs, branches, and logs that fall on the forest floor. Deadwood carbon has a lower value than AGB, BGB, and soil carbon. Reference [31] reported that deadwood carbon is the remaining tree biomass stored in the wood, twigs, and branches of dead trees that have fallen to the forest floor. Dead trees can no longer absorb carbon; consequently, deadwood carbon content is lower than other carbon values.

The average amount of mangrove carbon in the Lantebung area is 266.34 MgC/ha, with a total area of 14.18 ha [32]. According to [33], an estimated 137.9 MgC/ha is present above ground, while 79 MgC/ha is found below ground. Local communities actively participate in silvofishery activities in the Blanakan mangroves, farming fish and prawns, which yields them an average annual income of approximately USD 1513 per hectare. The carbon stock of the present study is significantly higher than that reported in the restored mangroves of Lubuk Kertang (26.4 MgC/ha) and Pulau Sembilan (42.5 MgC/ha) in North Sumatra [29]. This finding represents a total estimated carbon stock distribution of 3776.63 MgC/ha. According to [34], estimating representative values is crucial to show that mangrove forests possess substantial carbon storage potential [35]. Sustainable mangrove carbon stock estimation calculations can provide insights into carbon stocks and have implications for mangrove carbon stock knowledge in the context of climate change [36].

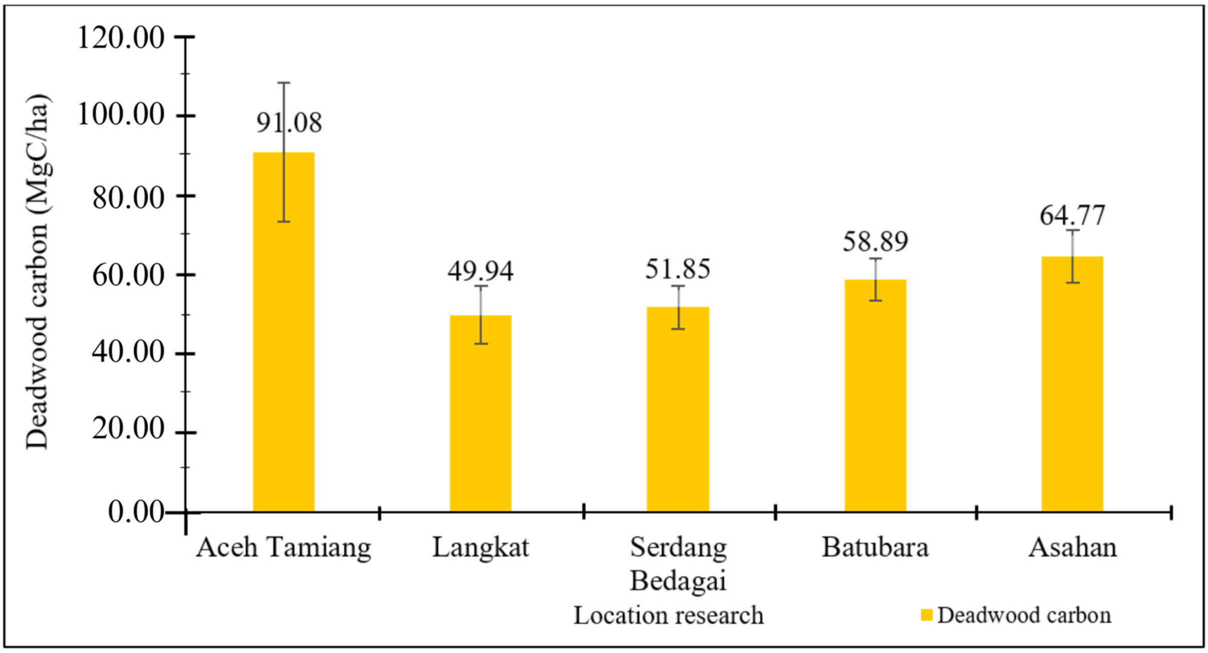


**Figure 5.** Deadwood carbon of mangrove forest in each location (data are mean ± SD (*n* = 15)).

## 4. Discussion

### *4.1. Biomass and Blue Carbon Storage*

Indonesia contributes approximately 1,619,882,727 MgC/ha to blue carbon potential, while Singapore and Timor-Leste contribute minimally, at 286,363.64 MgC/ha and 373,636.36 MgC, respectively. In Southeast Asia, environmental conditions affected the potential for carbon stock (above-ground carbon (AGC) and soil organic carbon (SOC)) [37,38]. Ref. [39] explained that the intricate relationships between the atmosphere, land, and oceans play a significant role in carbon exchange processes. Coastal regions are crucial in the dynamics of coastal carbon, particularly in the interchange of $CO_2$ between the atmosphere, water, and soil [40]. The mean $CO_2$ efflux in natural mangrove forest land covers was 866 ± 585 MgC/ha during low-tide conditions and 1137 ± 792 MgC/ha during high-tide conditions. $CO_2$ effluxes in coastal wetlands are highly dynamic and presumably driven by complex factors; therefore, understanding their magnitudes and drivers requires extensive measurement across large spatial and temporal scales.

Recent years have witnessed significant advancements in assessing biomass and blue carbon stores in mangrove forests, propelled by a growing recognition of the critical role these ecosystems play in mitigating climate change. Nonetheless, despite technical progress and enhanced methodologies, numerous limitations and obstacles persist in precisely estimating these carbon reserves, sparking ongoing debate among the scientific community [41].

A major point of discussion concerns the complexity of allometric models for estimating biomass. Allometric equations are frequently used to estimate the AGB of mangroves by assessing tree attributes such as diameter at breast height, height, and species classification. While effective in many cases, these equations are often region- and species-specific, limiting their broader applicability. For example, mangroves in the Indo-Pacific exhibit growth forms and wood densities different from those in the Americas, necessitating the development of distinct allometric models for different regions [42]. Applying a model developed for one region to another can either over- or under-estimate biomass and carbon stocks. Additionally, many existing models do not fully consider the variability in mangrove structures, such as the extensive aerial roots in species like Rhizophora, which significantly contribute to carbon storage [43].

### *4.2. Above- and Below-Ground Biomass Estimations*

The estimation of BGB presents further challenges. BGB, which includes root systems and soil organic carbon, is notoriously difficult to measure due to its location beneath the surface. Traditional methods of measuring BGB, such as root excavation or coring, are labor-intensive, time-consuming, and often destructive to the ecosystem. Hence, most studies rely on assumed ratios of BGB to AGB, which introduces uncertainty. These assumptions may not be accurate across different mangrove ecosystems, particularly given the variation in root biomass between species and regions. For instance, mangroves in sediment-rich areas tend to have more extensive root systems, which store more carbon than those in rocky or sandy environments [44]. The lack of reliable data on BGB significantly limits the accurate estimation of total biomass and carbon stocks.

Soil carbon stores represent one of the most substantial carbon reservoirs in mangrove ecosystems, frequently comprising up to 75% of the total ecosystem carbon. Mangrove soils have a high organic matter content from the gradual breakdown of plant material in the anaerobic, water-saturated environments characteristic of coastal wetlands. However, an accurate estimation of soil carbon stocks is complicated by the heterogeneity of soil characteristics, which vary widely across regions and even within small spatial scales. Factors such as soil type, sedimentation rates, tidal flushing, and historical land use affect soil carbon storage. The depth at which soil carbon is measured also influences the results significantly. For example, some studies have sampled only to a depth of 1 m, while others suggest that much of the carbon is stored at depths of 2 m or more [44]. This discrepancy in sampling depth can lead to large variations in estimated carbon stocks, underscoring the need for standardized methodologies in soil carbon assessments.

### *4.3. Future Directions for Carbon Storage*

The estimation of biomass and blue carbon stocks in mangrove forests presents a series of notable limitations, despite the increasing sophistication of methodologies and the global recognition of mangroves as key players in carbon sequestration. These limitations range from the complexity of ecological processes in mangrove ecosystems to technical challenges in data collection, measurement, and analysis, each contributing to uncertainties in carbon stock assessment. The variability in species composition and growth forms across different regions is one of the foremost challenges in estimating biomass and carbon stocks in mangrove forests. Mangrove forests are highly diverse, with species that differ in structural characteristics, wood density, and biomass allocation between AGB and BGB. This variability complicates the use of allometric equations, which are often species- and site-specific. Thus, a one-size-fits-all approach in applying these equations does not capture the true biomass potential of the diverse species and growth dynamics in mangrove ecosystems globally.

Protecting and restoring mangroves in this region is crucial, as these forests are not only vital for carbon sequestration but also provide essential ecosystem services, such as coastal protection, fisheries support, and biodiversity conservation. Ongoing monitoring and management efforts are key to maximizing their climate and environmental benefits, ensuring that the mangroves of North Sumatra and Aceh continue to serve as critical carbon sinks vis à vis increasing deforestation and degradation.

Finally, the absence of a standardized global methodology for assessing biomass and blue carbon stocks impedes data comparability across various geographies and investigations. While there have been endeavors to develop unified protocols, such as those suggested by [42], many studies still employ diverse methods for data collection, analysis, and reporting. Such inconsistency makes it challenging to compile accurate global estimates of mangrove carbon stocks or compare findings from different geographical areas. Further, deficiencies in data collection—particularly in under-researched areas such as West Africa and certain portions of Southeast Asia—constrain our capacity to comprehensively understand the global significance of mangroves in carbon sequestration.

## 5. Conclusions

Although the assessment of biomass and blue carbon reserves in mangrove ecosystems has progressed due to technological and methodological advancements, considerable hurdles and constraints persist. The intricacy of allometric models, challenges in quantifying BGB, the variability of soil carbon, and the absence of standardized procedures add to uncertainty in current estimations. Addressing these limitations through more robust data collection, standardized protocols, and improved modeling techniques is essential for accurately quantifying the role of mangroves in global carbon sequestration and guiding conservation and restoration efforts aimed at enhancing their carbon storage capacity. In this study, AGB and BGB at the observed sites were 1512.22 MgC/ha; soil carbon content ranged from 1175.72 MgC/ha to 2505.86 MgC/ha; and deadwood carbon content ranged from 49.94 MgC/ha to 91.08 MgC/ha. The mangrove forests of North Sumatra and Aceh, Indonesia, are critical ecosystems for carbon sequestration, storing substantial amounts of blue carbon in both biomass and soils. The region's extensive mangrove cover significantly contributes to global efforts to mitigate climate change by absorbing carbon dioxide and trapping it in its dense root systems and organic-rich soils.

Estimations of biomass and blue carbon stocks in these areas indicate that mangroves in North Sumatra and Aceh hold considerable carbon storage potential, highlighting their importance to national and international climate strategies. These data are essential for local conservation and restoration programs, as well as initiatives that integrate mangroves into carbon credit schemes.

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