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Mapping of mangrove forest and carbon stock estimation of east coast Surabaya, Indonesia

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Abstract. *Hidayah Z, Rachman HA, As-Syakur AR. 2022. Mapping of mangrove forest and carbon stock estimation of east coast Surabaya, Indonesia. Biodiversitas 23: 4826-4837.* The mangrove forests on Surabaya's east coast are an important protected area, providing habitat for a variety of marine organisms and water birds. This area is also vital for carbon storage and sequestration. The purpose of this research is to determine the changes in mangrove areas over the last 20 years and to calculate the amount of carbon stored in these mangrove forests. Changes in the area of mangrove forests and Normalized Difference Vegetation Indices (NDVI) were determined using Landsat-7 in 2000 and Landsat-8 in 2020. The vegetative carbon stock of mangrove stands was calculated using allometric measurements. The study results reveal that the mangrove forest area has increased significantly from 257.13 ha in 2000 to 753.48 ha in 2020. The results of regression models also show that NDVI has a significant influence on aboveground biomass (AGB), as indicated by the coefficient of determination (R^2) = 0.7 (F test, df = 28, p-value < 0.05). The estimated aboveground and belowground carbon stock is 46.35 ± 13.65 ton C ha^{-1} and 13.65 ± 6.74 ton C ha^{-1} respectively. Accordingly, it is observed that the mangrove forest of East Coast Surabaya can sequester at least a total of 192.72 tons CO_2 ha^{-1} in above and belowground biomass.

Keywords: Biomass, carbon stock, east coast Surabaya, Landsat, mangrove

INTRODUCTION

Mangrove forest is tropical coastal communities dominated by species of distinctive trees or shrubs that can grow in saline waters. Mangroves consist of 12 genera of flowering plants, including *Avicennia, Sonneratia, Rhizophora, Bruguiera, Ceriops, Xylocarpus, Lumnitzera, Laguncularia, Aegiceras, Aegialitis* and *Conocarpus*. Mangroves are mostly grown on muddy beaches located at river estuary, delta plain or frequently tidal inundated coastlines that provide a suitable microclimatic condition for mangroves to thrive (Giri et al. 2011; Warui et al. 2020; Long et al. 2021). Mangroves act as a filtering system that intercepts pollutants, sediments and excessive nutrients carried by river flow and prevent them from entering the sea (Rizal and Anna 2020; Samsudin et al. 2019). Mangroves produce organic matter, which is essential to support the nearshore food web (Marley et al. 2019). The existence of mangroves makes the aquatic environment relatively undisturbed by strong waves or currents and safeguard the coastal community from catastrophic events like cyclones and tsunami (Woodroffe et al. 2016). Mangrove forests are a habitat for the early development of several fish species, which in one phase of their lives migrate from the estuary to the open sea (Hutchison et al. 2014). The extensive root systems of mangroves provide stability to the substrate and protect the beach from abrasion and saltwater intrusion (Phan et al. 2015; Srikanth et al. 2016).

The most diverse and abundant mangrove forests can be found in tropical and wet climate zones (Saenger et al. 2019). Cold temperatures can cause the loss of aboveground biomass, interrupt the mangrove reproduction process and will eventually cause mangrove mortality (Lovelock et al. 2015; Osland et al. 2018). As per a recent estimate, the total area of mangrove forests across the globe in 2014 was 13.19 million ha (Hamilton and Casey 2016). Mangrove forests in Indonesia are one of the largest in the world, covering almost 26.44% of the total mangrove forest area or about 3.48 million ha in 2015 (Bunting et al. 2022).

Mangrove forests have an important role in sequestering and storing carbon. Through the sequestration process, CO_2 from the atmosphere is absorbed by trees and plants during photosynthesis. Some carbon is lost back to the atmosphere through respiration, while the rest is stored in the leaves, branches and roots of the plant. In addition, dead plant materials containing carbon are buried in the soil, which is frequently flooded by tidal waters. This oxygen-poor environment causes a very slow breakdown of the plant materials, resulting in significant carbon storage (Analuddin et al. 2020; Pricillia et al. 2021). Despite representing only about 0.7 percent of the world's forest area (Donato et al. 2011), mangrove forests could store approximately 20 billion tons of carbon, comprising nearly 10% of total forest carbon (Jones et al. 2014).

The dynamics of land use and land cover changes in coastal areas threaten the sustainability of mangrove forests. Population growth, illegal logging and land use change for aquaculture are the primary drivers of mangrove damage (Malik et al. 2017; Rudianto et al. 2020). In recent years there has been growing recognition of the vital functions of remote sensing and GIS-based analysis using multi-temporal data to monitor mangrove forests over a vast area. The use of multi-temporal satellite data allows for the detection of changes in mangrove cover (Giri 2016; Hidayah et al. 2015; Kanniah et al. 2015; Long et al. 2021). East Java Province has the largest existing mangrove area on Java Island, covering 2722 ha or roughly 48% of the total existing mangrove area on Java Island, with a potential area of mangrove habitat covering 5157 ha (Ministry of Environment and Forestry, 2021). Among the existing area, the mangrove forest in Surabaya has a particular characteristic which is located adjacent to a big city, therefore vulnerable to anthropogenic factors. Information on spatial distribution and community structures is critical for developing site-specific conservation and management strategies (George et al. 2019).

Despite the fact that the East Java Provincial Government has designated the mangrove forest on the east coast of Surabaya as a conservation area, relatively few studies have been carried out to assess the dynamic of mangrove cover of the area and are not even available on carbon stock data. For instance, Syamsu et al. (2018) conducted a recent study which compares satellite imagery to detect land cover changes on Surabaya's east coast. In addition, Wijaya and Huda (2018) has documented the distribution of mangrove species in some part of Surabaya's east coast rehabilitated area. Meanwhile, other studies focus on economic valuation and community participation in the development of ecotourism in the area (Idajati et al. 2016; Kusumawardani 2019; Umam et al. 2015). Based on a review of previous research at this location, information on the dynamics of mangrove cover, biomass and carbon sequestration is currently not available. In fact, data on carbon sequestration is critical to achieving the Sustainable Development Goals (SDGs), particularly in preventing environmental damage and supporting climate change actions. Therefore, the objectives of this study are to determine changes in mangrove forest area over time as well as to estimate the amount of carbon stored by mangrove forests in Surabaya. The detection of mangrove area change and carbon stock estimation is important to provide a scientifically based evaluation to support blue carbon initiatives. The research findings can also be used to formulate regional management planning and coastal area conservation policies.

MATERIALS AND METHODS

Study area

This study was conducted from July to October 2021 in a mangrove forest on the east coast of Surabaya City, East Java Province, Indonesia located at 112°49'43"E and 07°15'40"S. The dominant land use/land cover of the area were a thick mangrove forest, aquaculture ponds and settlements (Figure 1). The east coast of Surabaya (Pamurbaya) is a fertile estuary area, because of the continuous supply of nutrients carried by the rivers. The Wonokromo River, the Wonorejo River, the Dadapan River, and the Keputih River all have an impact on it. Morphology of the coast is a flat beach with a slope of 0-3°, a tidal range of around 1.67 meters dominated by homogeneous soil conditions (sandy clay) with penetrable soil up to 90 cm depth. The weather in the study area was characterized by the daily temperature ranging from 31ºC-33ºC and humidity levels varying from 71.02%-75.09%.

The mangrove forest of Pamurbaya is a protected area that provides a habitat for a variety of aquatic organisms, primates, and bird species. The area has also been appointed as Important Bird Area (IBA) which is an essential area for waterbirds, specifically migratory birds. Pamurbaya is home to approximately 84 bird species, 12 of which are protected under IUCN (International Union for Conservation of Nature) and CITES (Convention on International Trade in Endangered Species).

Satellite image analysis

In order to measure the change in mangrove forest area, this study utilized two sets of medium-resolution satellite images, namely Landsat-7 ETM+ (2000) and Landsat-8 OLI (2020). Both satellite images have been corrected geometrically and radiometrically. To differentiate mangrove vegetation from other types of land cover, on-screen digitation for both images was rigorously performed. Combinations of natural and infrared color bands were used to further distinguish mangrove vegetation cover from other classes. The polygon area of the digitized mangrove cover for each year was then calculated and compared to determine the occurrence of area changes. Furthermore, Normalized Difference Vegetation Index (NDVI) was calculated to determine the density level of mangrove forest based on the pixel value. The index was used in further analysis to create a biomass map based on NDVI. The NDVI formula for Landsat satellite image is as follows:

$$NDVI = \frac{Near\ Infra\ Red\ Band - Red\ Band}{Near\ Infra\ Red\ Band + Red\ Band}$$

Field data collection

The standard procedure for mangrove assessment was adapted from English et al. (1994). A total of twenty 100-meter-long transect lines were established perpendicular to the shore through the mangrove forests (Figure 1). This study is limited to rapid diversity assessment and does not consider mangrove forest zonation patterns. Three 10 m × 10 m quadrats were placed out in 50 m intervals along each transect line, resulting in a total of 60 plots. Individual species names were noted and diameters at breast height (DBH) were measured. However, mangrove saplings and seedlings were not included in this rapid mangrove assessment.

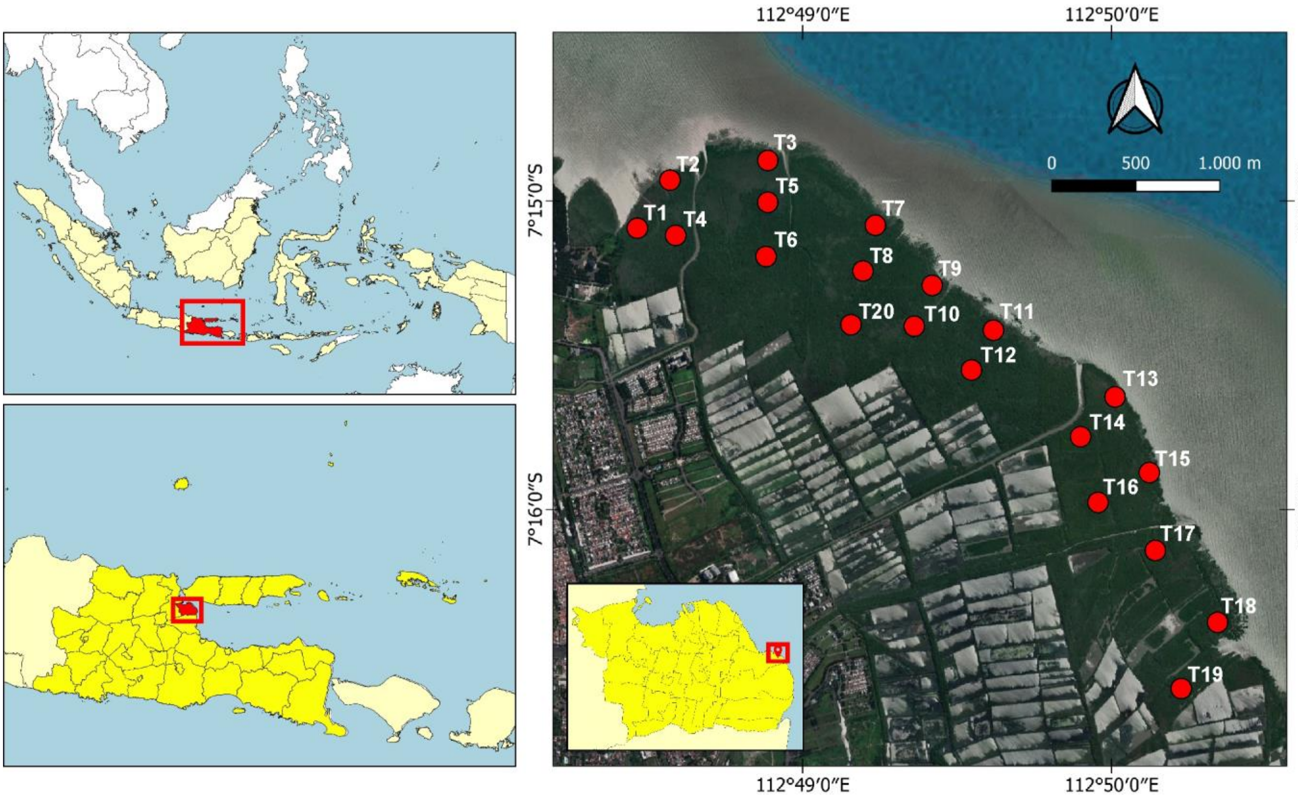

Figure 1. Study area the mangrove forest of east coast Surabaya City, East Java Province, Indonesia

Important Value Index (IVI)

The mangrove important value index (IVI) indicates the representativeness of certain mangrove species in the ecosystem and ranges between 0-300. The IVI for each species was calculated for each trasects using these formulas:

$$Di = \frac{ni}{A}; \quad RDi = \left[\frac{ni}{\sum n}\right] \times 100$$

Di: Species-i density
RDi: Relative density of species-i
ni: Total number of species-i
Σn: Total number of all species

A: Total sampling area ($300\ m^2$)

$$Fi = \frac{pi}{\sum F}; \quad RFi = \left[\frac{Fi}{\sum F}\right] \times 100$$

Fi: Species-i frequency
RFi: Relative frequency of species-i
pi: Number of plot where species-i found
∑F: Total number of plots in each transect (3)

$$Ci = \frac{\sum BA}{A}; \quad RCi = \left[\frac{Ci}{\sum C}\right] \times 100$$

Ci : Species-i coverage
RCi: Relative coverage of species-i
∑BA: πd^2/4 (π = 3,14: d= DBH)
∑C : Total coverage for all species
A : Total sampling area ($300\ m^2$)

$$IVI = RDi + RFi + RCi$$

Biomass and carbon stock estimation

The above and belowground biomass of each recorded species of mangrove was calculated using allometric methods with independent variables of DBH. Above Ground Biomass (AGB) is part of the living mangrove vegetation above the ground, namely stems, twigs and leaves, while Below Ground Biomass (BGB) is biomass from living roots. Table 1 shows the allometric models for estimating biomass for each species.

After calculating the mangrove biomass, then proceeded to estimate the amount of carbon content (Cn) and sequestration potential (Sn). The carbon stock measured in this study was only conducted on the mangrove vegetation and estimated according to the Indonesian National Standardization Agency (BSN) SNI 7724:2011.

Table 1. Allometric equations to calculate biomass (kg)

Mangrove species	AGB model	BGB model	References
Avicennia marina	$0.079211 \times D^{2.470895}$	$0.079211 \times D^{2.470895} \times 0.25$	(Sutaryo 2009)
Rhizophora mucronata	$0.43 \times D^{2.63}$	$0.196 \times \rho^{0.899} \times D^{2.22}$	(Komiyama et al. 2005; Putz and Chan 1986)
Sonneratia alba	$0.251 \times \rho \times D^{2.46}$	$0.3841 \times \rho \times D^{2.101} \times 0.25$	(Komiyama et al. 2005)
Sonneratia caseolaris	$0.1848 \times \rho \times D^{2.3524}$	$0.1848 \times \rho \times D^{2.3524} \times 0.25$	
Bruguiera gymnorhiza	$0.247 x \rho \times D^{2.505}$	$0.196 \times \rho^{0.899} \times D^{2.22}$	

Note: D=DBH (cm); ρ=specific wood density (gr/cm^2) *Avicennia marina* ρ=0.506, *Rhizophora mucronata* ρ=0.701; *Sonneratia alba* ρ=0.475, *Sonneratia caseolaris* ρ=0.340; *Bruguiera gymnorhiza* ρ=0.699

The equation is as follow:

$$C = B \times 0.47$$

$$C_n = \frac{C_x}{1000} \times \frac{10000}{L_{tr}}$$

$$SCO_2 = \frac{Mr\ CO_2}{Ar\ C} \times Cn$$

$$S_n = \frac{SCO_2}{1000} \times \frac{10000}{L_{tr}}$$

C: Carbon stock (kg)
C_x: Carbon amount for each transect (kg)
B: Biomass (kg)
L_{tr}: Transect total area (300 m^2)
C_n: Carbon per hektar (ton/ha)
Mr CO_2: relative molecule mass (44); Ar C: C atom mass (12)
S_n: Carbon sequestration (ton/ha)

RESULTS AND DISCUSSION

Mangrove area change

The results of analyzing Landsat satellite images from 2000 and 2020 showed that there had been a significant increase in mangrove forest cover on Surabaya's east coast over the last 20 years. In 2000, the mangrove area was approximately 257.13 ha, and by 2020, the area had nearly tripled to around 753.48 ha (Figure 2). This increase in mangrove forest area contrasts with the condition of mangroves in other major cities on Java Island, which continues to decline, for example, in Jakarta and Semarang (Aulia et al. 2015; Mulyaningsih et al. 2017). When many mangrove areas in major cities are threatened by land conversion, Surabaya's east coast mangrove forest is preserved and expanded. The high growth rate of mangroves on Surabaya's east coast can be explained by the rapid rate of sedimentation, high nutrient content in sediment, and suitable environmental parameters.

Furthermore, the east coast area of Surabaya is recognized as one of the city's green open spaces based on the 2009-2029 Surabaya City Spatial Plan. Formal regulations in Indonesia, namely the Law of the Republic of Indonesia No. 26 of 2007 on Spatial Planning require the proportion of urban green open space to be at least 30% and the proportion of public green open space in urban areas to be at least 20% of the total city area. The implementation of this policy has made the mangrove area on Surabaya's east coast less vulnerable to environmental degradation. Similar policies were also implemented in Perancak Bali's mangrove forest. Whereas, due in part to the local government's protection and rehabilitation efforts, the mangrove forest in the area has grown significantly between 2005 and 2015 (Suniada and Aden 2019).

Mangrove areas, particularly in major cities, are vulnerable to settlement expansion, the opening of industrial areas, and land clearing for fish ponds. The designation of Surabaya's east coast as a protected area directly prevents land conversion. This policy leaves the coastal area relatively undisturbed, allowing natural processes that support mangrove growth to continue in a secure environment. Furthermore, the implementation of the policy allows mangrove rehabilitation and planting programs to continue to receive funding from the government. The presence of protected areas, such as mangrove forests on Surabaya City's east coast, serves an important function not only for coastal protection, but also for maintaining ecological balance, which includes maintaining the hydrological cycle, improving air quality, and protecting various animal and plant species. The availability of nature conservation in urban areas can also improve the aesthetic quality of the urban landscape by serving as a location for recreation, experimentation, and environmental education.

Aboveground biomass and NDVI

Remote sensing technology has been widely used to collect data and estimate the condition of inland and coastal vegetation, such as density, canopy coverage and biomass (Situmorang et al. 2016; Pettorelli et al. 2005). Combination of band ratio and mathematical operations are applied to determine vegetation index. The satellite-derived NDVI, which is a normalized ratio of red and near-infrared (NIR) reflectance is considered the most functional vegetation index, particularly for mangroves. The NDVI is based on absorption in the red spectrum and very strong reflectance in the near-infrared spectrum. Plant productivity, photosynthetic activity, plant phenology, tropic interactions, biomass, and the global carbon cycle can be measured using the NDVI (Baniya et al. 2018). Figure 3 clearly depicts the expansion of mangrove forest area and density in the last 20 years based on NDVI. Non-vegetation objects are represented by negative NDVI values. Meanwhile, vegetation objects have values ranging from 0 to 1. The higher the NDVI value, the more dense the vegetation. Sedimentation in the northern and eastern parts of the study site causes an increase in land area. Over the years, the particular area has been overgrown by mangrove vegetation and is now transforming into a dense mangrove forest. In 2020, the majority of the mangrove forest areas on Surabaya's east coast had a high density, with NDVI ranges from 0.5 to 0.7.

In this study, further analysis was conducted to investigate the correlation between AGB estimation and NDVI derived from the 2020 Landsat-8 imagery data. Vegetation indices such as NDVI have the potential to identify plant characteristics and distribution features in particular canopy covers that are strongly related to biomass accumulation. Based on the coordinates, the estimated biomass from field data measurements was cross-referenced to NDVI in order to obtain a regression model. The model was then applied to create the NDVI-based AGB map. The results of regression models show that NDVI has a significant influence on AGB (Figure 4), as indicated by the coefficient of determination (R^2) = 0.7 (F test, df = 28, p-value < 0.05). The results also confirm previous studies' findings of a strong correlation between NDVI and AGB in mangrove vegetation (Balidoy et al. 2018; Muhd-Ekhzarizal et al. 2018). However, because NDVI is calculated solely based on canopy cover, other models have been developed using a combination of different indices (SAVI, EVI, GNDVI) to improve the accuracy of AGB estimation in mangroves (Bao et al. 2022; Muhsoni et al. 2018).

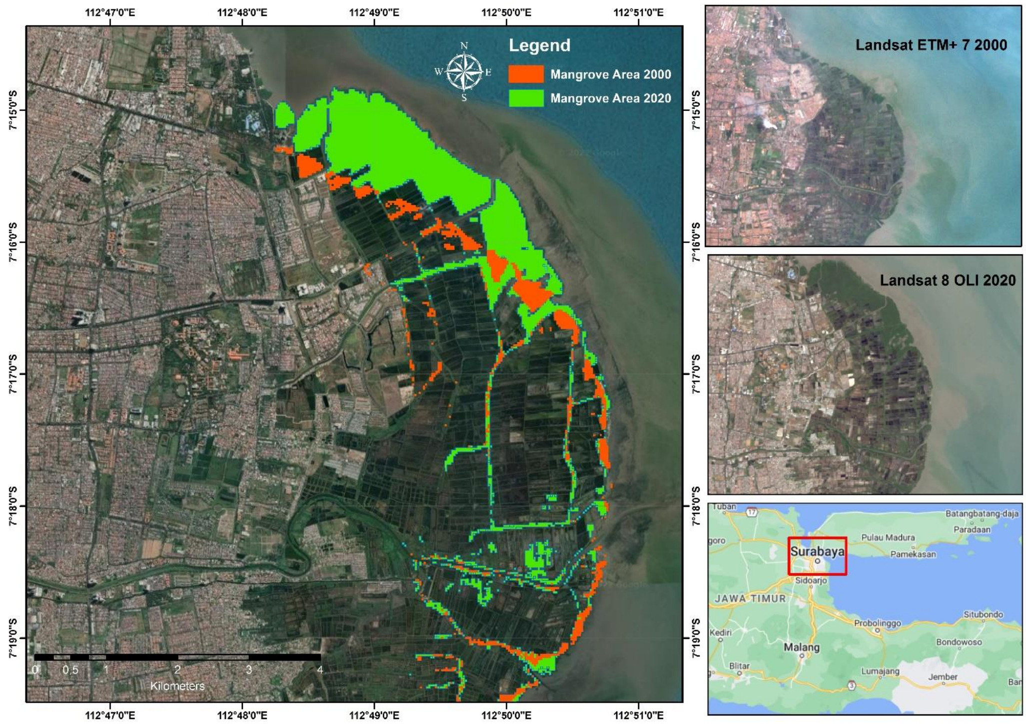

Figure 2. Mangrove area change of east coast Surabaya City, East Java Province, Indonesia

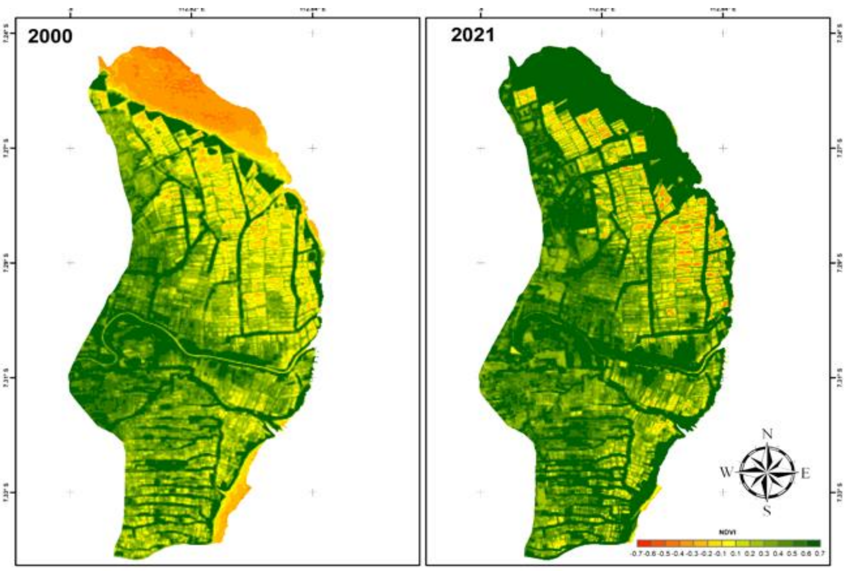

Figure 3. Temporal NDVI changes based on Landsat Images (2000 and 2020)

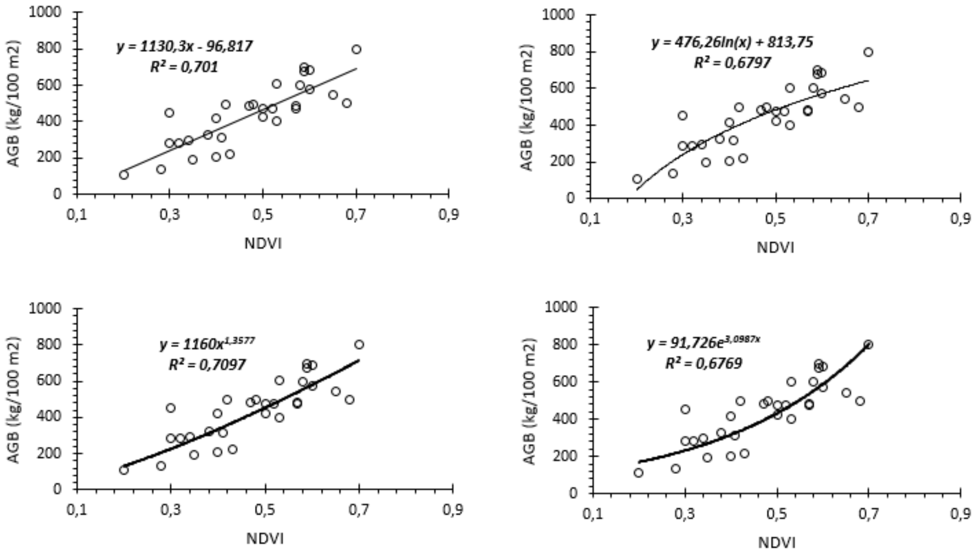

Figure 4. Regression model of AGB mangrove and NDVI

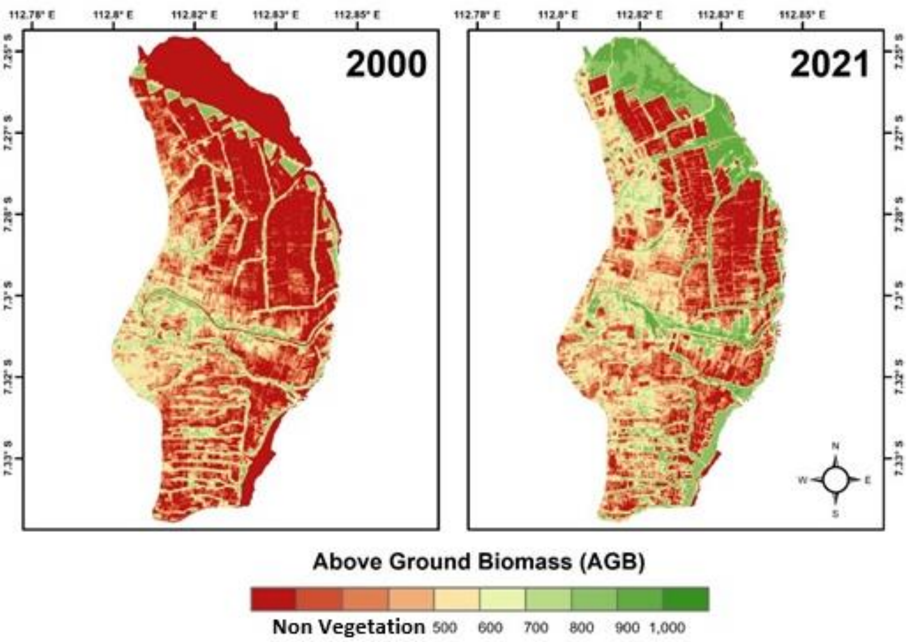

Figure 5. Spatial distribution of AGB (kg/100 m^2) based on the regression model with NDVI value from satellite imagery (2000 and 2021)

The map above (Figure 5) can be used to estimate the total amount of biomass and carbon stock derived from AGB on the east coast of Surabaya. In 2000, the average biomass for the area was approximately 725 ± 18 kg/100 m^2 (72.5 ± 1.8 ton ha^{-1}) . If the area of mangrove in 2000 was 257.13 ha, then the total amount of biomass at that time was 18641 ± 462 tons, therefore according to equation 5, the carbon content stored in AGB was estimated at around 8761.27 ± 217.14 tons. Meanwhile in 2021, the average biomass of the area was 945 ± 15 kg/100 m^2 (94.5 ± 1.5 ton ha^{-1}). Using the latest calculation of the mangrove area, which is 753.48 Ha, therefore the estimated amount of biomass was 71203 ± 1130 tons and carbon content stored in AGB was approximately 33465.81 ± 531.20 tons.

Mangrove community structure

In order to describe the condition of the mangrove ecosystem, analyzing the structure of the vegetation community using the calculation of the Important Value Index was performed. This index was determined based on the number of mangrove stands per species found in the area to obtain the level of species dominance in a coastal forest community. Field data collection from 20 transects with a total of 60 (10×10 m) plots was able to identify a total of 3741 individual mangrove stands from 5 species, namely *Avicennia marina, Bruguiera gymnorhiza, Rhizopora mucronata, Sonneratia alba* and *Sonneratia caseolaris.* Among those species, *A. marina* was considered the most dominant species, with IVI of 99.79.

In addition, *R. mucronata* was ranked second with IVI of 80.21 followed by *S. alba* and *S. caseolaris* with IVI of 45.89 and 37.48 respectively. *Bruguiera gymnorhiza* was counted as the least dominant species with IVI 36.66. The complete results of IVI calculation are shown in Table 2.

Mangrove species diversity is lower in forests located adjacent to urban areas or as a result of rehabilitation, such as Surabaya and Jakarta, than those in natural mangrove forests. This study in Surabaya has identified 5 species of mangroves, which is nearly identical to research in the nearest mangrove forest in Pasuruan (Isroni et al. 2019). Other studies on the coasts of major cities, namely Jakarta Bay and Muara Kapuk, have identified 5 to 9 mangrove species (Rumondang et al. 2021; Sari et al. 2019). The number of mangrove species found in remote areas with natural mangrove forests is considerably higher, as evidenced by studies in Mimika Papua (66 species), Segara Anakan Cilacap, Central Java (16 species) and Kutai National Park, East Kalimantan (17 species) (Poedjirahajoe et al. 2019; Setyadi et al. 2021; Widyastuti et al. 2018). Excellent water and sediment quality, low environmental pollution, and the absence of illegal logging are all factors that contribute to the optimal growth of mangrove forests in remote coastal areas.

The IVI results (Table 2) show that two mangrove species, *A. marina* and *R. mucronata* have the highest values when compared to other species found in the study area. Both of these species have been known to be capable of growing in the front zone of mangrove forests that are directly adjacent to the sea with a predominance of a muddy substrate. The association of *A. marina* and *R. mucronata* indicates that the site contains mud with a high concentration of organic matter. In addition, the extensive root structure of *R. mucronata* is very effective at preventing the entry of sediments and pollutants into the water. Moreover, according to recent studies, the roots of these species have sufficient ability to absorb heavy metals found in waters and sediments (Wilda et al. 2020).

Mangrove stand characteristics

Further analysis showed that there was a high variation in the characteristics of the mangrove stands for different species at the study location. The diameter of breast high (DBH) for all species ranged from 2.86 to 36.94 cm. *Avicennia marina* has the highest DBH mean with approximately 20.84 ± 6.21 cm followed by *S. alba* with DBH of 19.16 ± 9.46 cm, whereas *R. mucronata* has the lowest mean DBH of around 5.12 ± 2.64 cm (Figure 7). The data range of DBH was not normally distributed. However the difference in DBH for each species was significant (Kruskal Wallis median test, $p < 0.05$). The detail of statistical parameters for each mangrove species is presented in Table 3.

In addition, based on the distribution of DBH class, it can be seen that most of the mangrove stands from all species that were sampled in this study were in the range of DBH < 10 cm to 20 cm with a mean around 49.65% and 32.98% respectively (Figure 8). On the other hand, less than 5% in total of observed mangrove vegetation in the location has DBH of more than 30 cm. The range of DBH values less than 10 cm indicates that the mangrove vegetation is relatively young in comparison to mangrove stands with a larger DBH. This is consistent with satellite imagery analysis showing that the mangrove forest on Surabaya's east coast has only grown and developed well in the last 20 years.

Table 2. Characteristics of the mangrove community structure of east coast Surabaya, Indonesia

Familiy	Mangrove species	Estimated mean density (ind/ha)	Relative Density (RDi)	Relative Frequency (RFi)	Relatif Coverage (RCi)	IVI
Acanthaceae	*Avicennia marina*	11800 ± 460	29.74	38.27	31.78	99.79
Rhizophoraceae	*Bruguiera gymnorhiza*	4000 ± 530	19.86	10.56	6.24	36.66
	Rhizopora mucronata	10800 ± 190	27.70	23.11	29.40	80.21
Lythraceae	*Sonneratia alba*	1200 ± 270	12.70	16.11	17.08	45.89
	Sonneratia caseolaris	570 ± 130	10.02	12.04	15.43	37.48

Table 3. Statistic of the observed mangrove stand on east coast Surabaya, Indonesia

Statistical parameters of DBH (cm)	*A. marina*	*B. gymnorhiza*	*R. mucronata*	*S. alba*	*S. caseolaris*
Number of Stands (N)	1581	159	1348	490	163
Mean	20.84	10.72	5.12	19.16	10.65
Standard Deviation	6.21	2.80	2.64	9.46	5.69
Standard Error	0.15	0.16	0.14	3.15	1.98
Minimum	3.18	2.87	3.18	7.80	3.18
Maximum	46.31	21.66	14.08	31.21	36.94
Median	9.75	4.78	4.46	10.57	20.06
Sample Variance	38.55	7.84	6.99	89.54	46.26

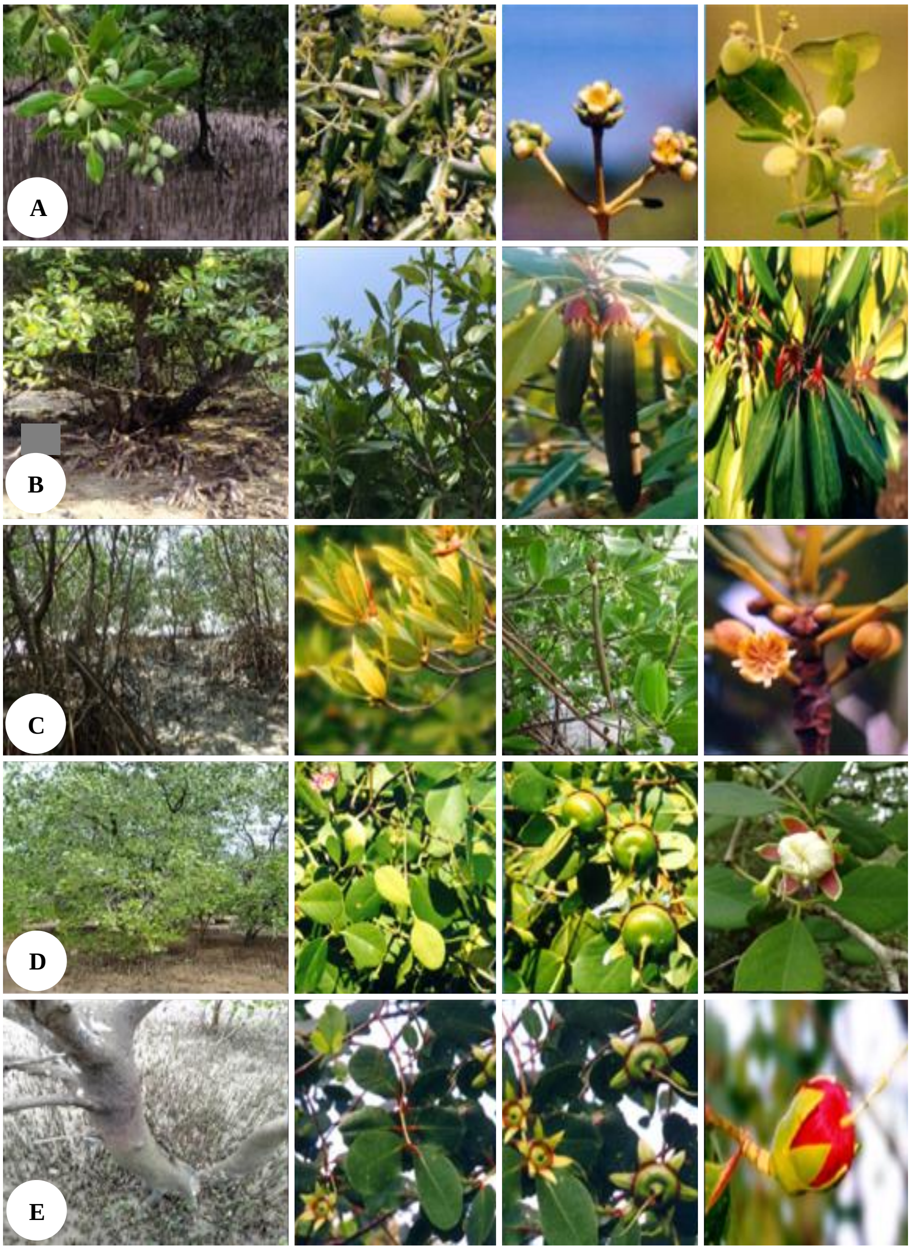

Figure 6. Mangrove species of east coast Surabaya, Indonesia. A. *Avicennia marina;* B. *Bruguiera gymnorhiza;* C. *Rhizopora mucronata;* D. *Sonneratia alba;* E. *Sonneratia caseolaris.* Photographs Source: Field Documentation (2021), Guidebook for the introduction of mangroves in Indonesia (Noor et al. 2007)

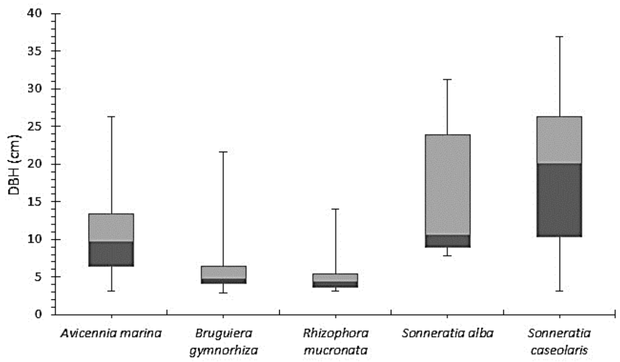

Figure 7. Distribution of DBH (cm) for each mangrove species on east coast Surabaya, Indonesia

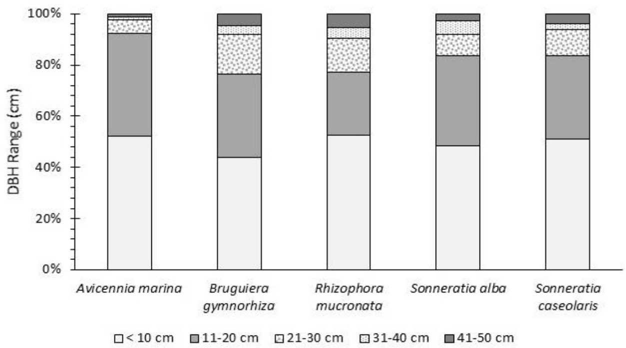

Figure 8. DBH classes of mangrove species on east coast Surabaya, Indonesia

Carbon stock and CO_2 sequestration estimation

Biomass measurement is required for carbon stock estimation and for calculating CO_2 sequestration potential by mangrove vegetation. The biomass content of tree stands increases with age. Furthermore, the substrate in the mangrove growing area influences the biomass potential of the mangrove trees. The more mud there is in the area, the bigger and taller the mangrove support roots will be. As a result, such root conditions will increase the biomass potential of mangrove forests. Based on the calculations from 20 observation transects, the AGB biomass at the study location is estimated in the range of 27.88-159.6 ton ha^{-1} with an average value 92.7 ± 27.3 ton ha^{-1}. Therefore, the carbon stock according to AGB is estimated in the range of 13.94-79.80 ton C ha^{-1} with an average value of 46.35 ± 13.65 ton C ha^{-1}. Meanwhile, carbon stock based on BGB ranged from 6.76-32.51 ton C ha^{-1} with an average of 13.65 ± 6.74 ton C ha^{-1}. According to the above results, the mangrove forest of the east coast Surabaya can sequester at least a total of 192.72 ton CO_2 ha^{-1} from above and belowground biomass. The distribution of carbon stock and sequestration for all transects have similar patterns and are displayed in Figure 9.

As can be seen from the results, above ground biomass accounted for approximately 77.25 %of the total average of 60.05 ton ha^{-1} carbon stock in the study area, with roots accounting for the remaining 22.75 %. The AGB value is generally greater than the BGB because the AGB value includes more biomass sources, such as leaves, branches, and stems, whereas the BGB value only includes root biomass. Komiyama et al. (2008) discovered that the majority of mangrove forest biomass is in the form of tree trunks that represent the tree stand. In addition to its wet weight, the amount of water content in each part of the tree can have a direct effect on its biomass potential or dry weight. Meanwhile, the low water content in the trunk is due to the fact that the stem contains more wood constituents than other tree parts in general (branches, twigs and leaves). These wood constituents can cause the cell cavity in the stem to be more abundant in wood components than water, resulting in a large stem biomass weight. The value of root biomass in plants in mangrove forests is an adaptation to growing on soft sedimentary substrates. Without the support of a dense root system, mangroves will be unable to stand upright and support the upper biomass. Additionally, soil moisture can increase biomass allocation to the roots due to increased cambial activity caused by ethylene production in submerged conditions (Komiyama et al. 2008; Mitra 2018).

The estimated carbon stock from AGB in this study was relatively higher compared to other locations in Indonesia, for example in Lamongan East Java (53.89 ton C ha^{-1}), Tanakeke South Sulawesi (37.6 ton C ha^{-1}) and Deli Serdang North Sumatra (40-50 ton C ha^{-1}) (Asadi et al. 2017; Cameron et al. 2019; Harefa et al. 2022). The above-mentioned locations have similarities in the growth of rehabilitated mangrove areas at a relatively young age (<30 years). However, when compared to natural mangrove forests in relatively undisturbed environments, the carbon stock in the mangrove forests of Surabaya's east coast is significantly lower. Table 4 summarizes a comparison of carbon stock from other locations in Indonesia and other countries in Asia.

The results of carbon stock calculation in this study are in the range presented by the IPCC for the wet tropics regions, which is 8.7-384 ton ha^{-1} (Alimbon and Manseguiao 2021). Different environmental factors (e.g., temperature, precipitation, tidal inundation, river flows, nutrient cycling and availability, salinity) and morphological characteristics (e.g., size) that affect productivity and rate of respiration of mangrove ecosystems can explain differences in measurements of biomass, carbon stock, and carbon dioxide sequestration potential across the globe (Alimbon and Manseguiao 2021; Alongi 2014). Mangrove forest biomass peaks at equatorial latitudes (Alongi 2014). This position is consistent with the high solar radiation and air temperature to which these forests are exposed due to their low latitude location. Moreover, mangrove forests in equatorial regions are influenced by the Inter-tropical Convergence Zone can generate high rainfall throughout the year as well as be influenced by large rivers and provide massive amounts of water and nutrients (Estrada and Soares 2017). Mitigation efforts are required to stabilize and preserve the condition of mangrove forests in order to maintain the potential of biomass and carbon stocks. Mangrove forests in excellent condition can absorb a significant amount of CO_2 in the atmosphere and store it in the form of biomass, consequently reducing the impact of global warming.

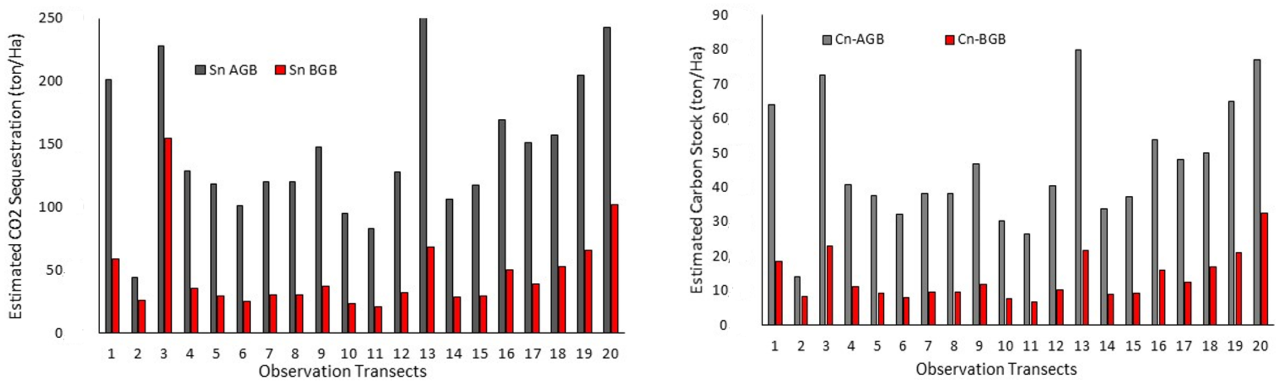

Figure 9. Carbon stock and CO_2 sequestration from 20 observation transects of east coast Surabaya, Indonesia

Table 4. Summary of mangrove forest carbon stocks from biomass in various locations

Locations	Coordinate		Estimated carbon stock (ton ha^{-1})		References
	Latitude	Longitude	AGB	BGB	
Panabo mangrove park, Davao del Norte Philipines[a]	07°16'20,57" N	125°40'50,98" E	37.8	-	Alimbon and Manseguiao (2021)
Wori mangrove forest North Sulawesi Indonesia[b]	01°35'44,16''N	124°50'48,97''E	129	50.2	Chen et al. (2018)
Demta Bay Papua Indonesia[b]	02º20'22,41''S	140º8'46,70''E	117.62	56.58	Indrayani et al. (2021)
Ca Mau mangrove forest Mekong Delta Vietnam[b]	08°33'4,45''N	105°03′54,00''E	84.5	32.9	Bao et al. (2022)
Tanakeke, South Sulawesi Indonesia[a]	05°29'57,14''S	119°17'21,67''E	37.6	-	Cameron et al. (2019)
Tiwaho, North Sulawesi Indonesia[b]	01°37'36,19''S	124°49'12,20''E	120.8	-	Cameron et al. (2019)
Deli Serdang, North Sumatra Indonesia[a]	03°45'12.7''N	98º44'60.12''E	31.83	31.20	Harefa et al. (2022)
Segara Anakan mangrove forest Cilacap, Central Java Indonesia[b]	07º40'57,01 S	108º57'24,00''E	129.19	-	Widyastuti et al. (2018)
Pahang forest reserves Malaysia[b]	03º58'36,46''N	103º24'22,55''E	180.80	-	Omar et al. (2016)
Sulaman Lake forest reserves, Sabah, Malaysia[b]	06º15'15,48''N	116º16'55,19''E	67.30	22.44	Suhaili et al. (2020)
Teluk Bintuni Papua Indonesia[b]	02º10'12,00''S	113º32'09,00''E	323.6	43.6	Murdiyarso et al. (2015)
Tanjung Puting National Park Central Kalimantan Indonesia[b]	02º51'30,00''S	111º42'02,00''E	140.9	21.3	Murdiyarso et al. (2015)
Rawa Aopa Watumohai National Park South East Sulawesi Indonesia[b]	04º33'12,10''S	122º03'20,04''E	130.29	92.57	Analuddin et al. (2020)
Sundarbans mangrove forest Bangladesh[b]	21º30'00''N	89º55'00,04''E	143.85	192.24	Rahman et al. (2015)
Bhittarnika forest reserve India[b]	20º41'36,70''N	86º92'8,96''E	131.06	-	Anand et al. (2020)
Andaman Islands, India[b]	11° 37' 24.15" N	92° 43' 35.34" E	469.20	166.78	Ragavan et al. (2021)
Surabaya East Coast mangrove forest East Java Indonesia[a]	07°15'40,00"S	112°49'43,00"E	46.35	13.65	*Present study*

Notes: [a]mangroves in the rehabilitated area; [b]mangroves in the natural area

In conclusion, the analysis of Landsat satellite images from 2000 to 2020 revealed a significant increase in mangrove forest cover on Surabaya's east coast over the last 20 years. The mangrove area was approximately 257.13 ha in 2000, and by 2020, it had nearly tripled to approximately 753.48 ha. According to NDVI, a high density of mangrove vegetation is dominant, with NDVI ranging from 0.5 to 0.7. Five mangrove species were identified namely *Avicennia marina, Bruguiera gymnorhiza, Rhizopora mucronata, Sonneratia alba* and *Sonneratia caseolaris.* Among those species, *A. marina* was considered the most dominant species, with IVI of 99.79%. According to field data collection and allometric measurement from 60 sampling plots, it is estimated that AGB biomass is in the range of 27.88-159.6 ton ha^{-1}, with an average of 92.7 ± 27.3 ton ha^{-1}. Therefore, the carbon stock, according to AGB is estimated in the range of 13.94-79.80 ton C ha^{-1} with an average value of 46.35 ± 13.65 ton C ha^{-1}. Carbon stock based on BGB ranged from 6.76-32.51 ton C ha^{-1} with an average of 13.65 ± 6.74 ton C ha^{-1}. Finally, the mangrove forest of east coast Surabaya can sequester at least a total of 192.72 tons CO_2 ha^{-1} from AGB and BGB.

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