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Ecosystem carbon stock and annual sequestration rate from three genera-dominated mangrove zones in Benoa Bay, Bali, Indonesia

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Abstract. *Sugiana IP, Prartono T, Rastina, Koropitan AF. 2024. Ecosystem carbon stock and annual sequestration rate from three genera-dominated mangrove zones in Benoa Bay, Bali, Indonesia. Biodiversitas 25: 287-299.* The mangrove ecosystem is an ecologically productive wetland system that serves as a carbon sink. However, various factors have contributed to the variation in values when calculating ecosystem carbon stock and the sequestration rate in the mangrove ecosystem. The presence of varying environmental conditions has resulted in the categorizing different species of mangroves, which may lead to variations in ecosystem carbon stock and sequestration rates. In this study, we aim to assess the ecosystem carbon stock and sequestration rate of the mangrove ecosystem in Benoa Bay, Bali, Indonesia. The ecosystem has been categorized into three zones based on the dominant genera: *Bruguiera*, *Rhizophora*, and *Sonneratia*. This research aimed to investigate the influence of mangrove zoning on the variability of carbon stock values and sequestration rates within the ecosystem. The allometric calculation technique and net primary productivity and soil organic carbon percentage values obtained using the Loss on Ignition (LOI) method are used to estimate each zone's ecosystem carbon stock and sequestration rate. The findings of our study indicate that there are notable variations in the carbon stock of ecosystems across different zones. However, we did not observe any substantial changes in the annual carbon sequestration rates. The *Sonneratia* zone exhibits the maximum value of ecosystem carbon stock and sequestration rate (1,570.9±248.0 tCO_2ha^{-1} and 81.8 $tCO_2ha^{-1}yr^{-1}$), while the *Bruguiera* zone demonstrates the lowest values (1,029.6±130.9 tCO_2ha^{-1} and 75.6 $tCO_2ha^{-1}yr^{-1}$). The three zones' average carbon stock and sequestration rate are estimated as 338.2 $tCha^{-1}$ (1239.9 tCO_2ha^{-1}) and 21.5 $tCha^{-1}yr^{-1}$ (78.9 $tCO_2ha^{-1}yr^{-1}$), respectively. In total, the carbon storage and absorption capacity of Benoa Bay amounts to 421,149 tC (equivalent to 1.5 million tCO_2), with an annual rate of 25,769.4 $tCyr^{-1}$ (equivalent to 94,573.6 tCO_2yr^{-1}). We recommended that future ecosystem carbon stock evaluations consider mangrove-type zoning characteristics due to significant value fluctuations in various mangrove zones found.

Keywords: Allometric technique, LOI method, net primary productivity

INTRODUCTION

Global warming is a well-documented occurrence characterized by the progressive elevation of the mean atmospheric temperature. This phenomenon is mainly attributed to increased greenhouse gases (GHG) within the Earth's atmosphere. Carbon dioxide (CO_2) is the major contributor to anthropogenic global warming. According to the Intergovernmental Panel on Climate Change (IPCC) report of 2021, the concentration of CO_2 has risen to 409.9 parts per million (ppm) since the pre-industrial period in 1750. This increase can be primarily attributed to anthropogenic activities, including the combustion of fossil fuels, transportation emissions, and deforestation. A range of measures have been implemented in response to the escalating issue of elevated carbon dioxide (CO_2) emissions in the Earth's atmosphere. Among these initiatives is the augmentation of productive wetlands' involvement in carbon sequestration through the strategic implementation of tree plantation. This measure is undertaken as a component of endeavors aimed at conserving and rehabilitating ecosystems, particularly mangrove forests, swamps, and other wetlands, capable of sequestering large amounts of carbon (Mitsch et al. 2013; Twilley et al. 2017).

The mangrove ecosystem is a notable wetland with high productivity as a carbon sink. It possesses inherent capabilities to trap and retain carbon effectively, accounting for around 14% of the total carbon in marine environments worldwide (Alongi 2014). According to Kauffman and Donato (2012), mangrove ecosystems exhibit a carbon absorption capability that is three times higher than that of terrestrial forests. Mangroves possess a remarkable capacity for carbon sequestration, rendering them a crucial ecosystem in mitigating climate change (Dinilhuda et al. 2020). This significance is particularly pronounced in Indonesia, which boasts the highest proportion of mangrove forests globally, accounting for approximately 19.5% of the global total (Bunting et al. 2018). The management and protection of mangrove ecosystems in Indonesia are being strengthened to maximize their capacity as a carbon sink (Arifanti et al. 2022).

Numerous studies have been conducted to assess the carbon stores present within mangrove ecosystems. Nevertheless, a limited number of individuals consider the zoning issues that contribute to the disparities in the valuation of carbon reserves and the rates at which they are sequestered. The carbon uptake rate of various mangrove vegetation types varies due to distinct environmental variables, including salinity and sediment type (Ewel et al. 1998; Srikanth et al. 2016; Raganas and Magcale-Macandog 2020). The structure of mangrove stands exhibits variation in proportions of mangrove species, hence exerting an influence on the extent of organic carbon contribution to the surrounding environment (Prasad et al. 2010; Mulya and Arlen 2018). Thus, it is anticipated that there will be fluctuations in the magnitude of carbon stocks and the rates at which they are absorbed within each distinct mangrove vegetation zone.

The mangrove ecosystem in Benoa Bay is encompassed by the Ngurah Rai Grand Forest Park (TAHURA) region, which boasts the largest mangrove forest in Bali, Indonesia. This ecosystem exhibits a well-defined zoning pattern that is easily discernible. Sugiana et al. (2022) classified three primary zones according to the prevailing mangrove genus: *Rhizophora*, *Bruguiera*, and *Sonneratia*. Distinct environmental conditions exist in each zone, particularly regarding salinity, pH, redox potential (ORP), and substrate type (Prinasti et al. 2020; Dewi et al. 2021; Sugiana et al. 2021). Prior studies have investigated the estimation of carbon stocks in vegetation, soil, greenhouse gas concentrations, and fluxes from soil in comparable geographical areas (Mahasani et al. 2016; Suartana et al. 2021; Sugiana et al. 2023a,b). However, the calculation of carbon sequestration rates, particularly in the three specified zones, has yet to be undertaken.

This study aims to evaluate the mangrove ecosystem's carbon stock and sequestration rates (vegetation carbon absorption and soil carbon burial rates) in Benoa Bay, Bali, separated into three zones: *Bruguiera*, *Rhizophora*, and *Sonneratia*. The findings of this study have the potential to significantly influence the evaluation of the total value of the three separate groups of mangrove vegetation in terms of their effectiveness in mitigating global warming through carbon sequestration. The main aim of this study is to supplement carbon budget data from mangroves in Indonesia, including those affected by anthropogenic impacts. The objective of this study was to make a scholarly contribution to the Indonesian government's FoLU (Forestry and Other Land Use) Net Sink 2030 effort by providing significant insights into the assessment of carbon stock and sequestration in mangrove forests.

MATERIALS AND METHODS

Study site

The research is located at Benoa Bay, Bali, Indonesia (8°42'50.46"-8°47'49.92"S, 115°10'9.42"-115°15'13.19" E). The mangrove forest area is the outcome of a restoration project on former shrimp ponds planted with mangrove seedlings during the past 30 years (1992 to 1999). This initiative was carried out by collaborating with the Japan International Cooperation Agency (JICA) and the Ministry of Forestry of Indonesia (JICA 1999). The mangrove forest exhibits a zonation pattern that is divided based on three dominant genera: *Bruguiera*, *Rhizophora*, and *Sonneratia*. The condition of vegetation based on the Mangrove Health Index (MHI) is classified as moderate (Sugiana et al. 2022), with environmental factors such as sediment types ranging from fine sand to gravel, with coarse sand being dominant (Imamsyah et al. 2020; Prinasti et al. 2020), as well as a gradient in water quality parameters (salinity and pH) that varies with distance from the sea (Sugiana et al. 2021). In general, we determined the sampling plots based on the proportional area of each mangrove zone, where the *Rhizophora* zone, covering an area of 603.56 ha (51%), was allocated 5 plots. The *Sonneratia* zone, covering an area of 532.55 ha (45%), was allocated 4 plots. Lastly, the *Bruguiera* zone, covering an area of 41.65 ha (4%), was allocated 3 plots. These plots have been designated permanent plots measuring 100m^2 (10m × 10m) since 2020 (Sugiana et al. 2022; Figure 1).

Forest structure measurement

The mangrove stand's structure, including the density of trees and saplings for each mangrove species, was assessed utilizing the Diameter at Breast Height (DBH) value (diameter at breast height ± 130 cm). The DBH of all stands was measured on each plot and subsequently categorized into two groups: trees (DBH ≥5cm) and saplings (DBH <5cm). The mangrove stand height was estimated using a trigonometric method, wherein many angles of the uppermost forest canopy were measured at a distance of 10 meters. The technique of hemispherical photography was utilized to assess the extent of mangrove canopy coverage in various zones. We captured photographs of the mangrove canopy from each observation plot using a smartphone camera with a resolution exceeding 3 megapixels. The photographs were taken from five different positions perpendicularly: each corner and center (Figure 2). Subsequently, the collected images were analyzed using the ImageJ software application (Jennings et al. 1999; Ishida 2004; Dharmawan 2020). The MHI calculation utilizes sapling density, DBH, and canopy cover data (Dharmawan and Ulumuddin 2021).

Biomass and carbon stock calculation

Biomass and carbon values in vegetation are estimated using the allometric equation proposed by Chave et al. (2005). This estimation involves the incorporation of the DBH value of each vegetation stand, as Hossain et al. (2015) reported. Additionally, the wood density of each mangrove species was obtained from the World Agroforestry Database (http://db.worldagroforestry.org/) in Table 1. These calculations are performed for each plot measuring 10 × 10 m^2, employing the following equation:

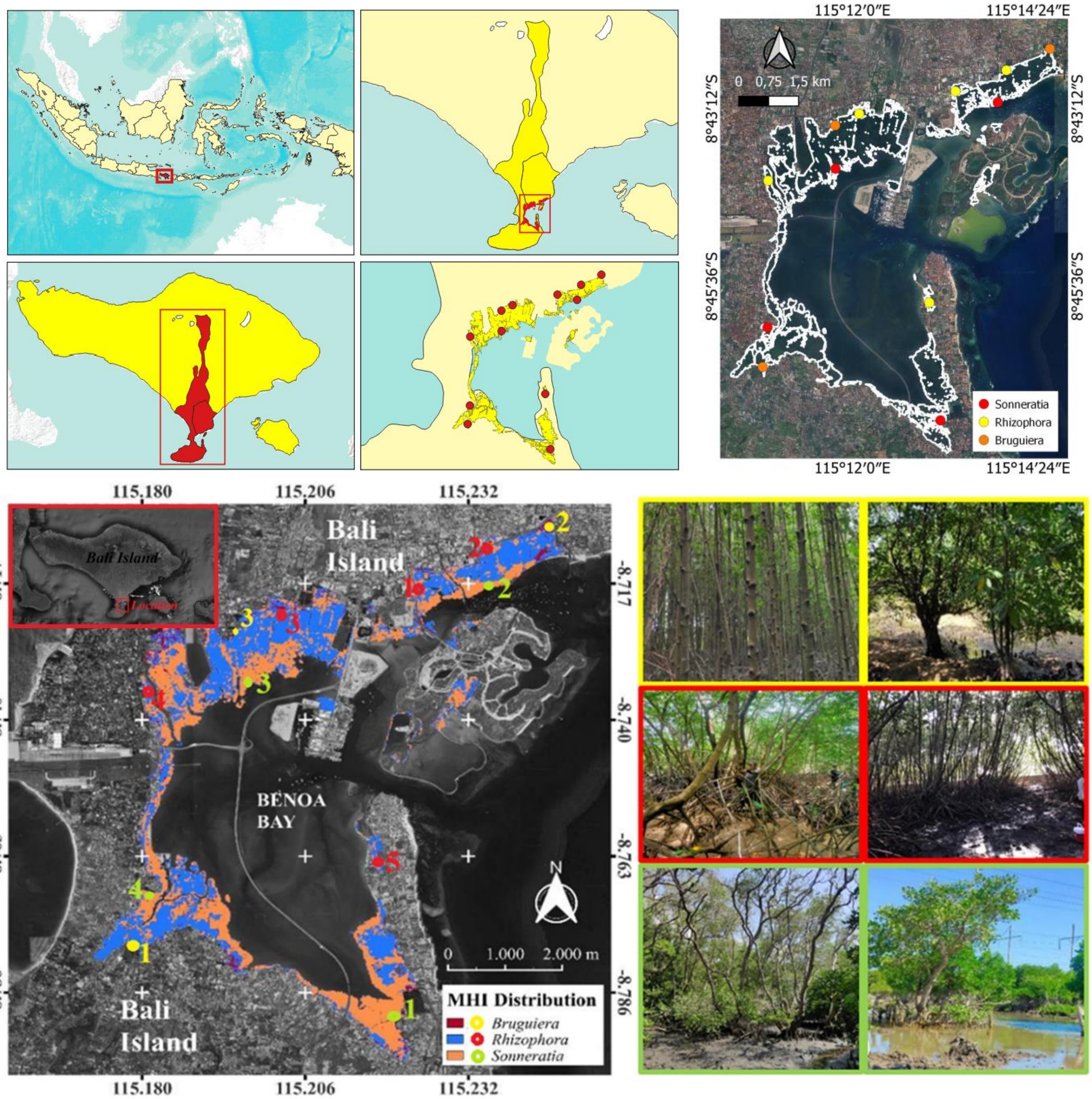

Figure 1. Distributions and conditions of research data collection plots (map modified from Sugiana et al. 2022)

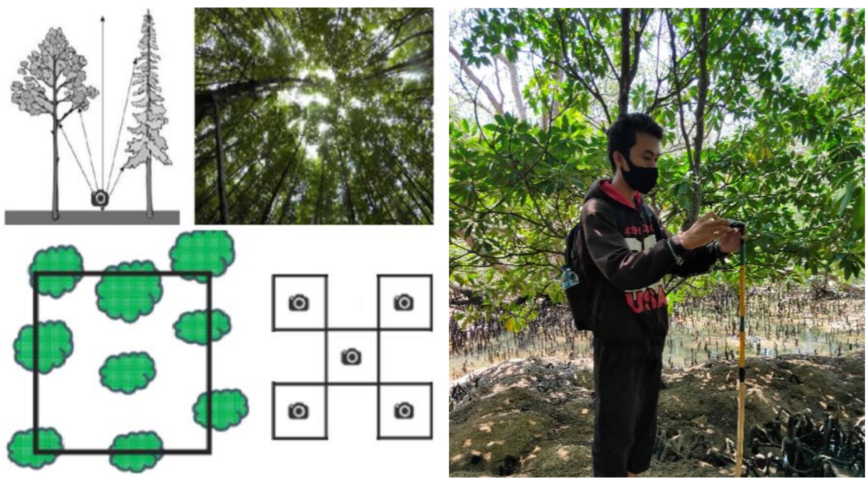

Figure 2. Illustration of canopy coverage data collection

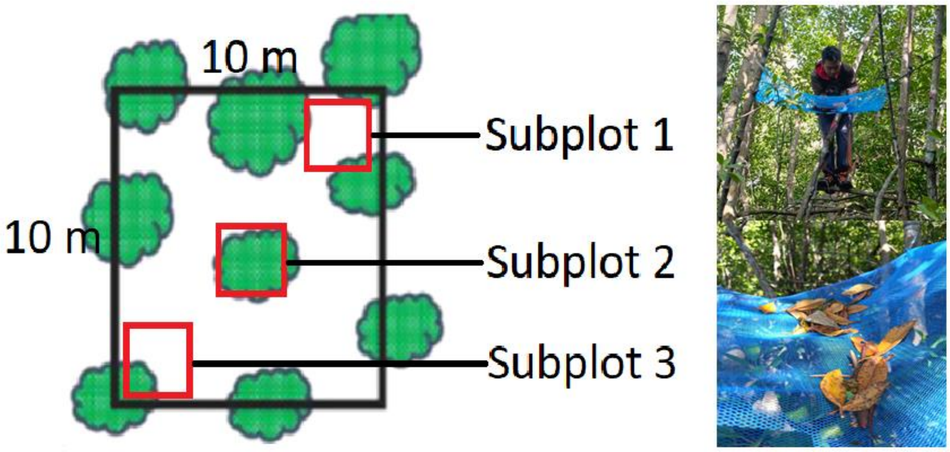

Figure 3. The position of mangrove litter collection on each plot

Table 1. Wood density of each mangrove species

Species	Wood Density (g.cm^{-3})
Bruguiera gymnorhiza	0.94
Rhizophora apiculata	0.88
Rhizophora mucronata	1.02
Rhizophora stylosa	0.94
Sonneratia alba	0.78

$$AGB = \rho \times \exp(-1.349 + 1.980\ln(D) + 0.207(\ln(D))^2 - 0.0281(\ln(D))^3)$$

$$BGB = 0.199 \times \rho^{0,899} \times D^{2,22}$$

Where:
AGB : aboveground biomass (g m^{-2} converted to t ha^{-1})
BGB : belowground biomass (g m^{-2} converted to t ha^{-1})
ρ : wood density (g cm^{-3})
D : diameter at breast height (cm)

Biomass data are categorized into three distinct vegetation classes, each characterized by varying initial diameters: 0-5 cm, 5-10 cm, and >10 cm. These categories are utilized to assess the respective contributions of different stand types to the overall carbon absorption capability. The conversion of biomass values, encompassing both Aboveground Biomass (AGB) and Belowground Biomass (BGB), into carbon stock values is achieved by multiplying them by the corresponding coefficients of 0.48 and 0.39, as documented by Kauffman et al. (2014). The difference in conversion factor is based on differences in the composition of carbon contained in each mangrove part, where AGB is taken from the mangrove stem and BGB from the root (Kauffman and Donato 2012). The biomass-to-carbon conversion formula can be seen in the equation below.

$$AGC = AGB \times 0.48$$

$$BGC = BGB \times 0.39$$

Where:
AGC : Aboveground carbon (gCm^{-2} converted to tCha^{-1})
BGC : Belowground carbon (gCm^{-2} converted to tCha^{-1})
AGB : aboveground biomass (g m^{-2} converted to t ha^{-1})
BGB : belowground biomass (g m^{-2} converted to t ha^{-1})

Calculation of biomass increment and measurement of litterfall production

Estimating vegetation biomass growth relies on the annual increase in stem diameter and the amount of litter generated by mangrove vegetation. The mangrove diameter growth was measured in August 2020 (referred to as T0) and August 2023 (referred to as T1). The diameter values (T0 and T1) were transformed into carbon stock values using the identical allometric equation employed for the biomass calculation mentioned before. To estimate the annual growth in vegetation biomass, we computed the difference between the biomass value at time T1 and the biomass value at time T0, which was then divided by the period of three years.

Mangrove litters were collected using a 1 mm litter trap net with a collection area measuring 1 × 1 m (totaling 3 × 3 m). These nets were positioned at two corners and th center of every observation plot, as depicted in Figure 3. Litter nets were strategically positioned at an elevation exceeding 1 meter to mitigate the impact of elevated tides. The accumulated litter was then retrieved at two-week intervals, with three collection events spanning six weeks between August and September 2023. The litter gathered was divided into three distinct components: leaves, stems or branches, and reproductive structures such as flowers and propagules. Subsequently, the collected litter samples were dried at a controlled temperature of 80°C until a constant weight (±48 hours).

Net primary productivity and CO_2 sequestration rate

Determining Net Primary Productivity (NPP) involves incorporating biomass growth values and litter generation rates across different vegetation zones. It is achieved by combining the cumulative biomass growth of vegetation with the amount of litterfall, as outlined in the methodology proposed by Matsuura and Kajimoto (2013).

$$NPP = \Delta y + \Delta L + \Delta G$$

Where:
NPP : net primary productivity (g $m^{-2}y^{-1}$ converted to t $ha^{-1}y^{-1}$)
Δy : annual AGB+BGB increment (g $m^{-2}y^{-1}$)
ΔL : litterfall production (g $m^{-2}y^{-1}$)
ΔG : grazing activity by herbivores (g $m^{-2}y^{-1}$), omitted in this study due to negligible value (Kamruzzaman et al. 2017a,b)

The primary productivity value is then used to calculate the rate of CO_2 uptake in vegetation using the equation of Chen et al. (2016) as follows:

$$RCO_2 = NPP \times C_{mangrove} \times 44/12$$

Where:
RCO_2 : CO_2 absorption rate ($gCO_2m^{-2}yr^{-1}$ converted to $tCO_2ha^{-1}yr^{-1}$)
NPP : net primary productivity (g $m^{-2}y^{-1}$)
$C_{mangrove}$: carbon in vegetation (%), 44/12 is the mass conversion ratio for C to CO_2

Soil characteristic determination

Soil samples were obtained at a depth of 0-100 cm using a soil auger with a diameter of 5 cm. The soil sample was collected in each observation plot, with three repetitions taken right below the installation of the litter net. pH measurements were conducted at depths of 0 cm, 50 cm, and 100 cm using a Lutron pH meter 212. The pH value of the soil was calculated as an average across all samples to assess the overall conditions of each mangrove zone. Subsequently, the three samples were homogenized into a single sample from each observation plot, resulting in a cumulative count of 12 soil samples. A quantity of 150 grams was obtained from each soil sample to measure bulk density and water content values. The 100-gram soil samples were dried at 105°C to determine their bulk density based on the dry weight ratio to volume, and then 50-gram samples were dried at 60°C for 48 hours to assess water content. Subsequently, 3 grams of soil, which have been used for water content assessment, are used again for organic carbon measurement. The soil is first filtered using a 2-mm sieve and then burned under 550°C, commonly known as the Loss on Ignition (LOI) method (Chen et al. 2016)

Soil carbon burial and stock calculation

The estimation of carbon burial rate in soil within the mangrove ecosystem is determined using a comprehensive calculation that incorporates the values of bulk density, percentage of organic carbon, and sediment accretion rate.

$$SCB = BD \times C_{org} \times SAR$$

Meanwhile, the calculation of soil carbon stock is calculated using the equation:

$$SCS = BD \times C_{org} \times H$$

Where:
SCB : soil carbon organic burial rate ($gCm^{-2}yr^{-1}$ converted to tC $ha^{-1}yr^{-1}$)
BD : bulk density (g cm^{-3})
C_{org} : percentage of soil organic carbon (%)
SAR : soil accretion rate (mm yr^{-1}), the worldwide soil accretion rate value of 2.5 mm yr^{-1} (Bouillon et al. 2008; Breithaupt et al. 2012; Perez et al. 2018) is used. We did not have access to instruments to utilize the lead isotope method.
SCS : soil carbon stocks (tC ha^{-1})
H : soil layer thickness (cm)

The soil carbon burial rate and stock values are transformed into CO_2 burial rate and stock through a conversion factor of 3.67, representing the carbon (C) to carbon dioxide (CO_2) ratio.

Total carbon stock and sequestration rate

To determine the comprehensive carbon stock value included within the mangrove ecosystem and its corresponding sequestration rate, we aggregated the carbon stock value present in vegetation and sediment with the absorption rate exhibited by vegetation and the burial process. The computation results were partitioned according to zoning to assess disparities in the overall carbon stock and sequestration rate values among the three observed mangrove zones.

Statistical analysis

Therefore, to ascertain the presence of statistically significant disparities in carbon stock levels and sequestration rates among the three distinct mangrove zones, an Analysis of Variance (ANOVA) was employed. The Shapiro-Wilk test determined that all the univariate data, including vegetation and sediment carbon stock values, vegetation carbon absorption rate, soil carbon stock, and burial rate, followed a normal distribution ($\rho>0.05$). The Tukey Honestly Significant Difference (HSD) post hoc test was conducted to determine the zones that exhibited statistically significant differences. Normality tests and ANOVA were conducted using RStudio version 4.0.2 software.

RESULTS AND DISCUSSION

Forest structure and soil characteristic

The observed vegetation composition exhibits distinct variations among different zones. The prevalence of *Bruguiera gymnorhiza* (L.) Lam. primarily characterizes the *Bruguiera* zone. In contrast, the *Rhizophora* zone is characterized by the coexistence of three dominant species: *Rhizophora apiculata* Blume (40.3%), *Rhizophora mucronata* Lam. (INP: 44%), and *Rhizophora stylosa* Griffith (15.7%). Similarly, the *Sonneratia* zone is exclusively dominated by *Sonneratia alba* Sm.. The *Rhizophora* zone exhibited the highest tree density, whereas the *Bruguiera* zone displayed the highest sapling density. The *Sonneratia* zone exhibited the lowest values for both tree and sapling density. The canopy cover measurements, height, and MHI followed a similar trend. In contrast to density, the DBH value exhibits an inverse relationship to the other variables, with the *Sonneratia* zone displaying greater values than the other two zones (Table 2).

The variation in the prevalence of different mangrove types has impacted many stand structural metrics, including density, stem diameter, canopy cover, and MHI. The *Sonneratia* zone has a lower density than the *Bruguiera* and the *Rhizophora* zones. This disparity can be attributed to pneumatophores in the *S. alba* species inside the *Sonneratia* zone. These pneumatophores create allelopathic substances that can impede the growth of neighboring mangroves (Zhang et al. 2018). Nonetheless, the density of mangroves exclusively controlled by *S. alba* was higher than that found on Middleburg-Miossu Island, West Papua, where it was recorded at a mere 800±100 stands per hectare (Nurdiansah and Dharmawan 2021). The density component influences the percentage value of canopy cover, with a positive correlation between tree stand density and canopy cover value (Andiani et al. 2021; Sugiana et al. 2022). This phenomenon has been seen across the three distinct mangrove zones, wherein the zone characterized by the lowest density (the *Sonneratia* zone) has a comparatively lower value of canopy cover when compared to the other two zones characterized by greater density values. In addition, variations in mangrove growth patterns also influence the extent of canopy cover. For instance, the *S. alba* mangrove species exhibit a spreading crown canopy growth extending to the surrounding area. On the other hand, the Rhizophoraceae group, consisting of *Rhizophora* and *Bruguiera*, displays a conical crown canopy growth that tapers upwards (Dharmawan 2020). From a vertical appearance, vegetation with spreading canopy growth (*Sonneratia* spp.) will look looser than mangroves that grow conically upwards, generally in the Rhizophoraceae family.

In morphometric analysis, it can be observed that the *Sonneratia* zone has a comparatively greater stem diameter when compared to the *Rhizophora* zone and the *Bruguiera* zone. The findings of this study align with the research conducted by Nurdiansah and Dharmawan (2021), wherein the *S. alba* zone exhibited the greatest stem diameter, measuring 24.67±4.96 cm. The *S. alba* species exhibits a notable expansion in its distribution and experiences regular submergence due to tidal activity. As a response, one of the strategies this species employs to enhance its structural stability is the augmentation of stem diameter. According to Dharmawan (2020), the *Rhizophora* zone exhibits greater height vegetation, in contrast, the *Sonneratia* zone has lower canopy cover and density, reducing sunlight competition. Differences in the values of canopy cover and sapling density, which are constituent components of the index, are responsible for the variation between the highest MHI observed in the *Bruguiera* zone and the lower MHI observed in the *Sonneratia* zone. Since the *Bruguiera* zone has the highest canopy cover and sapling density, the MHI value tends to be higher than the other zones.

Most soil types prevalent in the area are categorized as sand, except for the *Sonneratia* zone, which is characterized by a sandy loam type (Table 3). The soil pH values generally exhibit acidity, with the *Sonneratia* zone displaying the highest values and the *Rhizophora* zone exhibiting the lowest. This trend is also observed in terms of the percentage of water content. The relationship between bulk density and soil pH according to Perie and Ouimet (2008), an inverse relationship exists between Soil Organic Carbon (SOC) and bulk density, whereby a decrease in bulk density corresponds to an increase in SOC levels, and our findings follow this. A low bulk density means looser air spaces (pores) in the soil bonds. Hence, this condition supports a higher accumulation capacity of organic matter, including organic carbon.

Table 2. The forest structure of each mangrove zone

Parameter	Zone		
	Bruguiera	***Rhizophora***	***Sonneratia***
Dominance of mangrove	*B. gymnorrhiza*	*R. mucronata*	*S. alba*
Number of spp.	1	3	1
Tree density (stands ha^{-1})	3030±525	3576±583	2121±247
Sapling density (stands ha^{-1})	1414±175	1333±346	985±290
Diameter (cm)	8.3±0.6	8.8±0.7	11.5±0.8
Canopy coverage (%)	75.18±5.21	74.59±2.34	49.17±11.27
Height (m)	10.18±1.76	12.02±0.47	9.51±3.17
Mangrove health index (%)	56.03±4.57	55.99±3.67	42.13±3.81

Table 3. Soil characteristics of each mangrove zone

Parameter	Zone		
	Bruguiera	***Rhizophora***	***Sonneratia***
Dominant soil type	Sand	Sand	Sandy loam
Soil pH	6.32±0.25	6.23±0.22	6.66±0.26
Water Content (%)	42.8±2.9	37.4±4.8	50.9±12.5
Bulk density (g cm^{-3})	0.81±0.16	0.80±0.06	0.66±0.07
Soil organic carbon (SOC) (%)	1.24±0.47	1.16±0.40	1.96±0.36

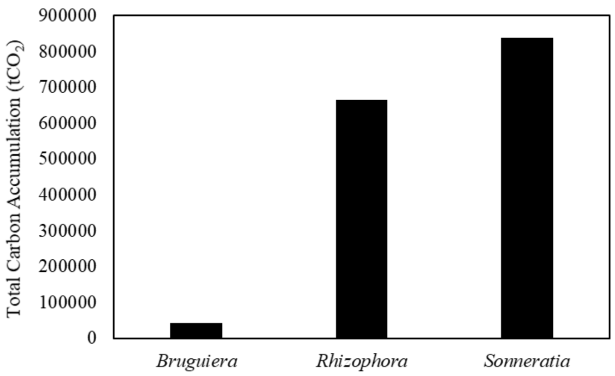

Figure 4. Total carbon accumulation of each mangrove zone in Benoa Bay

Total biomass and ecosystem carbon stock

Variations in biomass values were observed for Aboveground Biomass (AGB), Belowground Biomass (BGB), and tree biomass (TB), where TB = AGB + BGB across different mangrove zones. The *Sonneratia* zone has the highest AGB value and shows a significant difference (ANOVA: $F_{3,9} = 4.7$, $\rho = 0.04$) compared to the remaining two zones (Table 4). According to a study by Andiani et al. (2021) and Suartana et al. (2021), the AGB value observed in the *Sonneratia* zone also tends towards greater values than the other two zones in the same area. The variables BGB and TB were also determined to be statistically higher (BGB; ANOVA: $F_{3,9} = 5.7$, $\rho = 0.03$, and TB; ANOVA: $F_{3,9} = 0.3$, $\rho = 0.76$) in the *Sonneratia* zone when compared to the other two zones (refer to Table 4). This discrepancy arises because mangrove stands inside the *Sonneratia* zone have comparatively greater stem diameters than the *Bruguiera* and *Rhizophora* zones, as indicated in Table 4. In addition to this, it should be noted that various stand types, including saplings and trees, have a significant role in determining biomass levels. Specifically, mangroves predominantly composed of saplings tend to exhibit lower diameter values at breast height (DBH) than those dominated by trees, as Wijana et al. (2023) observed. However, it is worth noting that the three zoning regions exhibit an identical ratio of Aboveground Biomass (AGB) to Belowground Biomass (BGB), specifically 1.7.

Moreover, the AGC and BGC values are conversions of each biomass, and the distribution pattern between mangrove zones is relatively different between zones. AGC and BGC of the *Sonneratia* zone are almost twice and 150% higher than those of the *Bruguiera* zone, respectively. Interestingly, we also observed a comparable trend in the Soil Carbon Stocks (SCS) (ANOVA: $F_{3,9} = 3.9$, $\rho = 0.06$). Specifically, the total carbon stock, measured in terms of t ha^{-1} or tCO_2ha^{-1}, exhibited a similar pattern to AGB, BGB, and TB. The *Sonneratia* zone displayed the highest carbon stock value, while the *Bruguiera* zone showed the lowest value (Table 5). This finding suggests a correlation between Soil Carbon Stocks (SCS) and vegetation carbon content, as seen by the positive relationship observed along the Egyptian-African Red Sea coast (Afefe et al. 2020).

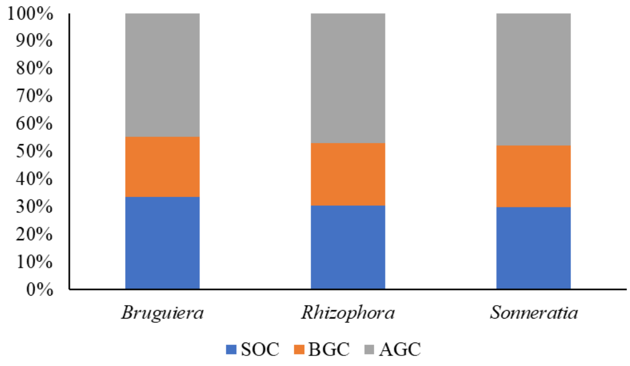

Figure 5. The mangrove ecosystem's vegetation and soil carbon storage percentage of each mangrove zone

Table 4. Mangrove biomass from each zone (superscript letters depict significant differences among zones with $\rho < 0.05$)

Zones	AGB (t ha^{-1})	BGB (t ha^{-1})	TB (t ha^{-1})	AGB/BGB (t ha^{-1})
Bruguiera	261.7±21.3^a	155.4±9.4^a	417.1±30.4^a	1.7
Rhizophora	293.2±81.5^{ab}	175.6±44.2^{ab}	468.8±125.6^{ab}	1.7
Sonneratia	427.7±98.1^b	245.9±42.3^b	673.6±130.4^b	1.7
Average	330.1±102.4	194.0±52.5	524.1±152.3	1.7

Table 5. Ecosystem carbon stock (AGC, BGC, SCS) from each mangrove zone (superscript letters depict significant differences among zones with $\rho < 0.05$)

Zones	AGC ($tCha^{-1}$)	BGC ($tCha^{-1}$)	SCS ($tCha^{-1}$)	Total ($tCha^{-1}$)	Total (tCO_2ha^{-1})
Bruguiera	125.6±10.2^a	60.6±3.7^a	94.6±21.9^a	280.8±35.7^a	1029.6±130.9^a
Rhizophora	140.7±39.1^a	68.5±17.2^a	91.2±22.7^a	300.4±74.4^a	1101.3±272.8^a
Sonneratia	205.3±47.1^b	95.9±16.5^b	127.2±15.7^b	428.4±67.6^b	1570.9±248.0^b
Average	158.5±49.1	75.6±20.5	104.0±25.3	338.2±89.5	1239.9±328.0

We calculated that the total accumulated carbon stock in the mangrove ecosystem in Benoa Bay, Bali, is 421,149 tC (1.5 million tCO_2 per 1.177,76 ha) over the three mangrove zones. The *Bruguiera* zone holds 11,695.3 tC (42,103.1 tCO_2) per 41.65 ha, the *Rhizophora* zone holds 181,309.4 tC (665,405.5 tCO_2) per 603.56 ha, and the *Sonneratia* zone holds 228,144.4 tC (837,289.9 tCO_2) per 532.55 ha (Figure 4). Another mangrove area in Bali, such as Nusa Lembongan, stored 54,792.33 tCO_2 per 164.57 ha (Kusumaningtyas et al. 2014), and Perancak stored around 329,723.6 tCO_2 per 178.6 ha of mangrove area (Suryono et al. 2018). The result means that Benoa Bay became the most productive mangrove for carbon accumulation in Bali. Meanwhile, the Anambas Islands in Indonesia have 766.32 ha of mangroves, and their overall CO_2 is 759,684.1 tCO_2 (Sinaga et al. 2023), which is still lower than Benoa Bay. Larger areas, like the Cananéia-Iguape lagoon in Brazil, which covers 15,000 ha, tend to store more CO_2, around 5.7 million tCO_2 (Rovai et al. 2021). This shows that the size of the mangrove area is the dominant factor, even if the species present have a lower storage capacity in tCO_2 measurement per hectare.

In general, the impact of vegetation and soil on proportional carbon storage does not exhibit significant variation among zones, as depicted in Figure 5. The contribution of SCS to the overall ecosystem carbon stock ranges from 24% to 36%. In comparison, vegetation comprising Aboveground Carbon (AGC) and Belowground Carbon (BGC) accounts for 64% to 76% of the total. The ratio mentioned is different from that found in the mangrove ecosystems in West-Central Africa and Bunaken, Indonesia, where 86% of the total carbon was found to be stored in soil (Murdiyarso et al. 2015; Kauffman and Bhomia 2017). Variations in the depth of data collection for SCS measurements across different regions can lead to differences in the calculated values because SCS calculations involve the accumulation of total SCS within specific depth intervals (Chen et al. 2020). In some circumstances, the surrounding greenery's density can also affect the SCS's. Therefore, the makeup of the dominant species affects the amplitude and scope of SCS (Weiss et al. 2016; Dermawan et al. 2023).

The range of AGC values in the higher *Sonneratia* zone is comparable to the findings of Suartana et al. (2021) and Andiani et al. (2021). In comparison, the SCS value is comparatively lower in comparison to the research conducted by Mahasani et al. (2016), which specifically examined rehabilitated mangroves in the *Rhizophora* zone of Benoa Bay and the Perancak Mangrove Ecosystem in Bali (Suryono et al. 2018).

We have conducted a comparative analysis of carbon stock values between various regions in Indonesia and globally (Table 6). Our findings indicate that the total carbon stock of mangroves in Benoa Bay tends to surpass that of Kerala (South West India), Perancak (Indonesia), Malaysia, Sofala Bay (Mozambique), and Yinluo Bay (China). However, it falls short compared to mangrove ecosystems in West-Central Africa, Cananéia-Iguape Lagoon (Brazil), China, and Bunaken (Indonesia). Based on a comprehensive analysis of many places, except Malaysia, it is evident that SCS, on average, significantly contributes over 50% to the overall carbon stock within the mangrove ecosystem.

Carbon sequestration rate in mangrove ecosystem

Vegetation Biomass and Carbon Increment (VBI & VCI)

No substantial variation is observed in mangrove plants' biomass and carbon levels across different zones. Nevertheless, when considering value, it is evident that the *Sonneratia* zone exhibits the highest value, whereas the *Bruguiera* zone demonstrates the lowest value (Table 7). Regarding the annual growth in DBH, it is seen that the *Sonneratia* zone, primarily characterized by the presence of *S. alba*, exhibits a range of 0.1-0.8 cm per year (cm yr^{-1}). Conversely, the remaining two zones have a comparable degree of 0.1-0.7 cm yr^{-1}, which means the *Sonneratia* zone could absorb more carbon than other zones. Therefore, considering the classification of vegetation size, it is observed that mangrove stands falling within the sapling category, with an initial size ranging from 0-5 cm, exhibit the lowest contribution to the annual biomass and carbon increment in comparison to mangrove stands categorized as trees, measuring 5-10 cm and greater than 10 cm (Dharmawan and Ulumuddin 2021; Table 7).

Table 6. Comparison of ecosystem carbon stock values with several other regions

Study Area	Dominated Mangrove Type	VegCS ($tCha^{-1}$)	SCS ($tCha^{-1}$)	TCS ($tCha^{-1}$)	References
Benoa Bay	*Bruguiera, Rhizophora, Sonneratia*	234.1±68.5	104.0±25.3	338.2±89.5	This study
Kerala, South West India	*Avicennia, Bruguiera, Rhizophora*	58.6±0.5	81.3±10.2	139.8±10.7	Harishma et al. (2020)
Perancak, Bali Indonesia	*Avicennia, Rhizophora*	46.6±18.7	119.7±42.9	166.3±60.4	Suryono et al. (2018)
West-Central Africa	*Avicennia, Rhizophora*	102±11	688±59	799±64	Kauffman and Bhomia (2017)
Peninsula Malaysia	*Avicennia*	126.52	119.69	246.21	Hong et al. (2017)
Cananéia-Iguape lagoon, Brazil	*Avicennia, Laguncularia, Rhizophora*	110	270	380	Rovai et al. (2021)
Mangrove Forest China	*Avicennia, Aegiceras*	84.6±30.7	270.4±76.3	355.3±82.2	Liu et al. (2014)
Sofala Bay, Mozambique	*Avicennia, Rhizophora, Bruguiera*	59.0	160.0	219.0	Sitoe et al. (2014)
Yinluo Bay, China	*Avicennia, Sonneratia, Bruguiera, Rhizophora*	80.5	243.2	232.7	Wang et al. (2013)
Bunaken, Indonesia	*Rhizophora, Bruguiera*	126.8	811.6	938.4	Murdiyarso et al. (2015)

Note: VegCS: Vegetation carbon stock, SCS: soil carbon stock, TCS: total carbon stock (VegCs+SCS)

Table 7. Vegetation biomass and carbon increment of each mangrove zone

Parameter	Diameter (cm)	Zone					
		Biomass (t $ha^{-1}yr^{-1}$)			Carbon ($tCha^{-1}yr^{-1}$)		
		Bruguiera	***Rhizophora***	***Sonneratia***	***Bruguiera***	***Rhizophora***	***Sonneratia***
AGB/AGC	0-5	0.8±0.2	1.1±0.4	0.4±0.1	0.4±0.1	0.5±0.2	0.2±0.0
	5-10	6.2±2.2	6.0±0.8	2.7±0.9	3.0±1.0	2.9±0.4	1.3±0.4
	>10	15.0±4.0	16.1±0.9	20.9±3.3	7.2±1.9	7.7±0.4	10.1±1.6
	Total	22.0±4.0[a]	23.2±4.4[a]	24.0±3.0[a]	10.5±1.9[a]	11.1±2.1[a]	11.5±1.4[a]
BGB/BGC	0-5	0.6±0.1	0.8±0.3	0.3±0.0	0.2±0.1	0.3±0.1	0.1±0.0
	5-10	3.7±1.3	3.6±0.5	1.6±0.5	1.5±0.5	1.4±0.2	0.6±0.2
	>10	7.7±1.9	8.4±0.5	11.0±1.4	3.0±0.8	3.3±0.2	4.3±0.5
	Total	12.0±2.0[a]	12.8±2.1[a]	12.9±1.1[a]	4.7±0.8[a]	5.0±0.8[a]	5.0±0.4[a]
Total Summary		34.0	36.0	36.9	15.2	16.1	16.5

This finding demonstrates that the age of vegetation plays a significant role in determining the degree of biomass or carbon uptake within individual mangrove stands. Nonetheless, the observed changes in vegetation biomass and carbon increment are similar, suggesting that including mangrove-type zoning may not be necessary when estimating carbon sequestration in future research.

The three zones' vegetation adds an average of 35.6 t $ha^{-1}yr^{-1}$ of biomass and 15.9 $tCha^{-1}yr^{-1}$ of carbon each year. Even though this number is higher than that found by researchers in the Province of Oriental Mindoro, Philippines, where it reached 4.32 $tCha^{-1}yr^{-1}$ (Salmo III et al. 2019), it is almost the same as that found by researchers in Northern Sumatra Coast, Indonesia, where it can reach 15.6 $tCha^{-1}yr^{-1}$ (Suprayogi et al. 2022). This variation shows significant changes caused by the type, age, and conditions of the environment in the mangrove ecosystem. These things also change the amount of carbon stored in plants, which changes the biomass and carbon build-up rate in mangroves. This shows that ecosystems naturally respond in different ways to different external factors.

Litterfall production

There was little difference between the litterfall component rates, except for branches (ANOVA: $F_{3,9} = 4.3$, $\rho = 0.05$). It was found that the zones of *Bruguiera* and *Rhizophora* had the most leaf litter, with 4.5 t $ha^{-1}yr^{-1}$. The *Sonneratia* zone had the least amount of waste. A similar pattern was seen in the fertile parts, like the flowers and propagules. Based on its phenology, the fertilized flower will be attached to the branch, resulting in low flower litter. Therefore, the uniflower species (*B. gymnorhiza* and *S. alba*) will produce less flower litter than the compound flower species (*Rhizophora*) because in the compound flower, only some (usually one) fertilized flower is attached to the branch, and the others will fall (Wang'ondu et al. 2013). We also found the opposite result in the branches, with the *Sonneratia* zone having the highest value and the *Bruguiera* zone having the lowest value. The overall litter output stayed relatively the same from one location to the next. The *Rhizophora* zone had the highest value, while the *Sonneratia* zone had the lowest (Table 8). According to Muliawan et al. (2020), the average amount of litter produced across the three components was 6.0 t $ha^{-1}yr^{-1}$. This is less than the 17.1 t $ha^{-1}yr^{-1}$ and 25.9 t $ha^{-1}yr^{-1}$ litter production rates seen in the *Rhizophora* and *Avicennia* zones of Muara Gembong. Even though the samples were only taken during the dry season, seasonal factors like weather and rainfall do not significantly affect litter production (Poungparn et al. 2020).

In all three zones, 68-73% of the litter comes from the leaves, while only 8-27% comes from the reproductive organs and 2-19% comes from the branch (Figure 6). A similar ratio was found in the *Rhizophora* zone of Rembang, Central Java, Indonesia, with 74-86% for leaf litter, 9-20% for reproductive organs, and 5-6% for branches (Ariyanto et al. 2019), and also in Eastern Thailand (Poungparn et al. 2020). Different types of mangroves and stand structures can cause differences in the amount of litter each type produces. The *Sonneratia* zone in Benoa Bay has the least leaf litter because it does not produce many leaves, and they tend to spread to other areas (Dharmawan 2020). This is clear from the fact that the canopy cover number is lower here than in the other two zones.

Table 8. Litterfall production of each mangrove zone (superscript letters depict significant differences among zones with $\rho < 0.05$)

Litterfall	*Bruguiera*	*Rhizophora*	*Sonneratia*
Leaf (t $ha^{-1}yr^{-1}$)	4.5±1.8[a]	4.5±1.0[a]	3.8±2.4[a]
Reproductive organ (t $ha^{-1}yr^{-1}$)	1.6±1.2[a]	1.8±2.2[a]	0.4±0.8[a]
Branch (t $ha^{-1}yr^{-1}$)	0.1±0.1[a]	0.3±0.2[ab]	1.0±0.7[b]
Total	6.2±3.1[a]	6.6±2.7[a]	5.3±3.2[a]

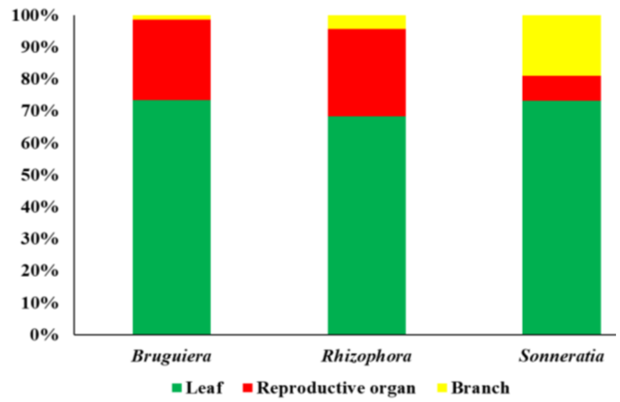

Figure 6. Percentage contribution of each type of litter from each mangrove zone

Table 9. Net primary productivity of each mangrove zone in t $ha^{-1}yr^{-1}$

Component	*Bruguiera*	*Rhizophora*	*Sonneratia*
Mean AGB Increment (Δy)	22.0	23.2	24.0
Mean litterfall (ΔL)	6.2	6.6	5.3
AGNPP	28.2	29.8	29.3
Mean BGB Increment	12.0	12.8	12.9
NPP	40.2	42.6	42.2

Net Primary Productivity (NPP)

There appears to be minimal variation in the net primary productivity, encompassing the increase of AGB, BGB, and litterfall production across different mangrove zones. In general, it can be observed that the *Rhizophora* zone exhibited the highest Net Primary Productivity (NPP) value. In contrast, the *Bruguiera* zone had the lowest NPP value (Table 9). The mean NPP throughout the three zones is 41.7 t $ha^{-1}yr^{-1}$, with the most significant factor contributing to this being the rise in Aboveground Biomass (AGB), accounting for 54.5-56.9%. The NPP value in this study is twice as high as the NPP value reported in a previous study conducted in the Sundarbans, Bangladesh, which was 21.0 t $ha^{-1}yr^{-1}$ (Kamruzzaman et al. 2017a). However, it is nearly equal to the NPP value reported in a study conducted in the Okukubi River, Okinawa Island, Japan, which was 42.5 t $ha^{-1}yr^{-1}$ (Kamruzzaman et al. 2017b). Based on the limited range of NPP values observed within each mangrove zone, it is evident that the zoning component associated with mangrove types does not significantly impact the computed NPP value. Consequently, zoning may be deemed inconsequential and disregarded in future analyses of NPP.

Vegetation Carbon Absorption rate (VCA)

The leading productivity values show few significant differences between mangrove zones regarding the rate of carbon uptake by plants. Assuming that 0.48 of the aboveground biomass and 0.39 of the belowground biomass are the biomass to carbon conversion factors, we estimate that the rates at which vegetation takes in carbon are 18.2±1.2 $tCha^{-1}yr^{-1}$ for the *Bruguiera* zone, 19.3±2.5 $tCha^{-1}yr^{-1}$ for the *Rhizophora* zone, and 19.1±2.3 $tCha^{-1}yr^{-1}$ for the *Sonneratia* zone. The average rate across all three zones is 18.9 $tCha^{-1}yr^{-1}$. It is higher than the mangrove ecosystem in Cananéia-Iguape lagoon, Brazil, and the Province of Oriental Mindoro, Philippines, which only has a value of 4.64 $tCha^{-1}yr^{-1}$ (Rovai et al. 2021) and 4.32 $tCha^{-1}yr^{-1}$ (Salmo III et al. 2019). However, it is about the same as that found by researchers on the Northern Sumatra Coast, Indonesia, where it could reach 15.6 $tCha^{-1}yr^{-1}$ (Suprayogi et al. 2022). These findings demonstrate that the value of carbon uptake rates in plants can change depending on the dominant mangrove type and where the observation was made.

Soil Carbon Burial (SCB)

No substantial difference is observed in the SCB among the various mangrove zones. The *Sonneratia* zone had the highest SCB rate at 3.2±0.4 $tCha^{-1}yr^{-1}$, while the *Rhizophora* zone demonstrated the lowest value at 2.3±0.6 $tCha^{-1}yr^{-1}$ (Figure 7). The mean SCB rate across the three zones is 2.6±0.6 $tCha^{-1}yr^{-1}$. This value is comparatively higher than findings from various studies conducted in the Red Sea (Saudi Arabia), Bintuni Bay Papua (Indonesia), Northern Sumatra Coast (Indonesia), Segara Anakan Lagoon, Berau District, and Kongsi Island (Indonesia). However, it is lower than the results obtained from research conducted in the Cananéia-Iguape lagoon (Brazil), Province of Oriental Mindoro (Philippines), Farasan Islands (Saudi Arabia), and Egyptian Red Sea Coast (as shown in Table 10). It is essential to recognize that the estimated value of Soil Carbon Burial may vary depending on the rate of soil accretion (SAR) seen during field measurements.

Nevertheless, it is worth noting that the obtained values may exhibit minimal variation, as evidenced by several studies conducted in proximate regions of Indonesia, specifically Bintuni Bay in Papua and North Sumatra. These studies reported SAR values of 2.5±0.3 mm yr^{-1} (Sasmito et al. 2020) and 3.7 mm yr^{-1} (Murdiyarso et al. 2018) within the interior of mangrove ecosystems, respectively. However, we think it is highly desirable that SAR measurements in Benoa Bay, Bali, be conducted with the ^{210}Pb dating method to enhance the precision of Soil Carbon Burial data.

Total carbon sequestration rate

By combining the carbon sequestration rates in vegetation and SCB, we find that the total carbon sequestration rates in the *Bruguiera*, *Rhizophora*, and *Sonneratia* zones are about the same, at 20.6, 21.6 and 22.3 $tCha^{-1}yr^{-1}$. Every year, 21.5 tC is added to the land, twice as much as in Cananéia-Iguape Lake, Brazil (Rovai et al. 2021). However, although it has three parts (VCA, Litterfall, and SCB), this amount is almost the same as the SCB number in the Philippines' Province of Oriental Mindoro. It is even lower by 2.5 $tCha^{-1}yr^{-1}$ if VCA is added (Table 10). Based on the circumstances, different mangrove ecosystems in different places may take in carbon at different rates.

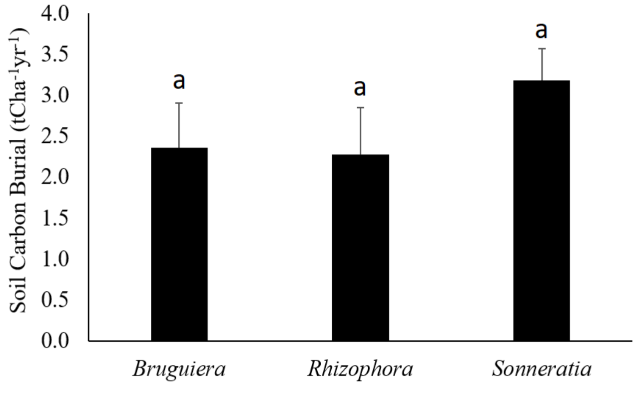

Figure 7. Soil carbon burial rate of each mangrove zone

Table 10. Carbon sequestration rate comparison at several areas in the world

Area	VCA ($tCha^{-1}yr^{-1}$)	Litterfall ($tCha^{-1}yr^{-1}$)	SCB ($tCha^{-1}yr^{-1}$)	Total ($tCha^{-1}yr^{-1}$)	References
Benoa Bay, Indonesia (Average)	15.9	3.0	2.6	21.5	This study
Bruguiera zone	15.2	3.0	2.4	20.6	This study
Rhizophora zone	16.1	3.2	2.3	21.6	This study
Sonneratia zone	16.5	2.6	3.2	22.3	This study
Cananéia-Iguape lagoon, Brazil	4.64	3.32	2.83	10.8	Rovai et al. (2021)
Kourou, French Guiana, South America	NA	NA	0.72-4.86	NA	Marchand (2017)
Red Sea, Saudi Arabia	NA	NA	0.03-0.15	NA	Almahasheer et al. (2017)
Bintuni Bay, West Papua, Indonesia	NA	NA	0.21-1.19	NA	Sasmito et al. (2020)
Province of Oriental Mindoro, Philippines	4.32	NA	19.68	NA	Salmo III et al. (2019)
Northern Sumatra Coast, Indonesia	8.03-15.6	NA	1.81	NA	Suprayogi et al. (2022)
Farasan Islands, Saudi Arabia	NA	NA	5.4	NA	Eid et al. (2020)
Egyptian Red Sea Coast	NA	NA	6.1	NA	Eid and Shaltout (2016)
Segara Anakan Lagoon, Berau District, and Kongsi Island, Indonesia	NA	NA	2.4	NA	Kusumaningtyas et al. (2019)

Note: NA: not available

The conversion of carbon into carbon dioxide (CO_2) results in a total CO_2 sequestration of 75.6, 79.3, and 81.8 $tCO_2ha^{-1}yr^{-1}$ for the *Bruguiera*, *Rhizophora*, and *Sonneratia* zones, respectively. The average CO_2 sequestration value across these zones is 78.9 $tCO_2ha^{-1}yr^{-1}$. When considering the proportion of area of each zone in Benoa Bay, it is observed that the *Bruguiera* zone has the lowest CO_2 absorption rate, amounting to 3,148.7 tCO_2yr^{-1}, which accounts for 3.3% of the total. On the other hand, the *Rhizophora* and *Sonneratia* zones exhibit higher total CO_2 absorption rates, with values of 47,862.3 tCO_2yr^{-1} (50.6%) and 43,562.6 tCO_2yr^{-1} (46.1%), respectively. Consequently, the combined CO_2 uptake in Benoa Bay amounts to 94,573.6 tCO_2yr^{-1}. The observed outcome demonstrates a relatively lower value than the mangrove ecosystem in Cananéia-Iguape lagoon, Brazil, which exhibited a carbon sequestration rate of 162,000 tCO_2yr^{-1} (Rovai et al. 2021). However, it remains higher than the carbon sequestration rate of 1,684.5 tCO_2yr^{-1} observed in the mangrove area of Mindoro Island, Philippines, which spans only 45 ha (Salmo III et al. 2019). It should be noted that this quantity remains very insignificant, amounting to less than 0.1% compared to the global annual carbon sequestration rate in mangrove forests, which has been reported to reach 13.6 $Gtyr^{-1}$ (Alongi 2012).

In summary, there are significant variations in the ecosystem carbon stock among the three zones, with the *Sonneratia* zone exhibiting the highest value. Nevertheless, there is no substantial variation in the carbon sequestration rate within different mangrove zones, with the highest values also observed in *Sonneratia* zone. Upon examining the relative proportions of the area, the carbon sequestration rates can be ranked from highest to lowest: *Rhizophora*, *Sonneratia*, and *Bruguiera* zones. The primary factor contributing to the valuation of ecosystem carbon stock and the pace at which carbon is sequestered is the storage and uptake of carbon in vegetation. It is essential to recognize that the data presented in this study is currently undergoing refinement due to various limitations. These limitations primarily pertain to the measurement of litter production rate and the utilization of SAR values, now based on a global scale. Consequently, these factors could impact the overall estimation of the total carbon sequestration rate.

Nevertheless, these findings can serve as a preliminary approximation due to the scarcity of comprehensive data on the overall carbon storage and sequestration rate in mangrove ecosystems worldwide. Future assessments of carbon stocks are recommended to consider the zoning characteristics of different mangrove types, given the substantial variations in carbon levels observed throughout these zones. Therefore, to improve this paper's quality, it is recommended to do more studies utilizing the ^{210}Pb dating method to measure the accurate sediment accumulation rates (SAR) and seasonal net primary productivity (NPP). We also suggest doing long-term monitoring of environmental conditions due to their importance, which could impact variation in mangrove zones and potentially lead to fluctuations in ecosystem carbon stock and sequestration rate. This approach will contribute to the refinement of the paper's findings.

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