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Sediment Carbon Stocks and CO_2 Sequestration Capacity in the Bagek Kembar Mangrove Essential Ecosystem Area, West Lombok

[1*]Eni Suyantri, [2]Gito Hadiprayitno, [3]Didik Santoso, [4]Karnan, [5]M. Liwa Ilhamdi, [6]Pahrurrozi
[1,2,3,4,5,6]Department of Biology Education, Faculty of Teacher Training and Education, Universitas Mataram, Mataram, Indonesia.
*Corresponding Author e-mail: enisuyantri@unram.ac.id
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Abstract: This study aimed to analyze and compare sediment organic carbon stocks, bulk density, and estimated carbon dioxide (CO_2) sequestration in natural and revegetated mangrove areas within the Bagek Kembar Mangrove Essential Ecosystem Area (KEE), Sekotong, West Lombok. Sediment samples were collected to a depth of 100 cm and analyzed using the Loss on Ignition (LOI) method. The results showed that bulk density ranged from 1.19 to 1.50 g/cm³ and tended to decrease with increasing sediment depth. Sediment organic carbon stocks were higher in the natural mangrove area (591.49 Mg C/ha) than in the revegetated mangrove area (575.39 Mg C/ha), with the greatest carbon accumulation observed at depths of 61–100 cm. This difference indicates that natural mangroves have a slightly greater capacity for carbon accumulation than revegetated areas, likely due to more stable stand structure and sediment dynamics. Estimated CO_2 sequestration followed a similar pattern, reaching 2,170.55 Mg CO_2/ha in the natural mangrove area and 2,111.68 Mg CO_2/ha in the revegetated mangrove area. These findings provide a scientific contribution by addressing data gaps on sediment organic carbon stocks and estimated CO_2 sequestration in mangrove ecosystems in Lombok. They also strengthen the basis for conservation- and restoration-oriented management to support climate change mitigation in coastal ecosystems.
Keywords: Carbon stock; CO_2 sequestration; SOCS; Bagek Kembar Mangrove Essential Ecosystem Area

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INTRODUCTION

Global climate change is primarily driven by increasing atmospheric concentrations of greenhouse gases, particularly carbon dioxide (CO_2), resulting from fossil fuel combustion, land-use change, and deforestation (Manuri et al., 2011; IPCC, 2021). Elevated CO_2 concentrations intensify the greenhouse effect and contribute to rising global mean temperatures. In the context of climate change mitigation, ecosystem-based mitigation has increasingly been recognized as an effective strategy because it harnesses natural processes to absorb and store carbon while also providing ecological and social co-benefits (IPCC, 2022).

The concept of blue carbon has emerged as a scientific framework that emphasizes the role of coastal and shallow marine ecosystems in long-term carbon sequestration and storage (Nellemann et al., 2009; McLeod et al., 2011). Mangroves, seagrass meadows, and tidal marshes are included in this category because they can accumulate carbon not only in aboveground and belowground biomass, but also in sediments, where carbon may be stored over long timescales (Alongi, 2014; Howard et al., 2014).

Among coastal ecosystems, mangroves are recognized as one of the most efficient blue carbon reservoirs. In addition to their ecological functions as coastal protection systems and biodiversity habitats (Rachmawati et al., 2014), mangroves have substantial carbon storage capacity in belowground compartments. Several studies have shown that the largest proportion of mangrove carbon is stored in sediments rather than in aboveground biomass (Donato et al., 2011; Kauffman et al., 2012). The anaerobic characteristics of mangrove sediments, together with high organic matter accumulation, enable carbon to be stored over extended periods (McLeod et al., 2011). Globally, approximately 60–80% of total mangrove carbon is estimated to be stored in subsurface sediments (Alongi, 2018; Sanders et al., 2014), making this component central to coastal ecosystem-based climate change mitigation strategies.

Scientifically, the distribution and magnitude of soil organic carbon (SOC) in mangrove sediments are influenced by vegetation type, stand structure, sediment deposition dynamics, and soil depth (Mahassani, 2016). Vertical variation in carbon stocks reflects the interaction among organic matter inputs, decomposition processes, and hydrodynamic conditions. Therefore, sediment carbon studies are important not only for estimating total ecosystem carbon stocks, but also for understanding the stability and long-term carbon storage potential of mangrove ecosystems within the blue carbon framework.

Although global interest in blue carbon has continued to increase, research on this topic in Lombok Island remains limited and has largely focused on estimating carbon in vegetation components. Athifah (2020) reported carbon stocks in natural and revegetated mangrove stands in the Bagek Kembar Mangrove Essential Ecosystem Area (Kawasan Ekosistem Esensial, KEE). Similarly, Farista and Virgota (2021) examined the CO_2 absorption capacity of mangrove vegetation and its associated economic value. These studies have made important contributions to understanding the role of mangrove vegetation in climate change mitigation. However, they did not include the sediment compartment, even though empirical evidence indicates that sediments represent the largest and relatively more stable carbon pool compared with aboveground biomass.

The absence of sediment carbon data represents an important scientific gap. Without incorporating belowground components, estimates of the total blue carbon capacity of an area remain incomplete and may underestimate the actual role of mangroves in climate change mitigation. Moreover, no study has comparatively evaluated differences in sediment organic carbon stocks between natural and revegetated mangroves on Lombok Island. Such information is essential for assessing the effectiveness of mangrove revegetation programs in supporting long-term carbon storage.

Based on this background, this study aims to analyze and compare sediment organic carbon stocks and estimated CO_2 sequestration capacity in natural and revegetated mangroves in the Bagek Kembar Mangrove Essential Ecosystem Area, Sekotong, West Lombok. Scientifically, this study contributes to filling the sediment carbon data gap for mangrove ecosystems in Lombok and strengthens understanding of blue carbon dynamics in natural and revegetated mangrove systems. From a policy perspective, the findings provide a scientific basis for conservation- and restoration-based mangrove management to support climate change mitigation strategies in coastal areas.

METHOD

This study employed a quantitative observational design with a comparative approach to assess sediment organic carbon stocks in two mangrove ecosystem types: natural mangroves and revegetated mangroves. An observational design was used because measurements were conducted under existing ecosystem conditions without experimental manipulation. The comparative approach enabled the evaluation of differences in carbon storage function between ecosystem types. This approach is commonly applied in mangrove ecology and blue carbon assessments to evaluate the effectiveness of coastal ecosystem revegetation (Alongi, 2009; Kauffman & Donato, 2012; Howard et al., 2014).

Study Period and Location

The study was conducted from April to September 2024 in the Bagek Kembar Mangrove Essential Ecosystem Area (Kawasan Ekosistem Esensial/KEE), Cendi Manik Village, Sekotong District, West Lombok Regency, West Nusa Tenggara, Indonesia. The Bagek Kembar Mangrove KEE covers an area of 86.46 ha. The study site was divided into two areas representing the main mangrove ecosystem conditions in the Bagek Kembar Mangrove KEE: a natural mangrove area and a revegetated mangrove area.

In each area, three observation transects were established perpendicular to the coastline to represent the tidal gradient and mangrove zonation. This approach is widely used in mangrove ecological studies because it captures spatial heterogeneity from the seaward fringe to the landward zone of mangrove forests (English et al., 1997; Alongi, 2009). The coordinates of the transects in the natural mangrove area were Transect 1 (116.0504312° E; 8.7604044° S), Transect 2 (116.0501466° E; 8.7595754° S), and Transect 3 (116.0496935° E; 8.7589539° S). The coordinates of the transects in the revegetated mangrove area were Transect 1 (116.0554127° E; 8.7662863° S), Transect 2 (116.0557443° E; 8.7658071° S), and Transect 3 (116.0569366° E; 8.7660866° S). The study location and transect points are shown in Figure 1.

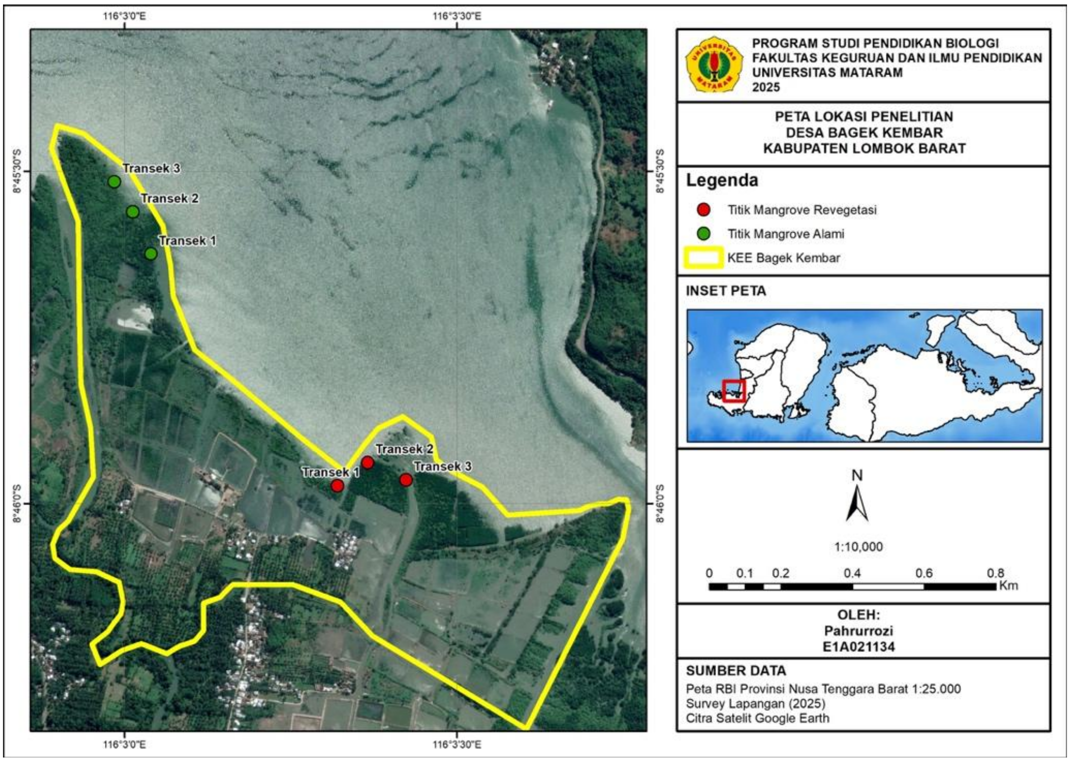

Figure 1. Study location in the Bagek Kembar Essential Ecosystem Area

Each transect consisted of three plots systematically positioned in the front, middle, and rear zones of the mangrove stand. Thus, nine plots were established in each ecosystem type, resulting in a total of 18 sampling points. This sampling intensity meets the minimum replication principle commonly applied in field ecological studies, allowing comparative statistical analysis while reducing bias caused by local spatial variation (Krebs, 1999). In addition, blue carbon measurement guidelines recommend the use of multiple transects and replicated plots to obtain representative estimates of organic carbon stocks and reduce spatial uncertainty (Kauffman & Donato, 2012; Howard et al., 2014).

Tools and Materials

The tools and materials used in this study included a sediment corer, labeled plastic sample bags, a GPS unit, stationery, a soil-drying oven, porcelain crucibles, an analytical balance, a desiccator, and a muffle furnace.

Sampling Technique

Sediment sampling was conducted through a field survey using purposive sampling based on mangrove canopy characteristics and substrate conditions (Howard et al., 2014; Kauffman & Donato, 2012). The sampling procedure followed established protocols for mangrove sediment and blue carbon assessment (Howard et al., 2014; Kauffman & Donato, 2012; Kristensen et al., 2008; Alongi, 2012), as described below:

1. Sampling plots measuring 10 × 10 m were established at each sampling point.
2. The soil surface was cleared of coarse litter, debris, and living leaves without disturbing the sediment layer.
3. Sediment samples were collected using a corer to a depth of 100 cm.
4. Each sediment core was divided into three depth intervals: 0–30 cm, 31–60 cm, and 61–100 cm. Representative subsamples were collected from depths of 10–20 cm, 40–50 cm, and 75–85 cm, respectively.
5. The samples were placed in labeled plastic bags, stored in a cooling container, and transported to the laboratory for further analysis.

Laboratory Analysis

Sediment organic carbon stocks were analyzed using the Loss on Ignition (LOI) method (Howard et al., 2014). This indirect estimation method assumes that mass loss during combustion represents sediment organic matter, which is subsequently converted into organic carbon. The analytical procedure was as follows:

1. Samples were oven-dried at 60 °C for 48 h until a constant weight was achieved.
2. The dried samples were homogenized, and approximately 3 g of each sample was weighed into a porcelain crucible.
3. The samples were combusted in a muffle furnace at 450 °C for 4 h.
4. After cooling in a desiccator, the samples were weighed again to calculate mass loss as an estimate of sediment organic matter content.
5. The percentage of organic matter was then converted into organic carbon using a standard conversion factor.

Data Analysis

After laboratory analysis, the data were analyzed using the following equations.

1. Bulk Density

Bulk density was calculated using the equation of Blake and Hartge (1986):

$$\text{Bulk Density (g/cm}^3\text{)} = \frac{oven\ dry\ mass\ (g)}{sampel\ volume\ (cm3)} \qquad (1)$$

Note:
Oven-dry mass = mass of the dried sample (g)
Sample volume = volume of the sample (cm)
Bulk density indicates the degree of sediment compaction and is an important parameter for determining carbon stock per unit area because it influences carbon accumulation within each depth interval.

Loss on Ignition

Sediment organic matter content was estimated using the Loss on Ignition method following Heiri et al. (2001):

$$\% \text{ OM} = \left(\frac{Wo - Wt}{Wo} \ x \ 100 \right) \qquad (2)$$

Note:
%OM = percentage of sediment organic matter lost during combustion
Wo = initial dry weight before combustion (g)
Wt = final weight after combustion (g)
This equation estimates sediment organic matter content based on mass loss during combustion, which is then used as the basis for calculating organic carbon content.

Conversion of Organic Matter to Organic Carbon

The percentage of organic matter was converted into organic carbon following Schumacher (2002):

$$\% \text{ C} = \left(\frac{1}{1{,}724} \ x \ \% \ \text{OM} \right) \qquad (3)$$

Note:
%C = organic carbon content
0.580 = conversion factor from organic matter to organic carbon
%OM = percentage of sediment organic matter determined by combustion
This conversion assumes that approximately 58% of organic matter consists of carbon, thereby enabling the estimation of sediment organic carbon from organic matter loss.

Sediment Carbon Stock

Sediment carbon stock was estimated using the equation of Don et al. (2011) and Howard et al. (2014):

$$\text{Soil C (Mg/ha)} = \% \text{ C x BD x SDI} \qquad (4)$$

Note:
Soil C = estimated carbon stock (Mg/ha)
Bulk Density = sediment bulk density (g/cm^3)
SDI = soil depth interval (cm)
%C = sediment organic carbon percentage
This equation integrates organic carbon content, sediment density, and sampling depth to calculate total carbon stock per unit land area.

Estimation of Sediment Carbon Dioxide Equivalent

Sediment carbon dioxide equivalent was estimated using the equation of IPCC (2006) and EPA (2024):

$$CO_2 = \text{Stock C x 3,67} \qquad (5)$$

Note:
CO_2 = estimated carbon dioxide equivalent (t CO_2 ha^{-1})
C = sediment organic carbon stock (t C ha^{-1})

3.67 = conversion factor from carbon atoms to CO_2 molecules
The conversion factor of 3.67 was used to convert carbon stock into CO_2 equivalent, allowing the results to be interpreted in the context of climate change mitigation.

RESULTS AND DISCUSSION

Bulk Density

Based on the results presented in Table 1, sediment bulk density in the natural and revegetated mangrove ecosystems varied among transects and soil depths, ranging from 1.19 to 1.50 g cm^{-3}. In general, both sites exhibited a similar pattern: the highest bulk density was recorded at a depth of 0–30 cm, followed by a decrease at 31–60 cm, and the lowest values at 61–100 cm. This pattern is consistent with the general characteristics of mangrove soils, where stronger compaction occurs in the surface layer due to tidal activity, root pressure, and more intensive sediment deposition. In contrast, deeper layers tend to contain higher organic matter stocks and have a looser structure, resulting in lower bulk density. These findings are consistent with Komiyama et al. (2008), who reported that mangrove soil bulk density generally decreases with increasing depth due to the accumulation of organic materials derived from root and litter decomposition.

Table 1. Sediment bulk density in the Bagek Kembar Mangrove Essential Ecosystem Area, Sekotong, West Lombok

Location	Transect	0–30 cm (g cm^{-3})	31–60 cm (g cm^{-3})	61–100 cm (g cm^{-3})	Total (g cm^{-3})	Mean (g cm^{-3})	Mean (g cm^{-3})
Natural mangrove	1	1.45	1.39	1.22	4.06	4.03	4.08
	2	1.36	1.38	1.27	4.01		
	3	1.42	1.36	1.24	4.02		
Revegetated mangrove	1	1.44	1.42	1.22	4.08	4.13	
	2	1.50	1.45	1.23	4.18		
	3	1.46	1.47	1.19	4.12		

In the natural mangrove ecosystem, bulk density values were relatively stable across transects, ranging from 1.22 to 1.45 g cm^{-3}, with total bulk density values of approximately 4.01–4.06 g cm^{-3}. This condition indicates that the sediment layers have developed naturally over a long period, as reflected by finer sediment texture and a greater contribution of organic matter from a well-established root system. Such stability reflects good ecosystem quality and supports ecological functions, including carbon storage. As explained by Alongi (2012), natural mangroves generally have more stable soil structures and higher organic matter stocks, resulting in relatively lower bulk density than newly revegetated areas.

In contrast, the revegetated mangrove ecosystem showed relatively higher bulk density, particularly in the surface layer of 0–30 cm, where values reached 1.50 g cm^{-3} in some transects. This indicates that sediments in the revegetated mangrove area are still in an early stage of development and have not yet fully undergone the formation of a stable soil structure. Higher compaction may be associated with recent sediment deposition, lower organic matter stocks, and a mangrove root system that is still developing. According to Donato et al. (2011), revegetated mangrove areas typically have higher bulk density because significant organic matter accumulation has not yet occurred, and root-driven soil loosening remains limited.

The difference in bulk density between natural and revegetated mangroves in this study reflects the level of ecosystem maturity. Lower bulk density in natural mangroves indicates more developed soil conditions, characterized by looser sediment structure and higher organic matter stocks. Conversely, higher values in the revegetated site indicate an early stage of ecosystem development, during which organic matter accumulation and soil structure stabilization are still ongoing (Alongi, 2014; Kauffman & Donato, 2012).

This condition has direct implications for carbon storage capacity because bulk density is generally inversely related to organic matter and organic carbon stocks in sediments (Craft et al., 1991). Sediments with lower bulk density tend to have higher porosity and greater organic matter accumulation, thereby increasing carbon stocks per unit volume (Chmura et al., 2003; Donato et al., 2011). In addition, organic-rich sediment structures support anaerobic conditions that slow decomposition processes, allowing carbon to be stored over long periods (McLeod et al., 2011; Alongi, 2018). Therefore, differences in bulk density not only reflect the physical condition of the ecosystem but also indicate differences in sediment organic carbon storage capacity between natural and revegetated mangroves. These findings confirm that bulk density is an important indicator for assessing mangrove ecosystem condition and carbon storage potential.

Sediment Organic Carbon Stock

Sediment organic carbon stock, or Soil Organic Carbon Stock (SOCS), in the natural and revegetated mangrove ecosystems of the Bagek Kembar Mangrove Essential Ecosystem Area indicates a high carbon storage capacity. Based on the transect-level calculations presented in Table 2, SOCS values in the natural mangrove ranged from 193.73 to 201.25 Mg ha^{-1}, whereas those in the revegetated mangrove ranged from 190.02 to 193.15 Mg ha^{-1}. The total SOCS values were 591.49 Mg C ha^{-1} and 575.39 Mg C ha^{-1}, respectively. These values indicate that both ecosystem types play an important role in long-term carbon storage, although the natural mangrove still showed a slightly higher capacity as a consequence of greater ecosystem maturity and more stable biogeochemical processes.

Table 2. Sediment carbon stock in the Bagek Kembar Mangrove Essential Ecosystem Area, Sekotong

Location	Transect	SOCS (Mg ha^{-1})	Total SOCS (Mg ha^{-1})
Natural mangrove	1	193.73	591.49
	2	201.25	
	3	196.45	
Revegetated mangrove	1	192.22	575.39
	2	193.15	
	3	190.02	

The high SOCS values in the natural mangrove reflect a more stable ecosystem condition, characterized by continuous litter input, a complex root system, and balanced decomposition processes. These conditions facilitate the long-term accumulation of organic matter in sediments. In contrast, the slightly lower SOCS values in the revegetated mangrove indicate that soil carbon formation is still progressing, particularly under the influence of stand age and root structure development (Komiyama et al., 2008; Alongi, 2012).

The vertical distribution of SOCS in both ecosystem types, as presented in Table 3, showed a consistent pattern, with carbon values increasing with sediment depth. In the natural mangrove, SOCS increased from 37.73 ± 1.43 Mg ha⁻¹ at 0–30 cm to 73.35 ± 2.64 Mg ha⁻¹ at 31–60 cm and reached 86.06 ± 2.61 Mg ha⁻¹ at 61–100 cm. A similar pattern was observed in the revegetated mangrove, with values of 34.76 ± 2.24 Mg ha⁻¹, 66.49 ± 1.76 Mg ha⁻¹, and 90.55 ± 3.49 Mg ha⁻¹, respectively. This increase indicates that deeper sediment layers have a greater capacity to store carbon because anaerobic conditions slow the decomposition of organic matter, allowing carbon to accumulate over long periods (Donato et al., 2011; Kauffman & Donato, 2012).

Table 3. Mean sediment carbon stock by depth in the Bagek Kembar Mangrove Essential Ecosystem Area, Sekotong

Location	0–30 cm ($Mg\ ha^{-1}$)	31–60 cm ($Mg\ ha^{-1}$)	61–100 cm ($Mg\ ha^{-1}$)	Total SOCS ($Mg\ ha^{-1}$)
Natural mangrove	37.73 ± 1.43	73.35 ± 2.64	86.06 ± 2.61	591.49
Revegetated mangrove	34.76 ± 2.24	66.49 ± 1.76	90.55 ± 3.49	575.39

When compared regionally, SOCS values in the Bagek Kembar Mangrove Essential Ecosystem Area can be classified as moderate to high within the context of Indonesian mangrove ecosystems. Primary mangroves in Papua, particularly in deltaic systems with high sediment supply, have been reported to contain sediment carbon stocks exceeding 800 Mg C ha⁻¹ (Murdiyarso et al., 2015; Sasmito et al., 2020). In Kalimantan, sediment carbon stocks range from 600 to 1,000 Mg C ha⁻¹, depending on geomorphological conditions and sediment depth (Donato et al., 2011; Kauffman et al., 2014). Meanwhile, in Sulawesi and Java, SOCS values tend to be lower due to anthropogenic pressures and land conversion, which lead to ecosystem degradation and disruption of carbon accumulation processes (Alongi, 2014; Friess et al., 2020a). Thus, SOCS values in Lombok indicate a mangrove system with competitive carbon storage capacity, particularly under the geomorphological conditions of a semi-enclosed bay that supports fine sediment deposition and substrate stabilization (Woodroffe, 1992; Alongi, 2008).

The relatively small difference in SOCS between natural and revegetated mangroves indicates that ecosystem recovery has progressed effectively. This condition may be explained by several factors. First, the relatively long period since revegetation has allowed progressive organic matter accumulation, enabling organic carbon stocks to approach those of natural mangroves. Previous studies have shown that revegetated mangroves can recover many ecological functions within 5–10 years, depending on environmental conditions and species suitability (Kusmana, 2018; Sasmito et al., 2020). Second, the deeper sediment layers may have stored historical carbon before revegetation activities were implemented. Therefore, SOCS values are not determined solely by current vegetation conditions but also by long-term sedimentation processes (Kauffman & Donato, 2012). This is reflected in the relatively high SOCS values at 61–100 cm depth in both mangrove types.

Third, anthropogenic disturbance in the Bagek Kembar Mangrove Essential Ecosystem Area is relatively low, allowing sedimentation and carbon accumulation processes to occur optimally. In contrast to coastal areas in Java and parts of Sulawesi, which experience land conversion pressures and hydrological disturbance, the Bagek Kembar Essential Ecosystem Area still maintains its ecological functions relatively well (Friess et al., 2020b). These conditions support the formation of organic-rich sediments and slow decomposition processes through anaerobic conditions, thereby increasing the efficiency of long-term carbon storage (McLeod et al., 2011; Alongi, 2018).

In addition to biological factors, the geomorphological condition of the Sekotong coastal area, which consists of a semi-enclosed bay with relatively low to moderate wave energy, also supports sediment deposition and carbon accumulation. Stable tidal dynamics allow sediments to be distributed more evenly, while mangrove root systems retain suspended particles and accelerate the formation of organic sediment layers (Furukawa & Wolanski, 1996; McKee et al., 2007; Krauss et al., 2014). The combination of these factors makes the Bagek Kembar Essential Ecosystem Area highly suitable for sediment carbon storage.

Estimation of Carbon Dioxide Uptake

The carbon dioxide (CO_2) uptake values of mangrove ecosystems in the Bagek Kembar Mangrove Essential Ecosystem Area, as presented in Table 4, indicate a high carbon sequestration capacity, with total uptake of 2,170.55 tons CO_2 ha^{-1} in the natural mangrove and 2,111.68 tons CO_2 ha^{-1} in the revegetated mangrove. At the transect level, CO_2 uptake values in the natural mangrove ranged from 710.99 to 738.59 tons CO_2 ha^{-1}, which were relatively higher than those in the revegetated mangrove, ranging from 697.37 to 708.86 tons CO_2 ha^{-1}. Nevertheless, the difference between the two ecosystem types was not substantial, indicating that both have comparable functional capacity for carbon sequestration.

Table 4. Sediment CO_2 uptake in the Bagek Kembar Mangrove Essential Ecosystem Area, Sekotong, West Lombok

Location	Transect	SOCS (Mg ha^{-1})	Uptake (tons CO_2 ha^{-1})	Total uptake (tons CO_2 ha^{-1})
Natural mangrove	1	193.73	710.99	2,170.55
	2	201.25	738.59	
	3	196.45	720.97	
Revegetated mangrove	1	192.22	705.45	2,111.68
	2	193.15	708.86	
	3	190.02	697.37	

The relatively small difference in CO_2 uptake indicates that the revegetated mangrove ecosystem in the Bagek Kembar Mangrove Essential Ecosystem Area has reached an advanced stage of recovery. In terms of carbon dynamics, this condition suggests that CO_2 uptake is not determined solely by current vegetation conditions but also by historical carbon accumulation stored in sediments. Mangrove sediment layers function as relatively stable long-term carbon reservoirs; therefore, past carbon contributions continue to influence present carbon sequestration capacity (Kauffman & Donato, 2012). Thus, CO_2 uptake in the revegetated mangrove reflects the combined effects of vegetation recovery and pre-existing sediment carbon reserves.

Ecologically, the high CO_2 uptake values in both mangrove types confirm the important role of mangrove ecosystems as effective carbon sinks. This capacity is mainly supported by carbon accumulation mechanisms in sediments under anaerobic conditions, which slow the decomposition of organic matter and allow carbon to be stored over long periods (Donato et al., 2011; McLeod et al., 2011). Compared with terrestrial ecosystems, carbon storage in mangrove sediments tends to be more stable, making its contribution to climate change mitigation more significant (Alongi, 2018).

In the context of climate change mitigation, CO_2 uptake values exceeding 2,000 tons CO_2 ha^{-1} indicate that mangrove areas in the Bagek Kembar Essential Ecosystem Area have substantial potential to reduce atmospheric carbon concentrations. However, this capacity is also associated with vulnerability. Disturbances to mangrove ecosystems, such as land conversion or habitat degradation, can release carbon stored in sediments into the atmosphere, thereby shifting the ecosystem function from a carbon sink to a carbon source (Pendleton et al., 2012). Therefore, the sustainability of mangrove ecosystem functions depends strongly on maintaining ecosystem integrity.

The findings of this study in the Bagek Kembar Mangrove Essential Ecosystem Area demonstrate that the conservation of natural mangroves and mangrove revegetation play complementary roles in supporting climate change mitigation. Natural mangroves should be prioritized for protection because they store more stable organic carbon stocks and may release substantial carbon emissions if degraded (Donato et al., 2011; Pendleton et al., 2012). At the same time, the ability of revegetated mangroves to achieve CO_2 uptake values approaching those of natural mangroves indicates that revegetation is an effective strategy for gradually increasing carbon sequestration capacity (Friess et al., 2020a).

Therefore, management of the Bagek Kembar Essential Ecosystem Area should integrate mangrove protection and revegetation in a balanced manner. An ecosystem-based approach is essential, particularly through long-term monitoring of sediment organic carbon stocks, vegetation structure, and sedimentation dynamics, to ensure the continued function of mangroves as carbon sinks. Furthermore, the organic carbon stock and CO_2 uptake data generated in this study can serve as a scientific basis for supporting climate change mitigation policies, particularly those related to the contribution of the forestry and land-use sectors to Indonesia's Nationally Determined Contribution (NDC) targets.

CONCLUSION

This study demonstrates that sediment organic carbon stocks were higher in natural mangroves (591.49 Mg C ha^{-1}) than in revegetated mangroves (575.39 Mg C ha^{-1}), with estimated CO_2 equivalents of 2,170.55 Mg CO_2 ha^{-1} and 2,111.68 Mg CO_2 ha^{-1}, respectively. The relatively small difference between the two mangrove types indicates that revegetation efforts have been effective in restoring sediment carbon storage functions to a level approaching that of natural mangrove ecosystems. Although natural mangroves still exhibit a more stable carbon storage capacity, revegetated mangroves show strong potential to attain comparable conditions as stand age increases and ecosystem structure continues to develop. These findings highlight the importance of protecting natural mangroves while ensuring the continuity of revegetation programs to support coastal ecosystem-based climate change mitigation.

RECOMMENDATION

Based on the findings of this study, future research should extend sediment sampling beyond the 100 cm depth assessed in the present work, as mangrove carbon may be stored at greater depths. Sampling to depths of 2–3 m would provide a more comprehensive estimate of sediment organic carbon stocks. In addition, subsequent studies should not be limited to sediment carbon alone but should also integrate aboveground biomass (AGB), belowground biomass (BGB), and litter carbon to obtain a more complete assessment of total carbon stocks in mangrove ecosystems.

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