Biomass carbon stocks in conserved and rehabilitated mangroves of Indonesia: case studies from Biduk-Biduk, Karimunjawa, Pati and Indramayu

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Abstract. Mangroves could potentially contribute to global climate change adaptation and mitigation by absorbing carbon with large amounts and storing it in the sediment and biomass for a long time. The purpose of this study is to estimate the potential stock of carbon and sequestration in conserved and rehabilitated mangroves. It was conducted at four locations including Biduk-Biduk, Karimunjawa, Pati, and Indramayu. The allometric equations method was used to calculate the potency of carbon stock and sequestration in the mangrove. Results show that mangroves in conservation areas have higher carbon stock and sequestration than mangroves in rehabilitated areas. Mangrove in Karimunjawa has higher diversity but the total carbon stock are lower than Biduk- biduk which has total carbon storage of 1,266,997.73 Mg C which potentially absorb 4.65 t CO_2e. Total carbon stock in Pati and Indramayu (rehabilitated mangroves) ranged from 2,878.31 to 43,885.63 Mg C which potentially absorb 0.01 to 0.16 t CO_2e. Regression analysis showed a positive correlation between mangrove density and carbon stock in conserved and rehabilitated mangroves. The results show that conserved mangroves are more effective in absorbing and storing carbon than rehabilitated mangroves. Monitoring of rehabilitated mangroves is important to maintain and enhance carbon absorption and storage.

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1 Introduction

Mangrove ecosystems are one of the ecosystems at coast that naturally contribute to climate change adaptation and mitigation efforts. The mangroves ability to store carbon is more effective than tropical forests [1–3]. Mangrove ecosystem was estimated to contribute about 5.03 Pg or 10-15% of the total global carbon storage (aboveground, belowground biomass and soil) in coastal areas, and Indonesian mangrove stored a quarter of this value [4,5]. Mangrove potentially store large amounts of carbon stock [6], It could absorb and store carbon in its biomass such as stems, leaves, branches, and roots. This can reach 77.9% of total carbon, while carbon stored in sediments reaches 39% [7]. Therefore, mangroves can potentially reduce emissions that trigger global warming in the atmosphere.

Conserved mangroves as a nature-based ecosystem have potential natural resources, high diversity and significant capacity to store and absorb carbon for a long period [8]. According to [9], Indonesia has a mangrove ecosystem in a conservation area of about 22%, it provides 0.82-1.09 Pg C ha^{-1}. Additionally, Rehabilitated areas also provide ecosystem services which contribute to climate change adaptation and mitigation, including resilience strengthening and capturing carbon [10]. Mangroves in rehabilitated areas are highly productive [11] and estimated it has a capacity of carbon sequestration rate averaging around 6-9 Mg CO_2 e/ha [12].

The Indonesian government has incorporate mangroves as one of the integrated sectors in the national Sustainable Development Goals (SDGs) strategy. It is important to carried out for support national strategies, especially addressing climate change (SDGs 13) and maintaining marine ecosystems (SDGs 14), which focus on climate resillience and marine ecosystem preservation. A sustainably maintained mangrove ecosystem will be able to absorb and store carbon for a long time. However, if mangrove ecosystems continue to be degraded, carbon would be oxidized and released back to the atmosphere contributing to climate change.

Anthropogenic factors, which also influence the mangrove ecosystem, must be taken into account in efforts to maintain and preserve the existence of ecosystems of mangrove. The area of mangrove forests in the tropics has decreased up to 50% in the last 50 years due to the development of areas of coastal land, land conversion to agriculture, aquaculture, urban development, excessive logging, also environmental pollution [2,13] .

Indonesia has lost mangrove estimated at 182.091 ha totalled from 2009 to 2019 with a rate of deforestation about more than 18,000 ha yr^{-1} [14] and a total loss of mangrove cover of 40% in the past three decades [5]. Mangrove deforestation and land conversion can cause seawater intrusion, coastal erosion, decreased coastal water productivity, reduced carbon sequestration from the atmosphere and carbon dioxide emissions [2]. The decrease of mangroves is still increase along with the growth and development of settlements in coastal areas. [14].

Globally, the reduction of Indonesia's mangrove forests area contributes to carbon 42% emissions of global greenhouse gas. Indonesia’s annual emissions from mangrove deforestation account for up to 20% of total converted emissions [5]. According to [15] Indonesia has the highest potential soil carbon emissions of 3410 Gg CO_2 yr^{-1}. Therefore, Indonesia needs to reduce deforestation and land conversion to decrease greenhouse gas emissions through the regulations and implementation activities to protect mangrove ecosystems.

Damaged mangrove forests can be naturally restored through secondary succession in a period of 15-20 years supported by unchanged tidal conditions and the availability of seeds (propagules) or seedlings [16]. Rehabilitation also needs to be attempted to restore environmental to their original natural condition, so it is important to apply to degraded coastal areas. In the form of conservation and rehabilitation, the protection and

sustainability of mangrove management needs to be prioritized to reduce emissions of carbon to mitigate climate change.

The aims of this research were to compare carbon stocks and sequestration of mangrove biomass in conserved and rehabilitated mangrove areas where there are still limited reseriach. The outcome of this research would increase human understanding of the importance of conservation.

2 Material and methods

2.1 Study site

This study was conducted in four locations, namely Biduk-Biduk (North Kalimantan), Karimunjawa Island, Pati Regency and Indramayu Coast in 2016 (Fig 1). Biduk-Biduk and Karimunjawa represent conserved mangroves while Pati and Indramayu represent rehabilitated mangroves. The purpose of selecting the location is to analyze carbon stock and sequestration stored in protected and rehabilitated mangrove ecosystems. Mangrove observations in Biduk-Biduk were conducted at 21 stations, Karimunjawa Island at 8 stations, Pati at 5 stations and Indramayu at 10 stations.

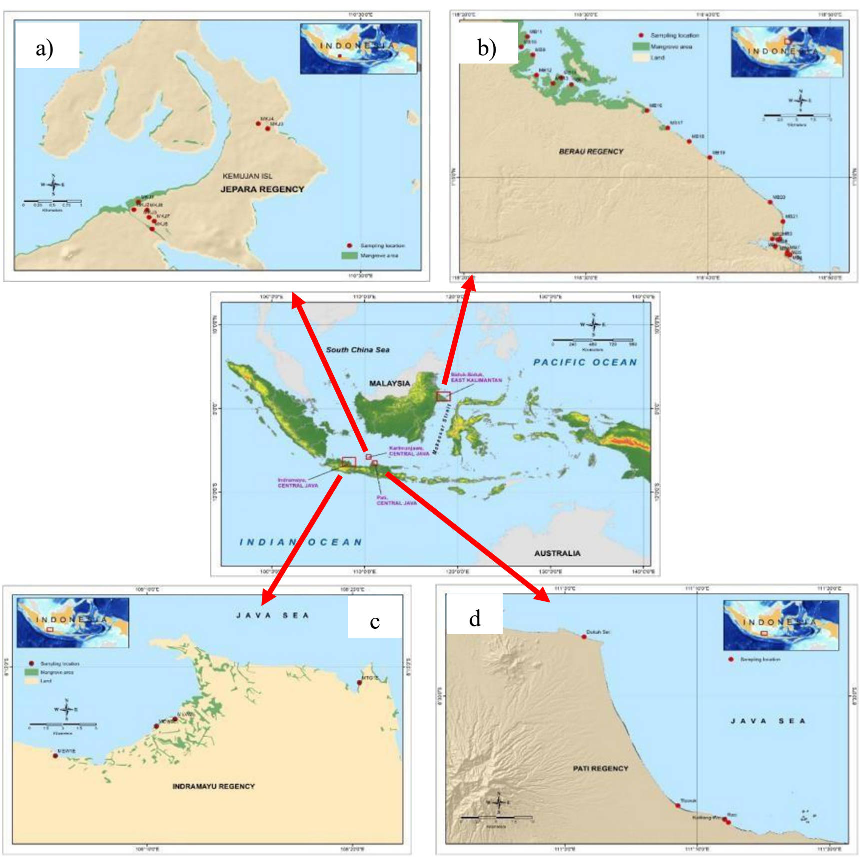

Fig 1. Research site in a) Biduk-Biduk ; b) Karimunjawa ; c) Pati and d) Indramayu

2.2 Methods

The data was collected using purposive sampling method. Sampling was conducted using the 100m transect line for each station, with 5 subplots measuring 10x10m. In each subplot, we identified the mangrove species and conducted the diameter breast height (DBH) measurement at ±1.3 m from the ground level in parallel and the same direction. Measurements were taken on each tree with a diameter of >10 cm. Mangrove growth performance was also calculated to describe species composition, including importance value index, richness, and evenness.

2.2.1 Biomass

The measurement of DBH was used to obtained biomass value of mangroves including biomass at above and belowground. Next, we calculated using the equation of allometric in each type of mangrove followed as references from [3,17–20].

2.2.2 Carbon stock

The estimated stock of carbon per species were calculated by doing multiplying the biomass (above and belowground) by the concentration of carbon (%). It can be estimated from the biomass of leaves, stems, flowers and fruits or general percent carbon assumption. This study used general percent carbon to estimate above and belowground biomass carbon stock. The dry weight of the component of carbon storage in a particular area was then converted to its value of carbon with the following equation [20]:

$$C \text{ aboveground} = W_1 \times 50\% \quad (1)$$
$$C \text{ belowground} = W_2 \times 39\% \quad (2)$$

where:
C = carbon stock (tons ha^{-1})
W_1 = above ground biomass (tons ha^{-1})
W_2 = belowground biomass (tons ha^{-1})

then conversion to Mg C ha^{-1} :

$$\text{carbon biomass (kgC/ha)x(Mg/1000kg)x(10.000m}^2\text{/ha)} \quad (3)$$

2.2.3 Carbon sequestration

Carbon stock data is used to determine carbon sequestration converted using the following equation:

$$CO_2 = (Bm.\ CO_2/Ba.\ C) \times C \quad (4)$$

where:
CO_2 = carbon sequestration (tonnes ha^{-1})
Bm. CO_2 = weight of C molecular (44)
Ba. C = weight of C atom (12)
C = carbon stock (tons ha^{-1})

3 Results and discussion

3.1 Description of Study site

Mangrove in Biduk-Biduk District – East Kalimantan were relatively in stable condition because this ecosystem is located in the protected area (MPA-Marine Protected Area). Mangroves can be found in Sulaiman Bay, Giring-giring, Biduk-Biduk, Pantai Harapan and Tanjung Perepat [21]. The mangrove ecosystem in Biduk-Biduk adjacent to the Sulawesi Sea and the Makassar Strait where socio-economic development activities continue to develop.

The Karimunjawa mangrove area is part of the Marine National Park and included in the protected area**.** Mangrove forests in the Karimunjawa National is in typical forests located along the river estuaries and coast affected by the tides [22]. Kemujan Island has a wide mangrove forest in the Karimunjawa Islands.

The mangrove ecosystem in Pati Regency needs more attention. The total area of mangroves along the coast of Pati within 7 sub-districts, (namely Tayu, Dukuhseti, Trangkil, Margoyoso, Juwana, Wedarijaksa, and Batangan) is only 162.64 ha [23]. Mangroves in Pati grow in river estuary areas with tidal mudflats. The local people in Pati Regency depend their daily lives on coastal areas as their source of income.

The mangrove ecosystem in Indramayu can be found in 4 sub-districts, namely Cantigi, Kandanghaur, Losarang and Sindang Districts. The conversion of mangroves into ponds has occurred along the coast of Java Island, including Indramayu Regency. The mangrove area of Cantigi District has experienced degradation and decrease in area due to abrasion, sedimentation, land conversion and differences in perception between the community and mangrove ecosystem management.

3.2 Mangrove species composition and growth performance

Conserved mangrove in Biduk-Biduk consists of 8 species of mangrove namely (*Aegiceras floridum, Bruguiera gymnorhiza, Rhizophora mucronata, Rhizophora apiculata, , Sonneratia alba, Lumnitzera littorea, Xylocarpus rumphii, Xylocarpus granatum*). Karimunjawa consists of 10 species (*Rhizophora apiculata*, *Sonneratia Alba*, *Ceriops tagal*, *Exoccaria agallocha*, *Xylocarpus granatum*, *Rhizophora mucronata*, *Xylocarpus moluccensis*, *Lumnitzera racemosa*, *Bruguiera gymnorhiza*, *Scyphipora hidrophyllaceae*).

Meanwhile, the composition of mangrove species in rehabilitated areas is lower than in conserved mangroves. There were 3 species of mangroves found in Pati district (*Rhizophora apiculata, Avicennia alba*, and *Rhizophora mucronata*) and 6 species in Indramayu (*Avicennia alba , Avicennia marina, Rhizophora mucronata*, *Rhizophora stlosa*, *Rhizophora apiculata*, *Xylocarpus granatum*).

The important value index (IVI) indicates the dominance or importance of a species in a community. IVI result shows the mangrove conservation area in Biduk-Biduk has two important mangrove species that dominate with an important index value of 117% and 106% from *R.mucronata* and *S. alba*, respectively with a DBH range of around 5.35-7cm for *R.mucronata* and *S. alba* range of 16-102cm. Karimunjawa has three types of dominant mangroves with a high important value index of 100.36% from *C. tagal*; 73.48% from *R. apiculata* and 70.44% from *E.agallocha* with an average DBH range of 1.2-50.3cm.

Rehabilitated mangroves have different conditions from conservated mangroves. Mangroves in rehabilitation areas grow densely with a short distance so that they have a relatively lower range of stem diameters than mangroves in conservation areas. Mangroves in Pati have an important index value of 5.39-266.88%. The highest score was recorded

from mangrove-dominant *A. alba* (266.88%) and *R. mucronata* (27.73%) with an average of DBH about 6.07cm. Meanwhile, mangroves in Indramayu have three important types of mangroves, namely *A. marina* (111.82%) as dominated species; *R. stylosa* (70.33%) and *R. mucronata* (63.94%) with an average DBH of 6.11 cm.

Mangrove growth performance analysis indicates the interesting point where Pati district as a representation of rehabilitated mangrove have a high average importance value index, with three types of mangrove. The conservation mangroves have a lower important index value than rehabilitation mangroves with a value of 38% in Biduk-Biduk, 30% Karimunjawa, 100% Pati and 50% Indramayu. However, the composition of mangroves in conservation areas is more diverse and grows with a larger diameter (Fig.2).

This result related to Kepel's research [24] which stated that mangrove sediments in Pati have a high value compared to the other three locations (Biduk-Biduk, Karimunjawa and Indramayu). The bulk density value of mangrove sediments in Pati was in the range of 0.71-0.85 g/m3 while the other three locations were in the range of 0.46-0.72 g/m3. This might be due to the increasing compaction in the inner sediment so that the bulk density value in the inner sediment is relatively high and also the accumulation of high litter on the surface sediment.

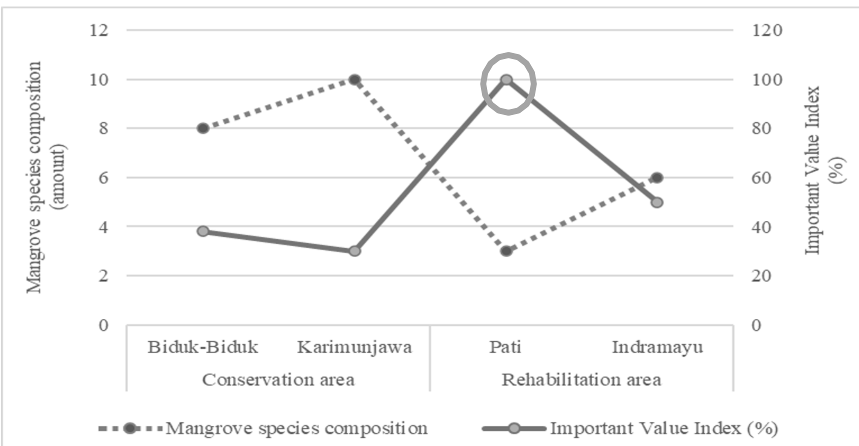

Fig 2. Mangrove species composition and important value index

The ecosystem's vegetation, leaf litter from aboveground, and fine roots from belowground that have decomposed due to microbial activity and soil environmental conditions are all interrelated in terms of soil carbon dynamics. This chemical composition process plays a role in determining the organic carbon stored in the soil. [25]. Therefore, intertidal sediments provide a major carbon sink than biomass vegetation [26].

An ecosystem's vegetation is always subject to environmental influences. Differences in the mangrove species and depth of the substrate cause the dominant vegetation that grows at various growth levels in an area to be different [27]. Mangrove in Pati has a clay substrate suitable for the growth of *Avicenniae* as the single largest family which has longitudinal roots, besides that this type is highly tolerant to salinity. According to [28] community structure of vegetation is specified by the diversity of species. It provides an indication of functional capacities like contribute to climate change due to potential high on carbon storage.

3.3 Carbon stocks in mangrove biomass

The carbon stored in the upper biomass came from stems, leaves, flowers and fruits while the lower biomass was from roots. Figure 3 and Table 1 present the results of the total mean value of stocks of carbon in the above and belowground biomass in each location. The analysis of biomass mangroves shows that the conserved mangroves have the highest value of stock of carbon in the above and belowground biomass compared to rehabilitated mangrove area.

Biduk-Biduk and Karimunjawa have mangrove area around 5867.85 ha and 420.05 ha, respectively while Pati and Indramayu in rehabilitated area have mangrove area around 78.7 ha and 786.12 ha, respectively.

Table 1. Mangrove stand and carbon stock in conserved and rehabilitated area

Study sites		Mangrove stand (ind)	Carbon stock (Mg C ha $^{-1}$)	Total carbon storage (Mg C)
Conservation area	Biduk-Biduk	1359	215,92	1,266,997.73
	Karimunjawa	1028	135,87	57,070,37
Rehabilitation area	Pati	850	36,57	2,878.31
	Indramayu	2004	55,83	43,885.63

Mangroves in Biduk-Biduk had higher carbon stock which have 1,359 stands, it can store carbon of 215.92 Mg C ha^{-1} with a total aboveground deposit of 138.59 Mg C ha^{-1} and a belowground of 77.33 Mg C ha^{-1}. The estimated total mangrove carbon stock of Biduk- biduk was 1,266,997.73 Mg C.

Karimunjawa has a carbon stock of 135.87 Mg C ha^{-1} from 1,028 stands with a total aboveground deposit of 91.25 Mg C ha^{-1} and a belowground of 44.61 Mg C ha^{-1}, the total carbon stock that has been converted to a mangrove area of 57,070.37 Mg C.

Rehabilitated mangrove shows lower stores amounts of carbon stock. Mangroves in Pati rehabilitation area grow at a close distance with the DBH size of trees in the range of 6.07cm. The results showed that as many as 850 trees have carbon stock of 36.57 Mg C ha^{-1} with aboveground carbon of 29.76 Mg C ha^{-1} and belowground carbon of 6.81 Mg C ha^{-1}. The total carbon storage of mangrove stock in Pati is 2,878.31 Mg C.

This value has a low range when compared to mangroves in Indramayu with a total of 2,004 stands, and carbon stock of 55.83 Mg C ha^{-1} with aboveground deposit of 40.93 Mg C ha^{-1},and belowground of 14.90 Mg C ha^{-1} and a total carbon storage of 43,885.63 Mg C.

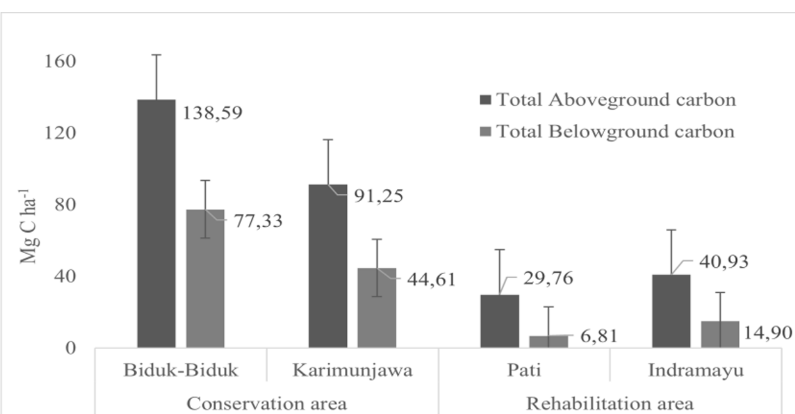

Fig 3. Total carbon stock in belowground and above biomass mangrove at the study sites

Figure 3 provides the value of biomass mangrove carbon stock in conservation areas is higher than rehabilitated mangroves. This result related with other study which analyse carbon sediment at Biduk-Biduk, Karimunjawa, Pati and Indramayu [24] that mentioned carbon storage in sediments in conservation areas is larger than in rehabilitation areas. The concentration of sedimentary carbon storage in Pati mangroves was ranged from 13.71-17.14%, Biduk-Biduk ranged from 12.54-15.16%, Karimunjawa ranged from 1.75-2.25% and Indramayu ranged from 12.54%-15.16%.

Mangroves in the rehabilitated areas are low in store and absorb, it may cause being planted at a close distance. So, mangrove grew with small stems, as seen from the average range of tree diameters in Indramayu and Pati.

According to [5] mangroves in conservation areas in Indonesia potentially store 0.82-0.89 Pg C ha^{-1} of carbon stock. Regarding [9] mentioned that mangrove ecosystem in Indonesia is preserved in conservation areas and provides about 22% or 0.82-1.09 Pg C ha^{-1} carbon stock. The carbon stock value on both study sites (conserved and rehabilitated mangrove) shows that mangrove carbon stock in the conserved area is in value of natural mangrove forest. There is a difference between carbon stock values in conserved and rehabilitated areas. Based on [9], carbon stock in conserved areas is produced higher than in rehabilitated mangrove areas. Carbon stock in the conserved mangrove area estimated of 171±43 Mg C ha^{-1}, while the area of rehabilitated mangrove is 52±15 Mg C ha^{-1}. The stock of mangrove carbon value in this study is still higher than tropical forests in the world which range from 243 t ha^{-1} [29].

3.4 Regression between mangrove density and carbon stock

The regression equation was obtained from mangrove density and carbon content at each study site. Biduk-Biduk and Karimunjawa represent conservation areas while Pati and Indramayu represent rehabilitation areas. The determination coefficient (r2) shows a close relationship between the two variables tested. The correlation of carbon stock and mangrove density at each location provided in Figure 4.

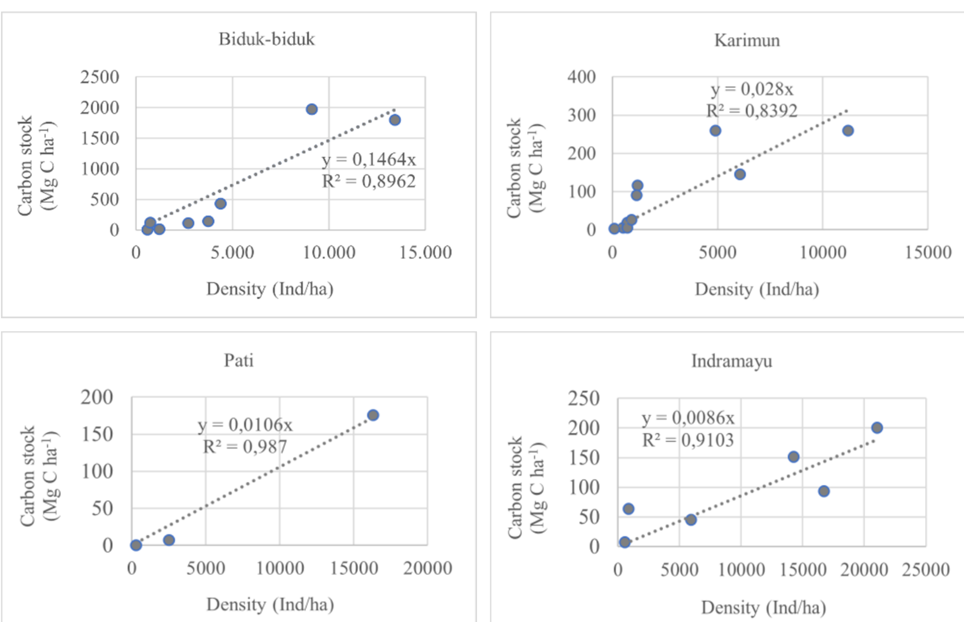

Fig 4. Regression between mangrove density and carbon stock at the study sites

The correlation value can be interpreted as the relationship between the two variables tested. This study showed a very strong and closely related relationship between the mangrove density and carbon stock in conservation and rehabilitation areas. DBH in mangrove ecosystem may determine a positive correlation with biomass and carbon stocks [30]. Based on this result, carbon stock value also has positive correlation with tree size, where the larger tree size and mangrove stand produced massive biomass and stocks of carbon.

The species composition in the ecosystem of mangrove plays a important role in carbon sequestration. Table 2 shows that *the Rhizoporaceae* family has high values of aboveground (ABG) and belowground (BLG) in conserved areas and *Avicenniaceae* in rehabilitated areas. Due to each species carbon storage capacities, these data can be used to select mangrove species for both conservation and rehabilitation projects.

Table 2. Mangrove species with a large amount of carbon stock at study sites

Study sites		Mangrove species	ABG carbon (Mg C ha^{-1})	BLG carbon (Mg C ha^{-1})
Conservation area	Biduk-Biduk	*Rhizophora mucronata*	1396.39	400.57
		Sonneratia alba	1079.51	889.89
	Karimunjawa	*Rhizophora apiculata*	123.69	135.42
		Ceriops tagal	191.92	67.77
Rehabilitation area	Pati	*Avicennia alba*	144.39	31.52
	Indramayu	*Avicennia marina*	167.07	33.54
		Rhizophora stylosa	108.60	42.55

*ABG =aboveground; BLG = belowground

3.5 Carbon sequestration in study sites

Result showed maximum carbon sequestration in mangrove Biduk-Biduk, which could potentially sequester 4.65 t CO_2e. The amount of absorption in this location is higher compared to Karimunjawa (0.21 t CO_2e), Pati (0.01 t CO_2e) and Indramayu (0.16 t CO_2e).

One of the factors that affects the amount of carbon absorbed is the size of the tree diameter. Mangrove in Biduk-Biduk has a DBH range of 10-320cm, while Karimunjawa has DBH range 1.2-50.3cm, Pati 6.07cm and Indramayu 6.11cm. According to [28], the age of the tree has a high influence on the potential for increased carbon sequestration in vegetation.

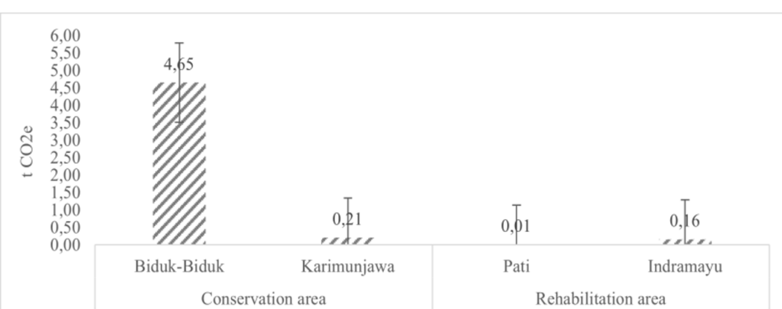

Fig 5. Carbon sequestration at the study sites

Mangroves can store carbon up to 1,000 tonnes per hectare in their biomass and soils [15]. Biduk-Biduk has a mangrove area of around 5867.85 ha and estimated that the carbon stock stored is 1,266,997.73 Mg C. The carbon stock in mangrove Biduk-Biduk is a massive amount. It makes conserved mangroves like Biduk-Biduk and also karimunjawa a critical asset in climate change. Carbon sequestration in conservation areas such as Biduk-Biduk and Karimunjawa can be even greater if the mangroves are not reduced. In fact, at the field, many large mangrove trees were cut down especially in Biduk-Biduk. Deforesting mangroves can affect carbon release into the atmosphere and decrease the amount of carbon sequestration

Based on data from [31] mentioned that if coastal ecosystems decreased can cause carbon dioxide gas to be released as much as 0.15-1.02 billion tons per year. Globally, the decline in mangroves area, tidal swamps, and seagrass area is only 2-6% of the area of tropical forests, but the degradation of these ecosystems causes up to 19% of carbon emissions from deforestation globally.

Natural mangrove provides an average of 14% of sequestration of carbon in the world than other coastal ecosystem [32]. Rehabilitated mangrove could provide an effective carbon storage like mangrove in conservation area if they have more capacity to store and absorb [33].

Rehabilitated mangrove in Pati and Indramayu still have a potential carbon sequestration function while the value is lower than conserved area. Both these locations are experiencing environmental degradation like high levels of coastal erosion and land conversion. Therefore, mangrove restoration in Pati and Indramayu must be prioritized in order to have opportunity to restore carbon sequestration function through rehabilitation programs.

Rehabilitated mangrove could be implemented with priority focus on critical condition areas such as ecological and services function, biophysical assessment and economic function [34] such as Pati and Indramayu. The improvement of rehabilitation techniques is also important to be consider as a key factor for successful restoration such site selection, planting propagule of dominant species, timing and distance due to planted mangrove can grow optimal [35] with a larger stem diameter, because it may increase carbon store and absorb capacity.

Conserved and rehabilitated mangroves provide potentially massive carbon sequestration, this condition can promote to estimate mangrove carbon price under the payment for ecosystem services mechanisms (PES) [36].

4 Conclusion

In conclusion, mangrove Biduk-Biduk in conservation area has the highest carbon sequestration value of 4.65 t CO_2e while Karimunjawa as conserved mangrove and rehabilitated mangrove showed the lowest value. It means that conserved mangroves are more effective in absorbing and storing carbon than rehabilitated mangroves. However, mangrove in Biduk-Biduk was also threatened due to illegal logging. Rehabilitated mangrove also plays an important role because mangrove in Pati has a highly important value index and mangrove in Indramayu has higher carbon stock and storage than in Pati. The mangrove plantation mangrove program needs to consider the planting distance, so that mangroves can grow optimally with a large stem diameter. The results showed a significant correlation between biomass and carbon sequestration capacity. Mangrove conservation and management programs need to periodically monitor, and community participation needs to be promoted to increase awareness about the importance of conservation of mangrove and the effect of land conversion that caused mangrove degradation. Initiative

programs through education and involvement of local communities on the value of mangrove, conservation and rehabilitation must be carried out continuously to increase awareness and sustainability. Continuous assessments will help ensure that rehabilitated areas develop optimally and effectively contribute to climate goals. Long-term strategies that consider both ecological and socio-economic factors are needed to balance mangrove protection with economic activities in coastal areas. It is important to integrate mangrove protection and coastal management to support national and international efforts in mitigation of climate change and adaptation in coastal areas. This result can be used for effective conservation and management policies in coastal ecosystems, especially for mangrove protection and restoration.

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