# Mangroves composition, biomass, carbon stock and their role in the climate change mitigation in Bengkulu City, Indonesia

[1]Agung H. Lukman, [1]Muhammad F. Hidayat, [2]Ayub Sugara, [3]Mochamad C. W. Arief

[1] Department of Forestry, Faculty of Agriculture, University of Bengkulu, Kandang Limun, Bengkulu, Indonesia; [2] Department of Marine Science, Faculty of Agriculture, University of Bengkulu, Kandang Limun, Bengkulu, Indonesia; [3] Department of Fisheries, Faculty of Fisheries and Marine Science, Padjadjaran University, Jatinangor, Sumedang, Indonesia. Corresponding author: A. H. Lukman, ahaslukman@unib.ac.id

**Abstract**. Mangroves have long been known as the important ecosystem for being home to aquatic and terrestrial biodiversity, as well as fisheries resources. It is also considered an efficient carbon pool in tropical regions such as Indonesia. However, recent developments in the coastal areas of Bengkulu City in Indonesia could potentially alter and erode mangrove functions, in particular, mangroves as a carbon sink. Previous studies on the role of mangrove forests concerning global warming in the area have not illustrated the distribution of biomass and carbon and its uncertainties. Hence, this study aimed to assess mangrove richness, biomass and carbon content to provide the current state and distribution and its role in climate change mitigation. Six sampling locations were determined reflecting area distribution and its status (conservation and non-conservation). A total of 60 nested quadrat plots were employed for the trees and saplings category. Above- and below-ground biomass was estimated by using the allometric model. The findings showed that a total of nine species were observed. The average biomass and carbon stocks were 302.27 t ha$^{-1}$ and 135.02 t C ha$^{-1}$, respectively, over seven-fold higher than the previous studies. Pantai Panjang station was the highest storing carbon at 235.95 t C ha$^{-1}$, while the lowest was in Teluk Sepang (74.61 t C ha$^{-1}$). These findings also suggest that non-protected mangrove forests also played a key role, similar to the conservation mangrove forests, regarding the climate change mitigation. It is, therefore, urgently required to enhance the strategy and program in order to maintain the current mangrove ecosystems within and beyond the conservation areas.

**Key Words**: mangrove carbon, species richness, tree biomass, mangrove conservation, climate change.

**Introduction**. Mangrove forests are widely known as an important ecosystem for delivering various vital benefits both in ecological and socioeconomic aspects bundled into ecosystem services (Lee et al 2014; UNEP 2014), such as provisioning services, e.g., providing nursery, spawning and feeding ground for coastal organisms and fishery resources (Hoque et al 2015), and in particular regulating services (MEA 2005). With regard to carbon and climate regulation, mangroves are considered remarkably efficient carbon sequestration pools in tropical regions (Komiyama et al 2008). It is also among the highest carbon-dense forests and could store up to three-fold carbon per hectare (ha) than other tropical forests (Donato et al 2011). Moreover, Indonesian mangrove forests deposit more (Murdiyarso et al 2015) and absorb carbon faster (Wahyudi et al 2018) than terrestrial tropical forests. To date, Indonesia is still the largest mangrove country in the world covering around 3–3.3 million ha (Rahardian et al 2019; Rahmanto 2020). In addition, Indonesia's mangroves at the country level could sequestrate up to 3.0 Gt C (Alongi et al 2016). Thus, mangrove forests in Indonesia have a great potential in relation to the climate change mitigation (Murdiyarso et al 2015). However, mangrove deforestation and degradation are expected to continue to take place (Ilman et al 2016).

Mangrove in Sumatra is one of the most degraded mangrove forests in the country and their carbon sequestration is also the lowest among the six main islands nationwide (LIPI 2018). On the other hand, maintaining and preserving the ecosystem as carbon sinking service provider, is considered an efficient way to mitigate greenhouse gas emissions (GHGs) and climate change (Duarte et al 2013). Carbon stock in mangroves and its changes, either driven by emission or sequestration, will eventually affect $CO_2$ concentration in the atmosphere (Alongi 2012; Krisnawati et al 2012). Therefore, as conserving and improving the existing mangrove forests are crucial to prevent carbon emissions for climate change mitigation (Alongi 2012), it is also pivotal to measure and monitor the carbon stock in mangrove forests, in order to update its recent conditions.

Mangrove forests in Bengkulu City are scattered in various places, forming patches within the coastal landscape. They spread along the coast, bay, delta and riverine in the estuary, that is divided into conservation and non-conservation areas. A previous study on mangrove carbon stock in Bengkulu by Senoaji & Hidayat (2016) suggested that the carbon content in biomass mangrove stands was 18.53 t C ha$^{-1}$. Although their study identified that the mangroves were dispersed into several blocks, it did not illustrate how the biomass and carbon stock were distributed among the areas. Moreover, recent development and land conversion, as well as mangrove rehabilitation programs in the region, could potentially contribute to the mangrove dynamics. In turn, it would have an impact on the biomass and carbon stock change in the mangrove forest. Therefore, this study aimed to assess the mangrove biomass and its carbon content, to provide the current status of carbon stock and its distribution in the mangrove forest of Bengkulu City.

## Material and Method

***Description of the study sites***. This study was conducted in Bengkulu City, Sumatera Island of Indonesia (Figure 1). The mangroves spreads from the estuary to the riverine. Six sampling locations consisting of two stations for each were determined, i.e., Pantai Panjang and Pulau Baai Nature Park or TWA (hereafter, Pantai Panjang and Pulau Baai), Kandang (conservation areas), and Sumber Jaya, Teluk Sepang and Padang Serai (non-conservation areas) to represent mangrove across areas. Of all stations, Pantai Panjang and Pulau Baai were the most widely known since it was designated as a nature park by the national government. The study was carried out from September to October 2021.

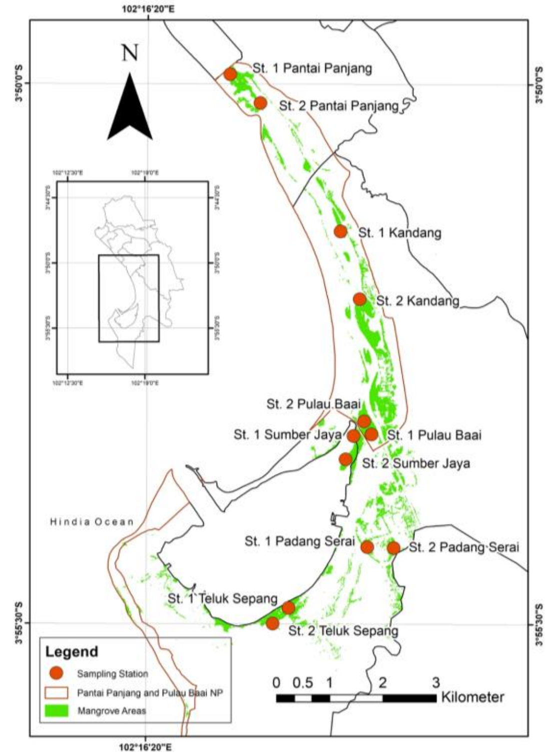

Figure 1. Map of study site.

***Methods and sampling design***. The sampling technique adopted the protocol of mangroves carbon measurement proposed by Kauffman & Donato (2012). The plot numbers are ideally within the 10% precision level, to get a better result. However, the preliminary calculation suggested that involving a large number of plots (around hundred plots) would require too many resources. Thus, we determined that the plot numbers fell within a 20% precision level (at 95% confidence level), as required by the Indonesian National Standard (SNI) 7724:2011 (BSN 2011). To the preliminary sample plots, the formula provided by Kauffman & Donato (2012) was applied as follows:

$$n = \left(\frac{\mathrm{t} * \mathrm{S}}{\mathrm{E}}\right)^2$$

Where:
n - the number of sampling plots required;
t - the sample of statistic for the 95% confidence interval (CI);
s - standard deviation (expected or known from previous or preliminary data);
E - allowable error/the desired half-width of the CI, obtained by multiplying the average of carbon stock by the desired precision.

***Data collection***. By applying the above formula, the required number was approximately 60 plots. These plots were designed into a nested quadrat where five plots were installed in every two stations of each location. The plot size was 10 x 10 $m^2$ and 5 x 5 $m^2$ for trees (DBH>10 cm) and saplings (DBH<10 cm), respectively (Istomo et al 2017). Plots were placed perpendicularly to the coastline or river body in each station, by using a linear transect reflecting proximal, medial and distal zones. If the mangrove layer is not thick, a modification of the plot emplacement, as suggested by Dharmawan & Pramudji (2014), was applied. Mangrove species were identified using a guidebook provided by Noor et al (2012).

***Stand biomass and carbon estimation***. Biomass and carbon stock were estimated by non-destructive sampling, through a direct approach using the allometric model. Njana (2016) argued that utilizing the direct method for biomass and carbon stock estimation is more recommended than the indirect method, e.g., volume model involving the form factor (FF) and the biomass expansion factor (BEF). Biomass allometric equations to generate the above-ground biomass ($W_{top}$) and below-ground biomass ($W_R$) of each species are described in Table 1. Since the allometric for some recorded species have not yet been developed, the common allometric proposed by Komiyama et al (2005) was used for those species. The common allometric equations take into considerations the density of the various species, according to Zanne et al (2009) and Komiyama et al (2005) as depicted in Table 2.

Table 1

Selected specific and common allometric equations

| *Species* | *Allometric* | *$r^2$* | *References* |
|---|---|---|---|
| *Avicennia marina* | $W_{top} = 0.1848\ D^{2.3524}$ | 0.98 | Dharmawan & Siregar (2008) |
| *Bruguiera gymnorhiza* | $W_{top} = 0.186\ D^{2.31}$ | 0.99 | Clough & Scott (1989) |
| *Ceriops tagal* | $W_{top} = 0.529\ D^{2.04}$ | 0.96 | Kangkuso et al (2018) |
| *Lumnitzera racemosa* | $W_{top} = 0.184\ D^{2.384}$ | 0.98 | Kangkuso et al (2016) |
| *Rhizophora apiculata* | $W_{top} = 0.235\ D^{2.42}$ | 0.98 | Ong et al (2004) |
| *Rhizophora* spp. | $W_{top} = 0.105 D^{2.68}$ | 0.99 | Clough & Scott (1989) |
| *Xylocarpus granatum* | $W_{top} = 0.1832\ D^{2.21}$ | 0.95 | Talan (2008) |
| Common equation | $W_{top} = 0.251\ \rho\ D^{2.46}$ | 0.98 | Komiyama et al (2005) |
| Common equation | $W_R = 0.199\ \rho^{0.899}\ D^{2.22}$ | 0.95 | Komiyama et al (2005) |

$W_{top}$-aboveground biomass; WR-belowground biomass; ρ-wood density; $r^2$-coefficient of determination.

Table 2

Wood density of several mangrove species

| *Species* | *Wood density (ton/m$^3$)* | *References* |
|---|---|---|
| *Avicennia marina* | $\rho = 0.65$ | Zanne et al (2009) |
| *Bruguiera gymnorhiza* | $\rho = 0.70$ | Komiyama et al (2005) |
| *Ceriops tagal* | $\rho = 0.75$ | Komiyama et al (2005) |
| *Lumnitzera racemosa* | $\rho = 0.71$ | Zanne et al (2009) |
| *Rhizophora apiculata* | $\rho = 0.77$ | Komiyama et al (2005) |
| *Rhizophora stylosa* | $\rho = 0.84$ | Zanne et al (2009) |
| *Xylocarpus granatum* | $\rho = 0.53$ | Komiyama et al (2005) |
| *Lumnitzera littorea* | $\rho = 0.67$ | Zanne et al (2009) |
| *Sonneratia alba* | $\rho = 0.47$ | Komiyama et al (2005) |

The amount of carbon stock (t C ha$^{-1}$) was estimated by multiplying the biomass species with their carbon fractions (CF). Usually, the CF used is the default value of all biomass parts, for instance as suggested by IPCC (2006) or SNI 7724:2011 developed by BSN (2011). However, the carbon concentration in root biomass ($W_R$) tends to be lower than above-ground biomass ($W_{top}$) (Kauffman & Donato 2012). Here, the default values of CF used were 0.47 for $W_{top}$ and 0.39 for $W_R$ (Komiyama et al 2005; IPCC 2006). Hence, the carbon stock of biomass was calculated as follows:

$$\mathrm{C\ stock} = (\mathrm{Wtop} \ * \ \mathrm{CF\ Wtop}) + (\mathrm{W_R} \ * \ \mathrm{CF\ W_R})$$

Where:

CF $W_{top}$ - carbon fraction of $W_{top}$ (0.47), IPCC (2006);

CF $W_R$ - carbon fraction of $W_R$ (0.39), Komiyama et al (2005).

***Measuring uncertainty***. Standard deviation (SD) and sampling error (SE) were also measured to calculate the uncertainty of the carbon stock at the stand level. In addition, inventorying emissions by mangroves that link to climate change mitigation could use $CO_2$ equivalent ($CO_2$e). These last two measurement equations presented by Kauffman & Donato (2012) are as follows:

$$Uncertainty(\%) = \sqrt{\left(\left[95\%\ CI_{CWtop}\right]^2 + \left[95\%\ CI_{CWR}\right]^2\right)}$$

Where:

95% CI half-width = 2*SE

$$CO2e = (\mathrm{Mw.CO2}\ /\ \mathrm{Aw.C})\ \mathrm{x\ Cstock}$$

Where:

Mw.$CO_2$ - molecular weight of $CO_2$ (44);

Aw.C - atomic weight of C (12);

C stock - carbon stock (ton C ha$^{-1}$).

## Results and Discussion

***Mangrove species richness***. A total of nine mangrove species representing five families was recorded at six locations as shown in Table 3. *Avicennia marina* and *Rhizophora apiculata* are two mangrove species found in all study sites. In contrast, *R. cf. stylosa* and *Lumnitzera racemosa* were only encountered at a single location. Of all mangrove studies in Bengkulu City, this study shares the most similarity with Senoaji & Hidayat (2016) regarding the mangrove trees diversity, who also recorded nine species. However, several different species have been recently discovered in this study, namely *A. marina*, *R. cf. stylosa* and *L. racemosa*.

Table 3

Mangrove species richness and presence in study site

| No | Species |  | Locations |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|
|  | Scientific name | Local name | PP | KD | PB | SJ | TS | PS |
| 1 | *Avicennia marina* | Api-api | + | + | + | + | + | + |
| 2 | *Rhizophora apiculata* | Bakau minyak | + | + | + | + | + | + |
| 3 | *Sonneratia alba* | Pidada | + | + | + | + |  | + |
| 4 | *Bruguiera gymnorrhiza* | Mangi-mangi |  | + | + | + | + |  |
| 5 | *Ceriops tagal* | Soga |  |  |  | + |  | + |
| 6 | *Lumnitzera littorea* | Teruntum merah |  |  | + |  | + |  |
| 7 | *Xylocarpus granatum* | Nyirih | + |  | + |  |  |  |
| 8 | *Lumnitzera racemosa* | Teruntum putih |  |  |  |  |  | + |
| 9 | *Rhizophora cf. stylosa* | Bakau pasir |  |  |  |  | + |  |

PP-Pantai Panjang; KD-Kandang; PBI-Pulau Baai; SJ-Sumber Jaya; TS-Teluk Sepang; PS-Padang Serai. (+): species presence.

The wide distribution of *A. marina*, *R. apiculata* and *S. alba* was likely due to their ecological adaptability. According to Noor et al (2012), the Avicennia genus is highly tolerant to salinity and *A. marina* could manage its growth in a salinity varying from seawater to freshwater. In addition, *R. apiculata* is generally found in a habitat with muddy substrate and inundated at normal tide (Giesen et al 2007; Noor et al 2012). Likewise, *S. alba* is regularly present in mud-sandy mix substrate, which is common in the study sites (Apriyanto et al 2021). These three species were highly encountered across the sampling locations. On the other hand, *R. cf. stylosa* and *L. racemosa* were the most rarely found at the study site. The lacks of presence of *R. cf. stylosa* may be due to anthropogenic factors, i.e., wood utilization, logging and land conversion, the rarity of *L. racemosa* is likely caused by its habitat preferences. Noor et al (2012) also suggested that *L. racemosa* preferred solid-muddy substrate. In fact, at the study site has mainly a light mud-sandy substrate which favors other species. Furthermore, Table 3 also presents that Pulau Baai was the station harboring the most numerous species, since it is located in the riverine, far away from the estuary, yet some of its parts are directly connected to the Sepang bay through the man-made tidal channel. Hence, it provides a wide range of salinity for many species to thrive. In contrast, Pantai Panjang and Kandang were the stations that possessed the fewest species (Table 3). While Pantai Panjang station is the estuarine itself, the proximity of Kandang to the estuary (i.e., Muara Jenggalu) explains the rarity of species. Therefore, the high salinity affected by the seawater tidal allows only tolerant species to saline water to grow (Noor et al 2012).

***Biomass and carbon stock***. The study revealed that the average mangrove biomass ($W_{tot}$) and carbon stock ($C_{stock}$) in the study site was 302.27 t ha$^{-1}$ and 135.02 t C ha$^{-1}$, respectively, as shown in Table 4. It was quite high considering that any carbon stock measurement passing a hundred marks figure could be viewed as high carbon. To put it into context, the High Carbon Stock (HCS) approach estimates that HCS area threshold is around 50 t C ha$^{-1}$. Land cover below this value is usually degraded forest, such as scrub vegetation or bare land with fewer tree density, although located in terrestrial forests or on agriculture land (Rosoman et al 2017). Table 4 also shows the average $W_{top}$ and $W_R$ and total uncertainty for the carbon stock measured.

Table 4

The average of biomass and carbon stock in study site

| Value | $W_{top}$ | $W_R$ | $W_{tot}$ | $CW_{top}$ | $CW_R$ | Cstock |
|---|---|---|---|---|---|---|
| Average (ton ha$^{-1}$) | 214.16 | 88.11 | 302.27 | 100.66 | 34.36 | 135.02 |
| Standard error | 18.48 | 6.65 | 25.09 | 8.69 | 2.59 | 11.26 |
| CI half-width | * | * | * | 17.37 | 5.19 | 18.13 |
| Total uncertainty (%) | * | * | * | * | * | 13.43 |

*not accounted.

Compared to previous studies, both biomass and carbon stock estimation results were surprisingly much higher. Senoaji & Hidayat (2016) estimated that the biomass and carbon stock in Bengkulu City was 37.06 t ha$^{-1}$ and 18.53 t C ha$^{-1}$, respectively. Apriyanto et al (2021) considered that the biomass mangrove was 32.9 t ha$^{-1}$, below seven-fold lower than in the current study, which suggested 302.27 t ha$^{-1}$ and 135.02 t C ha$^{-1}$ for biomass and carbon stock, respectively (Table 4). This huge difference may be driven by several factors, such as the growth of the mangroves themselves, the dynamics of mangrove covers or the distinction in the sampling design.

In terms of natural trunk increment, while it may contribute to the biomass increase, it is unlikely to be the primary cause, since for the above-identified mangroves it is usually around 0.4–1.8 cm year$^{-1}$ (Kesuma et al 2016; Efriyeldi et al 2021). Furthermore, the mean annual increment (MAI) of carbon for secondary mangrove forests is about 2.8 t C ha$^{-1}$ year$^{-1}$ (Ministry of Forestry and Environment/MoFE 2020). Considered the previous carbon mangrove estimations, at this increment value, the projection of carbon stock to date would be around 30-40 t C ha$^{-1}$.

Moreover, the dynamic of mangrove covers in the region may not also be the main factor. Sugara et al (2022) indicate that the extent of mangrove areas in Bengkulu City is around 242.35 ha. This number is slightly larger than Senoaji & Hidayat (2016) who estimate 214.62 ha, yet it supports a recent study that calculates around 255.24 ha (Srifitriani et al 2020). Although explaining the differences may need further investigation regarding which methods and satellite images were used, the results suggest that the mangrove dynamics in the region follow a positive rate. Nonetheless, if the mangroves were expanding by around 30-40 ha in the past five years, it is also probably not the major contributor to this huge gap of biomass and carbon stock estimation since it could not match the calculation. Thus, the contrast is more likely caused by the different sampling and study designs. These may include the differences in plot numbers, plot locations determination, data analysis, sampling techniques, and sampling bias or error (Manuri et al 2011).

Furthermore, these findings also appeared to support the relevance of providing the sampling error desired in the carbon stock study, as urged by Kauffman & Donato (2012). Presenting such value would not only be helpful to estimate the study accuracy, but also could be useful for further comparison with similar studies if necessary. Nevertheless, the uncertainty propagation of this study was at 13.43% with a 95% confidence interval (Table 4) meaning that although it was slightly beyond the ideal uncertainty value (below 10%), it was still in a fairly acceptable range, under the 20% error threshold stated by BSN (2011). It also means that the average carbon storage in the study area was between 116–153 t C ha$^{-1}$.

A fairly big amount of such result might be generated by both the high density and large diameter of the mangrove stands, as various studies suggest, such as Murdiyarso et al (2015) and Istomo et al (2017). The average density and tree diameter accounting for biomass and carbon stock result above were relatively high for both parameters, as presented in Table 5 below.

Table 5

Mean diameter and density between locations in study site

| *Location* | *Mean diameter (cm)* | | *Individuals counted* | | | *Density (ind ha$^{-1}$)* | | |
|---|---|---|---|---|---|---|---|---|
| *(n=60)* | *Sapling* | *Tree* | *Sapling* | *Tree* | *Total* | *Sapling* | *Tree* | *Total* |
| Sumber Jaya | 3.74 | 20.88 | 113 | 67 | 180 | 4520 | 670 | 5190 |
| Kandang | 5.08 | 19.24 | 102 | 60 | 162 | 4080 | 600 | 4840 |
| Pulau Baai | 3.81 | 19.38 | 109 | 48 | 157 | 4360 | 480 | 4680 |
| Teluk Sepang | 5.78 | 13.56 | 88 | 40 | 128 | 3520 | 400 | 3920 |
| Pantai Panjang | 5.61 | 25.57 | 65 | 62 | 127 | 2600 | 620 | 3220 |
| Padang Serai | 5.68 | 20.04 | 33 | 56 | 89 | 1320 | 560 | 1880 |
| Average | 4.74 | 20.22 | 85 | 55 | 140 | 3400 | 555 | 3955 |

Relating to density, as can be seen in Table 5, while the average number of the large trees was relatively moderate at 555 ind ha$^{-1}$, the sapling density was quite high at 3400 ind ha$^{-1}$ and correspondingly made up to 3955 ind ha$^{-1}$. Moreover, the mean diameters of the tree category in most locations were reasonably large around 20 cm. Consequently, the higher the trees density and the larger their diameters, the higher their biomass and carbon stock. It confirms other studies that the high tree biomass and carbon stock is dominantly influenced by the density and basal area (Kusmana et al 1992; Murdiyarso et al 2015; Istomo 2017).

With regard to the biomass within tree and sapling categories among locations, it is presented in Figure 2. Overall, biomass in tree category (W-tree) was more than 170 t ha$^{-1}$, except in Teluk Sepang, while saplings (W-sapling) were below 100 t ha$^{-1}$.

In general, the biomass stored at the tree level (DBH>10 cm) was higher than at the sapling level (DBH<10 cm). However, the opposite was observed in Teluk Sepang where biomass and carbon stocks were higher than at the sapling level (Figure 2). This is possibly because the number of individuals or the density at the sapling level is much higher than the tree level. In addition, as above-mentioned in Table 5, the diameter size of the tree level at this location was the smallest while the contrast was spotted in sapling category. As a result, the biomass, which was the carbon originated, of tree category were lower than the sapling level (Figure 2).

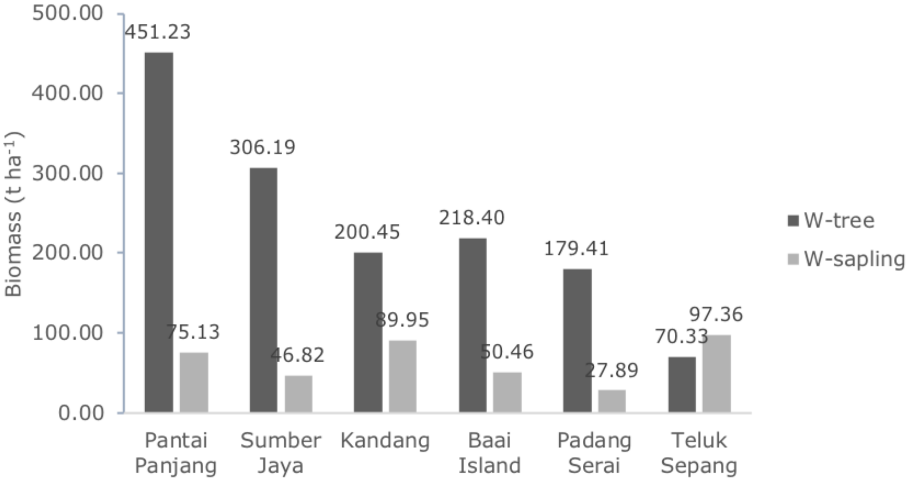

Figure 2. Biomass between tree and sapling category in study site (t ha$^{-1}$).

***Biomass and carbon stock distribution between locations***. This study showed that the highest and lowest biomass and carbon stock among six locations were Pantai Panjang and Teluk Sepang at 235.95 t C ha$^{-1}$ and 74.61 t C ha$^{-1}$, respectively. Meanwhile, the rest of four locations ranged around 92–158 t C ha$^{-1}$ as depicted in Figure 3.

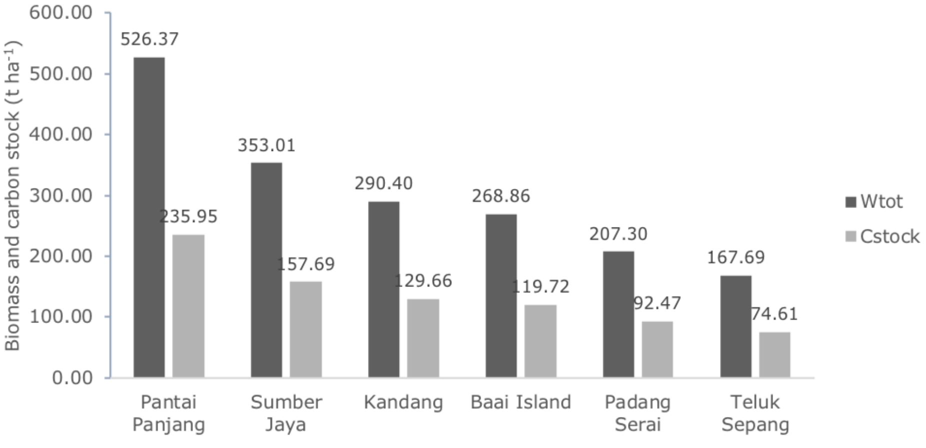

Figure 3. The biomass and carbon stock between locations (t ha$^{-1}$).

Interestingly, Pantai Panjang was also the second-lowest in terms of total density as previously shown in Table 5 despite being the highest carbon stored station (Figure 2). Regardless, it may be due to a large number of individual trees owning large diameters in Pantai Panjang station, resulting in the second-highest density (620 ind ha$^{-1}$) and the highest diameter (25.57 cm) within the tree category (Table 5). Hence, density is not always the sole criterion to produce such high biomass, as shown by other studies: carbon stock and biomass are directly proportional to the tree density, volume and basal area (Istomo et al 2017), thus to the tree diameter. The status of Pantai Panjang station as a conservation area and its proximity to the area management office, i.e., Pantai Panjang and Pulau Baai Nature Park office, is likely to prevent tree logging, land conversion and other extraction activities so that large mangrove trees remain intact.

Besides, the difference of biomass and carbon stock between protected and non-protected mangroves is presented in Figure 4 below. Conservation areas are represented by Pantai Panjang, Pulau Baai and Kandang stations, while the others are covered by non-conservation areas.

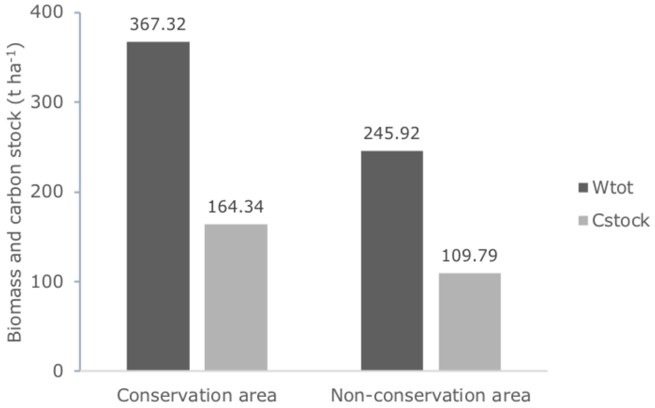

Figure 4. The biomass and carbon stock between conservation and non-conservation areas (t ha$^{-1}$).

Overall, the average mangrove carbon stock in conservation areas was still higher than in non-conservation areas: 164.34 t C ha$^{-1}$ compared to 109.79 t C ha$^{-1}$, respectively, as shown in Figure 4 above. Nevertheless, the carbon stock in non-protected areas was still relatively high, beyond hundred marks, considering its non-public status (community or private sectors owned). In fact, one of the sampling locations for non-conservation areas, Sumber Jaya, only separated by an access road from Pulau Baai, ranked the second highest carbon stock, at 157.69 t C ha$^{-1}$ (Figure 3). Various studies emphasize that mangroves beyond conservation areas also have the potential to be a source of high carbon storage (Kangkuso et al 2018; Dinilhuda et al 2020), whilst mangroves within conservation areas cover only 22% of the total mangrove surface of the country (Sidik et al 2018).

Regardless, it is also noteworthy that mangroves beyond conservation areas in the region need more preservation actions. It is important considering that changes in mangrove ecosystems can occur at any time, being privately owned. During the field survey, we observed several spots of cleared and degraded mangroves at the non-conservation sites designated for other land uses, such as fishery ponds, settlements and buildings. Thus, while Sidik et al (2018) suggest that the involvement of relevant stakeholders is crucial in achieving corporate efforts and management plans to maintain mangroves within conservation areas, is also important for the non-conservation areas. Hence, such management will not only be beneficial for carbon preservation but also for the community welfare through various programs, such as mangrove tourism and sustainable aquaculture or silvofishery system (fish and crab cultivation).

***Biomass distribution between tree growth class and species***. This study also revealed the distribution of biomass and carbon stored in each mangrove species identified in the research location. Three species were the highest biomass and carbon stored, namely *S. alba*, *R. apiculata* and *A. marina* as described in Figure 5a. Meanwhile, the remaining six species had relatively very low biomass and carbon stock. Their cumulative value was smaller than for *A. marina*.

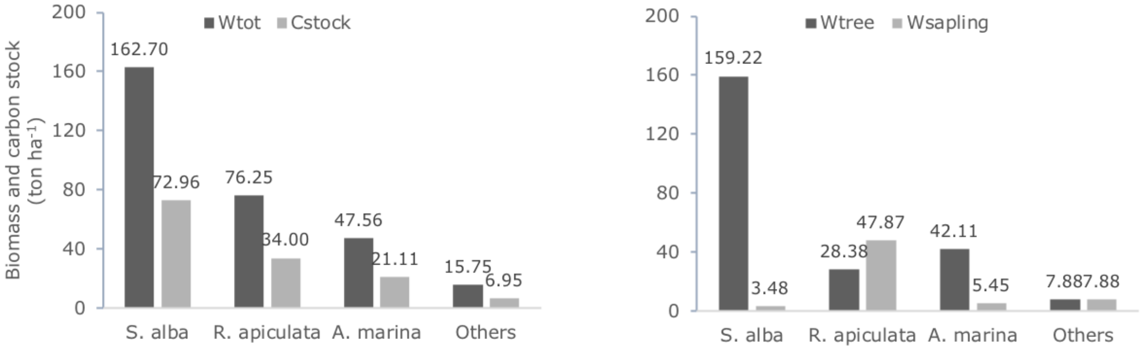

Figure 5. a) (left) Biomass and carbon stock between species; b) (right) Tree and sapling biomass between species in study site (t ha$^{-1}$).

With respect to the biomass and carbon stock in the growth category, the largest biomass was stored at the tree level, as observed in *S. alba*, *A. marina* and the other six other mangrove species (Figure 5b), contrasting with *R. apiculata*, which has higher sapling biomass than the tree category. It was potentially due to the higher number of *R. apiculata* sapling individuals than tree individuals, compared with the other species.

Table 6 presents the diameter and density average for each category of species encountered, and the total mangrove density in study site. S*. alba*, as also seen in Figure 5a, possessed the highest carbon stock among all species, due to its largest stem diameter, despite having a moderate density, as indicated in Figure 5b and Table 6. Most of this large individual species were recorded nearby the management office above-mentioned, hence, storing a quite high amount of carbon. The species holding the least carbon stock, *L. littorea, X. granatum, R. cf. stylosa, L. racemosa and C. tagal*had fewer number of individuals than the dominant species, although their trunk diameter might only be slightly different, as shown in Table 6.

Table 6

Mean diameter and density of mangrove species at the study site

| *Species* | *Mean diameter (cm)* | | *Density (ind ha$^{-1}$)* | | |
|---|---|---|---|---|---|
| | *Sapling* | *Tree* | *Sapling* | *Tree* | *Total* |
| *Rhizophora apiculata* | 5.18 | 13.04 | 2,000 | 160 | 2,160 |
| *Bruguiera gymnorhiza* | 3.16 | 12.14 | 727 | 13 | 740 |
| *Sonneratia alba* | 4.15 | 27.15 | 333 | 232 | 565 |
| *Avicennia marina* | 5.87 | 19.66 | 233 | 105 | 338 |
| *Lumnizera littorea* | 6.14 | 13.15 | 73 | 12 | 85 |
| *Xylocarpus granatum* | 7.64 | 13.56 | 20 | 20 | 40 |
| *Rhizhophora cf. stylosa* | 0.00 | 14.49 | 0 | 13 | 13 |
| *Lumnitzera racemosa* | 8.92 | 0.00 | 7 | 0 | 7 |
| *Ceriops tagal* | 5.10 | 0.00 | 7 | 0 | 7 |
| Total number of individual (ind ha$^{-1}$) | | | 3,400 | 555 | 3,955 |

As depicted in Table 6, the total mangrove number was quite high, at 3955 ind. ha$^{-1}$. Referring to the government regulation of mangrove status and monitoring (MoE 2004), it could be considered as a high mangrove density (>1,500 ind ha$^{-1}$). It is also in accordance with Apriyanto et al (2021), who also reported that the mangrove individual number in this area was high, at >2,500 ind ha$^{-1}$. However, due to a different of method applied for monitoring purposes, particularly the plot size and tree diameter threshold considered, the number is slightly different. In addition, Table 6 also indicates that *R. apiculata* and *B. gymnorhiza* could potentiailly replace *S. alba* as the dominant species in the future: they have sapling numbers multiple times higher than *S. alba*, as also suggested by Apriyanto et al (2021).

***Other similar studies in Sumatra region***. Several relevant studies have been compiled that could be used for comparison with the results of the current study, as presented in Table 7, which shows biomass and carbon stock in mangroves of the Sumatran region and their dominant species.

Table 7

Mangrove biomass and carbon stock studies in Sumatera regions

| *Location* | *Dominant species* | *Biomass ($t\ ha^{-1}$)* | *C stock ($t\ C\ ha^{-1}$)* | *References* |
|---|---|---|---|---|
| | | Total biomass | | |
| Bengkulu | *S. alba* | 302.27 | 135.02 | Current study |
| Bengkulu | *S. alba* | 37.06 | 18.53 | Senoaji & Hidayat (2016) |
| Seluma | *R. apiculata* | N/A | 114.70 | Senoaji (2016) |
| Banyu Asin | *E. agallocha* | N/A | 104.80 | Tiryana et al (2016) |
| Banyu Asin | *N. fruticans* | 228.39 | 107.34 | Farahisah et al (2021) |
| | | AGBC* | | |
| Bengkulu | *R. apiculata* | 32.9 | N/A | Apriyanto et al (2021) |
| Dumai | *X. granatum* | 38.62 | 19.30 | Mandari et al (2016) |
| Siberut Is. | *R. apiculata* | 49.13 | 24.56 | Bismark et al (2008) |
| E. Lampung | *A. marina* | 313.30 | 114.14 | Salsabilli Rh et al (2021) |
| Langsa | *R. mucronata* | 360.73 | 180.37 | Zurba et al (2017) |
| S. Bangka | *R. mucronata* | 365.20 | 194.75 | Heriyanto & Silvaliandra (2019) |
| E. Lampung | *A. marina* | 429.06 | 197.36 | Windarni et al (2018) |

*the study only measured aboveground biomass ($W_{top}$) for carbon content.

As shown in Table 7, the carbon stock in this study was quite high compared to the mentioned studies, ranging from 18.53 t C $ha^{-1}$ to 197.36 t C $ha^{-1}$. The lowest was observed at the same location as the current study, about six years ago, while the highest was recorded in East Lampung. In the areas within Bengkulu Province, the biomass and carbon stock in the mangrove were slightly different from Seluma (114.70 t C $ha^{-1}$), but much higher than at the same location in the previous studies, as discussed above.

***Carbon stock in Bengkulu and its relation to climate change mitigation***. A total of 135.02 t C $ha^{-1}$ of mangrove biomass carbon at the study site can be converted to 495.07 tons of carbon dioxide equivalent per hectare (t $CO_2e$ $ha^{-1}$). It means that any further mangrove degradation and cover losses will release large amounts of $CO_2$ into the atmosphere. In fact, the forestry sector, along with the agricultural and other land uses, is still the main contributor to greenhouse gasses (GHGs) emissions in Bengkulu Province (BAPPENAS 2014). Thus, keeping the mangrove ecosystem intact could support the continuation of the emissions-reducing target from the land-based sector, which was previously set at 32.64% by 2020 (Regulation of Governor of Bengkulu 2018). Nonetheless, the diverging results from previous studies may also provide an insight to the relevant stakeholder to clarify it further since it could contribute to current knowledge for reducing GHGs emission measures from the land-based sector in the region.

Moreover, a 2020 report of the Indonesian Ministry of Forestry and Environment (MoFE) on reducing GHGs emissions showed a positive contribution from the forestry sector nationwide by 37 million t $CO_2e$ in 2018. This figure is obtained from the difference between the GHGs inventory measurement and the Nationally Determined Contribution (NDC/BAU) emission baseline at 724 and 761 million t $CO_2e$, respectively. Although Bengkulu Province is not designated for the mangrove rehabilitation national acceleration program of approximately 637 ha areas, among nine others, it could deliver its contribution to the 10-31% emission reduction, estimated for the whole country, by the mangrove ecosystems (Murdiyarso et al 2015), also contributing to the GHGs emission reducing target of 497 million t $CO_2$e by the forestry sector until 2030 (MoFE 2020). Accordingly, such an ambitious target needs to leverage all remaining forests cover regardless of their conservation and non-conservation status.

The previous discussion section also highlighted the important role of non-conservation mangroves in the climate change mitigation in the region by sinking a large amount of carbon. In fact, mangroves beyond protected areas are more vulnerable to disturbance, such as land conversion, logging, and other anthropogenic activities, eventually leading to a high emission contribution (Alongi 2012). Thus, maintaining this forest will not only minimize the GHGs emissions, but will also strengthen the climate change mitigation (Adame et al 2021). Furthermore, Alongi et al (2016) emphasized that stabilizing current mangroves in Indonesia is urgently needed not only to maintain the nation's carbon stock and its various vital ecosystem services but also to avoid a massive fraction of the globally released carbon to the atmosphere. Cameron et al (2019) also expressed that decelerating mangrove deforestation would have a large positive impact on the carbon emission mitigation as mangroves' capacity to sequestrate and store carbon is higher than terrestrial vegetation's capacity. Therefore, a further appropriate strategy should be established and implemented for maintaining mangroves and the carbon stock in both non-conservation and conservation areas.

**Conclusions**. At the study site there were identified nine tree mangrove species, with an average current biomass and carbon stock of 302.27 t ha$^{-1}$ and 135.02 t C ha$^{-1}$, respectively, over seven-fold higher than in the previous studies. Further studies may be needed to clarify such a large difference, in order to take measures for a better conservation and GHGs emissions reduction. This study also suggested the importance of non-conservation mangrove forests playing a role in the climate change mitigation, despite the land cover changes. Developing appropriate strategies and programs is therefore urgently required to maintain the current mangrove ecosystem within and beyond the conservation areas that will benefit carbon preservation. Nevertheless, further works are needed to understand the nexus of this approach to biodiversity conservation and community welfare through various programs, such as silvofishery, sustainable aquaculture and tourism.

**Acknowledgements**. This study is under the scheme of Penelitian Pembinaan funded by PNBP of Faculty of Agriculture, Universitas Bengkulu, contract number: 5897/UN30.11/LT/2021. The authors are grateful to Dr. Gunggung Senoaji for a meaningful discussion regarding data analysis. The authors would like to thank Adi Kuswanto, Fitra Aliansyah, and Susanto for their technical assistance.

**Conflict of interest**. The authors declare no conflict of interest.

## References

Adame M. F., Connolly R. M., Turschwell M. P., Lovelock C. E., Fatoyinbo T, Lagomasino D., Goldberg L. A., Holdorf J., Friess D. A., Sasmito S. D., Sanderman J., 2021 Future carbon emissions from global mangrove forest loss. Global Change Biology 27(12):2856–2866.

Alongi D. M., 2012 Carbon sequestration in mangrove forests. Carbon Management 3(3):313–322.

Alongi D. M., Murdiyarso D., Fourqurean J. W., Kauffman J. B., Hutahaean A., Crooks S., Lovelock C. E., Howard J., Herr D., Fortes M., Pidgeon E., 2016 Indonesia's blue carbon: a globally significant and vulnerable sink for seagrass and mangrove carbon. Wetland Ecology Management 24(1):3–13.

Apriyanto E., Nugroho P. B. A., Siswahyono, 2021 Species composition, diversity and biomass of mangroves forest in Pulau Bai-Pantai Panjang natural conservation park of Bengkulu, Indonesia. AACL Bioflux 14(4):2012–2020.

Bismark M., Subiandono E., Heriyanto N. M., 2008 [Diversity, potential species and carbon content of mangrove forest at Subelen River, Siberut, West Sumatera]. Jurnal Penelitian Hutan dan Konservasi Alam 5(3):297–306. [In Indonesian]

Cameron C., Hutley L. B., Friess D. A., Brown B., 2019 High greenhouse gas emissions mitigation benefits from mangrove rehabilitation in Sulawesi, Indonesia. Ecosystem Services 40:101035.

Dharmawan I. W. E., Pramudji, 2014 [Guide for mangrove ecosystem monitoring]. CRITC COREMAP CTI LIPI, Bogor, 35 p. [In Indonesian].

Dharmawan I. W. S, Siregar C. A., 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. [In Indonesian].

Dinilhuda A., Akbar A. A., Jumiati, Herawati H., 2020 Potentials of mangrove ecosystem as storage of carbon for global warming mitigation. Biodiversitas 21(11):5353–5362.

Donato D. C., Kauffman J. B., Murdiyarso D., Kurnianto S., Stidham M., Kanninen M., 2011 Mangroves among the most carbon-rich forests in the tropics. Nature Geoscience 4(5):293–297.

Duarte C. M., Losada I. J., Hendriks I. E., Mazarrasa I., Marbà N., 2013 The role of coastal plant communities for climate change mitigation and adaptation. Nature Climate Change 3(11):961–968.

Efriyeldi E., Mulyadi A., Samiaji J., 2021 [The growth of Api-api (*Avicennia alba*) and benthic epifauna abundance of mangrove rehabilitated areas in Kedaburapat Village, Kepulauan Meranti District]. Dinamika Lingkungan Indonesia 8(2):113-122. [In Indonesian].

Farahisah H., Yulianda F., Effendi H., 2021 [Community structure, carbon stock, and mangrove economic valuation in Musi estuary]. Jurnal Ilmu Pertanian Indonesia 26(2):228–234. [In Indonesian].

Giesen W., Wulffraat S., Zierren M., Scolten L., 2007 Mangrove guidebook for Southeast Asia. FAO and Wetland International. RAP Publication, Bangkok, 769 p.

Hoque M. M., Kamal A. H. M., Idris M. H., Ahmed O. H., Saifullah, A. S. M., Billah M. M., 2015 Status of some fishery resources in a tropical mangrove estuary of Sarawak, Malaysia. Marine Biology Research 11(8):834-846.

Heriyanto N. M., Silvaliandra V., 2019 [Mangrove diversity and carbon stock in Lepar Pongok Islands, South Bangka District]. Buletin Plasma Nutfah 25(2):123–132. [In Indonesian].

Ilman M., Dargusch P., Dart P., Onrizal, 2016 A historical analysis of the drivers of loss and degradation of Indonesia’s mangroves. Land Use Policy 54:448–459.

Istomo, Kusmana C., Naibaho B. D., 2017 Biomass potential on several mangrove planting models in Java Island, Indonesia. AACL Bioflux 10(4):754–767.

Kangkuso A., Sharma S., Jamili, Septiana A., Sahidin I., Rianse U., Rahim S., Nadaoka K., 2018 Trends in allometric models and aboveground biomass of family Rhizophoraceae mangroves in the Coral Triangle ecoregion, Southeast Sulawesi. Journal of Sustainable Forestry 37(7):691–711.

Kauffman J. B., Donato D. C., 2012 Protocols for the measurement, monitoring and reporting of structure, biomass and carbon stocks in mangrove forests. Working Paper 86. CIFOR, Bogor, 40 p.

Kesuma R. A., Kustanti A., Hilmanto R., 2016 [Diameter increment growth of Bakau kurap (*Rhizophora mucronata*) in Lampung Mangrove Center]. Jurnal Sylva Lestari 4(3):97–106. [In Indonesian].

Komiyama A., Ong J. E., Poungparn S., 2008 Allometry, biomass, and productivity of mangrove forests: A review. Aquatic Botany 89(2):128–137.

Komiyama A., Poungparn S., Kato S., 2005 Common allometric equations for estimating the tree weight of mangroves. Journal of Tropical Ecology 21(4):471–477.

Krisnawati H., Adinugroho W. C., Imanuddin R., 2012 [Monograph: Allometric models for tree biomass estimation in various type of forest ecosystems in Indonesia]. Center for Research and Development of Conservation and Rehabilitation, Forest Research and Development Institute, Ministry of Forestry, Bogor, 119 p. [In Indonesian].

Kusmana C., Sabiham S., Abe K., Watanabe H., 1992 An estimation of above ground tree biomass of a mangrove forest in East Sumatra, Indonesia. Tropics 1(4):243–257.

Lee S. Y., Primavera J. H., Dahdouh-guebas F., Mckee K., Bosire J. O., Cannicci S., Diele K., Fromard F., Koedam N., Marchand C., Mendelsshon I., 2014 Ecological role and services of tropical mangrove ecosystems: a reassessment. Global Ecology and Biogeography 23(7):726–743.

Mandari D. Z., Gunawan H., Isda M. N., 2016 [Biomass and carbon stock estimation of mangrove ecosystem in Bandar Bakau Dumai]. Jurnal Riau Biologia 1(3):17–23. [In Indonesian].

Manuri S., Putra C. A. S., Saputra A. D., 2011 [Technique of Forest Carbon Stock Estimation]. Merang REDD Pilot Project. German International Cooperation – GIZ, Palembang, 91 p. [In Indonesian].

Murdiyarso D., Purbopuspito J., Kauffman J. B., Warren M. W., Sasmito S. D., Donato D. C., Manuri S., Krisnawati H., Taberima S., Kurnianto S., 2015 The potential of Indonesian mangrove forests for global climate change mitigation. Nature Climate Change 5(12):1089–1092.

Njana M. A., 2016 Indirect methods of tree biomass estimation and their uncertainties. Southern Forest: a Journal of Forest Science 79(1):41–49.

Noor Y. R., Khazali M., Suryadiputra I. N. N., 2012 [A Guidebook on mangrove in Indonesia]. PHKA/WI-IP, 3rd ed., Bogor, 220 p. [In Indonesian].

Rahardian A., Prasetyo L. B., Setiawan Y., Wikantika K., 2019 [A historical review of data and information of Indonesian mangrove area]. Media Konservasi 24(2):163–178. [in Indonesian].

Rahmanto B. D., 2020 [National mangrove map and the state of mangrove ecosystem in Indonesia]. Disampaikan Dalam Webinar Development for Mangrove Monitoring Tools in Indonesia, 22 p. [In Indonesian].

Rosoman G., Sheun S. S., Opal C., Anderson P., Trapshah R., 2017 The HCS approach toolkit. Module 1: The HCS approach: An introduction, overview and summary. HCS Approach Steering Group, Singapore, 27 p.

Salsabilli Rh. C. P. S., Widiastuti E. L., Wahyuningsih S., 2021 Carbon stock estimation due to changes in mangrove Labuhan Maringgai District, East Lampung Regency. International Conference on Sustainable Biomass (ICSB 2019), Atlantis Press, pp. 6–10.

Senoaji G., Hidayat M. F., 2016 [The role of mangrove ecosystem in the coastal city of Bengkulu in mitigating global warming through carbon sequestration]. Jurnal Manusia dan Lingkungan 23(3):327-333 [In Indonesian].

Sidik F., Supriyanto B., Krisnawati H., Muttaqin M. Z., 2018 Mangrove conservation for climate change mitigation in Indonesia. Wiley Interdisciplinary Reviews: Climate Change 9(5):1e529.

Srifitriani A., Parwito P., Supriyono S., Oktalia L., 2020 Mangrove density analysis using Landsat 8 the Operational Land Imager (OLI) a case study Bengkulu City. Sumatra Journal of Disaster, Geography and Geography Education 4(2):234-241.

Sugara A., Lukman A. H., Hidayat M. F., Nugroho F., Muslih A. M., Suci A. N. N., Anggoro A., Zuhendri R., 2022 Spatial distribution mapping and estimation of mangrove carbon stock using Sentinel 2B satellite image in Bengkulu City. Geosfera Indonesia (Under review).

Tiryana T., Rusolono T., Siahaan H., Kunarso A., Sumantri H., Haasler B., 2016 [Forest carbon stock and floristic diversity in South Sumatera]. Biodiversity and Climate Change (BIOCLIME) Project, GIZ BIOCLIME, Palembang, 70 p. [In Indonesian].

Wahyudi A. J., Afdal, Prayudha B., Dharmawan I. W. E., Irawan A., Abimanyu H., Meirinawati H., Surinati D., Syukri A. F., Yuliana C. I., Yuniati P. I., 2018 Carbon sequestration index as a determinant for climate change mitigation: Case study of Bintan Island. IOP Conference Series: Earth and Environmental Science 118(1):1–5.

Windarni C., Setiawan A., Rusita, 2018 [Carbon stock estimation of mangrove forest in Margasari Village, Labuhan Maringgai Subdistrict, Lampung Timur District]. Jurnal Sylva Lestari 6(1):66. [In Indonesian].

Zanne A. E., Lopez-Gonzalez G., Coomes D. A., Ilic J., Jansen S., Lewis S. L., Miller R. B., Swenson N. G., Wiemann M. C., Chave J., 2009 Global wood density database. https://datadryad.org/stash/dataset/doi:10.5061/dryad.234

Zurba N., Effendi H., Yonvitner, 2017 [Management of mangrove ecosystem potency in Kuala Langsa, Aceh]. Jurnal Ilmu dan Teknologi Kelautan Tropis 9(1):281–300. [In Indonesian].

*** BAPPENAS, National Development Agency, 2014 [A snapshot of regional action plan on reducing greenhouse gases emissions]. http://ranradgrk.bappenas.go.id/rangrk/admincms/downloads/publications/Potret_RAD-GRK.pdf. [In Indonesian].

*** BSN, National Standardization Agency, 2011 SNI 7724:2011 [Measurement and calculation of carbon stock–Field measurement for forest carbon stock estimation (ground-based forest carbon accounting)]. [In Indonesian].

*** IPCC, 2006 Guidelines for national greenhouse gas inventories. Volume 4, Agriculture, Forestry and Other Land Use. National Greenhouse Gas Inventories Programme. Egglestone H. S., Buendia L., Miwa K., Ngara T., Tanabe K. (eds). IGES, Japan, 83 p.

*** LIPI, Indonesian Institute of Sciences, 2018 [The potency of carbon stock and sequestration of mangrove and seagrass community in Indonesia]. http://oseanografi.lipi.go.id/haspen/01.%20Summary%20for%20policy%20maker-layout-20%20Juli-versi%20alfa%201.0%20release.pdf. Summary for policy maker. [In Indonesian].

*** MEA, Millennium Ecosystem Assessment, 2005 Ecosystems and Human Well-being: Biodiversity synthesis. World Resources Institute, Washington DC.

*** MoE, Ministry of Environment of Indonesia, 2004 [Ministerial decree No. 201/2004: Criteria and technical guide for evaluating mangrove forest in Indonesia]. [In Indonesian].

*** MoFE, Ministry of Forestry and Environment of Indonesia, 2020 [Report on greenhouse gases inventory and monitoring, reporting, verification (MRV) 2019]. Ministry of Forestry and Environment of Republic of Indonesia, Jakarta. [In Indonesian].

*** Regulation of Governor of Bengkulu No. 36 2018, [Sustainable development goals 2016–2021]. https://bappeda.bengkuluprov.go.id/wp-content/uploads/2018/08/RAD-TPB_SDGS-Provinsi-Bengkulu-tahun-2016-2021.pdf [In Indonesian].

*** UNEP, 2014 The importance of mangroves to people: A call to action. van Bochove J., Sullivan E., Nakamura T. (eds). United Nations Environment Programme World Conservation Monitoring Centre (UNEP-WCMC), Cambridge, 128 p.

Received: 05 April 2022. Accepted: 20 July 2022. Published online: 03 August 2022.

Authors:
Agung Hasan Lukman, University of Bengkulu, Faculty of Agriculture, Department of Forestry, Kandang Limun, Bengkulu 38371, Indonesia, e-mail: ahaslukman@unib.ac.id
Muhammad Fajrin Hidayat, University of Bengkulu, Faculty of Agriculture, Department of Forestry, Kandang Limun, Bengkulu 38371, Indonesia, e-mail: mfhidayat@unib.ac.id
Ayub Sugara, University of Bengkulu, Faculty of Agriculture, Department of Marine Science, Kandang Limun, Bengkulu 38371, Indonesia, e-mail: ayubsugara@unib.ac.id
Mochamad Candra Wirawan Arief, Padjadjaran University, Faculty of Fisheries and Marine Science, Department of Fisheries, Jatinangor, Sumedang 45363, Indonesia, e-mail: mochamad.candra@unpad.ac.id

How to cite this article:
Lukman A. H., Hidayat M. F., Sugara A., Arief M. C. A., 2022 Mangroves composition, biomass, carbon stock and their role in the climate change mitigation in Bengkulu City, Indonesia. AACL Bioflux 15(4):1975-1988.