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Carbon stock at several types of mangrove ecosystems in Bregasmalang, Central Java, Indonesia

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Abstract. *Sugiatmo, Poedjirahajoe E, Pudyatmoko S, Purwanto RH. 2023. Carbon stock at several types of mangrove ecosystems in Bregasmalang, Central Java, Indonesia. Biodiversitas 24: 182-191.* Mangrove ecosystems have an important role but are also faced with the conversion of use and impacts from climate change. Therefore, this research aims to determine the carbon stock above-ground, below-ground, and the soil at several types of mangrove ecosystems in Bregasmalang, Central Java. A total of 8 transect lines, each having a length of 125 m and consisting of six plots, were placed in four types of mangrove ecosystems to obtain data on the diameter of the vegetation and soil at five different depths. Allometric equations were used to analyze diameter data, while the soil compositions were analyzed in the laboratory. The results showed that the total carbon stock in Bregasmalang was 713.13 Mg ha^{-1} with the details as follows; above-ground 30.27 Mg ha^{-1} (4%), below-ground 10.99 Mg ha^{-1} (2%), and soil carbon 671.87 Mg ha^{-1} (94%). Meanwhile, the total carbon stock in conservation mangrove forests was 763.75 Mg ha^{-1}, rehabilitation mangrove 719.25 Mg ha^{-1}, silvofishery 680.71 Mg ha^{-1}, and ponds 688.81 Mg ha^{-1}. Based on the results, the high soil and total carbon stock in conservation mangroves showed the importance of protecting the ecosystems to mitigate climate change.

Keywords: Allometric equation, Bregasmalang, carbon stock, ecosystem, mangrove

INTRODUCTION

Based on mounting evidence of global warming in the late 1980s, various studies examined how mangroves would fare and adapt to climate change. Mangroves are one of the important ecosystems in coastal areas (Wilson 2017). According to Lovelock and Reef (2020), the potential services often offered by blue carbon ecosystems, such as mangroves, would be impacted by climate change. Mangroves provide food, fodder, storm protection, carbon sequestration, and storage, according to Krauss et al. (2017), while ecosystems store significant amounts of carbon in biomass and sediments (Nehren and Wicaksono 2018). Mangrove habitats, specifically in sediments, are significant natural carbon sinks, according to Kusumaningtyas et al. (2019). However, the potential of mangrove carbon has not been effectively maximized, particularly due to changes in land use (Cameron et al. 2019). The expansion of shrimp farming is one of the main causes of global mangrove loss (Elwin et al. 2019). Mangroves are being lost at rapid rates worldwide, including in Indonesia, which has the largest mangrove area (about 22.6% of the world's mangroves) (Miteva et al. 2015). In Java, one of the mangrove ecosystems that has decreased in size is in the North Coast area of the western part of Central Java Province, including Brebes District, Tegal District, Tegal City, and Pemalang District, known as Bregasmalang.

Despite playing a crucial role, the quantity of mangroves on the North Coast of Central Java is declining (Rahman et al. 2021). According to Suroso and Firman (2018), the predominant pattern of land use change on the north coast of Java Island is from mangrove forests to fish ponds, which is caused by the loss and is especially attributable to the conversion of mangroves to ponds. In specific coastal locations, the conversion may significantly impact coastal erosion (Solihuddin et al. 2021).

In addition, tidal flooding and abrasion are two additional effects of climate change that affect mangroves in the Bregasmalang. Climate change has brought flooding, and the risk of flooding in Bregasmalang is very high (Muktiali and Setiadi 2022). Abrasion from the North Coast of Central Java degrades coastal conditions (Rahman et al. 2021). This degradation is also supported by the study by Cerlyawati et al. (2017) that, in general, abrasion induced by sea level rise and the effects of global warming has changed the physical condition of the shoreline. Abrasion caused the coastline modifications in Brebes, and between 1985 and 1995, considerable abrasion affected Kaliwlingi, among other places (Susantoro et al. 2020; Nugroho et al. 2020). The region with the most noticeable coastline alterations on the North Coast of Central Java is Wanasari, which is also in Brebes, along with Suradadi in

Tegal (Solihuddin et al. 2021). Andreas et al. (2018) showed that tidal inundation and abrasion occur in various places on the North Coast of Java Island, including Brebes, Tegal, and Pemalang. Suroso and Firman (2018), concerning coastal inundation, also explained that fishing ponds mostly affected by flooding in Central Java were found in Brebes. In addition, inundations in Brebes, Tegal District, and Tegal City occur in protected areas, including mangroves. In Pemalang, one example of inundation in a protected area was observed in the Mangrove Essential Ecosystem Area (KEE) of Mojo Village. According to Febriana (2019), the presence of long-standing seawater in the area has killed several mangroves in the village. The state of the mangroves in Bregasmalang is impacted by the shrinkage of the area owing to conversion and the effects of climate change. Bregasmalang's mangrove cover is described by the Environment and Forestry Agency of Central Java (2017) as moderately degraded, medium, and dense. The sustainability of the carbon ecosystem services mentioned in the mangrove management regulations is impacted by this circumstance. Due to the lack of studies on carbon in Bregasmalang, this research seeks to ascertain the carbon stock in several mangrove habitat types in Central Java.

MATERIALS AND METHODS

Research area

This research was conducted in Bregasmalang, Central Java Province, which includes Brebes District (6°44'-7°21' S and 108°41'-109°11' E), Tegal City (6°50'-6°53' S and 109°08'-109°10' E), Tegal District (6°50'41"-7°15'30" S and 108°57'6''-109°21'30'' E), and Pemalang District (6°52'30"-7°20'11" S and 109°17'30"-109°40'30" E), on 23 February-26 March 2022 (Figure 1). The total area of Bregasmalang is approximately 4,982.32 km^2 or 15.19% of the area of Central Java, with various environmental ecosystems which are one unit and need to be preserved (Government of Central Java Province 2014). The research location was a mangrove ecosystem with a conservation function in the KEE of Mojo Village (Pemalang), which has an area of 14.5 ha. This village was also used for mangrove rehabilitation combined with Kaliwlingi (Brebes). The next ecosystem is a silvofishery system located in Pesantren (Pemalang) and Grinting Village (Brebes), while ponds are in Muarareja (Tegal City) and Dampyak Village (Tegal District). The four types of ecosystems represent the management of mangroves in Java Island (van Oudenhoven et al. 2015), especially Bregasmalang, with one of the ecosystem service provisions being carbon storage and sequestration. Conservation is an example of a natural mangrove management regime; rehabilitation and silvofishery are forms of high-intensity use of mangroves, while ponds or extensive aquaculture in this research refer to mangroves converted for aquaculture.

Procedures

Sampling design

The calculation of carbon stock was carried out on three carbon pools, namely, above-ground, below-ground, and the soil. Necromas in the form of dead trees and downed wood was included in the above-ground carbon calculation. Data were collected using the line transect method following the protocols for measuring, monitoring, and reporting structure, biomass, and carbon stocks in mangrove forests (Kauffman and Donato 2012).

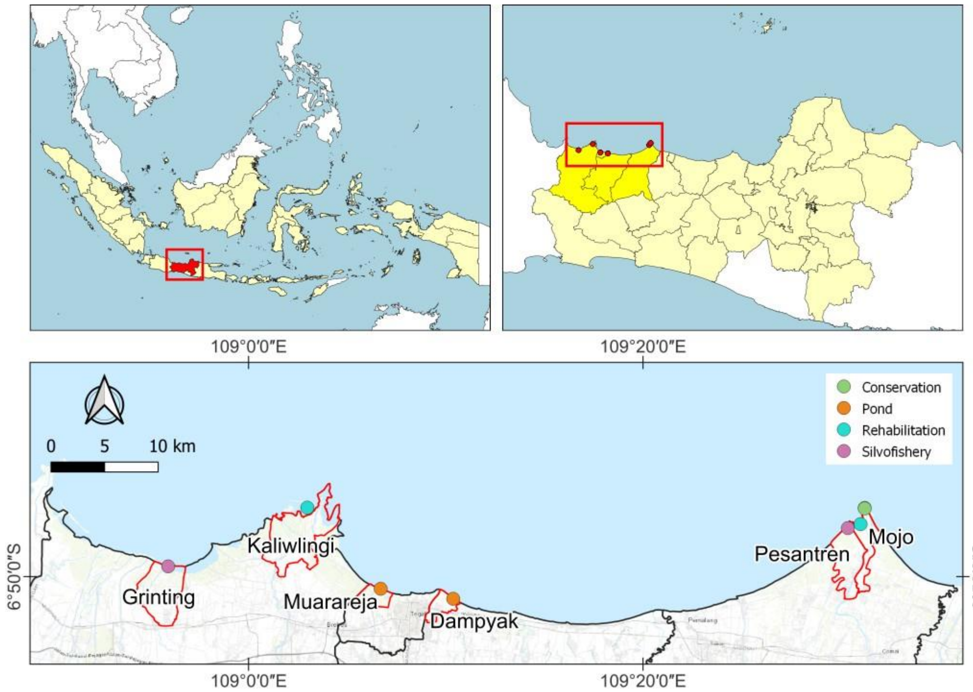

Figure 1. Research site in the Bregasmalang area (Brebes District, Tegal District, Tegal City, and Pemalang District), Central Java Province, Indonesia, which includes eight (8) transects placed in 4 (four) different mangrove ecosystem types

In this protocol, each transect consisted of six plots circular in shape and perpendicular to the marine-mangrove ecotone. The circle plot had a radius of 7 meters and another inside with a radius of 2 meters. In the center of each plot were four transects 14 meters long; the first transect was made at 45° from the azimuth of the main transect, while the other three were made 90° clockwise from the first one.

Moreover, the first plot was made 15 meters inland from the ecotone with a distance between plots of 25 meters, indicating the transect length reached 125 meters. A total of 8 transects were randomly placed in Bregasmalang with details of 2 in KEE of Mojo Village and 2 each in every other ecosystem, culminating in a total number of 48 plots (Figure 1). Although the extent was different, each type of ecosystem had the same ecological characteristics, such as mangrove species. Therefore, transects were established perpendicular to the marine-mangrove ecotone and taken into account the length of the mangrove landward.

Field data collection

Trees with a diameter at breast height (dbh=137 cm) >5 cm were measured in circular plots with a radius of 7 m, while those with dbh <5 cm were assessed in small circular plots with a radius of 2 m. For trees with roots exceeding 137 cm above ground level, the stem diameter measurement was carried out at the point above the highest root (Komiyama et al. 2005; Kauffman and Donato 2012). Furthermore, the species' name and the tree's current status, whether alive or dead, were also recorded. Dead and standing trees were recorded and measured the same way as the living mangroves. There were three statuses of decay of dead trees, where status 1 implies that there are still small branches and twigs except without leaves. Status 2 indicates no branches or small branches, while status 3 has few or no branches, only the trunk is standing, and the top might be damaged. Dead and downed wood were measured on four intersecting transects in each plot. There were four size classes, namely fine, small, medium, and large pieces of wood. For each piece that crossed the transect, the diameter was recorded at the point where the transect line crossed the midpoint of the log.

Soil samples were taken at a specified depth near the center of a plot, with the depth of the mangrove soil samples ranging from 0-15 cm, 15-30 cm, 30-50 cm, 50-100 cm, and >100 cm. A total of 240 soil samples were collected using a peat auger to determine soil carbon; when the auger cannot penetrate to its full depth due to obstruction by roots, it is moved to another location. Once at depth, the auger is rotated clockwise and then withdrawn to obtain a complete soil sample.

Data analysis

Above-ground and below-ground biomass

It is first necessary to determine the biomass of each component to determine the above-ground and below-ground carbon pools, including live and dead trees, as well as dead and downed wood using allometric equations for the three mangrove species present in the research area (Table 1). A different formula is used for Avicennia marina because there is a species-specific equation based on geographic origin. A different approach was taken to determine the biomass of dead trees in status 3 by first calculating the peak diameter and volume, then multiplying by the wood density (Kauffman and Donato 2012). In dead and downed wood, the Quadratic Mean Diameter (QMD) of wood particles was used to calculate the volume of wood size classes. Wood biomass was then calculated from the volume obtained multiplied by the average density. Furthermore, the above-ground carbon was obtained by multiplying the biomass of each component by the carbon concentration of 46%, except for dead trees and dead and downed wood by 50%. In contrast, the root carbon concentration value was 39% for below-ground carbon.

Soil

The soil samples in this research were sent to the laboratory for analysis using the Walkley Black method from 29 March to 7 June 2022. It is necessary to understand the depth, bulk density, and soil carbon concentration to calculate the mass of carbon in the soil. Total soil carbon was determined by adding up the mass of carbon at each depth of the soil sample. According to (Kauffman and Donato 2012), soil carbon per sample depth interval is calculated as follows:

Soil Carbon (Mg ha^{-1}) = Bulk density (g cm^{-3}) x Soil depth interval (cm) x Carbon concentration (%C)

Total carbon stock

The total carbon stock was estimated by adding all the components of the carbon pool, including above-ground, below-ground, and soil. First, each component set was averaged over all plots; then, these average values were added together to obtain the total (Kauffman and Donato 2012). Next, carbon units per plot were converted into units commonly used in carbon stock assessment (Mg ha^{-1}) and converted to CO_2e by multiplying the carbon stock by 3.67.

Table 1. The allometric equation used in this research

Mangrove species	B_{AT}	B_{BT}	References
Avicennia alba Blume	$0.251*\rho*D^{2.46}$	$0.199*\rho^{0.899}*D^{2.22}$	Komiyama et al. (2008)
Avicennia marina (Forssk.) Vierh	$0.1848D^{2.3524}$	$0.1682D^{1.7939}$	Dharmawan and Siregar (2008)
Rhizophora mucronata Lam.	$0.251*\rho*D^{2.46}$	$0.199*\rho^{0.899}*D^{2.22}$	Komiyama et al. (2008)

Note: B_{AT}: Above-ground tree biomass (kg); B_{BT}: Below-ground tree biomass (kg); D: Diameter at breast height (cm); ρ: Specific gravity of wood

RESULTS AND DISCUSSION

Species composition

The results showed that three species of mangroves were found in Bregasmalang, namely *Avicennia alba*, *Avicennia marina*, and *Rhizophora mucronata* (Table 2). According to the Environment and Forestry Agency of Central Java (2017), these three species are more predominant in Central Java Province, both in the form of expanses and in embankments of ponds as well as river channels. Mangrove ecosystems, mainly *A. marina*, occur on mud substrates as narrow basins in the tidal reaches of rivers and streams discharging directly onto the North Coast of Java (Solihuddin et al. 2021). Yulianto et al. (2020) also said that *A. marina* and *R. mucronata* were the dominant species encountered in Brebes. Specific mangrove management regimes (van Oudenhoven et al. 2015) at the location of this research are conservation, rehabilitation (planting), silvofishery, and extensive ponds. In mangrove forests with conservation aims, the species found based on the results strengthen previous research by Febriana (2019), which stated that the most common mangrove species in KEE Mangrove Mojo are *R. mucronata*. The planting years in KEE Mojo are 2001, 2002, and 2003.

Meanwhile, the three species in the rehabilitation mangrove ecosystem are found in Pemalang because they can adapt adequately to habitat conditions (Poedjirahajoe et al. 2017). The research location for mangrove rehabilitation in Mojo Village has the planting year of 2008. The preference for using *R. mucronata* to plant mangroves also makes this species more dominant in Muarareja Village (Tegal City). The findings of Purwanto et al. (2022) suggest that *R. mucronata* might be a good choice. Since 1997 to enhance the likelihood of success in mangrove rehabilitation programs, mangroves have been planted in Brebes as a measure intended to prevent further abrasion (Susantoro et al. 2020). Susantoro et al. (2020) conducted field observations and showed that communities had intensively planted mangroves, government and related institutions in more than 36 locations between 2005 and 2017. Based on the planting data, more than 3,000,000 mangrove trees were estimated to be planted. Kaliwlingi Village, another location for the rehabilitation types, has a species of mangrove *Rhizophora* and *Avicennia* with the planting year of 2008, following Nurfitriani et al. (2019). According to Suyono et al. (2015), these species are used for mangrove rehabilitation activities based on the type of substrate and coastal conditions, namely accretion or abrasion. Suyono et al. (2015) also explained that *R. mucronata* had become a species used to rehabilitate mangrove forests in Brebes District since 2004. In the Silvofishery type in Pesantren and Grinting Villages, which had the planting year of 2005, the results are following Harefa et al. (2022), Perwitasari et al. (2020), and Basyuni et al. (2018). Meanwhile, the two species found in the pond type at the research site, namely *Avicennia* and *Rhizophora*, which were planted in 2007, strengthen the results obtained by Isworo and Oetari (2020), who conducted research around Tegal Port.

Above-ground and below-ground carbon

The results showed above-ground carbon of 30.27 Mg ha^{-1} or 4% of the total carbon stock and below-ground carbon of 10.99 Mg ha^{-1} or 2%. This value is lower than the global average carbon stock, according to Alongi (2020), and different from several other locations, as shown in Table 3. According to Alongi (2020), globally, above-ground carbon stock is 109.3 Mg ha^{-1}, amounting to 14.8% of total carbon stock, while below-ground is only 80.9 Mg ha^{-1} or 8.7%. The vegetation carbon stock in this research, including above and below-ground, is lower than in other locations such as India, Sri Lanka, Myanmar, Philippines, and Thailand.

Table 2. Mangrove descriptions of research sites

Research site	Latitude (S)	Longitude (E)	pH	Salinity (ppt)	Species
KEE Mojo Transect 1	6° 46' 30.772"	109° 31' 15.125"	6.5 ± 0.25	16 ± 4.2	*Avicennia alba* *Avicennia marina* *Rhizophora mucronata*
KEE Mojo Transect 2	6° 46' 32.400"	109° 31' 15.120"	6.5 ± 0.2	16.3 ± 4.63	*Avicennia alba* *Avicennia marina* *Rhizophora mucronata*
Mojo	6° 47' 20.047"	109° 31' 2.442"	6.6 ± 0.3	16 ± 5.51	*Avicennia alba* *Avicennia marina* *Rhizophora mucronata*
Kaliwlingi	6° 46' 29.910"	109° 2' 58.841"	6.7 ± 0.22	8.2 ± 5.08	*Avicennia alba* *Avicennia marina* *Rhizophora mucronata*
Pesantren	6° 47' 32.140"	109° 30' 23.782"	7.1 ± 0.11	7.7 ± 0.82	*Avicennia alba* *Rhizophora mucronata*
Grinting	6° 49' 28.620"	108° 55' 55.320"	7.2 ± 0.38	7.5 ± 1.52	*Avicennia alba* *Avicennia marina* *Rhizophora mucronata*
Muarareja	6° 50' 36.720"	109° 6' 42.180"	7.7 ± 0.22	7 ± 1.9	*Avicennia marina* *Rhizophora mucronata*
Dampyak	6° 51' 7.200"	109° 10' 22.800"	7.6 ± 0.22	6.8 ± 1.33	*Avicennia alba* *Rhizophora mucronata*

According to Harishma et al. (2020), the carbon stock of vegetation in the Kerala mangroves, specifically on the southwest coast of India, is higher than the results of this research, namely 58.56 ± 0.51 Mg ha^{-1}. This value then increased to 194.03 Mg ha^{-1} when Sreelekshmi et al. (2022) re-examined at the same location. The below-ground carbon stock in the mangrove estuary of Malwathu Oya, Sri Lanka, according to Perera and Amarasinghe (2021), was 29.27 ± 1.57 Mg ha^{-1}. Meanwhile, above and below-ground carbon stock in the natural mangrove forest in Kanhlyashay (Myanmar) is 150.25 ± 81.35 Mg ha^{-1} (Aye et al. 2022). This value is twice that of the vegetation carbon stock in conservation mangroves in this research. Another natural mangrove forest in Tambunan Sanctuary, Zamboanga del Sur (Philippines), has above-ground carbon stocks of 90.52 ± 1.42 Mg ha^{-1} (Mariano et al. 2022). This value is close to the above-ground carbon stock in the conservation area along the western coast of the Gulf of Thailand, which is 81.73 Mg ha^{-1} (Swangjang and Panishkan 2021), while the value of the below-ground is 32.54 Mg ha^{-1}. Furthermore, in the rehabilitated mangrove ecosystem, the above-ground carbon stock in Balong-balong, Zamboanga del Sur, was 87.84 ± 1.09 Mg ha^{-1} (Mariano et al. 2022), making it more than half the average value obtained in this research. At the national level, the values of above and below-ground carbon stocks in this research are lower than those obtained in Indonesia, according to Alongi et al. (2016), namely 159.1 Mg ha^{-1} and 16.7 Mg ha^{-1} as well as other locations such as Maluku and Papua. The above-ground carbon stocks at Marsegu Island, West Seram (Maluku), in the proximal, middle, and distal zones are 51.11 Mg ha^{-1}, 70.5 Mg ha^{-1}, and 140.13 Mg ha^{-1}, respectively (Irwanto et al. 2021). Meanwhile, the below-ground values in the middle and distal zones are 13.48 Mg ha^{-1} and 24.36 Mg ha^{-1}, respectively. The above and below-ground carbon stock in Demta Bay (Papua) is 87.1 ± 34.07 Mg ha^{-1} (Indrayani et al. 2021). Compared to other forest types, the value of the above-ground carbon stock in conservation mangrove forests is also lower. According to Asner et al. (2018), unlogged forests in the Malaysian state of Sabah contain an average above-ground carbon density of over 200 Mg ha^{-1}, with a maximum value of 500 Mg ha^{-1}. Critically, more than 40% of the highest forest carbon stock is found outside the areas designated for maximum protection; also, in logged-over forests, the carbon density is still high, reaching 60-140 Mg ha^{-1}.

Above and below-ground carbon values in this research are still in the global range of 37-255 Mg ha$^{-1,}$ according to Kauffman et al. (2020). This research's average above-ground carbon stock is also within the range obtained in four Chinese provinces, from 12.0 to 150.2 Mg ha^{-1} (Meng et al. 2021). Meanwhile, the below-ground carbon stock is within the range in Sri Lanka, according to Cooray et al. (2021), i.e., 7.9-14.3 Mg ha^{-1}. The vegetation in conservation mangrove forests is also in the range obtained in Rufiji Delta (Tanzania), namely 28.18-299.43 Mg ha^{-1} and 16-164.51 Mg ha^{-1} (Monga et al. 2022). These values are close to those obtained at Ruposhi Mangrove Plantation (RMP) in Bangladesh, namely 37.3 ± 2.4 Mg ha^{-1} and 11.8 ± 1.4 Mg ha^{-1} (Ahmed et al. 2022). Furthermore, the above and below-ground carbon stocks in conservation mangroves in KEE Mojo Transect 1, i.e., 63.73 Mg ha^{-1} and 21.85 Mg ha^{-1}, are similar to the results obtained by (Suhaili et al. 2020) in Sulaman Lake Forest Reserve, Sabah, Malaysia, with values of 67.3 Mg ha^{-1} and 22.44 Mg ha^{-1}. At the national level, the above-ground carbon stock in conservation mangroves of 60.31 Mg ha^{-1} is close to that of Tiwoho Village, North Sulawesi, at 62.57 Mg ha^{-1} (Yusuf 2016). The higher carbon value in Mojo compared to other locations is directly proportional to the salinity value, which reaches an average of 16 ppt. That is consistent with research by Natarajan et al. (2022), which states that total organic carbon has a significant positive correlation with salinity. Rahman et al. (2015) also stated that salinity was found to enhance below-ground carbon stock, as revealed by the lowest proportion of below-ground carbon stock (57.2%) concerning ecosystem carbon in the freshwater zone and by the highest (71.9%) in strong salinity zone. In general, nutrient availability and pore-water salinity are the potentially important factors that may regulate organic matter production, thereby determining the carbon stock of mangrove systems (Sanders et al. 2016).

The vegetation carbon stock in this research was higher than that of three mangrove forests in the north Persian Gulf (Iran) which were 34.92, 12.50, and 27.54 Mg ha^{-1}, respectively (Mahmoudi et al. 2022). The values in conservation mangroves were also higher than in the Santa Cruz closed canopy mangrove dominated by *R. mucronata* in Honda Bay, Palawan (Philippines), at 49.58 Mg ha^{-1} and 18.88 Mg ha^{-1} (Castillo et al. 2018). In Indonesia, the above-ground carbon in the Bregasmalang mangrove ecosystem is higher than in other locations such as Paliat Island Sumenep East Java, which is 10.8 Mg ha^{-1} (Hidayah and Andriyani 2019); Ciletuh West Java at 14.93 Mg ha^{-1} (Kusmana et al. 2019); the secondary mangrove forest of Pulau Sembilan Village, North Sumatra 23.73 Mg ha^{-1} (Basyuni and Simanjutak 2021); and Pannikiang Island (South Sulawesi) 5.34 ± 0.17 Mg ha^{-1} (Malik et al. 2022). Meanwhile, in the pond mangrove ecosystem, the average above-ground carbon stock in Bregasmalang at 17.31 Mg ha^{-1} was higher than in Tanjung Nipah and Sepatin (East Kalimantan) at 11.6 Mg ha^{-1} and 6.25 Mg ha^{-1}, respectively (Diana et al. 2021).

The difference in the value of the above and below-ground carbon stocks is partly due to the biomass estimation method. According to Adame et al. (2017), the highest estimate of below-ground biomass was obtained when the combined live and dead roots were sampled and then measured. Compared to the estimated value, the average of the allometric equation was 40±12% greater than the value of direct measurements in the field. The uncertainty of the estimated below-ground biomass from the allometric equation was 4-15% of the ecosystem carbon stock, including trees and soil. Factors affecting the relationship between above and below-ground carbon in mangrove forests are latitude, tide, climatic characteristics, dominant species, and the number of total groups (Meng et al. 2021). Previous research also revealed that the ratio between both biomass is 3:1 (Kusmana et al. 2018), and the estimated carbon is 50%. Root biomass is lower than above-ground because roots are exposed to high salinity and groundwater. The comparison between both biomass in this research is almost the same as the value presented by Kusmana et al. (2018). According to Meng et al. (2021), the above and below-ground carbon ratio is influenced by stand structural characteristics comprising diameter breast height, average tree height, and tree density, as well as geomorphic settings.

Soil carbon

The results showed a soil carbon stock of 671.87 Mg ha^{-1} or 94% of the total number; this value is higher than the global soil carbon stock, according to Alongi (2020), which is 565.4 Mg ha^{-1}, and in the Persian Gulf, namely 612.6 Mg ha^{-1} (Mahmoudi et al. 2022). Mahmoudi et al. (2022) also examined sediment carbon stocks in two other mangrove forests in the northern Persian Gulf, which showed higher yields than this research, at 867.4 Mg ha^{-1} and 728.4 Mg ha^{-1}, respectively. However, the value in this research is still within the range of soil carbon in Sri Lanka, according to Cooray et al. (2021), which is 643.6-1253.6 Mg ha^{-1}. Furthermore, Cooray et al. (2021) explained that soil carbon stocks are substantially higher in places where vegetation biomass and stand density are high. Soil comprises 83-90% of the total mangrove carbon stock at all sites and has a high potential for release into the atmosphere as carbon dioxide when this habitat is disturbed. The percentage of soil carbon stock in this research at 94% was higher than the results obtained by Pratiwi and Haryono (2020) in Bogowonto Lagoon, Kulonprogo District (Indonesia), which had 516.56 Mg ha^{-1}. Meanwhile, the landward value in the Bogowonto Lagoon was 607.41 Mg ha^{-1} which strengthens the statement of Donato et al. (2012) that soil carbon stock increases slightly with increasing distance from the sea for marine mangroves due to rising soil depth.

This research's soil carbon stock value is lower than in Indonesia, which is 774.7 Mg ha^{-1} (Alongi et al. 2016); several factors influence the difference. According to Ouyang and Lee (2020), sediment carbon stocks in mangroves vary by geography, climate, and environmental factors. In addition, there are also significant differences in sediment carbon stocks between mangroves under different categories of salinity, forest condition, and mangrove type. Carnell et al. (2022) stated that mangrove age has a significant effect, with older mangrove stands aged 17 and 35 years having a total carbon stock and soil absorption rate twice as younger ones aged 13 years. Based on the results, the soil carbon stock in conservation and rehabilitation mangroves did not differ significantly, namely 682.45 Mg ha^{-1} and 671.25 Mg ha^{-1}, respectively, although the value in conservation mangroves was higher than in rehabilitation. That follows the results of Tinh et al. (2020) in Vietnam, which showed no significant difference between soil carbon stocks in rehabilitated mangrove forests of older-aged (20-25) years and intact or natural. Sasmito et al. (2020) also stated that mangroves allowed to regenerate for more than 25 years achieved the same level of biomass carbon as undisturbed forests. The average age of mangroves in this research in the four types of ecosystems is 16.5 years, with conservation, silvofishery, pond, and rehabilitation in order from oldest. The soil carbon stock result, starting from the largest, is conservation, rehabilitation, silvofishery, and pond. Although the pond has the lowest average soil carbon stock (664 Mg ha^{-1}), the pond in Muarareja Village has the highest value, namely 711.16 Mg ha^{-1}, which is close to the value in KEE Mojo (706.14 Mg ha^{-1}), which proves its important role, not only in conservation areas. These results strengthen the research conducted by Mutiatari et al. (2018) in Trimulyo (Semarang City) that there was no significant difference between soil carbon stock in vegetation and non-vegetation mangrove land uses (fish ponds and mudflats). It showed that the water column on the coast has great potential as a carbon store.

Total carbon stock

The results showed a total carbon stock of 713.13 Mg ha^{-1} with details for each location as shown in Table 4; this value is lower than the global average (Kauffman et al. 2020 and Alongi 2020). According to Kauffman et al. (2020), based on research conducted globally in 190 locations on five continents, the average ecosystem carbon stock is 856 ± 32 Mg ha^{-1}. Meanwhile, Alongi (2020) stated that the average global mangrove carbon stock based on an investigation performed in 52 countries is 738.9 Mg ha^{-1}. Despite significant data limitations, the role of mangrove ecosystems in mitigating climate change is small on a global scale but more significant in tropical coastal seas and effective at national and regional scales, specifically in areas with high rates of deforestation and degradation (Alongi 2020).

Table 3. Comparison of carbon stock with other research (Mg ha^{-1})

Location	AGC	BGC	SC	TECS	Reference
Bregasmalang, Central Java (Indonesia)	30.27	10.99	671.87	713.13	Present Research
West-Central Africa	112	-	688	799	Kauffman and Bhomia (2017)
Batticaloa Lagoon (Sri Lanka)	131.6	26.96	347.83	506.4	Perera and Amarasinghe (2018)
Sulaman Lake Forest Reserve (Malaysia)	67.3	22.44	351.98	441.72	Suhaili et al. (2020)
Malwathu Oya (Sri Lanka)	162.17	29.27	345.54	536.95	Perera and Amarasinghe (2021)
Asalouyeh, North Persian Gulf (Iran)	AGC+BGC=34.92		867.4	902.32	Mahmoudi et al. (2022)
Ruposhi Mangrove Plantation (Bangladesh)	37.3	11.8	-	-	Ahmed et al. (2022)
Zamboanga del Sur (Philippines)	89.18	-	274.8	-	Mariano et al. (2022)

Note: AGC: Aboveground carbon; BGC: Belowground carbon; SC: Soil carbon; TECS: Total Ecosystem Carbon Stock

The carbon stocks obtained in this research are also lower than those in West-Central Africa and Gabon, but higher than the results from Sri Lanka and Amazon. Kauffman and Bhomia (2017) explained that the average total ecosystem carbon stock in West-Central Africa is 799 Mg ha^{-1}. Meanwhile, Trettin et al. (2021) added that the ecosystem carbon density in Pongara National Park (Gabon) ranges from 644 ± 89.5 Mg ha^{-1} to 943 ± 90.9 Mg ha^{-1} with an average of 739 Mg ha^{-1}. Perera and Amarasinghe (2018), which conducted research in Batticaloa Lagoon (Sri Lanka), provided information on the total carbon stock reaching 506.4 ± 36.04 Mg ha^{-1}. Perera and Amarasinghe (2021) also investigated the mangrove estuary of Malwathu Oya, Sri Lanka, with a value of 536.95 ± 29.02 Mg ha^{-1}. The average carbon stock in the Amazon mangrove forest is 511 Mg ha$^{-1,}$ with the highest being 746 Mg ha^{-1} (Kauffman et al. 2018).

At the regional level in Southeast Asia, the values obtained in this research are higher than those of Rozainah et al. (2018) in Peninsular Malaysia. The carbon stock value in Johor Park was 427.88 Mg ha^{-1} or 89% of the soil carbon percentage, while in Delta Kelantan, it was 512.51 Mg ha^{-1} or 80%. These results are similar to those of Suhaili et al. (2020) in Sulaman Lake Forest Reserve, Sabah, Malaysia. This location was reportedly dominated by *Rhizophora* species with a carbon stock of 441.72 Mg ha^{-1}, while the highest stock was found in soil with 80%. According to Alongi et al. (2016), the median value of mangrove carbon storage in Indonesia is 950.5 Mg ha^{-1}.

Furthermore, Kauffman et al. (2017), based on research conducted in five countries, namely Dominican Republic, Costa Rica, Honduras, Mexico, and Indonesia, in intact mangrove forests as well as those converted to ponds and agricultural land, the average ecosystem carbon stock reached 858 Mg ha^{-1}. Soil carbon accounts for the largest proportion of 89%, with the highest value of 1564 Mg ha^{-1} in Indonesia; this value is higher than the average soil carbon stock obtained from this research.

The total carbon stock in this research is lower than the results obtained in West Papua and the average carbon for marine mangroves. Sasmito et al. (2020), in a research conducted in West Papua, Indonesia, showed that undisturbed mangrove has ecosystem carbon stocks of 1087 ± 584 Mg ha^{-1}, with large variations driven by hydrogeomorphic settings. The research location was dominated by *Rhizophora apiculata*, while in Bregasmalang, it was dominated by *R. mucronata*. Moreover, Donato et al. (2012) explained that the average carbon for marine mangroves is 990 ± 96 Mg ha^{-1}, with the average above-ground value reaching 159 Mg ha^{-1}. The research location in Bregasmalang follows the type of marine mangroves. Differences in measurements of potential biomass, carbon stock, and carbon dioxide sequestration between regions around the world can be due to different environmental factors such as temperature, rainfall, tidal inundation, river flow, cycles, nutrient availability, salinity, and even morphological characteristics e.g., the size that affects the productivity and respiration rate of mangrove ecosystems (Alongi 2012).

In addition, Kauffman and Bhomia (2017) attributed this difference to environmental variability. According to Swangjang and Panishkan (2021), mangrove structure, land use, and soil properties are basic factors that affect carbon stocks. Species distribution also plays an important role in carbon stocks in mangrove ecosystems.

The total carbon stock in mangrove forests with conservation status reached 763.75 Mg ha^{-1}, in rehabilitated mangroves 719.25 Mg ha^{-1}, silvofishery 680.71 Mg ha^{-1}, and ponds 688.81 Mg ha^{-1} with details per carbon pool as shown in Figure 2. The results obtained in the pond ecosystem were higher than Arifanti et al. (2019) in Delta Mahakam, Indonesia, which stated that the average ecosystem carbon stock in shrimp ponds was 499 ± 56 Mg ha^{-1}. However, the value was lower than that of relatively intact mangroves in the Mahakam Delta with 1023 ± 87 Mg ha^{-1}.

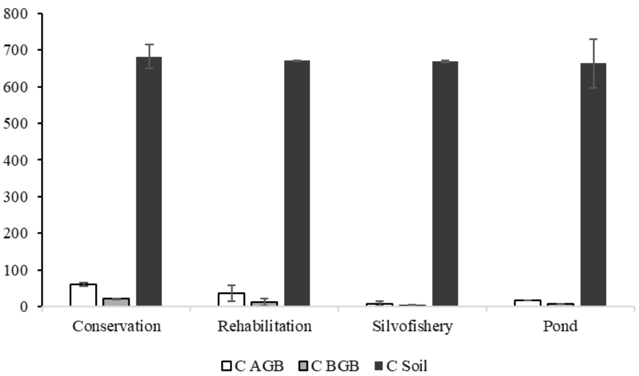

Figure 2. Carbon stock at four mangrove ecosystems in Bregasmalang (Mg ha^{-1})

Table 4. Carbon stocks (mean ± SE) (Mg ha^{-1}) according to mangrove ecosystems in the research site

Research site	AGC	BGC	SC	TECS	CO_2 Equivalent
Conservation					
KEE Mojo Transect 1	63.73 ± 27.23	21.85 ± 7.73	706.14 ± 61.84	791.71 ± 40.14	2905.58
KEE Mojo Transect 2	56.88 ± 5.67	20.14 ± 2.89	658.76 ± 27.33	735.78 ± 28.56	2700.32
Rehabilitation					
Mojo	50.76 ± 19.87	19.19 ± 7.46	670.43 ± 132.29	740.38 ± 155.53	2717.21
Kaliwlingi	20.42 ± 5.81	5.64 ± 1.16	672.07 ± 75.36	698.12 ± 77.8	2562.1
Silvofishery					
Pesantren	11.73 ± 10.11	4.53 ± 3.77	667.86 ± 47.21	684.12 ± 40.66	2510.71
Grinting	4.01 ± 2.28	1.56 ± 0.89	671.73 ± 84.76	677.3 ± 87.12	2485.68
Pond					
Muarareja	16.82 ± 11.08	7.21 ± 4.44	711.16 ± 156.51	735.19 ± 154.64	2698.14
Dampyak	17.81 ± 15.1	7.77 ± 5.85	616.85 ± 132.15	642.43 ± 148.76	2357.72

According to Hanggara et al. (2021), which conducted research in North Sumatra, Indonesia, above-ground carbon stocks in mangrove rehabilitation and conservation were 79.4 Mg ha^{-1} and 92.26 Mg ha^{-1}, respectively, and these values are higher than those obtained in this research. The above-ground carbon stock values in the rehabilitation and conservation mangroves were 35.59 Mg ha^{-1} and 60.31 Mg ha^{-1}, respectively. In silvofishery ponds, the results of this research are lower than those of Harefa et al. (2022) in Deli Serdang District, North Sumatra, which reached 14.53 Mg ha^{-1} and 13.6 Mg ha^{-1}, respectively. Based on the results, the silvofishery above-ground carbon stock was 7.87 Mg ha^{-1}, while the below-ground was 3.04 Mg ha^{-1}. In conclusion, the total carbon stock reached 713.13 Mg ha^{-1}, with the above and below-ground values being 30.27 Mg ha^{-1} and 10.99 Mg ha^{-1}, while the soil carbon was 671.87 Mg ha^{-1}. Soil carbon contributes the largest stock at 94%, followed by above-ground at 4% and below-ground carbon at 2%. Meanwhile, the total carbon stock in conservation mangrove forests was 763.75 Mg ha^{-1}, rehabilitation 719.25 Mg ha^{-1}, silvofishery 680.71 Mg ha^{-1}, and ponds 688.81 Mg ha^{-1}.

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REFERENCES

Adame MF, Cherian S, Reef R, Stewart-Koster B. 2017. Mangrove root biomass and the uncertainty of below-ground carbon estimations. For Ecol Manag 403: 52-60. DOI: 10.1016/j.foreco.2017.08.016.

Ahmed S, Kamruzzaman M, Rahman MS, Sakib N, Azad MS, Dey T. 2022. Stand structure and carbon storage of a young mangrove plantation forest in coastal area of Bangladesh: the promise of a natural solution. Nat-Based Solutions 2, 100025. DOI: 10.1016/j.nbsj.2022.100025.

Alongi DM. 2012. Carbon sequestration in mangrove forests. Carbon Manag 3: 313-322. DOI: 10.4155/cmt.12.20.

Alongi DM. 2020. Global significance of mangrove blue carbon in climate change mitigation. Sci 2 (3): 67. DOI: 10.3390/sci2030067.

Alongi DM, Murdiyarso D, Fourqurean JW, Kauffman JB, Hutahaean A, Crooks S, Lovelock CE, Howard J, Herr D, Fortes M, Pidgeon E, Wagey T. 2016. Indonesia's blue carbon: a globally significant and vulnerable sink for seagrass and mangrove carbon. Wetl Ecol Manag 24: 3-13. DOI: 10.1007/s11273-015-9446-y.

Andreas H., Abidin HZ, Sarsito DA, Pradipta D. 2018. Adaptation of 'early climate change disaster' to the Northern Coast of Java Island Indonesia. Eng J 22 (3): 207-219. DOI: 10.4186/ej.2018.22.3.207.

Arifanti VB, Kauffman JB, Hadriyanto D, Murdiyarso D, Diana R. 2019. Carbon dynamics and land use carbon footprints in mangrove-converted aquaculture: the case of the Mahakam Delta, Indonesia. For Ecol Manag 432: 17-29. DOI: 10.1016/j.foreco.2018.08.047.

Asner GP, Brodrick PG, Philipson C, Vaughn NR, Martin RE, Knapp DE, Heckler J, Evans LJ, Jucker T, Goossens B, Stark DJ, Reynolds G, Ong R, Renneboog N, Kugan F, Coomes DA. 2018. Mapped above-ground carbon stocks to advance forest conservation and recovery in Malaysian Borneo. Biol Conserv 217: 289-310. DOI: 10.1016/j.biocon.2017.10.020.

Aye WN, Tong X, Tun AW. 2022. Species diversity, biomass and carbon stock assessment of Kanhlyashay Natural Mangrove Forest. Forests 13: 1-16. DOI: 10.3390/f13071013.

Basyuni M, Simanjutak EO. 2021. Species composition and carbon stock estimation in Pulau Sembilan secondary mangrove forests, North Sumatra, Indonesia. IOP Conf Ser: Earth Environ Sci 713, 012014. DOI: 10.1088/1755-1315/713/1/012014.

Basyuni M, Yani P, Hartini KS. 2018. Evaluation of mangrove management through community-based silvofishery in North Sumatra, Indonesia. IOP Conf Ser: Earth Environ Sci 122, 012109. DOI: 10.1088/1755-1315/122/1/012109.

Cameron C, Hutley LB, Friess DA, Brown B. 2019. High greenhouse gas emissions mitigation benefits from mangrove rehabilitation in Sulawesi, Indonesia. Ecosyst Serv 40, 101035. DOI: 10.1016/j.ecoser.2019.101035.

Carnell PE, Palacios MM, Waryszak P, Trevathan-Tackett SM, Masqué P, Macreadie PI. 2022. Blue carbon drawdown by restored mangrove forests improves with age. J Environ Manag 306, 114301. DOI: 10.1016/j.jenvman.2021.114301.

Castillo JAA, Apan AA, Maraseni TN, Salmo SG. 2018. Tree biomass quantity, carbon stock and canopy correlates in mangrove forest and land uses that replaced mangroves in Honda Bay, Philippines. Reg Stud Mar Sci 24: 174-183. DOI: 10.1016/j.rsma.2018.08.006.

Cerlyawati H, Anggoro S, Zainuri M. 2017. Mangrove rehabilitation program in North Coast, Central Java-Indonesia (case study in Regency of Brebes, Pemalang and Demak). J Appl Environ Biol Sci 7 (5): 131-139.

Cooray PLIGM, Kodikara KAS, Kumara MP, Jayasinghe UI, Madarasinghe SK, Dahdouh-Guebas F, Gorman D, Huxham M, Jayatissa LP. 2021. Climate and intertidal zonation drive variability in the carbon stocks of Sri Lankan mangrove forests. Geoderma 389, 114929. DOI: 10.1016/j.geoderma.2021.114929.

Dharmawan IWS, Siregar CA. 2008. Soil carbon and carbon estimation of *Avicennia marina* (Forsk.) Vierh. stand at Ciasem, Purwakarta. Jurnal Penelitian Hutan dan Konservasi Alam 5 (4): 317-328. DOI: 10.20886/jphka.2008.5.4.317-328. [Indonesian]

Diana R, Matius P, Syahrinudin, Karyati, Hendra M, Melsitiara R. 2021. Species diversity and estimation of carbon stock in abandoned shrimp pond of mangrove ecosystem in East Kalimantan. IOP Conf Ser: Earth Enviro Sci 800, 012042. DOI: 10.1088/1755-1315/800/1/012042.

Donato DC, Kauffman JB, Murdiyarso D, Kurnianto S, Stidham M, Kanninen M. 2012. Mangroves are one of the most carbon-rich forests in the tropics. CIFOR Brief. DOI: 10.1038/ngeo1123. [Indonesian]

Elwin A, Bukoski JJ, Jintana V, Robinson EJZ, Clark JM. 2019. Preservation and recovery of mangrove ecosystem carbon stocks in abandoned shrimp ponds. Sci Rep 9 (1): 18275. DOI: 10.1038/s41598-019-54893-6.

Environment and Forestry Agency of Central Java. 2017. Preparation of Standard for Mangrove Damage in Central Java in 2017. Environment and Forestry Agency of Central Java, Semarang. [Indonesian].

Febriana I. 2019. Coastline Changes and Its Impact on Mangrove Succession and Vulnerability in the Mangrove Essential Ecosystem Area, Mojo Village, Ulujami District, Pemalang District. [Thesis]. Diponegoro University, Semarang. [Indonesian]

Government of Central Java Province. 2014. Academic Paper on the Draft Regional Regulation of Central Java Province Concerning the Spatial Plan for the Bregasmalang Region of Central Java Province 2014-2033. Government of Central Java Province, Semarang. [Indonesian]

Hanggara BB, Murdiyarso D, Ginting YR, Widha YL, Panjaitan GY, Lubis AA. 2021. Effects of diverse mangrove management practices on forest structure, carbon dynamics and sedimentation in North Sumatra, Indonesia. Estuar Coast Shelf Sci 259, 107467. DOI: 10.1016/j.ecss.2021.107467.

Harefa MS, Nasution Z, Mulya MB, Maksum A. 2022. Mangrove species diversity and carbon stock in silvofishery ponds in Deli Serdang District, North Sumatra, Indonesia. Biodiversitas 23 (2) 655-662. DOI: 10.13057/biodiv/d230206.

Harishma KM, Sandeep S, Sreekumar VB. 2020. Biomass and carbon stocks in mangrove ecosystems of Kerala, southwest coast of India. Ecol Proc 9 (1): 1-9. DOI: 10.1186/s13717-020-00227-8.

Hidayah Z, Andriyani L. 2019. Carbon stock analysis of mangrove ecosystems in Paliat Island Sumenep East Java. IOP Conf Ser: Earth Environ Sci 276, 012034. DOI: 10.1088/1755-1315/276/1/012034.
Indrayani E, Kalor JD, Warpur M, Hamuna B. 2021. Using allometric equations to estimate mangrove biomass and carbon stock in Demta Bay, Papua Province, Indonesia. J Ecol Eng 22 (5): 263-271. DOI: 10.12911/22998993/135945.
Irwanto, Paembonan SA, Ngakan PO, Maulany RI. 2021. Estimated carbon stock of various mangrove zonation in Marsegu Island, West Seram, Maluku. IOP Conf Ser: Earth Environ Sci 807, 022044. DOI: 10.1088/1755-1315/807/2/022044.
Isworo S, Oetari PS. 2020. Mangrove vegetation and bird communities around Tegal Port, Central Java, Indonesia. Biodiversitas 21 (4): 1551-1560. DOI: 10.13057/biodiv/d210436.
Kauffman JB, Adame MF, Arifanti VB, Schile-Beers LM, Bernardino AF, Bhomia RK, Donato DC, Feller IC, Ferreira TO, Garcia MdCJ, MacKenzie RA, Megonigal JP, Murdiyarso D, Simpson L, Trejo HH. 2020. Total ecosystem carbon stocks of mangroves across broad global environmental and physical gradients. Ecol Monogr 90 (2). DOI: 10.1002/ecm.1405.
Kauffman JB, Arifanti VB, Trejo HH, García MdCJ, Norfolk J, Cifuentes M, Hadriyanto D, Murdiyarso D. 2017. The jumbo carbon footprint of a shrimp: carbon losses from mangrove deforestation. Front Ecol Environ 15 (4): 183-188. DOI: 10.1002/fee.1482.
Kauffman JB, Bernardino AF, Ferreira TO, Giovannoni LR, Gomes LEdO, Romero DJ, Jimenez LCZ, Ruiz F. 2018. Carbon stocks of mangroves and salt marshes of the Amazon region, Brazil. Biol Lett 14: 20180208. DOI: 10.1098/rsbl.2018.0208.
Kauffman JB, Bhomia RK. 2017. Ecosystem carbon stocks of mangroves across broad environmental gradients in West-Central Africa: global and regional comparisons. PLoS ONE 12 (11): e0187749. DOI: 10.1371/journal.pone.0187749.
Kauffman JB, Donato DC. 2012. Protocols for the measurement, monitoring and reporting of structure, biomass and carbon stocks in mangrove forests. Working Paper 86. CIFOR, Bogor. [Indonesian]
Komiyama A, Poungparn S, Kato S. 2005. Common allometric equations for estimating the tree weight of mangroves. J Trop Ecol 21 (4): 471-477. DOI: 10.1017/S0266467405002476.
Komiyama A, Ong JE, Poungparn S. 2008. Allometry, biomass, and productivity of mangrove forests: a review. Aquat Bot 89: 128-137. DOI: 10.1016/j.aquabot.2007.12.006.
Krauss KW, Cormier N, Osland MJ, Kirwan ML, Stagg CL, Nestlerode JA, Russell MJ, From AS, Spivak AC, Dantin DD, Harvey JE, Almario AE. 2017. Created mangrove wetlands store below-ground carbon and surface elevation change enables them to adjust to sea-level rise. Sci Rep 7: 1030. DOI: 10.1038/s41598-017-01224-2.
Kusmana C, Hidayat T, Hikmah WF. 2019. Above-ground biomass and carbon stock of Ciletuh Mangrove Forest, West Java, Indonesia. IOP Conf Ser: Earth Environ Sci 394, 012005. DOI: 10.1088/1755-1315/394/1/012005.
Kusmana C, Hidayat T, Tiryana T, Rusdiana O, Istomo. 2018. Allometric models for above- and below-ground biomass of *Sonneratia* spp. Glo Ecol Conserv 15, e00417. DOI: 10.1016/j.gecco.2018.e00417.
Kusumaningtyas MA, Hutahaean AA, Fischer HW, Pérez-Mayo M, Ransby D, Jennerjahn TC. 2019. Variability in the organic carbon stocks, sources, and accumulation rates of Indonesian mangrove ecosystems. Estuar Coast Shelf Sci 218: 310-323. DOI: 10.1016/j.ecss.2018.12.007.
Lovelock CE, Reef R. 2020. Variable impacts of climate change on blue carbon. One Earth 3 (2): 195-211. DOI: 10.1016/j.oneear.2020.07.010.
Mahmoudi M, Pourebrahim S, Khorasani N, Danehkar A, Etemadi H, Ziyarati MT, Moeinaddini M. 2022. Carbon stock in three mangrove forests in north Persian Gulf. Environ Earth Sci 81 (1): 1-14. DOI: 10.1007/s12665-021-10132-8.
Malik A, Sideng U, Jaelani. 2022. Biomass carbon stock assessment of mangrove ecosystem in Pannikiang Island South Sulawesi Indonesia. Indones J Geograph 54 (1): 11-19. DOI: 10.22146/ijg.46989.
Mariano H, Aguilos M, Dagoc FL, Sumalinab B, Amparado R. 2022. Abandoned fishpond reversal to mangrove forest: will the carbon storage potential match the natural stand 30 years after reforestation?. Forests 13 (6): 847. DOI: 10.3390/f13060847.
Meng Y, Bai J, Gou R, Cui X, Feng J, Dai Z, Diao X, Zhu X, Lin G. 2021. Relationships between above- and below-ground carbon stocks in mangrove forests facilitate better estimation of total mangrove blue carbon. Carbon Balance Manag 16 (1): 1-14. DOI: 10.1186/s13021-021-00172-9.
Miteva DA, Murray BC, Pattanayak SK. 2015. Do protected areas reduce blue carbon emissions? a quasi-experimental evaluation of mangroves in Indonesia. Ecol Econ 119: 127-135. DOI: 10.1016/j.ecolecon.2015.08.005.
Monga E, Mangora MM, Trettin CC. 2022. Impact of mangrove planting on forest biomass carbon and other structural attributes in the Rufiji Delta, Tanzania. Global Ecol Conserv 35, e02100. DOI: 10.1016/j.gecco.2022.e02100.
Muktiali M, Setiadi R. 2022. Strategy to improve regional resilience against flood disasters in the North Coast of Central Java. IOP Conf Ser: Earth Environ Sci 1016, 012039. DOI: 10.1088/1755-1315/1016/1/012039.
Mutiatari DP, Pribadi R, Martuti NKT. 2018. C stock of top soil and it spatial distribution in mangrove community of Trimulyo, Semarang City. E3S Web Conf 73, 03006. DOI: 10.1051/e3sconf/20187303006.
Natarajan M, Ayyappan S, Vajiravelu M. 2022. Carbon stock assessment on natural mangrove species of *Avicennia marina* in Pichavaram mangrove forest Southeast Coast of India. Res Square 1-13. DOI: 10.21203/rs.3.rs-1274783/v1.
Nehren U, Wicaksono P. 2018. Mapping soil carbon stocks in an oceanic mangrove ecosystem in Karimunjawa Islands, Indonesia. Estuar Coast Shelf Sci 214: 185-193. DOI: 10.1016/j.ecss.2018.09.022.
Nugroho AD, Helmi M, Suprijanto J. 2020. Evaluation of emerge land for mangrove conservation program in Kaliwlingi, Brebes District, Brebes Regency. J Fish Sci Technol 16 (3): 192-198.
Nurfitriani S, Lili W, Hamdani H, Sahidin A. 2019. Density effect of mangrove vegetation on gastropods on Pandansari Mangrove Ecotourism Forest, Kaliwlingi Village, Brebes Central Java. World Sci News 133: 98-120.
Ouyang X, Lee SY. 2020. Improved estimates on global carbon stock and carbon pools in tidal wetlands. Nat Commun 11 (1): 1-7. DOI: 10.1038/s41467-019-14120-2.
Perera KARS, Amarasinghe MD. 2018. Ecosystem carbon stock of mangroves at the Batticaloa Lagoon, Sri Lanka. OUSL J 13 (2): 81-100. DOI: 10.4038/ouslj.v13i2.7441.
Perera KARS, Amarasinghe MD. 2021. Assessment of blue carbon stock of mangroves at Malwathu Oya estuary, Sri Lanka. OUSL J 16 (1): 75-90. DOI: 10.4038/ouslj.v16i1.7519.
Perwitasari WK, Muhammad F, Hidayat JW. 2020. Silvofishery as an alternative system of sustainable aquaculture in Mororejo Village, Kendal Regency. E3S Web Conf 202, 06043. DOI: 10.1051/e3sconf/202020206043.
Poedjirahajoe E, Marsono D, Wardhani FK. 2017. Usage of principal component analysis in the spatial distribution of mangrove vegetation in North Coast of Pemalang. Jurnal Ilmu Kehutanan 11: 29-42. DOI: 10.22146/jik.24885. [Indonesian]
Pratiwi HF, Haryono E. 2020. The potential contribution of the lagoon ecosystem as mangrove carbon sinks in Java. IOP Conf Ser: Earth Environ Sci 451, 012064. DOI: 10.1088/1755-1315/451/1/012064.
Purwanto RH, Mulyana B, Satria RA, Yasin EHE, Putra ISR, Putra AD. 2022. Spatial distribution of mangrove vegetation species, salinity, and mud thickness in mangrove forest in Pangarengan, Cirebon, Indonesia. Biodiversitas 23 (3): 1383-1391. DOI: 10.13057/biodiv/d230324.
Rahman B, Karmilah M, Kautsary J, Ridlo MA. 2021. The tidal flooding causes in the North Coast of Central Java: a systematic literature review. J Southwest Jiaotong Univ 56 (6): 184-194. DOI: 10.35741/issn.0258-2724.56.6.15.
Rahman MM, Khan MNI, Hoque AKF, Ahmed I. 2015. Carbon stock in the Sundarbans mangrove forest: spatial variations in vegetation types and salinity zones. Wetl Ecol Manag 23: 269-283. DOI: 10.1007/s11273-014-9379-x.
Rozainah MZ, Nazri MN, Sofawi AB, Hemati Z, Juliana WA. 2018. Estimation of carbon pool in soil, above and below ground vegetation at different types of mangrove forests in Peninsular Malaysia. Mar Pollut Bull 137: 237-245. DOI: 10.1016/j.marpolbul.2018.10.023.
Sanders CJ, Maher DT, Tait DR, Williams D, Holloway C, Sippo JZ, Santos IR. 2016. Are global mangrove carbon stocks driven by rainfall?. J Geophys Res: Biogeosci 121: 2600-2609. DOI: 10.1002/2016JG003510.
Sasmito SD, Sillanpää M, Hayes MA, Bachri S, Saragi-Sasmito MF, Sidik F, Hanggara BB, Mofu WY, Rumbiak VI, Hendri, Taberima S, Suhaemi, Nugroho JD, Pattiasina TF, Widagti N, Barakalla, Rahajoe JS, Hartantri H, Nikijuluw V, Jowey RN, Heatubun CD, zu

Ermgassen P, Worthington TA, Howard J, Lovelock CE, Friess DA, Hutley LB, Murdiyarso D. 2020. Mangrove blue carbon stocks and dynamics are controlled by hydrogeomorphic settings and land-use change. Global Change Biol 26: 3028-3039. DOI: 10.1111/gcb.15056.

Solihuddin T, Husrin S, Salim HL, Kepel TL, Mustikasari E, Heriati A, Ati RNA, Purbani D, Mbay LON, Indriasari VY, Berliana B. 2021. Coastal erosion on the North Coast of Java: adaptation strategies and coastal management. IOP Conf Ser: Earth Environ Sci 777, 012035. DOI: 10.1088/1755-1315/777/1/012035.

Sreelekshmi S, Harikrishnan M, Nandan SB, Kaimal VS, Hershey NR. 2022. Ecosystem carbon stock and stable isotopic signatures of soil organic carbon sources across the mangrove ecosystems of Kerala, Southern India. Wetlands 42 (4): 1-12. DOI: 10.1007/s13157-022-01540-y.

Suhaili NS, Fei JLJ, Sha'ari FW, Idris MI, Hatta SM, Kodoh J, Besar NA. 2020. Carbon stock estimation of mangrove forest in Sulaman Lake Forest Reserve, Sabah, Malaysia. Biodiversitas 21 (12): 5657-5664. DOI: 10.13057/biodiv/d211223.

Suroso DSA, Firman T. 2018. The role of spatial planning in reducing exposure towards impacts of global sea level rise case study: Northern Coast of Java, Indonesia. Ocean Coast Manag 153 (201): 84-97. DOI: 10.1016/j.ocecoaman.2017.12.007.

Susantoro TM, Wikantika K, Yayusman LF, Tan A, Ghozali MF. 2020. Monitoring of mangrove growth and coastal changes on the North Coast of Brebes, Central Java, using landsat data. Intl J Remote Sens Earth Sci 16 (2) 197-214. DOI: 10.30536/j.ijreses.2019.v16.a3221.

Suyono, Supriharyono, Hendrarto B, Radjasa OK. 2015. Mapping of mangrove ecosystem degradation and coastal abrasion based on geographic information system in Brebes District-Central Java. Oceatek 9 (01): 90-102. [Indonesian]

Swangjang K, Panishkan K. 2021. Assessment of factors that influence carbon storage: an important ecosystem service provided by mangrove forests. Heliyon 7, e08620. DOI: 10.1016/j.heliyon.2021.e08620.

Tinh PH, Hanh NTH, Thanh VV, Tuan MS, Quang PV, Sharma S, MacKenzie RA. 2020. A comparison of soil carbon stocks of intact and restored mangrove forests in Northern Vietnam. Forests 11 (6): 660. DOI: 10.3390/f11060660.

Trettin CC, Dai Z, Tang W, Lagomasino D, Thomas N, Lee SK, Simard M, Ebanega MO, Stoval A, Fatoyinbo TE. 2021. Mangrove carbon stocks in Pongara National Park, Gabon. Estuar Coast Shelf Sci 259, 107432. DOI: 10.1016/j.ecss.2021.107432.

van Oudenhoven APE, Siahainenia AJ, Sualia I, Tonneijck FH, van der Ploeg S, de Groot RS, Alkemade R, Leemans R. 2015. Effects of different management regimes on mangrove ecosystem services in Java, Indonesia. Ocean Coast Manag 116: 353-367. DOI: 10.1016/j.ocecoaman.2015.08.003.

Wilson R. 2017. Impacts of climate change on mangrove ecosystems in the coastal and marine environments of Caribbean Small Island Developing States (SIDS). Caribb Clim Change Rep Card: Sci Rev 61-82.

Yulianto B, Prayogi, Harnadi L, Sunaryo, Santosa A, Nuraini RAT, Radjasa OK, Soegianto A. 2020. Increase in mangrove area on the North Coast of Central Java analyzed using geospatial based approach. Ann Biol 36 (2): 317-323.

Yusuf. 2016. Comparative Analysis of Carbon Stock in Natural Mangrove Areas and Rehabilitation in Tiwoho Village, Wori District, North Minahasa District, North Sulawesi Province. [Thesis]. Hasanuddin University, Makassar. [Indonesian]