EREM 79/3

Journal of Environmental Research,
Engineering and Management
Vol. 79 / No. 3 / 2023
pp. 24–34
DOI 10.5755/j01.erem.79.3.33123

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Received 2023/01 | Accepted after revisions 2023/05

https://doi.org/10.5755/j01.erem.79.3.33123

Species Composition and Carbon Stock of Rehabilitated Mangrove Forest in Kupang District, East Nusa Tenggara, Indonesia

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Since 1994, the community around the mangrove forest in Kupang District, East Nusa Tenggara Province, Indonesia, has rehabilitated the mangrove forest. Unfortunately, almost three decades of the success story of mangrove rehabilitation has not followed appropriate documentation on biodiversity and potential carbon stock. This research aimed to describe the species composition and estimate the carbon stock of rehabilitated mangrove forests. Forty-five sampling plots were distributed using purposive sampling based on mangrove zonation (distal, middle, proximal) and year of rehabilitation (2004, 2006, 2008). The findings revealed that there are ten mangrove species. Two species, namely *Avicennia marina* and *Sonneratia alba*, showed a high importance value index. The average aboveground carbon stock was 454.712 t/ha, distributed in seedlings, saplings, poles, and trees at 0.04%, 2.41%, 51.61%, and 45.94%, respectively. Mangrove rehabilitation in Kupang district, East Nusa Tenggara Province, has successfully increased the richness, heterogeneity, and carbon stock.

Keywords: biodiversity indices, climate change mitigation, vegetation diversity, wetland ecosystem.

Introduction

Mangrove rehabilitation was one of the essential issues at the G20 summit meeting in Bali, Indonesia, in December 2022. President of the Republic of Indonesia, H. E. Joko Widodo, invited the leaders of G20 to plant mangroves as a side event of the G20 summit meeting. The government of the Republic of Indonesia, through the Ministry of Environment and Forestry (MoEF), has set an ambitious target to rehabilitate 600,000 ha of mangrove forest by 2024 (Nurbaya et al., 2022).

To realize the ambitious target, the government needs tremendous efforts, including support from the community around the mangrove forest. To increase the community participation to support the mangrove rehabilitation program, Indonesia's government has issued a social forestry scheme that allows the community to develop ecotourism in rehabilitated mangrove forest areas (Nurbaya et al., 2022). Community forestry has been an essential strategy for promoting mangrove rehabilitation (Hagger et al., 2022).

In general, Indonesia's community empowerment strategy surrounding mangrove forests is collaborative mangrove forest management, such as ecotourism activity. Mangrove forest for ecotourism has benefited the economy and ecology (Harahab et al., 2021; Sumarmi et al., 2022; Utami et al., 2022). For example, a small mangrove area in Cirebon district, West Java, Indonesia, provides a suitable habitat for flora and fauna and the potential for an ecotourism site (Purwanto et al., 2021, 2022). Mangrove ecotourism has been applied not only in Java island, but also in West Sulawesi (Malik et al., 2019), Maluku (Arkwright and Kaomaneng, 2018), Sumatra (Sahputra et al., 2022; Subadyo and Aini, 2022), Kalimantan (Subadyo and Aini, 2022), and Nusa Tenggara (Sukuryadi et al. 2021a; Sukuryadi et al., 2021b).

Another strategy to attract community participation around the mangrove forest is mangrove rehabilitation projects. During the pandemic of COVID-19, the government of Indonesia issued a social safety net program through National Economic Recovery Program (*Program Pemulihan Ekonomi Nasional*/PEN) in 2020 (Kementerian Lingkungan Hidup dan Kehutanan, 2021). Mangrove rehabilitation in the PEN program has to replant 17,241 ha of mangrove forest, and 2965 people have been trained to enhance their capacity through agroforestry/silvofishery/silvopasture and non-timber forest products utilization programs (Kementerian Lingkungan Hidup dan Kehutanan, 2021). The mangrove rehabilitation project is also conducted by the private sector using the corporate social responsibility (CSR) program or funded by the local government.

The local community has conducted mangrove rehabilitation in Nusa Tenggara Province (Sadono et al., 2020a) in the natural and planted mangrove ecosystem (Matatula et al., 2021). Furthermore, Sadono et al. (2020a) described the initial mangrove rehabilitation in the Southeastern Gulf of Kupang East Nusa Tenggara in 1994 by the local community as a voluntary activity. Since 2004, the Kupang district government has provided financial support, and Politeknik Pertanian Negeri Kupang has assisted the local community with technical knowledge of mangrove rehabilitation. The collaboration between the community and local government will benefit the mangrove forest by reducing mangrove degradation and preserving the mangrove ecosystem (Cudiamat et al., 2022).

For almost three decades, mangrove rehabilitation in the Kupang district has been developed. However, the information on environmental services of rehabilitated mangroves, either biodiversity or carbon stock, is unavailable. This study aimed to describe the species composition and carbon stock of rehabilitated mangrove forests in the Kupang district.

Methods

Research site

The research was conducted in a mangrove forest in Kupang district, East Nusa Tenggara, Indonesia. Nusa Tenggara Islands has been classified as a dry region where the average precipitation in 2021 was 166 mm per month, with a precipitation rate above 100 mm per month occurring for six months (Badan Pusat Statistik Provinsi Nusa Tenggara Timur, 2022). During 2018–2020, the average temperature was 27.7°C, and the humidity was 76.7% (Badan Pusat Statistik Kota Kupang, 2022). Topographically, most of the mangrove forest slope in Kupang district is 0–3% (Sadono et al., 2020a). The research site is displayed in *Fig. 1*.

Fig. 1. *Map of the research site*

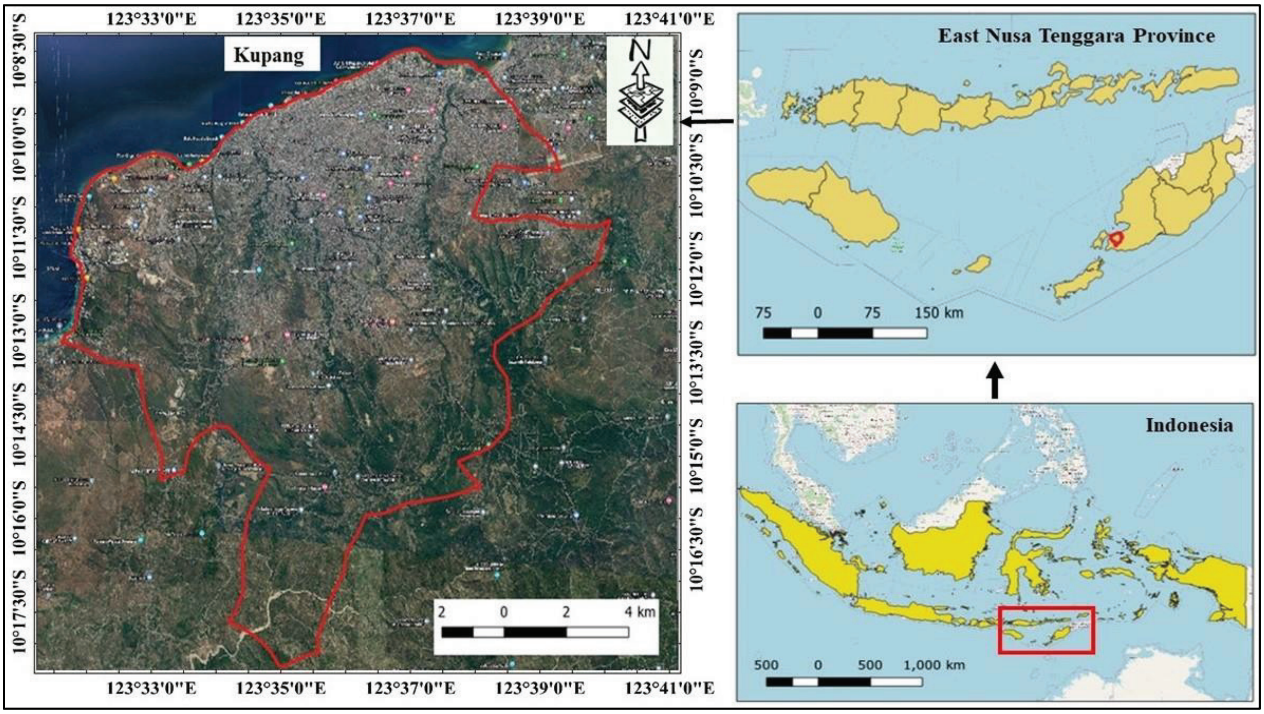


Table 1. *Sampling plot distribution in the mangrove forest*

		Year of rehabilitation			Total
		2004	2006	2008	
Zone	Distal	5	5	5	15
	Middle	5	5	5	15
	Proximal	5	5	5	15
Total		15	15	15	45

Data collection

Data on species composition and carbon stock were collected through the survey method. Fieldwork was conducted at the mangrove forest of Kupang district, East Nusa Tenggara, in 2022. Mangrove forest in Kupang district was affected by seawater from the gulf of Kupang and freshwaters from some watershed areas (Konkreo, Osmo, Namosain, Oebobo, Tuai, and Batugang). Mangrove forest inventory was done using 45 sampling plots placed using purposive sampling. The criteria of sampling plots should represent the mangrove zonation and year of rehabilitation.

According to Matatula et al. (2019, 2021) and Sadono et al. (2020b), the measurement of biodiversity, physico-chemical conditions, and species composition in the mangrove forest at Nusa Tenggara Timur has been divided into three zones, namely front, middle, and back zone. Mangrove zonation is important because each zone has different vegetation composition (Candri et al., 2020; Kusumaningtyas et al., 2019; Poedjirahajoe et al., 2017).

In this research, the mangrove forest in Kupang district is also grouped by year of rehabilitation into 2004, 2006, and 2008. The classification mangrove ecosystem by year of rehabilitation was used to describe the vegetation composition and its productivity in producing extractive compounds (Poedjirahajoe et al., 2011). Thus, in this research, there were 45 sampling plots distributed based on zonation and year of rehabilitation (*Table 1*).

Referring to Indonesian National Standard on ground-based forest carbon accounting, the sampling plot shape was nested sampling where the sub-plot for seedlings, saplings, poles, and trees were 4, 25, and 100 m^2 (Badan Standarisasi Nasional, 2011). The nested sampling has been applied to estimate forest carbon stock and species composition in mangrove forests (Matatula et al., 2021; Purwanto et al., 2021; Sadono et al., 2020b), forest plantation (Mulyana et al., 2020; Sadono et al., 2021), natural forest (Nugroho et al., 2022), and community forest (Wirabuana et al., 2021a; Wirabuana et al., 2021b). Data collection from the sampling plot to describe the species composition and estimate carbon stock included species names, species density, diameter at breast height (DBH), and total height.

Data analysis

The data of the mangrove forest inventory was analyzed to describe the biodiversity indices and estimate carbon stock. Biodiversity indices, namely importance value index, richness, heterogeneity, and evenness, have been applied in Indonesia for tropical rain forests (Nugroho et al., 2022), mangrove forests (Matatula et al., 2021; Sadono et al., 2020), mining reclamation area (Nugroho et al., 2021; Suyanto et al., 2022), and community forest (Wirabuana et al., 2021). The equation to calculate the richness, heterogeneity, and evenness (Shannon and Weaver, 1949; Margalef, 1958; Pielou, 1966) can be displayed as follow:

$$Species\ density = \frac{number\ of\ individual}{sampling\ plot\ size} \quad (1)$$

$$Relative\ density = \frac{species\ density}{Total\ species\ density}\ x\ 100 \quad (2)$$

$$Species\ frequency = \frac{number\ of\ plot\ the\ species\ exist}{total\ sampling\ plot} \quad (3)$$

$$Relative\ frequency = \frac{species\ frequency}{Total\ species\ frequency}\ x\ 100 \quad (4)$$

$$Species\ dominance = \frac{Total\ basal\ area\ of\ species}{Total\ sampling\ plot} \quad (5)$$

$$Relative\ dominance = \frac{species\ dominance}{Total\ species\ dominance}\ x\ 100 \quad (6)$$

$$Important\ value\ index = relative\ density + + relative\ frequency + relative\ dominance \quad (7)$$

$$Dmg = \frac{S-1}{\ln(N)} \quad (8)$$

$$H' = \sum\left(\frac{n_i}{N}\ x \ln\frac{n_i}{N}\right) \quad (9)$$

$$J' = \frac{H'}{\ln(S)} \quad (10)$$

where: *Dmg* – Margalef index for species richness; *H'* – Shannon-Winner index for species heterogeneity; *J'* – Pielou-Evenness index for species evenness; *n* – number of trees for each species; *N* – total tree population; *S* – number of species.

Carbon storage was estimated using the allometric equation for saplings, poles, and trees. At the same time, the carbon storage of seedlings was calculated by multiplying the number of species by 0.009 kg/seedling (Mulyana et al., 2021). The allometric models to estimate the aboveground carbon stock of mangrove species have used some equations (*Table 2*). The carbon stock on mangrove plants was calculated by multiplying dried-weight biomass with the percentage carbon content. In this research, the value percentage of carbon content was 50% (Intergovernmental Panel on Climate Change, 2006).

Table 2. *The allometric equation to estimate aboveground carbon of mangrove species*

Species	Equations	References
Rhizophora mucronata	Y = 0.251 ρ $D^{2.46}$	Komiyama et al. (2005)
Avicennia marina	Y = 0.251 ρ $D^{2.46}$	Komiyama et al. (2005)
Avicennia Alba	Y = 0.251 ρ $D^{2.46}$	Komiyama et al. (2005)
Soneratia spp	Y = 0.258 $D^{2.287}$	Kusmana et al. (2018)
Other species	Y = ln(a) + b ln(D)	Rahman et al. (2021)

Note: Y is dried-weight biomass, ρ is wood density (World Agroforestry, 2022), D is the diameter at breast height

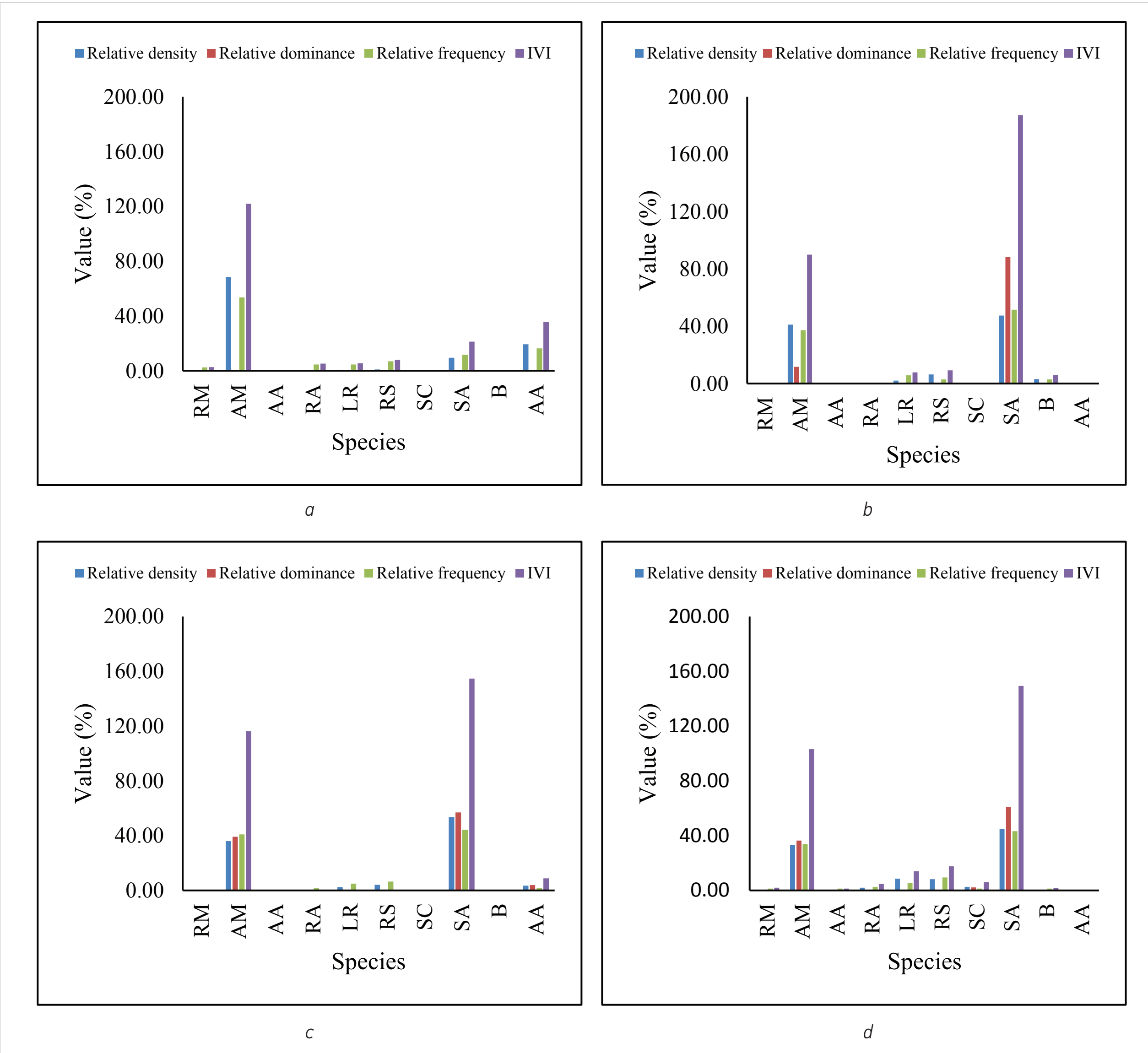
Results and Discussion

Species composition of rehabilitated mangrove forest

The vegetation species in the mangrove forest at East Nusa Tenggara, Indonesia, comprised 10 species. *Avicennia marina* was found in all life stages (seedlings, saplings, poles, and trees) and was shown as the second dominant species. The most dominant species, *Sonneratia alba*, showed the highest importance value index (IVI) at the life stages of saplings, poles, and trees. The rest of the species, namely *Rhizophora mucronata, Avicennia alba, Rhizophora apiculata, Lunnitzera racemosa, Rhizophora stylosa, Sonneratia caseolaris, Bruguier sp., and Aegialitis annulate*, were less dominant and can be found in the life stages in a small number (*Fig. 2*).

The species composition of rehabilitated mangrove forests in Indonesia diverges for each location. For example, in the Pangarengan mangrove forest in Cirebon district, West Java, Indonesia, the dominant species were *Avicen-*

Fig. 2. *Importance value index of (a) seedlings, (b) sapling, (c) poles, (d) trees*



Note: RM is *Rhizophora mucronata*; AM is *Avicennia marina*; AA is *Avicennia alba*; RA is *Rhizophora apiculata*; LR is *Lumnitzera racemosa*; RS is *Rhizophora stylosa*; SC is *Sonneratia caseolaris*; SA is *Sonneratia alba*; B is *Bruguiera sp*; AA is *Aegialitis annulata*.

nia marina and *Rhizophora mucronata*, and *Sonneratia alba* was not found (Purwanto et al., 2021, 2022). In the Segara Anakan mangrove forest at Cilacap district, Central Java, Indonesia, the dominant species for seedlings and saplings were *Rhizophora apiculata*, and *Avicennia alba* dominated in the tree stage (Hidayat et al., 2010).

However, the species composition of rehabilitated mangrove forests in Nusa Tenggara Islands also varies among sites. In this study, the highest IVI was for *Sonneratia alba*, followed by *Avicennia marina* for saplings, poles, and trees (*Fig. 2*). A similar pattern of IVI for the life stage of the tree has been found in the mangrove forest of East Lombok district, West Nusa Tenggara province, but the species composition was different (Aminuddin et al., 2019). The IVI in Lembar Bay mangrove forest at West Lombok, West Nusa Tenggara province, has shown different patterns where *Rhizophora stylosa, Ceriops tagal* and *Rhizophora mucronata* were the three dominant species (Sukuryadi et al., 2021b). Moreover, in Sikka district, East Nusa Tenggara province, the highest IVI for natural mangrove forests were for *Rhizophora mucronate* and *Avicennia marina*, while in the planted mangrove forest, these were *Sonneratia alba* and *Rhizophora apiculata* (Matatula et al., 2021). Nevertheless, the species composition varies among the sites; *Lumnitzera racemose* can be found in the sites.

According to Yuliana et al. (2019) and Djufri et al. (2016), a specific high importance value plays a vital role in the wetland ecosystem. In this study, the *Avicennia marina* dominated the whole research area for the seedling stage. The seedling of the *Avicennia marina* can be the source of natural regeneration, while other species need human intervention. Although *Sonneratia alba* dominated in the sapling, poles, and tree stages, the number of seedlings is still low. *Sonneratia alba* needs more light to support the natural regeneration of seedlings and saplings (Imai et al., 2006).

The two dominant species for sapling, poles and tree stages were *Sonneratia alba* and *Avicennia marina*. The importance values of *Sonneratia alba* at the sapling, poles and tree stages were 187.06%, 154.80%, and 149.29%, respectively. In contrast, the importance value of *Avicennia marina* was 89.93% (sapling), 116.30% (poles), and 103.14% (tree). In this study, *Avicennia marina* and *Sonneratia alba* can be found in all the sampling sites (*Table 3*). This finding can explain the high value of IVI for *Avicennia marina* and *Sonneratia alba* compared to other species in the mangrove forest in the Kupang district (*Fig. 2*). Not only did *Avicennia marina* and *Sonneratia alba* show the presence in all sampling sites, according to *Fig. 2*, but also high density and a bigger size of the basal area. The density of *Avicennia marina* and *Sonneratia alba* were 650 and 842 trees/ha. Moreover, the average basal area of *Avicennia marina* and *Sonneratia alba* were 2.421 and 3.918 m^2/ha, respectively.

Table 3. *Species presence in Kupang district mangrove forest*

Species	Sampling plots								
	D4	M4	P4	D6	M6	P6	D8	M8	P8
Rhizophora mucronata	√	–	–	–	–	–	–	–	–
Avicennia marina	√	√	√	√	√	√	√	√	√
Avicennia alba	√	–	–	–	–	–	–	–	–
Rhizophora apiculata	–	–	–	√	–	–	√	–	–
Lunnitzera racemosa	–	–	–	√	–	–	√	–	–
Rhizophora stylosa	√	√	–	√	–	–	√	–	–
Sonneratia caseolaris	–	–	–	√	–	–	–	–	–
Sonneratia alba	√	√	√	√	√	√	√	√	√
Bruguiera sp.	–	–	–	–	–	–	√	–	–
Aegialitis annulata	√	√	–	–	–	√	√	√	√

Note: D4 is distal zone and year of rehabilitation 2004, M4 is middle zone and year of rehabilitation 2004, P4 is proximal zone and year of rehabilitation 2004, D6 is distal zone and year of rehabilitation 2006, M6 is middle zone and year of rehabilitation 2006, P6 is proximal zone and year of rehabilitation 2006, D8 is distal zone and year of rehabilitation 2008, M8 is middle zone and year of rehabilitation 2008, P8 is proximal zone and year of rehabilitation 2008, √ is found, and – refers to not found.

The heterogeneity of the mangrove forest in the Kupang district was very low to the middle (*Table 4*). In reference to Djufri et al. (2016), the heterogeneity value (H') ranged within 0–7, where the H' less than 1 was categorized as very low, while the 1 < H' < 2 was classified as low, and H' within 2–3 was medium. In this research, based on zonation, the distal zone was categorized as having low heterogeneity, while the middle and proximal zones were very low. Furthermore, based on the year, rehabilitation in 2004 resulted in very low heterogeneity, and rehabilitation in 2006 and 2008 showed low heterogeneity.

Table 4. *Comparison of biodiversity indices in the Kupang district mangrove forest*

Groups	Compartments	Richness	Heterogeneity	Evenness
Zone	Distal	0.89	1.52	0.69
	Middle	0.19	0.61	0.55
	Proximal	0.18	0.77	0.70
Year	2004	0.38	0.27	0.17
	2006	2.12	1.12	0.58
	2008	1.36	1.13	0.58

Based on physical and chemical parameters, namely mud thickness, salinity, and slope, the mangrove forest habitat in Nusa Tenggara is suitable for the growth of mangrove species (Matatula et al., 2019). In the future, rehabilitation projects should consider enriching the species composition. *Avicennia marina* can regenerate through natural regeneration, while the *Sonneratia alba* seedling should be placed with less canopy cover to get more light. At the same time, other species have low seedling stock and need more attention from human intervention to ensure their growth.

Carbon stock in the rehabilitated mangrove forest

Based on the zonation, the highest aboveground carbon stock in the Nusa Tenggara mangrove forest was in the back zone (176.949 t/ha), followed by the middle (68.776 t/ha) and front zones (15.615 t/ha) (*Table 5*). It was similar to the mangrove forest in Maluku, Indonesia, in which the aboveground carbon stocks in the back, middle, and front zones were 179.936, 70.498, and 52.106, respectively (Irwanto et al., 2021). The average aboveground carbon stock in the mangrove plant from eight locations in Indonesia (Sumatra, Kalimantan, Java, Sulawesi, and Papua) was 211 ± 135 t/ha (Murdiyarso et al., 2015).

Table 5. *Carbon stock of mangrove forest for each stage of life based on zonation and year of rehabilitation*

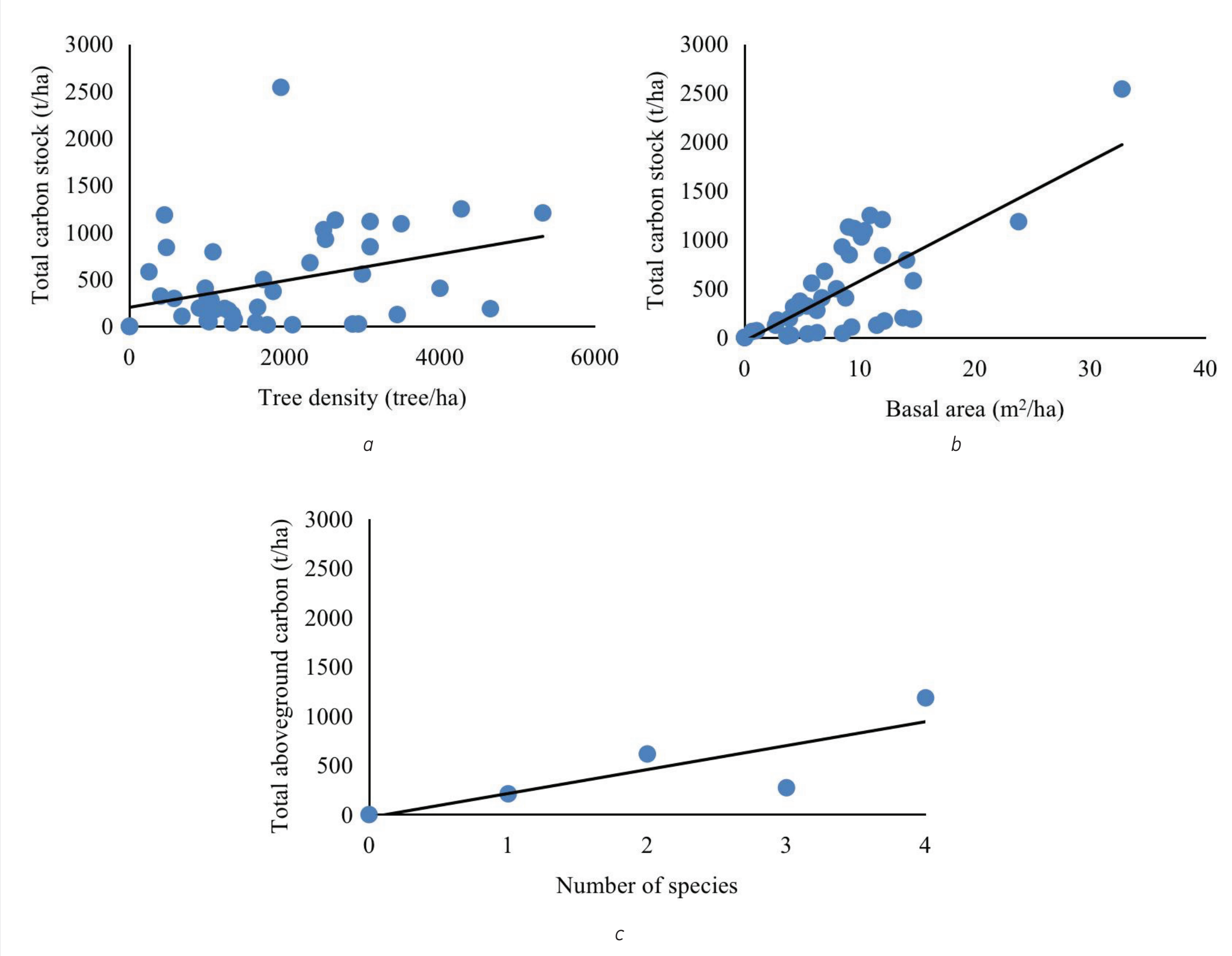
Groups	Compartments	Carbon stock (t/ha)			
		Seedling	Sapling	Poles	Trees
Zone	Distal	0.0225	0.154	43.026	176.949
	Middle	0.146	5.865	224.715	68.776
	Proximal	0.113	11.299	58.080	15.615
Year	2004	0.105	0.177	6.476	29.387
	2006	0.037	13.819	182.740	171.076
	2008	0.126	1.009	139.243	89.819

In the year of the rehabilitation program, the highest to the lowest aboveground carbon stock was in the mangrove forest in 2006, 2008, and 2004. It can be explained by *Table 3* that the richness, heterogeneity, and evenness values of the mangrove forest rehabilitated in 2004 were low.

The aboveground biomass will increase following the increase in the value of IVI. In the natural mangrove forest in Sikka district, East Nusa Tenggara province, the relationship between IVI and aboveground biomass was non-linear, while planted mangrove forests showed a linear regression (Matatula et al., 2021). This study elaborated on the relationship between total carbon with tree density and basal area (*Fig. 3*).

The relationship between total carbon stock and tree density showed an irregular pattern. In contrast, the relationship between the total carbon basal area and the number of species showed a better shape. The predictor of the basal area was better than tree density in estimating the total carbon. The linear regression equation to estimate total aboveground carbon stock using predictor tree density (X_1) and basal area (X_2), and the number of species (X_3) were $Y = 0.1415X_1 + 201.99$ ($R^2 = 0.131$), $Y = 61.283X_2 - 35.934$ ($R^2 = 0.550$), $Y = 243.03 X_3 - 29.577$ ($R^2 = 0.689$), respectively. A positive correlation between biomass or carbon with IVI has also been shown in mangrove forests (Purwanto et al., 2021), community forests (Wirabuana et al., 2021), dry forests (Dimobe et al., 2019; Yasin and Mulyana, 2022), forest plantation (Behera et al., 2017), and tropical forest (Pragasan, 2022). However, the predictor of tree density (X_1) in this research is not recommended to estimate the total aboveground biomass and carbon.

Fig. 3. *Relationship between carbon stock and a) tree density, b) basal area, c) number of species*



Conclusions

Mangrove forest in Kupang district, East Nusa Tenggara province, consisted of 10 species, namely *Rhizophora mucronata, Rhizophora apiculata, Rhizophora stylosa, Avicennia marina, Avicennia alba, Lumnitzera racemosa, Sonneratia caseolaris, Sonneratia alba, Bruguier* sp., and *Aegialitis annulata*. In general, the species of *Avicennia marina* and *Sonneratia alba* had a high IVI value for saplings, poles, and trees. Both species can be found in all sampling plots and mangrove forests.

Based on mangrove zonation, the distal zone has the highest value for richness and heterogeneity. Meanwhile, based on the year of rehabilitation, mangrove areas rehabilitated in 2006 and 2008 showed a high value for richness, heterogeneity, and evenness. In terms of carbon stock, the distal and middle zones had high carbon stock compared to the proximal area. Furthermore, the carbon stock in rehabilitation of 2006 showed a high value for poles and tree life stages. In the future, the periodic forest inventory for a long term period is important to get a better understanding on species composition and aboveground carbon dynamic in the rehabilitated mangrove forest.

Acknowledgments

We want to express our gratitude to those who helped us with the fieldwork. We also send our thanks to the reviewers for the constructive comments.

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