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Research Article

Carbon Stock in Oceanic Mangrove of Gili Sulat-Lawang Marine Tourism Park, Sembelia-Eastern Lombok

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Abstract
Mangroves are highly productive coastal ecosystems that play a critical role in carbon sequestration and climate change mitigation. This study quantified carbon stocks in oceanic mangroves of the Gili Sulat–Lawang Marine Tourism Park, characterized by strong tidal influence and absence of freshwater input. Carbon pools were assessed in living and dead vegetation, as well as soils across three management zones. The biomass and carbon content of living mangrove were estimated using species-specific allometric equations. The dead mangrove carbon pool was estimated based on the biomass of standing dead wood and downed wood. Soil organic matter was analyzed using the loss on ignition method, in which soil samples are combusted at high temperature to determine organic content. The total carbon stock was estimated at 379.137 Mg C/ha, with living vegetation contributing 53.55%, soils 44.26%, and dead biomass 2.19%. The highest carbon stock was recorded in the utilization zone, followed by the core and fisheries zones. These findings highlight the substantial carbon storage potential of oceanic mangroves, emphasizing their relevance to Indonesia's Nationally Determined Contribution (NDC) targets and the importance of incorporating mixed-species restoration strategies to enhance ecosystem resilience and sustainability.

Keywords: carbon stock, gili lawang, gili sulat, oceanic mangroves

1. INTRODUCTION

Mangrove ecosystems play a vital role in global climate regulation by sequestering atmospheric CO_2 through photosynthesis and storing it as carbon stock in biomass and soils [1][2]. Although mangroves cover only 0.5% of the world's coastline, they are among the most productive ecosystems and can store organic carbon up to three times greater than tropical terrestrial forests [3][4]. The carbon storage rate of mangrove in Indonesia is 67.7 metric tons per year [5], which is the optimal storage rate of 155 kg C per day per hectare [6]. The highest carbon stocks are in the substrate, with a percentage range between 49–89% of the total ecosystem carbon [4]. These ecosystems are thus crucial for supporting Indonesia's climate commitments, including the Forestry and Other Land Use (FOLU) Net Sink 2030 and the Nationally Determined Contribution (NDC) under the Paris Agreement [7].

The Gili Sulat–Lawang Marine Tourism Park (MTP), located in eastern Lombok, hosts one of the largest mangrove ecosystems in West Nusa Tenggara, covering over 870 ha [8]. These mangroves are unique because they represent an oceanic overwash forest type, shaped primarily by tidal regimes rather than freshwater or river inputs. This exposure to prolonged salinity and tidal inundation creates highly dynamic ecological conditions where *Rhizophora* species dominate due to their adaptive root structures [9]. However, oceanic mangroves are highly vulnerable to climate change, particularly sea-level rise. Model projections indicate that a 0.3 °C increase in atmospheric temperature may raise sea level by 6 cm per decade, amounting to 1.1 m by 2100, which could submerge 115 small islands and inundate 90,620 km² of Indonesia's coastal areas [10][11]. Such chronic inundation threatens mangroves by submerging roots for extended periods, disrupting respiration and nutrient cycling, increasing physiological stress, and reducing productivity and survival. Over time, these stresses may alter zonation and species composition, ultimately diminishing critical ecosystem services such as carbon storage, shoreline protection, and fisheries support [12]. This risk is particularly acute in Gili Sulat–Lawang, where the absence of freshwater and sediment input amplifies vulnerability to inundation.

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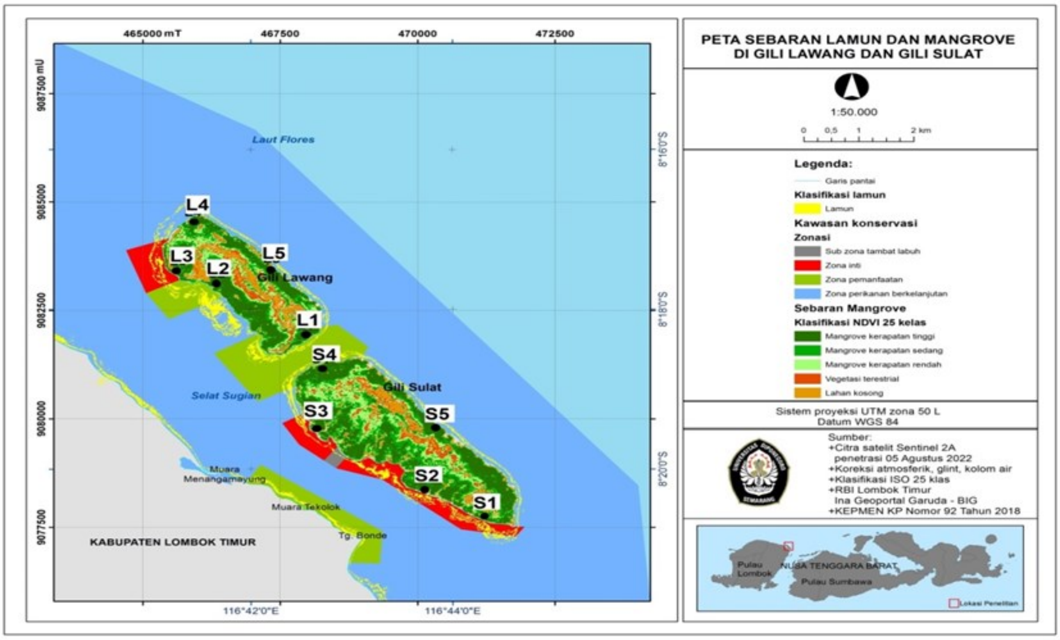

Figure 1. MTP of Gili Sulat-Lawang. Core zone are marked with red areas, utilization zone are marked with green areas and fisheries zone are marked with blue areas.

Table 1. Ten stations at three zones of TWP Gili Sulat-Lawang.

Zones	Stations	Longitude	Latitude
Core	Sulat 1 (S1)	116.737000	-8.342677
	Sulat 2 (S2)	116.725970	-8.336930
	Sulat 3 (S3)	116.714157	-8.328131
	Lawang 3 (L3)	116.688567	-8.293744
Utilization	Sulat 4 (S4)	116.710737	-8.312048
	Lawang 1 (L1)	116.706737	-8.307910
	Lawang 2 (L2)	116.693300	-8.294771
Fisheries	Sulat 5 (S5)	116.730818	-8.324717
	Lawang 4 (L4)	116.689615	-8.281759
	Lawang 5 (L5)	116.706535	-8.295160

Despite their ecological and climate importance, quantitative assessments of carbon stocks in oceanic mangrove ecosystems remain limited. Previous studies have largely focused on estuarine or riverine mangroves, while oceanic mangroves—especially those on small islands—are underrepresented in carbon stock research. This knowledge gap constrains accurate reporting for NDC targets and the development of blue carbon financing schemes. Therefore, this study aims to quantify the carbon stock of mangroves in the Gili Sulat–Lawang MTP across three major carbon pools—living biomass, dead biomass, and soil—within different conservation zones. By providing robust estimates, this research contributes novel insights into the carbon storage capacity of oceanic mangroves and supports evidence-based strategies for climate mitigation, conservation planning, and sustainable management of marine tourism parks.

2. MATERIALS AND METHODS

2.1. Study Area

MTP of Gili Sulat-Lawang consists of two satellite islands (Gili Sulat and Gili Lawang) which are located in the northeast of Lombok. The study of the carbon stock of mangrove has been conducted from June to August 2023 in the MTP of

Gili Sulat-Lawang lying between 116.685487 E to 116.744493 E and -8.279985 S to -8.345725 S (Figure 1 and Table 1).

2.2. Procedures

The data on mangrove carbon stock was carried out at ten stations representing three conservation zones, including core, utilization, and fishery zones. In each station, two transect lines 100 m long were made perpendicular to the coastline. The distance between transect lines in each station is 50 m. In each transect line, five square plots of 100 m^2 were made, where the distance between plots is 25 m. The total number of plot in ten stations are 100 plots. Carbon stock of mangrove at MTP of Gili Sulat-Lawang was measured in three carbon pools they are living mangrove vegetation, dead mangrove vegetation, and soil carbon pools.

Biomass of living mangrove was estimated by measuring the trunk diameter of mangrove at 1.3 m height (diameter at breast-height/DBH) for each tree included in the plot. Specifically for *Rhizophora* spp, which have stilt-root characteristics, the trunk diameter was measured at 30 cm above the highest prop roots [13]. For some cases such as trees growing at an angle, trees growing upright on sloping land, and trees with many or abnormal trunks, DBH is measured following the protocol established based on the Indonesian National Standard (SNI) number 7724 of 2019 [14]. Aboveground biomass (AGB), including trunk, branch, leaves, and fruits, and also belowground/root biomass (BGB) of the mangrove, were estimated using species-specific allometric

Table 2. Allometric equations of mangrove.

Species	Allometric Equations	Locations
A. marina	$AGB = 0.185 \times DBH^{2.352}$ [19]	West Java, Indonesia
	$BGB = 0.168 \times DBH^{1.794}$ [19]	West Java, Indonesia
B. gymnorrhiza	$AGB = 0.186 \times DBH^{2.31}$ [20]	Australia
	$BGB = 0.199 \times \rho^{0.899} \times DBH^{2.22}$ [21]	Indonesia &Thailand
C. tagal	$AGB = 0.529 \times DBH^{2.04}$ [22]	Sulawesi, Indonesia
	$BGB = 0.199 \times \rho^{0.899} \times DBH^{2.22}$ [21]	Indonesia &Thailand
E. agallocha	$\text{Log } AGB = (1.0996 \times (\text{Log } DBH^2)) - 0.8572$ [23]	Bangladesh
	$BGB = 0.199 \times \rho^{0.899} \times DBH^{2.22}$ [21]	Indonesia &Thailand
H. littoralis	$AGB = 0.251 \times \rho \times DBH^{2.46}$ [21]	Indonesia &Thailand
	$BGB = 0.199 \times \rho^{0.899} \times DBH^{2.22}$ [21]	Indonesia &Thailand
L. racemosa	$AGB = 0.184 \times DBH^{2.384}$ [24]	Sulawesi, Indonesia
	$BGB = 0.199 \times \rho^{0.899} \times DBH^{2.22}$ [21]	Indonesia &Thailand
P. acidula	$AGB = 0.251 \times \rho \times DBH^{2.46}$ [21]	Indonesia &Thailand
	$BGB = 0.199 \times \rho^{0.899} \times DBH^{2.22}$ [21]	Indonesia &Thailand
R. apiculata	$\text{Log } AGB = -1.34 + 2.60 \text{ Log } DBH$ [25]	Borneo, Indonesia
	$BGB = 0.0078 \times DBH^{3.09}$ [26]	Riau, Indonesia
R. mucronata	$AGB = 0.143 \times DBH^{2.52}$ [22]	Sulawesi, Indonesia
	$BGB = 0.0008 \times DBH^{3.64}$ [27]	Riau, Indonesia
R. stylosa	$AGB = 0.045 \times (DBH^{2.868})$ [28]	Philippines
	$BGB = 0.134 \times (DBH^{2.40})$ [28]	Philippines
S. alba	$AGB = 0.258 \times DBH^{2.287}$ [29]	Cilacap, Indonesia
	$BGB = 0.199 \times \rho^{0.899} \times DBH^{2.22}$ [21]	Indonesia &Thailand
X. granatum	$AGB = 0.1832 \times DBH^{2.21}$ [30]	Borneo, Indonesia
	$BGB = 0.199 \times \rho^{0.899} \times DBH^{2.22}$ [21]	Indonesia &Thailand

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Table 3. Species richness of mangrove in MTP of Gili Sulat-Lawang.

No	Species	Stations									
		Core Zone				Utilization Zone			Fisheries Zone		
		S1	S2	S3	L3	S4	L1	L2	S5	L4	L5
Family Rhizophoraceae											
1	*B. gymnorhiza*	-	+	+	+	+	+	+	+	+	+
2	*C. tagal*	+	-	-	-	+	+	-	-	+	-
3	*R. apiculata*	+	+	+	+	+	+	+	-	+	-
4	*R. mucronata*	+	+	+	+	+	+	+	+	+	+
5	*R. stylosa*	+	+	+	-	+	+	+	+	+	+
Family Sonneratiaceae											
6	*S. alba*	+	+	+	+	+	+	-	-	+	-
Family Avicenniaceae											
7	*A. marina*	+	-	-	-	-	-	-	-	-	-
Family Euphorbiaceae											
8	*E. agallocha*	+	-	-	+	-	-	-	-	-	-
Family Combretaceae											
9	*L. racemosa*	-	-	-	+	-	-	-	-	-	+
Family Lythraceae											
10	*P. acidula*	-	-	-	+	-	-	-	-	-	-
Family Sterculiaceae											
11	*H. littoralis*	-	-	-	+	-	-	-	-	-	-
Family Meliaceae											
12	*X. granatum*	-	-	-	+	-	-	-	-	-	-

Note: S is a station in Gili Sulat comprised by five stations (S1 to S5) whereas L is a station in Gili Lawang comprised by five stations (L1 to L5).

equations (Table 2). Allometric equations were selected based on species identity, with preference for regionally derived models. Where unavailable, published equations from ecologically similar environments (e.g., Philippines and Thailand) were applied. Carbon stock in aboveground (CAG) and belowground (CBG) of living mangrove vegetation is estimated by multiplying the AGB or BGB with the carbon conversion factor (0.47), it means 47% of living mangrove biomass is organic carbon [15]. The total carbon of living mangrove vegetation is calculated by summing the CAG and CBG. Mangrove species identification was verified by mangrove experts using the Field Guide to Mangroves in Indonesia; ambiguous individuals were categorized as undetermined and excluded from biomass calculations [16].

The dead mangrove carbon pool was estimated based on the biomass of standing dead wood (W_{DT}) and downed wood (W_{WD}). The W_{DT} procedure is similar to the aboveground biomass estimation of living mangrove, with some correction factors. Correction factors of 0.9, 0.8, and 0.7 were used for dead trees with branches and twigs, main branches, and those without branches and twigs, respectively [17]. The W_{WD} was calculated by measuring all downed wood in the plot with a diameter of more than 5 cm and a minimum length of 0.5 m. The sample of wood was taken to determine its wood density [18]. Biomass was then calculated by Equation (1).

$$\text{Biomass of downed wood } (W_{WD}) = \pi \, x \, d^2 \, x \, h \, x \, \rho/40 \quad \mathbf{(1)}$$

Table 4. Density and carbon stock of mangrove species in the living mangrove vegetation of MTP of Gili Sulat-Lawang.

No	Species	Gili Sulat				Gili Lawang			
		DBH (cm)	Density (Ind/ha)	Carbon Stock (Mg C/ha)		DBH (cm)	Density (Ind/ha)	Carbon Stock (Mg C/ha)	
				C_{AG}	C_{BG}			C_{AG}	C_{BG}
1	*S. alba*	17.2±16.0 (3 to 78)	102	19.7	9.44	26.3±23.7 (2 to 92.5)	38	18.1	8.5
2	*R. apiculata*	10.6±6.8 (2 to 37)	848	16.5	12.2	8.7±9.7 (2 to 75)	704	19.8	19.9
3	*R. mucronata*	9.3±6.0 (2 to 35)	1234	42.9	6.45	13.4±7.5 (2 to 37.5)	1194	90.6	16.4
4	*R. stylosa*	9.3±5.0 (3.5 to 28)	518	12.6	10.4	9.3±5.6 (2 to 21.5)	42	1.09	0.09
5	*B. gymnorhiza*	15.3±8.5 (4 to 40)	182	12.7	7.82	16.4±15.3 (2 to 102.5)	332	45.5	26.6
6	*A. marina*	4.7±1.7 (2 to 10)	170	0.67	0.32	0 (0)	0	0	0
7	*C. tagal*	6.5±2.2 (4 to 9)	10	0.12	0.05	3.0±0.0 (3 to 3)	6	0.01	0.005
8	*L. racemosa*	0 (0)	0	0	0	4.8±2.3 (2 to 12)	94	0.47	0.22
9	*P. acidula*	0 (0)	0	0	0	2.8±1.0 (2 to 4.5)	10	0.02	0.01
10	*E. agallocha*	4.9±2.7 (2 to 12)	46	0.14	0.08	6.3±0.3 (6 to 6.5)	6	0.02	0.01
11	*H. littoralis*	0 (0)	0	0	0	7.4±4.4 (3 to 13.5)	8	0.17	0.08
12	*X. granatum*	0 (0)	0	0	0	8.1±6.1 (2 to 23)	30	0.46	0.37

Table 5. Regression analysis of living mangrove carbon stock, mangrove density and mangrove size in MTP of Gili Sulat-Lawang.

	Coefficient	Standard Error	t-value	p-value
Intercept	-8.94586	0.38064	-23.50	7.85e-14***
Average of DBH	2.55594	0.19357	13.20	5.09e-10***
Average of Tree Density	1.00493	0.06186	16.25	2.30e-11***

Table 6. Carbon stock of living mangrove vegetation on each zone in MTP of Gili Sulat-Lawang.

No	Stations	Densit (ind/Ha)	Basal Area (m^2/Ha)	Biomass (Mg /Ha)		Carbon Stock (Mg C/Ha)		
				W_{AG}	W_{BG}	C_{AG}	C_{BG}	Ctot
1	**Core Zone**							
	S1	3990	38.1	244.3	135.0	114.8	55.8	170.6
	S2	3650	43.8	242.8	131.7	113.8	61.6	175.4
	S3	3620	36.7	220.8	118.3	103.8	55.6	159.4
	L3	2590	51.2	381.3	178.6	138.7	74.1	212.8
	Avaerage	**3462.5**	**42.4**	**272.3**	**140.9**	**117.8**	**61.8**	**179.6**
2	**Utilization Zone**							
	S4	1710	30.3	163.3	77.7	76.3	36.5	112.8
	L1	2150	69.4	545.6	314.9	256.4	148.0	404.5
	L2	2160	51.1	409.3	133.5	192.3	62.7	255.1
	Average	**2006**	**50.5**	**372.7**	**175.4**	**175.0**	**82.4**	**257.5**
3	**Fisheries Zone**							
	S5	2680	31.7	251.3	50.2	118.1	23.6	141.7
	L4	2360	37.3	257.6	85.2	121.1	40.0	161.1
	L5	2260	43.3	366.2	92.2	172.1	43.3	215.4
	Average	**2433.3**	**37.4**	**291.7**	**75.9**	**137.1**	**35.7**	**172.8**

Note: W_{AG} (Aboveground Biomass); W_{BG} (Belowground Biomass); C_{AG} (Carbon of Aboveground); C_{BG} (Carbon of Belowground); Ctot (Total Carbon in Living Mangrove Tree which was accumulated of C_{AG} and C_{BG}).

where h is the wood length (m), d is wood diameter (cm), ρ is Wood density (g/cm^3), and 40 is a mathematical constant. Carbon content of standing dead wood (C_{DT}) and downed wood (C_{WD}) is estimated by multiplying the W_{DT} or W_{WD} with the carbon conversion factor (0.47) [14].

Soil carbon pools were collected at each station. Soil depth was measured using an open-face peat auger with a 6 cm diameter at the plot center [31]. Soil samples were then taken at depth intervals of 0–5, 5–15, 15–30, 30–50, and 50–100 cm [13]. At each interval, a 5 cm-thick sub-sample was collected for laboratory analysis of bulk density and organic matter content, expressed as loss on ignition (LOI). LOI is defined as the mass of soil lost after combustion at high temperature (450 °C for 4 h) and is used to estimate soil organic matter content [32]. Dry bulk density (BD) was calculated by dividing the mass of dry soil (g) by the volume of soil sampled (cm³). Mangrove soil carbon was calculated using the Equation (2) - (6):

$$\% LOI = \frac{Dry\ mass\ soil\ before\ combustion\ (mg) - Dry\ mass\ soil\ after\ combustion\ (mg)}{Dry\ mass\ soil\ before\ combustion\ (mg)} \times 100\ \% \quad (2)$$

$$\% C_{org} = 0.415 \times \% LOI + 2.89 \quad (3)$$

$$BD = \frac{Dry\ mass\ soil\ sampled\ (g)}{Volume\ of\ soil\ sampled\ (cm^3)} \quad (4)$$

$$C_{density} = BD \times (\frac{\% C_{org}}{100}) \quad (5)$$

$$C_{soil} = \% C_{org} \times The\ thick\ of\ soil\ sample\ (cm) \quad (6)$$

where, % LOI is organic matter content; % C_{org} is organic carbon content; BD is dry bulk density (g/cm^3); $C_{density}$ is soil organic carbon density (g/cm^3); and C_{soil} is a soil organic carbon (g/cm^3). Total carbon stock at each zone in the mangrove ecosystem of MTP of Gili Sulat-Lawang was calculated by accumulating the carbon content in each carbon pool [33].

2.3. Data Analysis

All data on mangrove carbon stock in the MTP of Gili Sulat-Lawang were presented using tables and graphs. Regression analysis was used to understand the influence of tree density and tree size on living mangrove carbon stock. Differences in tree density, basal area, and carbon stock among zones (core, utilization, and fisheries zones) were assessed utilizing analysis of variance (ANOVA) and multivariate analysis of variance (MANOVA). A post-hoc Tukey's honest significant difference (HSD) test was applied to determine the significance of means when the ANOVA or MANOVA result was significant. All statistical analysis was conducted using R 4.2.0.

3. RESULTS AND DISCUSSIONS

Mangrove forest in MTP of Gili Sulat-Lawang is divided into three conservation zones they are core, utilization, and fisheries zones. Ten stations are used to measure carbon stock in mangrove ecosystems covering two satellite islands of Lombok (Gili Sulat and Gili Lawang), which represent each zone. The core zone comprises four stations (Sulat 1, Sulat 2, Sulat 3, and Lawang 3), the utilization zone comprises three stations (Sulat 4, Lawang 1, and Lawang 2), and the fisheries zone comprises three stations (Sulat 5, Lawang 4, and

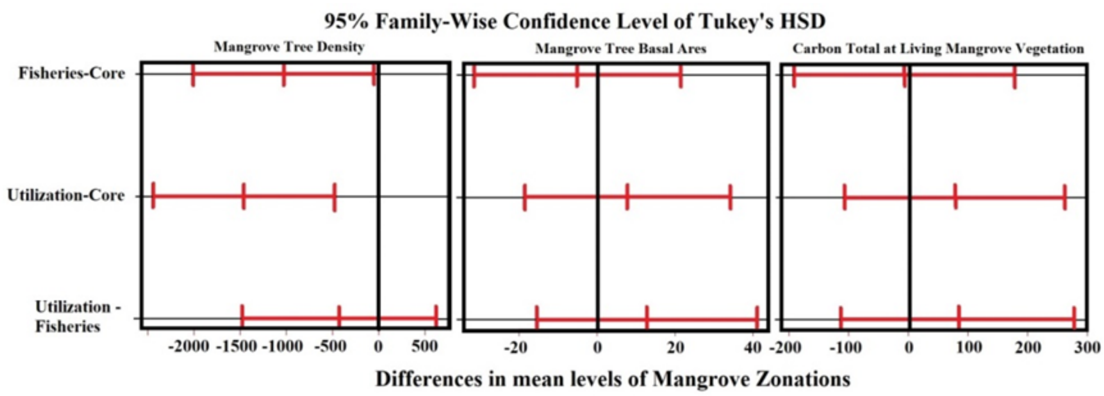

Figure 2. Tukey's HSD test of mangrove density, basal area and living vegetation carbon stock among mangrove zonation.

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Table 7. Carbon stock of death mangrove vegetation on each zone in MTP of Gili Sulat-Lawang.

No	Stations	Standing Dead Tree		Downed Wood		Total of Necromass Carbon (Mg C/ha)
		W_{DT} (Mg/ha)	C_{DT} (Mg C/ha)	W_{WD} (Mg/ha)	C_{WD} (Mg C/ha)	
Average of C in Core Zone			**12.21**		**2.78**	**14.99**
1	S1	16.83	7.91	6.05	2.84	10.75
2	S2	46.26	21.74	4.73	2.23	23.97
3	S3	22.00	10.34	0	0	10.34
4	L3	18.85	8.86	12.88	6.05	14.91
Average of C in Utilization Zone			**2.01**		**0.72**	**2.74**
5	S4	0	0	0	0	0
6	L1	7.66	3.60	3.03	1.43	5.03
7	L2	5.19	2.44	1.58	0.74	3.18
Average of C in Fisheries Zone			**5.56**		**1.60**	**7.16**
8	S5	6.81	3.20	0	0	3.20
9	L4	26.25	12.34	0.81	0.38	12.72
10	L5	2.40	1.13	9.40	4.42	5.55

Note: W_{DT} (Total Biomass of Dead Tree); C_{DT} (Total Dead Tree Carbon Pool); W_{WD} (Total Biomass of Downed Wood); C_{WD} (Total Downed Wood Carbon Pool).

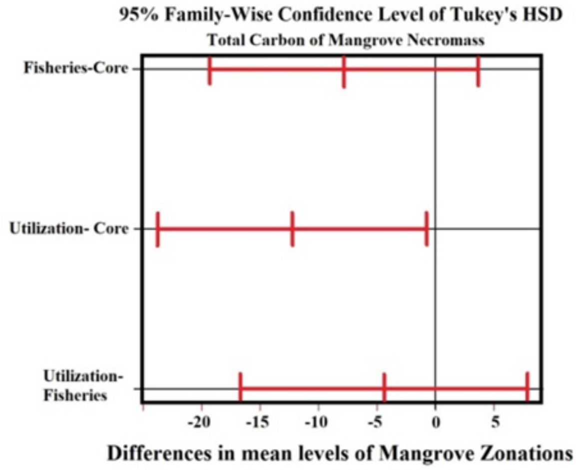

Figure 3. Tukey's HSD test of total carbon in mangrove necromass among mangrove zonation.

Lawang 5).

3.1. Species Richness of Mangrove Forest in Gili Sulat and Gili Lawang

A total of twelve mangrove species representing eight families were recorded at ten stations of the mangrove forest in MTP of Gili Sulat-Lawang. Station of 3rd Lawang (L3) has the highest species richness with nine species of mangrove and followed by 1st Sulat Station (S1) with seven species of mangrove. Meanwhile, Station of 5th Sulat (S5) has the lowest species richness, with only three species of mangrove (Table 3). Family Rhizophoraceae has dominated the mangrove forest and almost found in almost all stations, with *Rhizophora mucronata* having the highest density, followed by *R. apiculata* and *R. stylosa*. Whereas *Pemphis acidula* and *Heritiera littoralis* have the lowest density and are only found in one station (Table 4). The dominance of *Rhizophora* spp in oceanic mangroves is due to the buoyant ability of their propagules, which allows for wide dispersal and serves as the first colonizers in the oceanic islands. They also have high tolerance to salinity, making them successful in thriving in saline with tide-influenced waters. After establishment, Rhizophora will form dense stands to crowding out the other species with their canopy dominance [8].

3.2. Carbon Stock of Mangrove Forest in MTP of Gili Sulat-Lawang

Estimating the carbon stock of mangroves typically involves measuring the biomass of living mangrove plants, measuring mangrove necromass (dead organic matter), and depositing carbon in the soil. Mangrove ecosystem produces organic carbon through the photosynthetic process of mangrove trees and accumulates their carbon production in the biomass of leaves, twigs, stems, trunks, and roots. Furthermore, mangrove vegetation continuously drops leaves and twigs as litter onto the forest floor, as well as several trees are dead and downed. The decay of litter and dead trees by bacteria and fungi will transfer the organic carbon of mangrove into the soil. Therefore, the stock of carbon in the mangrove ecosystem needs to be measured in these three main carbon pools. The data of mangrove carbon stock estimation is crucial for Indonesia's NDC targets, as these ecosystems provide significant blue carbon storage while supporting climate mitigation and sustainable management of MTPs such as Gili Sulat–Gili Lawang.

3.2.1. Carbon Pool in Living Mangrove Vegetation

Carbon stock in living mangrove vegetation was measured using allometric equations to estimate the C_{AG}, including stems, branches, leaves, flowers, and fruit, and also C_{BG}, including mangrove roots. The carbon stock of each species of mangrove in the ecosystem was influenced by tree density and tree size. *R. mucronata* recorded the highest carbon stock in both gilis than the other species because this species had the highest tree density at MTP of Gili Sulat-Lawang. In relatively similar density, *R. mucronata* in Gili Lawang (1194 ind/ha of tree density) with 13.43 cm of DBH average having twice times greater of total organic carbon (106.94 Mg C/ha) than the similar species in Gili Sulat

(1234 ind/ha of tree density) who have a 0.7-fold lower of average DBH (9.28 cm) which only accumulated 49.38 Mg C/ha of total organic carbon. On the other hand, although *R. apiculata* had 8-fold higher of tree density (848 ind/Ha) than *S. alba* (102 ind/ha), both of them having relatively similar total carbon stock on living mangrove vegetation which around 29 Mg C/ha, even though the difference in DBH of *R. apiculata* (DBH average is 10.62 cm) is only 0.6 times lower than *S. alba* which having DBH average is 17.17 cm (Table 4). The regression analysis result showed that both tree density and tree size significantly influenced the carbon stock in living mangrove vegetation, with a p-value less than 0.05, and the regression coefficient (R^2) is 0.981. The DBH has a 2.5 times greater influence on the carbon stock of mangrove in the MTP of Gili Sulat-Lawang than their tree density (Table 5).

Tree density refers to the number of trees per unit area. The higher of tree density showed the more individual trees in the area. It means more carbon was stored in the biomass of living vegetation. However, not all trees are the same size, so tree density does not always directly relate to carbon stocks. Small trees (in terms of diameter or basal area) will store less carbon, even though they are numerous. On the other hand, basal area (BA) refers to the total cross-sectional area of tree trunks in a forest. It was measured at a height of about 1.3 m from the ground (DBH). Basal area is often used as an indicator of the size or volume of trees in a forest. BA is a more direct indicator for estimating carbon stocks; the trees with larger diameters will have more biomass and also more carbon stored. Therefore, basal area is usually more strongly correlated with carbon stocks than tree density.

MTP of Gili Sulat-Lawang is separated into three mangrove zonations: the core, utilization, and fisheries zones. The utilization zone (especially in the stations of L1 and L2) had the highest carbon content in living mangrove vegetation than the other zones because these areas had the widest basal area. LI and L2 have a lowest of average mangrove density than the other stations but have the highest mangrove size. The regression analysis showed the mangrove size is stronger to influenced the carbon stock than the mangrove density. The core zone had the highest mangrove tree density among other zones (Table 6). Based on the average of BA, the mangrove trees in the core and fisheries zones were younger than the utilization zone. In young forests

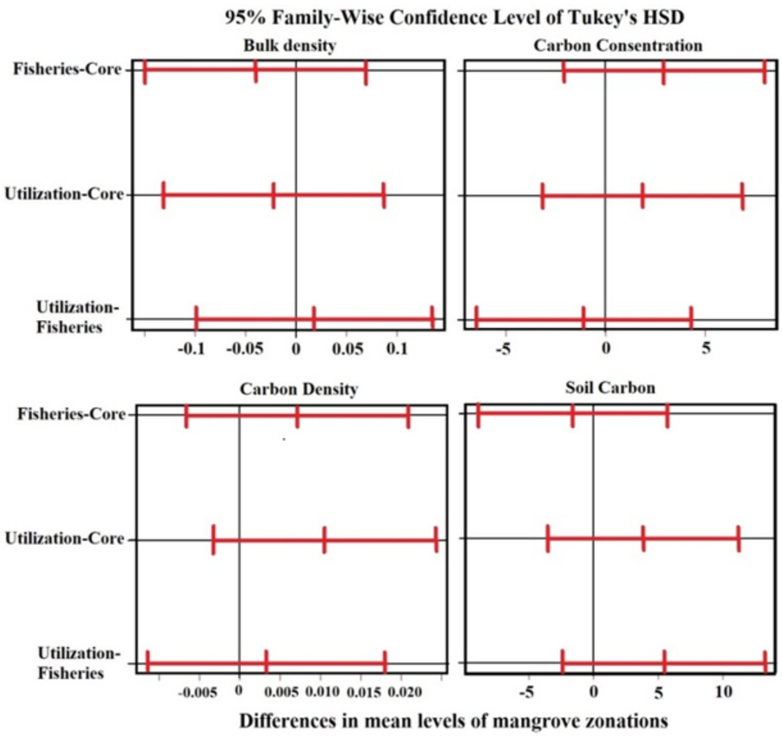

Figure 4. Tukey's HSD test of soil bulk density, soil carbon consentration, soil carbon density and soil carbon stock among mangrove zonation.

Table 8. Soil carbon stock of MTP of Gili Sulat-Lawang.

No	Stations	Soil Depth (cm)	Bulk Density (g/cm^3)	% C_{org}	$C_{density}$ (g/cm^3)	C_{soil} (Mg C/ha)
C_{SOIL} Average of Core Zone			**0.42**	**14.93**	**0.06**	**164.16**
1	S1	0–5	0.39	5.80	0.02	27.91
		5–15	0.38	8.11	0.03	28.74
		15–30	0.40	9.03	0.04	25.64
		30–50	0.61	7.41	0.05	25.22
		50–100	0.49	8.46	0.04	29.63
		Total of S1				**137.14**
2	S2	0–5	0.20	25.08	0.05	25.03
		5–15	0.23	25.18	0.06	28.33
		15–30	0.37	17.69	0.07	32.68
		30–50	0.33	12.23	0.04	20.21
		50–100	0.44	15.45	0.07	33.73
		Total of S2				**139.98**
3	S3	0–5	0.30	20.43	0.06	31.09
		5–15	0.35	20.08	0.07	35.46
		15–30	0.32	19.70	0.06	32.20
		30–50	0.29	35.15	0.10	51.12
		50–100	0.32	19.38	0.06	31.27
		Total of S3				**181.14**
4	L3	0–5	0.54	6.65	0.04	25.67
		5–15	0.57	12.71	0.07	51.42
		15–30	0.58	12.64	0.07	52.36
		30–50	0.56	11.11	0.06	44.60
		50–100	0.70	6.38	0.05	24.35
		Total of L3				**198.40**
C_{SOIL} Average of Utilization Zone			**0.40**	**16.77**	**0.07**	**183.19**
5	S4	0–5	0.37	27.50	0.10	50.21
		5–15	0.31	18.55	0.06	28.42
		15–30	0.34	22.34	0.08	38.42
		30–50	0.33	20.76	0.07	33.80
		50–100	0.48	21.44	0.10	51.74
		Total of S4				**202.59**
6	L1	0–5	0.40	12.60	0.05	25.33
		5–15	0.40	17.68	0.07	35.84
		15–30	0.42	16.32	0.07	33.90
		30–50	0.41	15.15	0.06	31.14
		50–100	0.40	15.78	0.06	31.44
		Total of L1				**157.66**
7	L2	0–5	0.38	14.51	0.06	46.06

Table 8. *Cont.*

No	Stations	Soil Depth (cm)	Bulk Density (g/cm^3)	% C_{org}	$C_{density}$ (g/cm^3)	C_{soil} (Mg C/ha)
		5–15	0.42	9.35	0.04	32.49
		15–30	0.45	10.90	0.05	24.58
		30–50	0.46	13.06	0.06	49.91
		50–100	0.37	15.56	0.06	36.29
		Total of L2				**189.32**
C_{SOIL} Average of Fisheries Zone			**0.33**	**17.86**	**0.06**	**156.12**
8	S5	0–5	0.29	16.61	0.05	23.98
		5–15	0.29	16.90	0.05	24.40
		15–30	0.35	23.45	0.08	41.48
		30–50	0.29	18.20	0.05	26.47
		50–100	0.20	17.89	0.04	18.23
		Total of S5				**134.57**
9	L4	0–5	0.36	13.93	0.05	24.84
		5–15	0.59	12.93	0.08	38.21
		15–30	0.67	12.31	0.08	41.43
		30–50	0.81	11.34	0.09	46.28
		50–100	0.44	15.10	0.07	33.47
		Total of L4				**184.23**
10	L5	0–5	0.27	22.71	0.06	31.18
		5–15	0.30	21.80	0.06	32.48
		15–30	0.31	18.08	0.06	27.76
		30–50	0.26	24.01	0.06	30.93
		50–100	0.24	22.67	0.05	27.20
		Total of L5				**149.55**

with high tree density, carbon stocks may not be as high as in older forests with large trees, despite the lower density, because young trees store less carbon than large, mature trees.

Although the utilization zone recorded the highest carbon stock, MANOVA analysis results showed no significant difference in both total carbon stock in living mangrove vegetation and the total value of mangrove basal area (tree sizes) between mangrove zonation. On the other hand, there is a significant difference in mangrove density between the core zone and other zones (Figure 2). It means the core and fisheries zones had a higher tree density than the utilization zone, but that zones are dominated by young mangrove trees.

3.2.2. Carbon Pool in Death Mangrove Vegetation

When mangrove trees die, the carbon stored in their biomass is not immediately released into the atmosphere (in the form of CO_2 gas) because decomposition in the mangrove ecosystem generally occurs anaerobically. This carbon can remain locked in dead biomass until decomposition transfers the carbon into substrate [34]. Therefore, measurement of carbon stock in dead mangrove vegetation is a part of the evaluation of carbon stock in the mangrove ecosystem. Carbon stock in dead mangrove vegetation comprises two pools, the standing dead trees (C_{DT}) and downed wood (C_{WD}). The highest carbon content in dead mangrove vegetation is found in the core zone, with an average necromass carbon is 14.99 Mg C/ha, followed by the fisheries zone with 7.16 Mg C/ha and the utilization zone with 2.74 Mg C/ha (Table 7).

ANOVA analysis result showed a significant difference in mangrove necromass carbon between core and utilization zones, and no significant difference between the fisheries zone with both core and utilization zones (Figure 3). Utilization and fisheries zones have higher human activities than the core zone, the deadwood harvesting in these zones than in the core zone. Core zones are more protected from these interventions, so dead biomass remains in place for longer periods.

3.2.3. Carbon Pool in the Soil of Mangrove Forest

Mangrove substrates accumulate carbon through the decomposition of organic matter such as mangrove stems, twigs, and leaves. In mangrove ecosystems, the decomposition process is slow because organic matter is always submerged in water, and the process runs anaerobically. This causes carbon to be stored in the substrate for a long time. The highest of soil carbon was found in the utilization zone (183.19 Mg C/ha), followed by the core zone (164.16 Mg C/ha) and fisheries zone (156.12 Mg C/ha). Although the utilization zone recorded the highest carbon stock in the mangrove substrate, MANOVA analysis results showed no significant difference in soil bulk density (BD), soil carbon concentration (% C_{org}), soil carbon density ($C_{density}$) and soil carbon stock (C_{soil}) among mangrove zonation (Figure 4; Table 8).

Three main parameters commonly used to determine soil carbon stock are bulk density, carbon concentration, and carbon density. Bulk density describes how dense the soil is, carbon concentration describes how much carbon is in the soil, and carbon density provides an overview of the total carbon stored in a volume of soil. All three of these variables are very important to estimate the carbon stock of mangrove substrates. The regression analysis result showed that both carbon density and bulk density significantly influenced the soil carbon stock with a p-value less than 0.05, and the R^2 is 0.9734. The variable of carbon density has a greater influence on the soil carbon stock than bulk density in MTP of Gili Sulat-Lawang (Table 9).

Mangrove substrates generally have low bulk density due to the high content of organic matter (humus), which has a low density. Soils with lower bulk density tend to store more organic carbon in their pore spaces. Conversely, denser soils (with higher bulk density) have less pore space, which reduces their capacity to store carbon. This research recorded the average bulk density in each mangrove zonation range between 0.33 to 0.42 g/cm^3. The bulk density in this study relatively lower if we compared to the other area such as mangrove soil in Bintuni Bay Papua which had bulk density range between 0.3–0.9 g/cm^3 [35], mangrove soil of Nusa Lembongan, Bali which had bulk density 1.1 g/cm^3 [36], in Segara Anakan, Cilacap which had average bulk density 0.69 g/cm^3, in Berau which had bulk density 1.2 g/cm^3, and Kongsi island which had bulk density 1.35 g/cm^3 [37].

Carbon concentration refers to the percentage of carbon contained in the substrate. A higher carbon concentration value means high carbon content in each gram of soil. The average of carbon concentration in this study ranges between 14.93% to 17.86%. The percentage of carbon soil value in this study is relatively similar to the soil carbon concentration in Bintuni Bay Papua, with average %C is 16.4%, and higher than the percentage of carbon soil in Nusa Lembongan Bali, with a range of %C between 2.30% to 2.70% [36], Segara Anakan Cilacap, with %C is 2.4%, Berau had %C with 5.7% [37]. Both Bulk density and carbon concentration will influence the value of carbon density in the mangrove substrate.

Mangrove with mixed stands had 20% higher soil carbon than the mangrove ecosystem with a single genus. Besides that, mangrove forest

Table 9. Regression analysis of soil carbon stock, bulk density and carbon density in MTP of Gili Sulat-Lawang.

	Coefficient	Standard Error	t-value	p-value
Soil Bulk Density	20.844	5.459	3.818	0.000386***
Soil Carbon Density	410.104	36.360	11.279	4.26e-15***

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Table 10. Total carbon stock of mangrove in MTP of Gili Sulat-Lawang.

No	Zones	Carbon Pools (Mg C/ha)					
		Living Mangrove Carbon		Death Mangrove Carbon		Soil Carbon	Carbon Total
		C_{AG}	C_{BG}	C_{DT}	C_{WD}	C_{SOIL}	
1	Core Zone	117.83	61.03	12.21	2.78	164.16	**358.01**
2	Utilization Zone	175.03	82.42	2.01	0.72	183.19	**443.37**
3	Fisheries Zone	137.09	35.66	5.56	1.60	156.12	**336.03**
	Average	**143.316**	**59.703**	**6.593**	**1.700**	**167.823**	**379.137**

Note: C_{AG} (Aboveground vegetation carbon pool); C_{BG} (Belowground vegetation carbon pool); C_{DT} (The dead tree carbon pool); C_{WD} (The downed wood carbon pool); C_{SOIL} (Total soil carbon pool).

comprised by *Rhizophora* and *Bruguiera* had higher soil carbon storage per unit area than the mangrove stand with other genera [38]. *Rhizophora* spp possesses stilt roots, which adapt to various substrate types from muddy to sandy substrates. Their extensive and complex root systems help stabilize sediment, reduce erosion, and have the highest potential for carbon accumulation of the other root systems.

3.2.4. Total carbon stock at the mangrove ecosystem in MTP of Gili Sulat-Lawang

The total carbon stock of the mangrove ecosystem in this study was accumulated from three carbon pools (living mangrove vegetation, dead mangrove vegetation, and soil carbon) in each mangrove zonation. Average carbon stock in MTP of Gili Sulat-Lawang is 379.137 Mg C/ha with the percentage of carbon in living mangrove vegetation is 53.55%, followed by soil carbon with 44.26%, and the smallest one is carbon in dead mangrove vegetation only has 2.19% (Table 10, Figure 5). This percentage value is slightly different from the other research who stated that the highest percentage of carbon stock was in carbon soil, with a percentage between 49%–89% [4]. The mangrove ecosystem in TWP of Gili Sulat-Lawang is an oceanic mangrove that grows in an oceanic island where little or no sediment is supplied from inland areas. The percentage of soil carbon in the oceanic mangrove is lower than the estuary mangrove [34]. Carbon in the mangrove ecosystem can come from autochthonous or allochthonous sediment or litter. Autochthonous is sediment and litter produced by the mangrove ecosystem itself, while allochthonous is sediment and litter from other places that then enter the mangrove ecosystem. Oceanic mangroves such as the MTP of Gili Sulat-Lawang have autochthonous sediment and litter sources. Litter such as leaves, flowers, twigs, and branches falls continuously in mangrove forests. Litter input in mangrove forests ranges from 4 to 13 tons/ha/year [39]. The litter production of mangrove forest in Sepi Bay, southern Lombok, is 9.9 tons/ha/year [40].

The estimation of carbon stocks in mangrove ecosystems holds strategic significance for supporting Indonesia's NDC targets. NDC represents a country's national commitment under the Paris Agreement to reduce greenhouse gas emissions in accordance with its capacity and development priorities [9]. Indonesia has pledged to reduce emissions by up to 31.89% unconditionally, or 43.20% with international support by 2030, with the forestry and coastal–marine sectors playing a key role [11]. Mangroves, as a critical blue carbon ecosystem, are capable of sequestering and storing disproportionately large amounts of carbon compared to terrestrial ecosystems. In the MTP of Gili Sulat–Lawang, the total carbon stock of mangrove ecosystems is estimated at 379,137 Mg C/ha, highlighting their substantial role in carbon sequestration and their potential contribution to national emission reduction targets. Thus, robust quantitative data on mangrove carbon stocks are not only relevant for NDC reporting but also provide opportunities to leverage blue carbon markets as innovative financing mechanisms for conservation. Furthermore, carbon stock assessments can serve as a scientific basis for the planning and management of MTPs, such as Gili Sulat–Gili Lawang, ensuring that mangrove conservation contributes simultaneously to climate change mitigation, ecotourism sustainability, and the livelihoods of local communities. This study has limitations, including (1) a relatively short sampling duration (June–August) without temporal replication, which may overlook seasonal variability in biomass and soil carbon; (2) the absence of interannual replication, which limits detection of long-term variability; and (3) restricted generalizability of the results to other mangrove ecosystems beyond the studied MTP. These limitations should be carefully considered when interpreting the findings and in designing future research to strengthen the reliability of mangrove carbon stock estimates for national and global climate policy frameworks.

4. CONCLUSIONS

The mangrove ecosystems of the MTP Gili Sulat –Lawang store an average of 379.137 Mg C/ha, with the highest carbon stock in living vegetation (53.55%), followed by soil (44.26%) and dead biomass (2.19%). The dominance of Rhizophora enhances resilience to oceanic conditions through high salinity tolerance and effective sediment stabilization. However, restoration and management should avoid monoculture; a mixed-species approach is recommended to promote biodiversity, ecosystem stability, and long-term sustainability. While the study provides important insights into the contribution of oceanic mangroves to Indonesia's NDC and blue carbon initiatives, its short temporal scope and limited replication highlight the need for

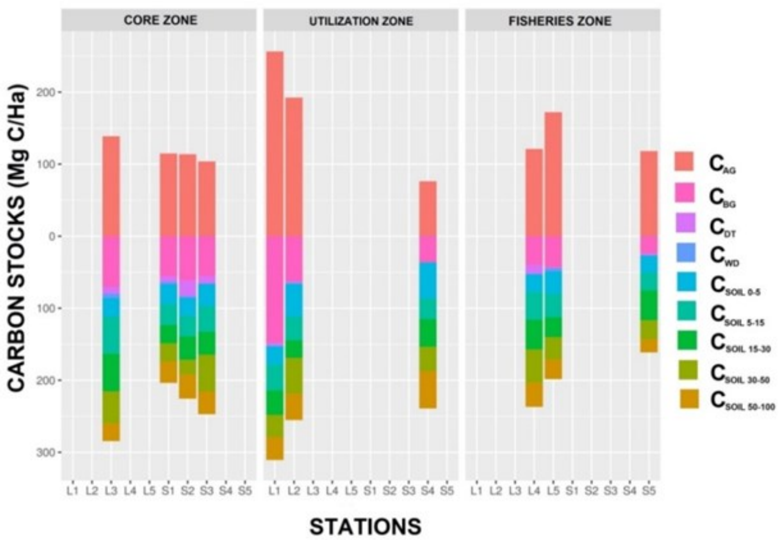

Figure 5. Distribution of carbon stock at each pools in MTP of Gili Sulat-Lawang. C_{AG} (Aboveground vegetation carbon pool); C_{BG} (Belowground vegetation carbon pool); C_{DT} (The dead tree carbon pool); C_{WD} (The downed wood carbon pool); C_{SOIL} 0-5 (Soil carbon pool at 0 to 5 cm in depth); C_{SOIL} 5-15 (Soil carbon pool at 5 to 15 cm in depth); C_{SOIL} 15-30 (Soil carbon pool at 15 to 30 cm in depth); C_{SOIL} 30-50 (Soil carbon pool at 30 to 50 cm in depth); C_{SOIL} 50-100 (Soil carbon pool at 50 to 100 cm in depth).

further research to strengthen the reliability and scalability of carbon stock estimates.

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Conflicts of Interest

The authors declare no conflict of interest. The funding sponsors had no role in the research design, data collection, analysis, interpretation, manuscript writing, or decision to publish the research findings.

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DECLARATION OF GENERATIVE AI

Not applicable.

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