

# Ecological insights post-restoration from two decades of mangrove forest succession in Pangpang Bay, East Java, Indonesia

HARI SULISTIYOWATI<sup>1,\*</sup>, RENDY SETIAWAN<sup>1</sup>, ARIF MOHAMMAD SIDDIQ<sup>1</sup>,  
RETNO WIMBANINGRUM<sup>1</sup>, MUHAMMAD AFRIYANTO<sup>1</sup>, ELA APRILIYANTI HASANAH<sup>1</sup>,  
BUDI PUTRA MULYADI<sup>1</sup>, ABDILLAH BARAAS<sup>2</sup>

<sup>1</sup>Department of Biology, Faculty of Mathematics and Natural Sciences, Universitas Jember. Jl. Kalimantan 37, Tegalboto, Jember 68121, East Java, Indonesia. Tel./fax.: +62-331-334293, \*email: harisulissyahri@gmail.com

<sup>2</sup>Jen Geopark Centre. Jl. Jenderal Ahmad Yani 50, Taman Baru, Banyuwangi 68416, East Java, Indonesia

Manuscript received: 23 January 2025. Revision accepted: 7 May 2025.

**Abstract.** Sulistiyowati H, Setiawan R, Siddiq AM, Wimbaningrum R, Afriyanto M, Hasanah EA, Mulyadi BP, Baraas A. 2025. *Ecological insights post-restoration from two decades of mangrove forest succession in Pangpang Bay, East Java, Indonesia. Biodiversitas* 26: 2299-2308. The Mangrove Pangpang Bay (MPB) in Banyuwangi District, East Java, Indonesia, has suffered significant degradation from anthropogenic pressures. A restoration project was launched in the late 1990s, and between 2000 and 2003, approximately 300,000 trees were planted across 70 ha. However, 22 years later, little is known about the structural and functional dynamics of the mangrove forest's succession. This study assesses the structural complexity, ecological functionality, and environmental resilience of the restored mangrove forest in MPB. Tree vegetation data were collected using 10x10 m<sup>2</sup> plots, and functional data were obtained through a semi-destructive method. Secondary data on species conservation status and geographic distribution were sourced from the IUCN Red List, while abiotic factors, including temperature, pH, and salinity, characterized environmental conditions. The MPB comprises 11 mangrove species from 5 families and 7 genera, dominated by *Rhizophora mucronata* and *Sonneratia alba*. Abiotic conditions, salinity (31.85‰), soil pH (7.96), and temperature (29.89°C) are favorable for mangrove growth, particularly for the *Rhizophora*. The Shannon-Wiener Diversity Index (H') was low (0.98), indicating secondary succession influenced by human-led planting. Mangrove tree density averaged 3,719 trees/ha, with 1,392 seedlings/ha, and vegetation volume was 18,556.10 m<sup>3</sup>/ha. The estimated carbon stock was 104.58 Mg C/ha, equating to 383.49 Mg CO<sub>2</sub>/ha and 277.42 Mg O<sub>2</sub>/ha. Salinity correlated positively with carbon stock and tree volume, while pH, temperature, and diversity showed negative correlations, indicating potential trade-offs in shaping the restored ecosystem of MPB. Additionally, the total biodiversity value of MPB was calculated to be 9,733,952,191.99 IDR per hectare.

**Keywords:** Biodiversity value, ecology, mangrove, Pangpang Bay, succession

## INTRODUCTION

The Mangrove Pangpang Bay (MPB), located in the Muncar Sub-district of Banyuwangi District, East Java, Indonesia, has been designated as an Essential Ecosystem Area (Rodiana et al. 2019). The MPB area covered approximately 207.5 hectares in 1989, which increased to 282.8 hectares by 2011 (Raharja et al. 2014). Mangrove forests play an important role as a natural green belt, protecting coastlines from erosion (Getzner and Islam 2020). Furthermore, this ecosystem served as a nursery and feeding ground for numerous marine species (Juan et al. 2022). In this case, the mangrove forest of MPB provides crucial habitat for several gastropod species (Setiawan et al. 2021, et al. 2024), fish (Rofiqoh et al. 2020), primate (Siddiq et al. 2022), and bird communities (Siddiq et al. 2023, et al. 2024).

The MPB experienced significant degradation due to anthropogenic pressures, leading local or international stakeholders to launch a large-scale restoration project in the late 1990s. Rodiana et al. (2019) reported that the Banyuwangi District Fisheries and Maritime Service started mangrove (mostly *Rhizophora* sp.) planting

activities in 2000 covering an area of 5 ha and in 2001 covering an area of 30 ha with a total of 150,000 trees in the MPB. This was followed in 2002 by an area of 10 ha, featuring 50,000 trees, and in 2003 by an area of 30 ha, encompassing 100,000 trees. Recently, 22 years after these efforts began, it is crucial to assess the ecological value of the MPB succession. The structural complexity (species composition, density, and diversity), ecological functionality (carbon stock and sequestration), and environmental resilience (temperature, pH, and salinity) are ecological value indicators that provide a comprehensive framework for assessing MPB succession (Sulistiyowati and Buot 2013, 2016).

Mangrove diversity, density, and composition all reveal the structural intricacy of the succession. Mangrove species diversity is a crucial indicator of ecological recovery (Barnuevo et al. 2017; Bai et al. 2021; Pimple et al. 2022). High diversity suggests that a restored area supports a wide range of life forms, reflecting improved habitat quality. The mangrove density, as revealed by Marasabessy et al. (2021), can provide information on the abundance and growth potential of mangroves in an area. Higher densities often provide greater root coverage, which can enhance silt

trapping, coastal protection, and habitat for marine life. On the other hand, low densities may indicate poor survival rates or a lack of regeneration. The species composition is important in mangrove restoration because it indicates how effectively the ecosystem is moving toward a reference or natural condition. Other mangrove species outside of *Rhizophora* may begin to establish themselves after 22 years of planting.

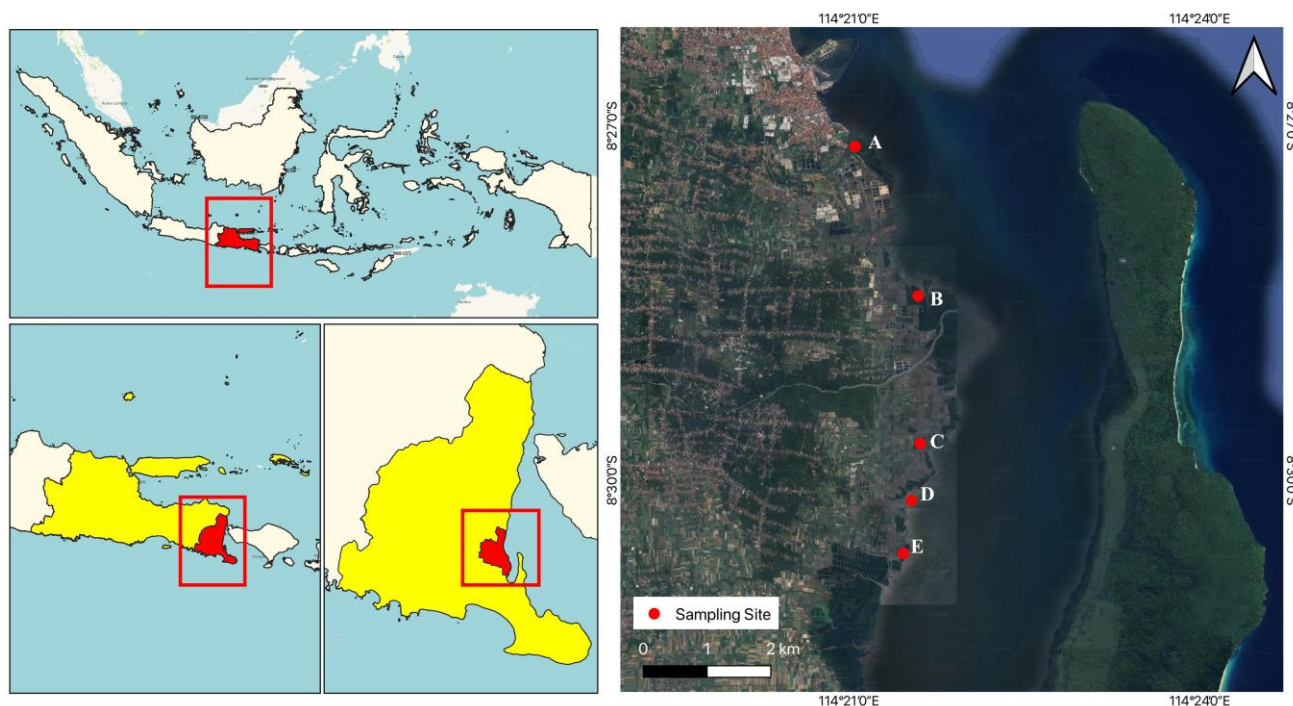
The survival of mangroves depends on their ecological functions during succession. The mangrove's ability to sequester carbon in both above- and below-ground biomass is one of their most significant ecological roles (Wylie et al. 2016; Himes-Cornell et al. 2018). This ecosystem plays a role in mitigating the greenhouse gas effect by sequestering carbon dioxide through natural processes (Zhu and Yan 2022). An indication of long-term ecological function is the buildup of carbon in the mangrove as biomass. Carbon stocks should rise as the mangroves expand and the ecosystem stabilizes over time, indicating that the ecosystem is actively regulating the climate through carbon storage (Wang and Yan 2022). In the face of environmental changes such as rising sea levels, climate change, or increased pollution, environmental resilience ensures the long-term viability of the mangrove ecosystem. Mangrove forest adaptation to environmental factors such as temperature, pH, and salinity is essential for understanding its resilience and long-term sustainability. It helps in evaluating how well the forest is recovering and adapting to external conditions (Xu et al. 2020). Therefore, based on the mangrove forest's structural complexity, ecological functionality, and environmental resilience, the study aimed to evaluate the ecological value of the 25-year

mangrove forest succession in Mangrove Pangpang Bay (MPB) following restoration.

## MATERIALS AND METHODS

### Study area

This study was conducted in May 2023 at the MPB, located in the Banyuwangi area of Indonesia. The research area was systematically studied using 31 plots that were randomly distributed across five different sites: site 1 (8°27'10.42"S, 114°21'3.27"E), site 2 (8°28'26.32"S, 114°21'35.58"E), site 3 (8°29'41.27"S, 114°21'36.69"E), site 4 (8°30'10.07"S, 114°21'32.13"E), and site 5 (8°30'37.05"S, 114°21'27.97"E) (Figure 1). This strategic placement ensured that data collection covered a broad representation of the area's ecological conditions. These five sites were selected based on specific criteria, likely considering their ecological significance, accessibility, and potential to represent the regional species diversity. This strategic placement ensured that data collection covered a broad representation of the area's ecological conditions. These five sites were selected based on specific criteria, likely considering their ecological significance, accessibility, and potential to represent the regional species diversity. The plots provided a structured framework for sampling and observation, allowing researchers to systematically analyze the area's mangrove structure, function, and environmental characteristics being investigated. Figure 1 likely provides a visual map or spatial representation of the study area, helping to contextualize the locations of the sites and their relationship to the broader geography of Pangpang Bay.



**Figure 1.** Research site location at Pangpang Bay, Banyuwangi District, East Java, Indonesia. A. Site 1; B. Site 2; C. Site 3; D. Site 4; E. Site 5

### Data sampling

Data sampling was conducted using a combination of the transect and plot methods along the coastline to achieve a detailed understanding of mangrove forest structure while ensuring systematic and replicable sampling. Observations were made in 20x20 m<sup>2</sup> plots, with a 20-meter distance between adjacent plots. Within each plot, all trees with a Diameter at Breast Height (DBH) ≥ 5 cm were measured and recorded. The tree species of mangroves are identified using a guide by Noor et al. (2012), titled "Panduan Pengenalan Mangrove di Indonesia" or "A Guide to the Introduction of Mangroves in Indonesia". The conservation status and geographic distribution of all recorded tree species were referenced in the IUCN Red List of Threatened Species, following the classification by the International Union for Conservation of Nature (IUCN 2024). Additionally, abiotic factors, including temperature, pH, and salinity, were measured to characterize the environmental conditions of the MPB at the time of sampling. These abiotic parameters were measured three times in each plot to ensure accuracy and reliability.

### Structure complexity analysis

Next, to assess species composition in Pangpang Bay, data for all mangrove tree species were compiled and categorized by family, genus, and species. Tree species dominance was calculated using the method outlined by Barbour et al. (1998). The Importance Value Index (IVI), a measure of a species' ecological importance and dominance, was determined as the sum of its relative density, dominance, and frequency. Vegetation diversity was assessed using the Shannon-Wiener index using RStudio 4.3.6 (Oksanen 2016). The tree vegetation in MPB consists of a variety of unique species characterized by their geographic distribution (Gd), encounter rate (Fr), and conservation status (Cs). To assess these characteristics, the existence factor (Ef) equation proposed by Sulistiyowati and Buot (2016) was applied. The coverage or basal area of each tree species was calculated using the basal area formula described by Barbour et al. (1988), as shown below:

$$BA = \pi(D^2)/4(100)^2$$

Where,

BA : Basal Area (m<sup>2</sup>)

π : Constant (3.142)

D : Diameter at breast height (cm)

The total basal area of each species was determined by summing the basal areas of individual trees. Additionally, the total tree volume was estimated using a standard volume estimation method specifically designed for mangroves.

### Ecological functionality analysis

Carbon storage, carbon sequestration, and oxygen production were estimated as functional values of tree vegetation. Allometric equations from Komiyama et al. (2005) and et al. (2008) were used to estimate above-ground and below-ground biomass for various mangrove species:

$$AGB_{est} = 0.251 (\rho D)^{2.46}$$

$$BGB_{est} = 0.199 \rho^{0.899} D^{2.22}$$

Where,

AGB: Above-Ground Biomass (kg)

BGB: Below-Ground Biomass (kg)

ρ : Wood density (g/m<sup>3</sup>), and D is DBH (cm)

The wood density (ρ) of each mangrove species was determined using values reported by Komiyama et al. (2005). For species not listed in their study, wood density data were sourced from the Global Wood Density Database by Zanne et al. (2012). Biomass was converted to carbon stock using a factor of 0.50, and carbon stock was subsequently converted to carbon sequestration using a factor of 3.667. Based on the photosynthesis equation, the release of 1 g of CO<sub>2</sub>e corresponds to the production of 0.727 g of O<sub>2</sub> into the atmosphere.

### Correlations between abiotic factors and structure-function values

Principal Component Analysis (PCA) was used to analyze the relationships among diversity, carbon stock, tree volume per species, and environmental factors, including salinity, pH, and temperature. Additionally, RStudio 4.3.6 (R Core Team 2021) was used to examine correlations between abiotic factors and structural and functional values using PCA. Differences were considered significant at α: 0.05.

## RESULTS AND DISCUSSION

### Structure complexity of Mangrove Pangpang Bay

A total of 11 mangrove species belonging to 5 families and 7 genera were found in MPB (Table 1). Most of these species belong to the Rhizophoraceae family. In addition to the previously planted *Rhizophora* species (*R. stylosa*, *R. apiculata*, and *R. mucronata*), other mangrove species such as *Avicennia*, *Sonneratia*, *Xylocarpus*, *Bruguiera*, *Ceriops*, and *Scyphiphora* were observed (Table 1). These new species contribute to the biodiversity and ecological resilience of the mangrove ecosystem. The average abiotic conditions in MPB, including a salinity of 31.85%, a soil pH of 7.96, and a temperature of 29.89°C, are highly suitable for mangrove growth, particularly for planted *Rhizophora* populations.

Among the mangrove species observed in the MPB, *R. mucronata* and *S. alba* were identified as the dominant and codominant populations, with the highest Important Value Index (IVI) recorded at 181.89% and 44.05%, respectively (Figure 2). These elevated IVI values can be attributed to their large basal area, high number of individuals, and wide distribution across their habitat. The dominance of *R. mucronata* was primarily due to its large number of individuals and total basal area, which measured 2,043.57 m<sup>2</sup> from 2,748 stand trees per hectare. Similarly, *S. alba*, as the codominant population, had a basal area of 570.20 m<sup>2</sup>, corresponding to 442 stand trees per hectare.

**Table 1.** Species composition of tree vegetation in Mangrove Pangpang Bay, Banyuwangi District, East Java, Indonesia

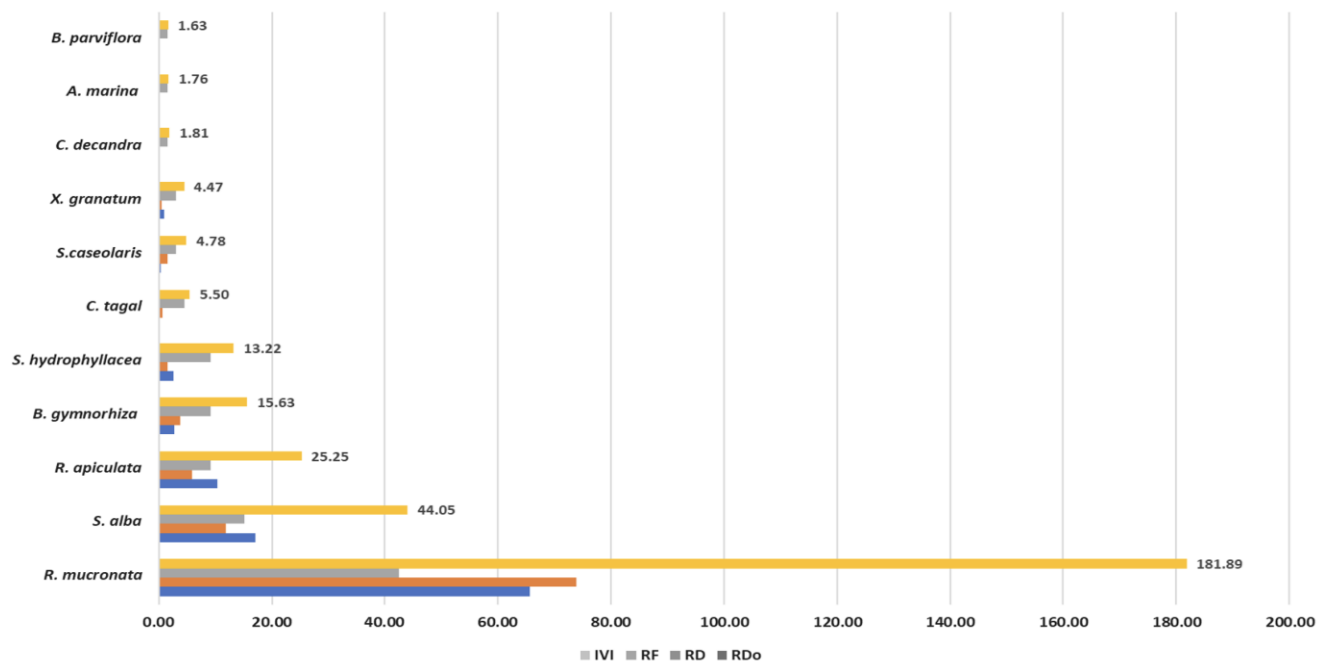
Family	Species	IUCN Red List Status
Acanthaceae	<i>Avicennia marina</i>	Least Concern
Lythraceae	<i>Sonneratia alba</i>	Least Concern
	<i>Sonneratia caseolaris</i>	Least Concern
Meliaceae	<i>Xylocarpus granatum</i>	Least Concern
Rhizophoraceae	<i>Bruguiera gymnorhiza</i>	Least Concern
	<i>Bruguiera parviflora</i>	Least Concern
	<i>Ceriops decandra</i>	Near Threatened
	<i>Ceriops tagal</i>	Least Concern
	<i>Rhizophora apiculata</i>	Least Concern
Rubiaceae	<i>Rhizophora mucronata</i>	Least Concern
	<i>Scyphiphora hydrophyllacea</i>	Least Concern

According to Cheng et al. (2018), dominant species significantly influence productivity and diversity by shaping and maintaining the community. This study's findings align with those of Kusmana and Azizah (2022) and Rahim et al. (2024), who also reported *R. mucronata* as the dominant species in their research areas, resulting in a high IVI. The dominance of the genus *Rhizophora* has been widely documented, attributed to its superior propagative ability and survivability (Uche et al. 2023). For example, *Rhizophora* dominance has been observed in North Minahasa, Sulawesi, Indonesia (Mandagi et al. 2024), and Kutai National Park, East Kalimantan, Indonesia (Edwin et al. 2021). These findings underscore the critical ecological role of *R. mucronata* in mangrove ecosystems. As noted by Guo et al. (2017), Rhizophoraceae is an important mangrove family characterized by highly developed

morphological and physiological adaptations, which enable survival in harsh conditions.

In contrast, the isolated population of *B. parviflora* exhibited a low basal area of only 0.96 m<sup>2</sup> from three individuals. This result indicates that the area is more suitable for the growth and propagation of *R. mucronata*, while *B. parviflora* is less adapted. This disparity can be attributed to the higher salinity tolerance of *R. mucronata*, which is reported to be up to 55%, compared to the salinity tolerance of *B. parviflora*, which is limited to 20% (Noor et al. 2012). Additionally, new populations from surrounding ecosystems, such as *B. gymnorhiza* and *S. hydrophyllacea*, have successfully adapted to the environment, resulting in moderate IVI values, as shown in Figure 2.

The low diversity of H' index (0.98) observed in MPB is predominantly attributed to the effects of secondary succession, driven by human-led planting initiatives. These restoration efforts often focus on a limited range of fast-growing or commercially favorable species, particularly those from the *Rhizophora* genus, resulting in reduced species richness and evenness. Such practices inadvertently decrease overall species diversity. Natural mangrove ecosystems are characterized by a rich variety of species, which contributes to both the structural and functional complexity of the habitat (Janne et al. 2023). Therefore, when replanting initiatives prioritize a narrow range of species, such as *Rhizophora* spp., less dominant but ecologically significant species are excluded. This leads to a simplified ecosystem structure, as observed in this research area. Planted mangroves often exhibit dominance by one or two species, suppressing the growth of other potential colonizers due to competition for light, nutrients, and space.



**Figure 2.** Important Value Index (IVI), Relative Frequency (RF), Relative Density (RD), and Relative Dominance (RDo) of mangrove vegetation

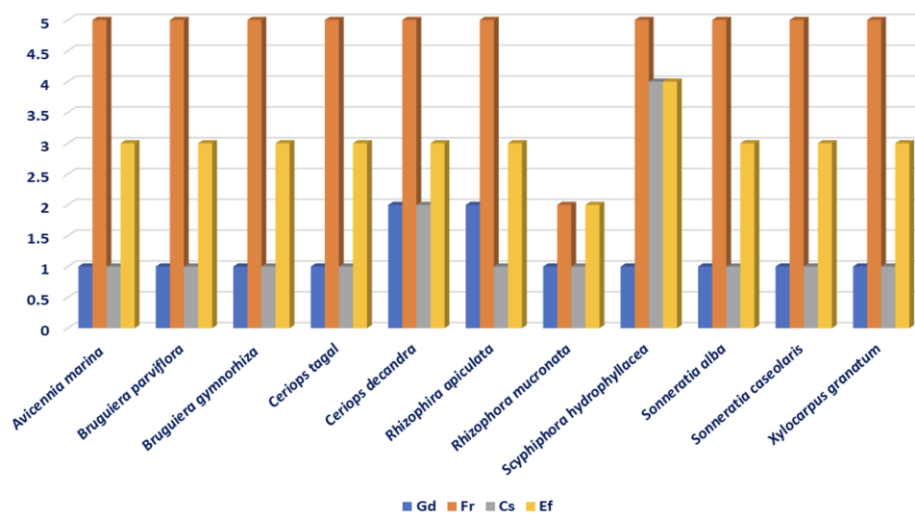
The encounter frequency, conservation status, and geographical distribution of each species were analyzed to determine its uniqueness level using the existence factor (Ef). Species with low encounter frequency levels, urgent conservation status (such as near threatened to endangered), and narrow geographical distribution were considered the most unique. The uniqueness level of mangrove trees in Pangpang Bay averaged 3 (three), indicating that the mangrove vegetation in this area is relatively unique (Figure 3). Among these, *C. decandra* demonstrated a significant contribution to its Cs level. This species is classified as near threatened on the IUCN Red List and is distributed exclusively in Asia. On the other hand, *R. mucronata* had an Ef value of 2 (two), indicating that it is less unique compared to other species due to its high encounter frequency. Despite this, the existence of *R. mucronata* is crucial to maintaining its population and ensuring the overall health of the habitat and other species within the ecosystem. As suggested by Yan et al. (2016), the growth of *R. mucronata* population not only impacts their population but also has broader consequences for the entire mangrove forest ecosystem. The notable characteristics of this species, including viviparous seeds, aerial roots, and stilt roots (Shamin-Shazwan et al. 2021), support its effective establishment in the environment, enhancing its ability to stabilize sediments and contribute to the overall resilience of the MPB.

The structural value of mangrove vegetation can be effectively assessed through its volume, which serves as an indicator of biomass, carbon sequestration potential, and habitat complexity. As observed, the total volume of mangrove tree vegetation was 18,556.10 m<sup>3</sup>/ha. Among the species found, *R. mucronata* population contributed the largest volume (10,741.42 m<sup>3</sup>/ha) to the community, while the smallest volume was contributed by *B. parviflora* (15.53 m<sup>3</sup>/ha), as seen in Figure 4. Tree volume reflects the size and growth of individual mangrove trees, contributing to the overall structural integrity and ecological function of the ecosystem. Larger stem volumes are typically associated with older and more mature trees, which provide

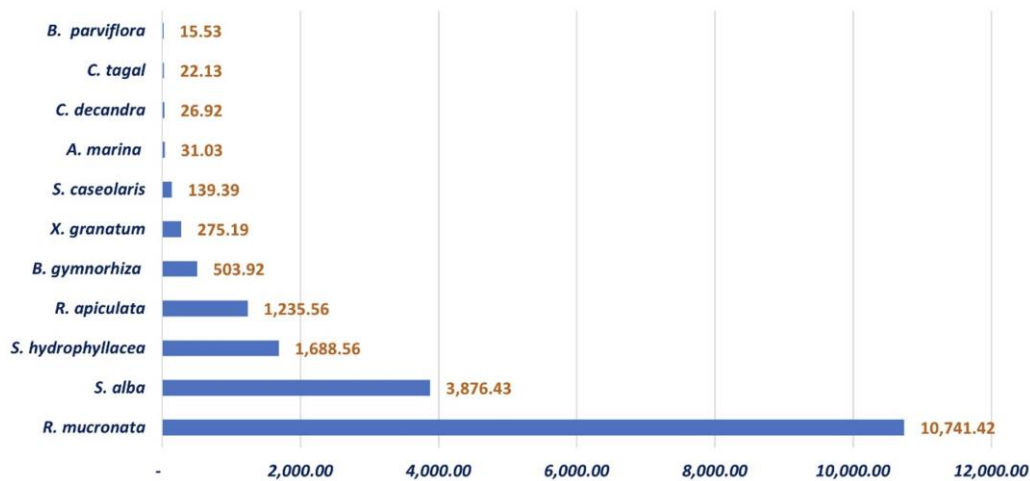
greater habitat complexity for fauna and higher ecosystem services. Forest functioning in the context of natural and anthropogenic changes is closely linked to large trees, as they play a critical role in many key ecological processes in global forests (Lutz et al. 2018; Arshad and Wang 2021). Additionally, variations in stem volume among different species can indicate the dominance of particular taxa, stand composition, and succession stage, offering insights into the ecosystem's health and management needs.

Approximately 3,719 trees and 1,392 mangrove seedlings per hectare were observed at the site, representing 11 recruited species (Figure 5). As expected, the most abundant species was *R. mucronata*, which was planted in 2000. Most of the seedlings belonged to the Rhizophoraceae family. However, the results showed a low recruitment rate compared to achievements in other restoration projects. This density has not yet reached the typical mangrove forest recovery range, which is generally between 5,000 to 10,000 propagules or seedlings per hectare. This range is commonly used as a guideline in mangrove restoration projects to ensure adequate coverage and ecological functionality.

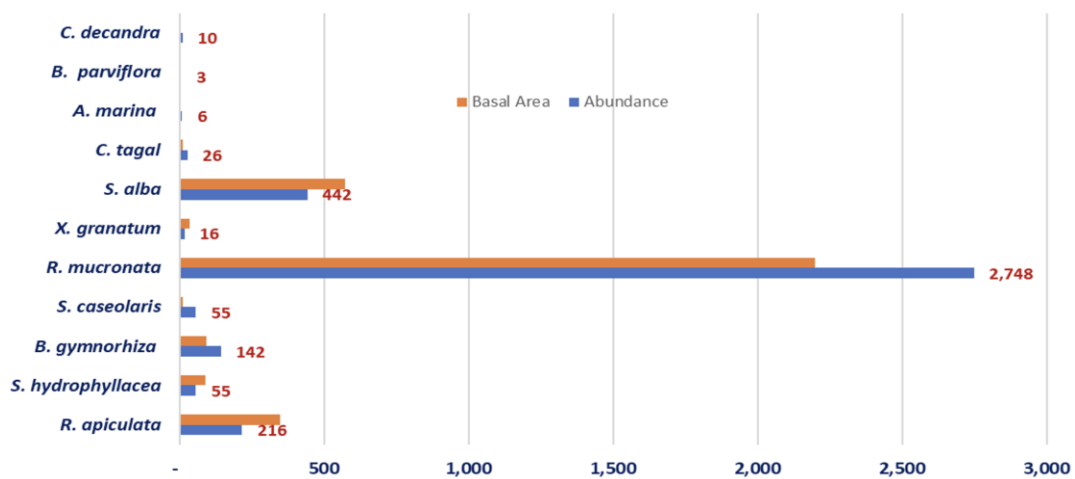
Across all species, *R. mucronata* dominated with a recorded count of 2,748 individuals, accounting for most of the population (Figure 5). In contrast, *B. parviflora* had the lowest abundance, with only 3 individuals, reflecting its limited presence in the ecosystem. Other notable species, such as *S. alba* and *R. apiculata*, exhibited significant abundances of 442 and 216 individuals, respectively. The total basal area (BA) for all mangrove species was approximately 3,351 m<sup>2</sup>. Among the species, *R. mucronata* contributed the highest BA. At the same time, both *B. parviflora* and *C. decandra* had the lowest basal area, with only 1 m<sup>2</sup> each, likely due to their smaller size or limited distribution. Notable contributions were also made by *S. alba* and *R. apiculata* with BAs of 570 m<sup>2</sup>/ha and 347 m<sup>2</sup>/ha, respectively. The variety of tree basal area is a crucial indicator of structural attributes, reflecting the health and biomass distribution within a mangrove forest (Rouzbeh et al. 2020; Moncada et al. 2023).



**Figure 3.** The uniqueness levels or existence factor (Ef) (1: not unique, 2: less unique, 3: quite unique, 4: unique, and 5: very unique) of mangrove vegetation based on the geographic distribution (Gd), encounter frequency (Fr), and conservation status (CS)



**Figure 4.** Total volume (m<sup>3</sup>/ha) of mangrove tree vegetation in Mangrove Pangpang Bay, Banyuwangi District, East Java, Indonesia



**Figure 5.** Total abundance (individual) and basal area (m<sup>2</sup>/ha) of mangrove tree vegetation in Mangrove Pangpang Bay, Banyuwangi District, East Java, Indonesia

The high abundance of *R. mucronata* indicates that this species is well-adapted to the environmental conditions of the study area. This adaptability could be attributed to factors such as greater tolerance to salinity, effective reproductive strategies, or competitive superiority. Its substantial BA highlights its role in contributing to the structural complexity of the MPB, which is essential for providing habitat and resources for various marine and terrestrial species. In contrast, the extremely low abundance, and BA of *B. parviflora* suggest challenges in its establishment within the MPB. This challenge may stem from specific microhabitat requirements, competition with dominant species, or vulnerability to environmental stressors.

#### Ecological functionality of Mangrove Pangpang Bay

The functional value of mangrove vegetation can be estimated by its ability to sequester CO<sub>2</sub> through photosynthetic processes, resulting in the storage of carbon in its bodies and the production of oxygen. In the MPB, the estimated carbon stock of mangrove vegetation was approximately 104.58 Mg C/ha. As seen in Figure 6, this

carbon stock was primarily composed of *R. mucronata* (42.37%, 44.31 Mg C/ha), followed by *S. hydrophyllacea* (22.86 Mg C/ha) and *R. apiculata* (17.89 Mg C/ha). These results indicate that carbon stock is influenced not only by the number of individual trees but also by the size of each tree stand. For example, *S. hydrophyllacea* contributed the second-highest carbon stock with only 17 individual trees, whereas *R. mucronata* contributed the most with 852 individual trees. The ability of *Rhizophora* sp. to rapidly propagate and establish dense stands makes it the genus with the highest carbon stock in this ecosystem. This finding aligns with previous studies. Purnamasari et al. (2020) and Rijal et al. (2024) reported that *Rhizophora* sp. contributed significantly to carbon stocks in Alas Purwo National Park, with values of 34.73 Mg C/ha and 114.09 Mg C/ha, respectively. Similarly, Asadi et al. (2019) found that *Rhizophora* sp. accounted for 96.3% of the carbon stock on Poteran Island, East Java, Indonesia. These findings highlight the importance of the *Rhizophora* sp. as a key species in mangrove ecosystems, with significant potential to store more carbon than the other species.

This study estimated the stock carbon resulting from CO<sub>2</sub> sequestration by mangrove vegetation, which amounts to approximately 383.49 Mg CO<sub>2</sub>/ha. Among the species analyzed, *R. mucronata* demonstrated the highest CO<sub>2</sub> sequestration capacity (162.48 Mg CO<sub>2</sub>/ha), while *B. parviflora* had the lowest (0.1 Mg CO<sub>2</sub>/ha) (Figure 6). The CO<sub>2</sub> sequestration capacity of Mangrove vegetation in MPB is lower than the estimate by Hapsari and Permatasari (2020) (571.68 Mg CO<sub>2</sub>/ha) in Pangpang Bay, Banyuwangi using Landsat-8 Imagery but higher than the estimate by Trissanti et al. (2020) (64,416.36 Mg CO<sub>2</sub>/ha) in Karawang Regency and by Safitri et al. 2024 in Santong Bay Mangrove Ecotourism Area Sumbawa Regency (76.52 Mg CO<sub>2</sub>/ha). However, this value represents only 63.98% of the average CO<sub>2</sub> sequestration capacity of mangroves on Java Island, which is 599.38 Mg CO<sub>2</sub>/ha (Maulana et al. 2020).

The CO<sub>2</sub> sequestration capacity of the MPB is expected to increase as the number and the size of mangrove stand trees grow, aided by the ongoing rehabilitation program, which is currently 22 years old. The presence of *R. mucronata* and *R. apiculata* in this research area indicates a high potential for carbon sequestration, given their significant carbon storage capacity. These species can also be propagated to enhance the mangrove population in the forest (Isnani and Masjud 2024). Sugiana et al. (2024) studied the mangrove restoration in Benoa Bay, Bali, 30 years after its implementation, and reported that the restored mangrove could absorb up to 1.5 million metric tons of CO<sub>2</sub>. These findings suggest that the MPB still has significant potential to absorb more atmospheric CO<sub>2</sub>, provided that its mangrove vegetation remains undamaged and intact.

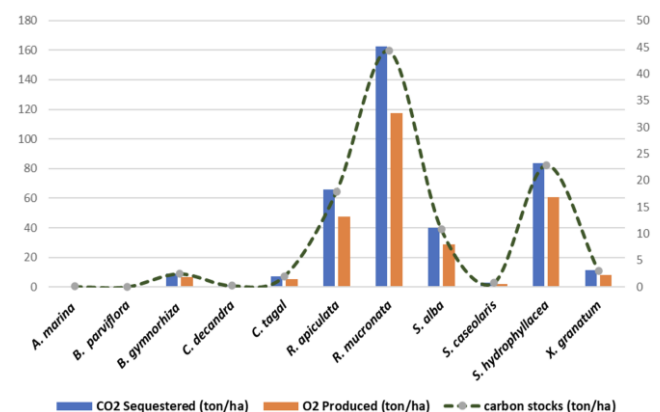
The CO<sub>2</sub> sequestration of MPB contributes significantly to reducing atmospheric CO<sub>2</sub> levels, while its role in O<sub>2</sub> production amounts to approximately 277.42 Mg O<sub>2</sub>/ha. This level of O<sub>2</sub> production surpasses that of mangrove vegetation in Central Kalimantan, which produces 121.88 Mg O<sub>2</sub>/ha (Junaedi et al. 2020), community forests in Central Kalimantan at 88.01 Mg O<sub>2</sub>/ha (Junaedi et al. 2024), and urban forests in Palangka Raya City at 49.84 Mg O<sub>2</sub>/ha (Ludang et al. 2016). The highest oxygen production was contributed by *R. mucronata* at 117.54 Mg O<sub>2</sub>/ha, followed by *S. hydrophyllacea*, *R. apiculata*, *R. apiculata*, and *S. alba*, which produced 60.65 Mg O<sub>2</sub>/ha, 47.45 Mg O<sub>2</sub>/ha, and 28.76 Mg O<sub>2</sub>/ha, respectively (Figure 5). This oxygen production plays a vital role in maintaining the Earth's life-sustaining ecosystems, supporting both human well-being and environmental health. It is widely recognized as an ecosystem service, one of the many benefits derived from ecosystem activities, processes, or features that provide value to people (Costanza et al. 2017, et al. 2021).

The mangrove ecosystem provides numerous benefits, including carbon sequestration through tree vegetation stock, which plays a crucial role in mitigating climate change. The carbon stock in vegetation depends on factors such as the number of individual trees and the size of the tree stands. In this study, *R. mucronata* had the largest population, comprising 2,748 trees and contributing the highest carbon stock in the area at 44.31 Mg C/ha (Figure 6). On average, each stand tree of *R. mucronata* stores

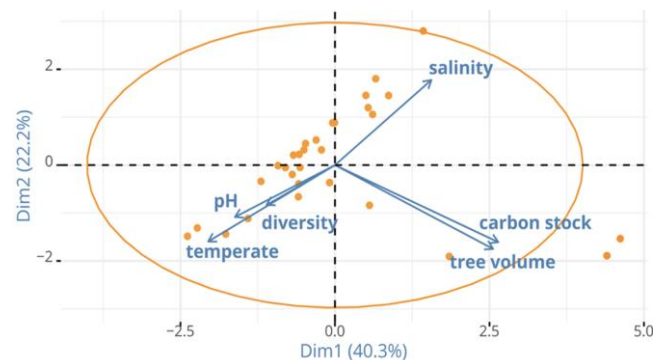
approximately 0.02 Mg C/ha. In comparison, *S. hydrophyllacea* had a much smaller population of 17 trees but contributed the second-highest stock carbon at 22.86 Mg C/ha (Figure 6), with each tree storing an average of 1.34 Mg C/ha. These findings suggest that individual trees with larger dimensions and volumes can store significantly more carbon.

### Correlations between abiotic factors and structure-function values of Mangrove Pangpang Bay

Mangrove forests are complex ecosystems characterized by intricate relationships between vegetation and its environment. These interactions encompass biogeochemical cycles and abiotic factors, including salinity, pH, and temperature. This study analyzed the relationships between abiotic factors and key ecosystem parameters- diversity, carbon stock, and tree volume- using Principal Components Analysis (PCA) to assess the condition of MPB. Based on Figure 7, salinity exhibited a strong positive relationship with both carbon stock and tree volume, as evidenced by the alignment of their respective vectors along the first principal component (Dim1, which explains 40.3% of the variance). In contrast, pH, temperature, and diversity displayed negative relationships with salinity, carbon stock, and tree volume as their vectors pointed in nearly opposite directions.



**Figure 6.** Carbon stock, CO<sub>2</sub>eq and O<sub>2</sub>eq of mangrove vegetation in Mangrove Pangpang Bay, Banyuwangi District, East Java, Indonesia (Mg/ha)



**Figure 7.** PCA analysis of abiotic factors and the structure-function of Mangrove Pangpang Bay, Banyuwangi District, East Java, Indonesia

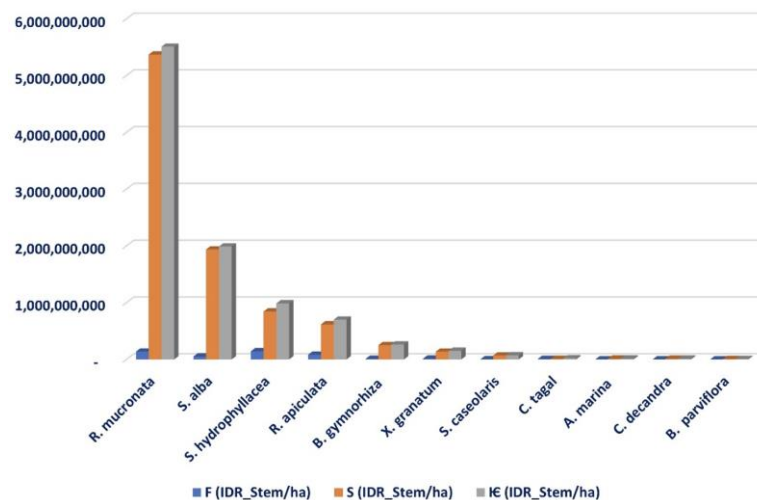
Salinity influences mangrove diversity by limiting the growth, development, and propagation of mangroves. At extreme salinity levels, the survivability of mangrove seedlings significantly decreases (Kodikara et al. 2018; Matto et al. 2023). Moreover, salinity affects mangrove communities at a broader level; elevated salinity reduces average tree height, DBH, basal area, and carbon stock (Ahmed et al. 2023). These findings suggest that elevated salinity levels affect mangrove forests at both individual and community levels by reducing growth, development, and survival rates. Consequently, this results in mangrove forests that are less diverse, composed of smaller trees, and less effective in carbon sequestration.

The PCA biplot (Figure 7) reveals several significant relationships between abiotic factors and key ecosystem parameters in the mangrove ecosystem. One notable observation is the positive correlation between salinity and tree volume. This relationship suggests that higher salinity levels may be associated with larger tree volumes. This can be attributed to the dominance of salt-tolerant mangrove species such as *Rhizophora*, which thrive in saline conditions and significantly contribute to biomass and tree volume. Adaptive traits of these species, such as salt-excreting leaves, enable them to grow well in saline environments (Surya and Hari 2018; Sudhir et al. 2022). However, this positive relationship may have a threshold effect, as extremely high salinity levels could also hinder growth in some mangrove species.

Furthermore, the PCA biplot (Figure 7) indicates a strong positive correlation between salinity and carbon stock, suggesting that areas with higher salinity tend to exhibit greater carbon storage potential. In saline environments, mangroves tend to allocate more resources to root systems, enhancing below-ground carbon storage. The dominance of large, salt-tolerant species, such as *R. mucronata*, further contributes to higher biomass and carbon sequestration. This relationship highlights the crucial role of saline mangrove forests in mitigating climate change by acting as effective carbon sinks.

According to Devaney et al. (2021), high salinity often leads to decreased stomatal conductance and reduced photosynthetic efficiency, thereby hindering seedling growth and the rapid development of the mangrove ecosystem, particularly during early succession. Conversely, the PCA biplot reveals a negative correlation between salinity and species diversity. As salinity increases, species diversity tends to decrease. High salinity imposes physiological challenges, limiting the number of species that can tolerate such conditions. Consequently, only a few salt-tolerant species, such as *Rhizophora*, dominate, leading to reduced overall species diversity in highly saline areas (Raganas and Damasa 2020).

The graph depicts the biodiversity value of mangrove trees in this ecosystem, assessed using the replacement cost method (Figure 8). This approach monetizes the ecological structure and functions of mangroves by estimating their market-equivalent value, such as wood pricing and carbon sequestration potential. Ecological valuation combines both structural and functional aspects of biodiversity. According to Sulistiyowati and Buot (2016), tree vegetation in a specific habitat can be evaluated based on structural dimension and carbon sequestration capacity. In this study, the total biodiversity value of MPB was calculated to be 9,733,952,191.99 IDR/ha. This high value suggests that the area likely has an abundance of species, diverse communities, and/or substantial ecological resources. This makes it a valuable location for conservation and ecological protection, primarily due to its inherent structural attributes. This total comprises structural values (9,278,050,002.42 IDR/ha) and functional values (455,902,189.57 IDR/ha) (Figure 8). The results demonstrate that structural biodiversity contributes significantly more to the total value compared to functional biodiversity. Functional biodiversity's smaller contribution remains a crucial aspect of the ecosystem's overall health and sustainability. Its relatively lower value could imply that either the functional processes in this area are underrepresented, less economically quantifiable, or not functioning at their full capacity.



**Figure 8.** The structural (S), functional (F), and biodiversity values (IE) in IDR/ha of Mangrove Pangpang Bay, Banyuwangi District, East Java, Indonesia

The high structural biodiversity value is predominantly attributed to five large mangrove tree species: *R. mucronata*, *S. alba*, *S. hydrophyllacea*, *R. apiculata*, and *B. gymnorhiza*, which together contribute 9,022,949,634.87 IDR/ha. Similarly, the top contributors to functional biodiversity value are *S. hydrophyllacea*, *R. mucronata*, *R. apiculata*, *S. alba*, and *X. granatum*, with a combined contribution of 429,633,576.30 IDR/ha. Conversely, the species with the lowest combined contributions to both structural and functional biodiversity are *B. parviflora*, *C. tagal*, *C. decandra*, *A. marina*, and *S. caseolaris*, with values of 117,503,202.81 IDR/ha and 14,610,633.18 IDR/ha, respectively.

In conclusion, MPB comprises 11 mangrove species belonging to 5 families and 7 genera, with *R. mucronata* and *S. alba* being the dominant species. The abiotic conditions, including salinity, soil pH, and temperature, are favorable for mangrove growth, particularly for the *R. mucronata*. The Shannon-Wiener Diversity Index was low, indicating a recovering ecosystem, likely due to human-assisted restoration efforts. Mangrove tree density averaged 3,719 trees/ha, with 1,392 seedlings/ha, and vegetation volume was 18,556.10 m<sup>3</sup>/ha. The estimated carbon stock was 104.58 Mg C/ha, equivalent to 383.49 Mg CO<sub>2</sub>/ha and 277.42 Mg O<sub>2</sub>/ha. Salinity correlated positively with carbon stock and tree volume, while pH, temperature, and diversity showed negative correlations, indicating potential trade-offs in shaping the restored ecosystem of MPB. Furthermore, the total biodiversity value of MPB was estimated at 9,733,952,191.99 IDR/ha, highlighting its ecological and economic significance.

## ACKNOWLEDGEMENTS

This research is financially supported by a Research Group Grant (4153/UN25.3.1/LT/2022) of the Institute for Research and Community Service, Universitas Jember, East Java, Indonesia. The authors also thank Ali Teluk Biru for assisting with data collection in Pangpang Bay, East Java. The Sentra Tropical Natural Resources Conservation-UPA CDAST, Universitas Jember, Indonesia was used for data analysis and manuscript writing.

## REFERENCES

- Ahmed S, Sarker SK, Kamruzzaman M, Ema JA, Naabeh CSS, Cudjoe E, Chowdhury FI, Pretzsch H. 2023. How biotic, abiotic, and functional variables drive below ground soil carbon stocks along stress gradients in the Sundarbans Mangrove Forest? *J Environ Manag* 337 (1): 117772. DOI: 10.1016/j.jenvman.2023.117772.
- Arshad A, Wang L-Q. 2021. Big-sized trees and forest functioning: Current knowledge and future perspectives. *Ecol Indic* 127: 107760. DOI: 10.1016/j.ecolind.2021.107760.
- Asadi MA, Sukandar S, Lutfi OM, Handayani M, Dewi CSU, Saputra DK, Rahmandika MRA. 2019. Mangrove forest inventory and estimation of carbon storage in Poteran Island, East Java, Indonesia. *J Biol Environ Sci* 14 (3): 9-16.
- Bai J, Meng Y, Gou R, Lyu J, Dai Z, Diao X, Zhang H, Luo Y, Zhu X, Lin G. 2021. Mangrove diversity enhances plant biomass production and carbon storage in Hainan Island, China. *Funct Ecol* 35 (3): 774-786. DOI: 10.1111/1365-2435.13753.
- Barbour MG, Burk JH, Pitts WD. 1998. *Terrestrial Plant Ecology*, 3rd Edition. Benjamin Cummings, San Francisco.
- Barnuevo A, Asaeda T, Sanjaya K, Kanesaka Y, Fortes M. 2017. Drawbacks of mangrove rehabilitation schemes: Lessons learned from the large-scale mangrove plantations. *Estuar Coast Shelf Sci* 198: 432-437. DOI: 10.1016/j.ecss.2017.02.015.
- Cheng Y, Zhang C, Zhao X. 2018. Biomass-dominant species shape the productivity-diversity relationship in two temperate forests. *Ann For Sci* 75: 97. DOI: 10.1007/s13595-018-0780-0.
- Costanza R, de Groot R, Braat L, Kubiszewski I, Fioramonti L, Sutton P, Farber S, Grasso M. 2017. Twenty years of ecosystem services: How far have we come and how far do we still need to go? *Ecosyst Serv* 28: 1-16. DOI: 10.1016/j.ecoser.2017.09.008.
- Costanza R, Ida K, Rifaee R. 2021. Commentary: The future of changes in global ecosystem services. *Glob Environ Change* 71: 102399. DOI: 10.1016/j.gloenvcha.
- Devaney JL, Marone D, McElwain JC. 2021. Impact of soil salinity on mangrove restoration in a semiarid region: A case study from the Saloum Delta, Senegal. *Restor Ecol* 29 (2): e13186. DOI: 10.1111/rec.13186.
- Edwin M, Sulistyorini IS, Poedjirahardjo E, Faida LRW, Purwanto RH, Imanuddin. 2021. Structure and dominance of species in mangrove forest on Kutai National Park, East Kalimantan, Indonesia. *Jurnal Manajemen Hutan Tropika* 27 (1): 59-68. DOI: 10.7226/jtfm.27.1.59.
- Getzner M, Islam MS. 2020. Ecosystem services of mangrove forests: Results of a meta-analysis of economic values. *Intl J Environ Res Publ Health* 17 (16): 5830. DOI: 10.3390/ijerph17165830.
- Guo H, Weaver C, Charles SP, Whitt A, Dastidar S, D'Odorico P, Fuentes JD, Kominoski JS, Armitage AR, Pennings SC. 2017. Coastal regime shifts: rapid responses of coastal wetlands to changes in mangrove cover. *Ecology* 98: 762-772. DOI: 10.1002/ecy.1698.
- Hapsari KCP, Permatasari DA. 2020. Changes of mangrove area in Pangpang Bay, Banyuwangi 2014-2018 using Landsat-8 imagery. *J Phys Conf Ser* 1528: 012063. DOI: 10.1088/1742-6596/1528/1/012063.
- Himes-Cornell A, Grose SO, Pendleton L. 2018. Mangrove ecosystem service values and methodological approaches to valuation: Where do we stand? *Front Mar Sci* 5: 376. DOI: 10.3389/fmars.2018.00376.
- Isnani S, Masjud Y. 2024. Atmospheric carbon dioxide uptake by mangrove trees. *Mangrove Watch* 1 (1): 27-32. DOI: 10.61511/mangrove.v1i1.2024.657.
- Janne N, Carlijn L, Robin L, Marjolijn JAC, Annieke B, Leon PML, van Lavieren H, Sieuwath N, Laura LG. 2023. Habitat complexity drives food web structure along a dynamic mangrove coast. *Mar Pollut Bull* 196: 115597. DOI: 10.1016/j.marpolbul.2023.115597.
- Juan AP, Fernandes G, Vieira J, Guedes EHL, Terra BF, Pessanha MAL. 2022. Importance of pneumatophore fringe-mudflat continuum for an estuary-dependent fish species. *Mar Biol Res* 18 (1): 252-265. DOI: 10.1080/17451000.2022.2076882.
- Junaedi A, Hidayat N, Mediawati Y, Wibowo A, Rizal M, Setiarno, Surasana IN. 2020. Biomass, carbon stock and oxygen produced by mangrove vegetation in tropical forest in Central Kalimantan, Indonesia. *Asian J Crop Sci* 12 (1): 26-33. DOI: 10.3923/ajcs.2020.26.33.
- Junaedi AJ, Yosep A, Penyang I, Surasana N, Rizal M. 2024. Komposisi jenis, serapan karbon dioksida dan produksi oksigen vegetasi berkayu di Hutan Kemasyarakatan Batu Bulan Kabupaten Gunung Mas Kalimantan Tengah. *Jurnal Manajemen Hutan Tropika* 19 (1): 19-26. DOI: 10.36873/jht.v19i1.13188. [Indonesian]
- Kodikara ASK, Jayatissa LP, Huxham M, Dahdouh-Guebas F, Koedam N. 2018. The effects of salinity on growth and survival of mangrove seedlings changes with age. *Acta Bot Bras* 32 (1): 37-46. DOI: 10.1590/0102-33062017abb0100.
- Komiyama A, Pongpan S, Kato S. 2005. Common allometric equations for estimating the tree weight of mangroves. *J Trop Ecol* 21 (4): 471-477. DOI: 10.1017/S0266467405002476.
- Komiyama A, Ong JE, Pongpan S. 2008. Allometry, biomass, and productivity of mangrove forests: A review. *Aquat Bot* 89 (2): 128-137. DOI: 10.1016/j.aquabot.2007.12.006.
- Kusmana C, Azizah NA. 2022. Species composition and vegetation structure of mangrove forest in Pulau Rambut Wildlife Reserve, Kepulauan Seribu, DKI Jakarta. *IOP Conf Ser Earth Environ Sci* 950 (1): 012020. DOI: 10.1088/1755-1315/950/1/012020.
- Ludang Y, Junaedi A, Putir PE. 2016. Potency estimation on oxygen production of tree stages vegetation at the Himba Kahui Urban Forest in Palangka Raya. *Acta Scientiae et Intellicus* 2 (6): 93-100.

- Lutz JA, Furniss, TJ, Johnson DJ, Davies SJ, Allen D, Alonso A. 2018. Global importance of large-diameter trees. *Glob Ecol Biogeogr* 27: 849-864. DOI: 10.1111/geb.12747.
- Mandagi C, Winny L, Timpal T, Rompas V, Talimpong A, Gumolili Y, Mait N. 2024. The role of diversity structure, dominance, and diameter of mangrove trees and mitigation of coastal abrasion at Darunu Village. *Jurnal Ilmiah Platax* 12 (2): 261-272. DOI: 10.35800/jip.v12i2.58232.
- Marasabessy I, Badarudin I, Rumlus A. 2021. Tingkat kerapatan dan tutupan relatif mangrove di Taman Wisata Klawalu Kota Sorong Papua Barat. *Grouper* 12 (1): 1-10. DOI: 10.30736/grouper.v12i1.76. [Indonesian]
- Matto AA, Jaikishun S, Ram M. 2023. Impacts of different salinity levels on seedling growth and survival of black mangrove (*Avicennia germinans*). *Asian J For* 7 (1): 67-73. DOI: 10.13057/asianjfor/r070108.
- Maulana MI, Auliah NL, Onrizal. 2020. Potential carbon storage of Indonesian mangroves. *IOP Conf Series Earth Environ Sci* 782 (3): 032014. DOI: 10.1088/1755-1315/782/3/032014.
- Moncada M, Villarin R, Rodrigo R, Moreno MO, Dapar L, Sabejon F. 2023. Forest structure, above-ground biomass, and carbon potential of Sangalang mangrove forest in Biliran Island Philippines. *J Biol Environ Sci* 22 (5): 118-125.
- Noor YR, Khazali M, Suryadiputra INN. 2012. Panduan Pengenalan Mangrove Indonesia. *Perlindungan Hutan Konservasi Alam WI-IP, Bogor*. [Indonesian]
- Oksanen J. 2016. *Vegan: Ecological Diversity*. R-package Vignette. <http://debian.ustc.edu.cn/CRAN/web/>.
- Pimple U, Leadprathom K, Simonetti D, Sitthi A, Peters R, Pungkul S, Pravinongvuthi T, Dessard H, Berger U, Siri-on K, Kemacheevakul P, Gond V. 2022. Assessing mangrove species diversity, zonation, and functional indicators in response to natural, regenerated, and rehabilitated succession. *J Environ Manag* 318: 115507. DOI: 10.1016/j.jenvman.2022.115507.
- Purnamasari E, Kamal M, Wicaksono P. 2020. Relationship analysis of vegetation structural properties and the above-ground carbon stock of mangrove forest. *E3S Web Conf* 200: 02020. DOI: 10.1051/e3sconf/202020002020.
- R Core Team. 2021. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna.
- Raganas AFM, Damasa BM. 2020. Physicochemical factors influencing zonation patterns, niche width and tolerances of dominant mangroves in southern Oriental Mindoro, Philippines. *Ocean Life* 4 (2): 51-62. DOI: 10.13057/oceanlife/o040201.
- Raharja AB, Widigdo B, Sutrisno D. 2014. Study on the potency of mangrove ecosystem in the coastal area of Gulf Pangpang, Banyuwangi. *Depik* 3 (1): 36-45.
- Rahim A, Soeprubowati TR, Putranto TT, Al Falah MH, Gell P. 2024. Contribution of mangrove forest carbon stocks on climate change mitigation: A case study at Tuntang Estuary, Central Java. *J Coast Conserv* 28: 65. DOI: 10.1007/s11852-024-01059-w.
- Rijal SS, Furqon MT, Kadhafi M, Supriatin FE, Aprilianto AY. 2024. Mangroves in Alas Purwo National Park, Indonesia: Diversity and its potential carbon services. *Hayati* 31 (3): 589-595. DOI: 10.4308/hjb.31.3.589-595.
- Rodiana L, Yulianda F, Sulistiono S. 2019. Kesesuaian dan daya dukung ekowisata berbasis ekologi mangrove di Teluk Pangpang, Banyuwangi. *J Fish Mar Res* 3 (2): 194-205. [Indonesian]
- Rouzbeh KA, MacKenzie RA, Apwong M, Hughes E, Van Aardt J. 2020. Stem and root assessment in mangrove forests using a low-cost, rapid-scan terrestrial laser scanner. *Wetl Ecol Manag* 28: 883-900. DOI: 10.1007/s11273-020-09753-w.
- Safitri DS, Latifah S, Valentino N. 2024. Estimation of carbon content in mangrove stands in the Santong Bay Mangrove Ecotourism Area Sumbawa Regency. *Jurnal Biologi Tropis* 24 (4): 712-716. DOI: 10.29303/jbt.v24i4.7917.
- Setiawan R, Siddiq AM, Wimbaningrum R, Sulistiyowati H, Aditiya MY. 2021. Diversity of gastropod types in Mangrove Forest Jatipapak Resort Kucur Alas Purwo National Park. *Bioeducience* 5 (3): 257-262. DOI: 10.22236/j.bes/536235.
- Setiawan R, Wimbaningrum W, Sulistiyowati H, Siddiq AM, Rani C, Baraas A. 2024. Species diversity of gastropods in the mangrove forest of Pangpang Bay Ijen Geopark, Banyuwangi Indonesia. *Jurnal Kelautan Tropis* 27 (2): 277-286. DOI: 10.14710/jkt.v27i2.22471.
- Shamin-Shazwan K, Shahari R, Amri CNAC, Kassim Z, Ahmad Z. 2021. Morphological structure of *Rhizophora apiculata* Blume. and *Rhizophora mucronata* Lam. *Sci Herit J* 5 (1): 1-4. DOI: 10.26480/gws.01.2021.01.04.
- Siddiq AM, Wati DE, Sulistiyowati H, Wimbaningrum R, Setiawan R, Supriadi D. 2022. Habitat Characteristics of long-tailed macaque (*Macaca fascicularis* Raffles, 1821) in Kucur Resort at Alas Purwo National Park. *Berkala Saintek* 12 (2): 94-100. DOI: 10.19184/bst.v10i2.31613. [Indonesian]
- Siddiq AM, Wimbaningrum R, Sulistiyowati H, Setiawan R, Febriyanti SD, Sabila FSN. 2023. The diversity of birds in mangrove forest at Biosite Pangpang Bay, Ijen Geopark. *Life Sci Biotechnol* 1 (2): 52-58. DOI: 10.19184/lb.v1i2.44165.
- Siddiq AM, Wimbaningrum R, Sulistiyowati H, Setiawan R, Sari AG, Siregar NH, As-Singkily M. 2024. Shorebird records from Pangpang Bay, East Java, Indonesia. *BIO Web Conf* 101: 03002. DOI: 10.1051/bioconf/202410103002.
- Sudhir S, Arunprasath A, Vel VS. 2022. A critical review on adaptation, and biological activities of the mangroves. *J Nat Pestic Res* 1: 100006. DOI: 10.1016/j.napere.2022.100006.
- Sugiana IIP, Prartono T, Rastina, Koropitan AF. 2024. Ecosystem carbon stock and annual sequestration rate from three genera-dominated mangrove zones in Benoa Bay, Bali, Indonesia. *Biodiversitas* 25 (6): 2670-2678. DOI: 10.13057/biodiv/d250637.
- Sulistiyowati H, Buot Jr IE. 2013. Integrated biodiversity valuation framework: Ecological approach. *J Wetl Biodivers* 3: 7-16.
- Sulistiyowati H, Buot Jr IE. 2016. Ecological valuation tools to appraise biomass, necromass and soil organic matter in a natural forest ecosystem. *J Wetl Biodivers* 6: 97-108.
- Surya S, Hari N. 2018. Ecological characterization of true mangrove species in Kerala. *Star Intl J* 6 (4): 14-16.
- The IUCN Red List of Threatened Species. 2024. <https://www.iucnredlist.org/>.
- Trissanti VN, Amalo LF, Handayani LDW, Nugroho D, Yuliani AR, Mulyana D. 2020. The estimation of biomass and carbon stocks in mangrove forest ecosystem of Karawang Regency, West Jav. *IOP Conf Ser Earth Environ Sci* 1109 (1): 012099. DOI: 10.1088/1755-1315/1109/1/012099.
- Uche IB, Uche OA, Okoye UO, Ukoha-Kalu BO. 2023. Incarcerated individuals and education programs in Nigeria: A task for social workers. *Plos One* 18 (7): e0288693. DOI: 10.1371/journal.pone.0288693.
- Wang X, Yan L. 2022. Driving factors and decoupling analysis of fossil fuel related-carbon dioxide emissions in China. *Fuel* 314: 122869. DOI: 10.1016/j.fuel.2021.122869.
- Wylie LJ, Bailey SJ, Kelly J, Blackwell JR, Vanhatalo A, Jones AM. 2016. Influence of beetroot juice supplementation on intermittent exercise performance. *Eur J Appl Physiol* 116 (2): 415-425. DOI: 10.1007/s00421-015-3296-4.
- Xu S, Wang J, Guo Z, He Z, Shi S. 2020. Genomic convergence in the adaptation to extreme environments. *Plant Comm* 1 (6): 100117. DOI: 10.1016/j.xplc.2020.100117.
- Yan YB, Duke NC, Mei S. 2016. Comparative analysis of the pattern of population genetic diversity in three Indo-West Pacific *Rhizophora* Mangrove Species. *Front Plant Sci* 7: 1434. DOI: 10.3389/fpls.2016.01434.
- Zanne AE, Lopez-Gonzalez G, Coomes D, David J, Jansen I, Lewis KS, Miller RB, Swenson N, Wiemann MC, Chave J. 2012. Data from: Towards a worldwide wood economics spectrum. *Global Wood Density Database*. DOI: 10.5061/dryad.234.
- Zhu JJ, Yan B. 2022. Blue carbon sink function and carbon neutrality potential of mangroves. *Sci Total Environ* 822: 153438. DOI: 10.1016/j.scitotenv.2022.153438.
- Rofiqoh MA, Kurnia TID, Nurmasari F. 2020. Inventarisasi jenis ikan bakau di Teluk Pangpang Taman Nasional Alas Purwo Banyuwangi. *J Biosense* 3 (2): 51-61. DOI: 10.36526/biosense.v3i2.1160.