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Association and distribution patterns of nipah (*Nypa fruticans*) in a degraded protected mangrove forest

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Abstract. *Eddy S, Milantara N, Setiawan AA, Taufik M, Rosanti D, Putri SAD, Rahmawati. 2024. Association and distribution patterns of nipah (*Nypa fruticans*) in a degraded protected mangrove forest. Biodiversitas 25: 4525-4534.* The invasion of nipah (*Nypa fruticans*) serves as an indicator of mangrove forest degradation that has occurred globally, impacting biodiversity. Therefore, understanding the population dynamics of nipah is essential for controlling its growth. This study aims to classify land cover types in the Air Telang Protected Forest (ATPF), analyze the association of nipah with other plants, and examine its distribution patterns. We employed a descriptive research method, utilizing Geographic Information Systems (GIS) for land cover change analysis, alongside field surveys to collect data on plant species associated with nipah. Drone photography was used to document nipah populations across various land cover types. Our findings revealed four land cover types in ATPF: primary forest, secondary forest, open area (shrub), and plantation, with 29 plant species associated with nipah. Nipah has spread across various land cover types through multiple mechanisms. We estimate that nipah will dominate nearly all degraded areas of ATPF and hinder the succession process if restoration efforts are not implemented promptly. However, with the right strategies, there is hope for successful restoration. This research contributes to understanding nipah's population dynamics, the implications of its dominance, and strategies for controlling its growth. In addition, this study is more widely useful for information on mangrove ecosystem management, ecological risk assessment, ecosystem restoration efforts, and conservation policy development.

Keywords: Air Telang Protected Forest, association and distribution patterns, invasive species, mangrove forest, nipah

Abbreviations: ATPF: Air Telang Protected Forest

INTRODUCTION

Indonesia is home to the largest mangrove forest in the world, estimated to cover approximately 2.7 million hectares in 2020 (Basyuni et al. 2022; Sasmito et al. 2023). These forests thrive along muddy coastlines with low hydrodynamic intensity, particularly in regions with extensive river estuaries and deltas that regularly receive sediments from highland catchments (Eddy et al. 2021a). Mangrove forests provide aesthetic value and serve as critical habitats for various organisms, while also protecting coastal populations from climate change effects, regulating nutrients, enhancing primary productivity, and preventing coastal erosion (Basyuni et al. 2018; Ouyang et al. 2018; Hochard et al. 2019; Kusmana et al. 2019; Mai et al. 2019; Eddy and Basyuni 2020; Nwobi et al. 2020; Basyuni et al. 2021).

Globally, half of all mangrove forests have been lost since the mid-20th century (Friess et al. 2019). Similarly, mangrove forests in Indonesia, including Air Telang Protected Forest (ATPF), have suffered degradation due to anthropogenic activities, particularly conversion into plantations such as oil palm and coconut (Eddy et al. 2017, 2019, 2020, 2021a,b,c, 2022, 2023a,b, 2024; Mai et al. 2019). Coastal ecosystems are among the most vulnerable natural systems worldwide, facing rapid biodiversity decline due to human impacts (Almond et al. 2020; Cooley et al. 2022).

Degraded mangrove ecosystems are particularly susceptible to invasions by nipah (*Nypa fruticans* Wurmb) and other invasive species. The widespread distribution of nipah indicates mangrove forest degradation. Nipah produces a large number of seeds that are easily dispersed by tidal currents, allowing it to dominate mangrove areas (Numbere 2019). Approximately 30% of Indonesia's four million hectares of mangrove forests are home to nipah (Wijana et al. 2023). Nipah has surpassed almost all mangrove forests along the east coast of South Sumatra, Indonesia including ATPF (Eddy et al. 2024). The nipah palm invasion is a clear sign of mangrove forest destruction (Numbere 2019; Eddy et al. 2024). Although nipah is found in nearly all mangrove forests globally, it has also spread beyond its natural range (Ebana et al. 2015). The loss of mangrove forests due to nipah invasion has led to declines in fish populations and jeopardized the safety of coastal tourism (Numbere and Moudingo 2023). Invasive species significantly reduce ecosystem services and biodiversity (Gallardo et al. 2024).

Studying the association and distribution patterns of nipah with other plants is crucial for understanding its key role in the ecosystem, including its competition dynamics, interspecies interactions, the impact of dominance, its ecological functions, and its contributions to blue carbon production and conservation efforts. A mechanistic understanding of mangrove distribution, involving biotic and abiotic interactions, is essential for supporting mangrove protection and restoration (Cui et al. 2024). Chowdhury et al. (2023) noted that mixed mangrove associations have the largest blue carbon pool. Invasive species are known to cause significant ecological and economic losses (Heringer et al. 2024). Monitoring the spread of invasive species, such as nipah, is a vital control method (Myint et al. 2008). When researching species distribution, it is essential to consider modeling techniques, environmental factors, and species traits (Liu et al. 2020). Furthermore, nipah has considerable potential for landscape restoration, rapid atmospheric carbon dioxide sequestration, coastal protection from severe weather, the restoration of abandoned aquaculture ponds, and the promotion of sustainable aquaculture (Rahman et al. 2024). This study aims to analyze the association and distribution patterns of nipah in ATPF and map the land cover distribution. The findings will aid in planning effective restoration programs and monitoring and preventing invasions. In addition, the results of this research are useful in understanding the dynamics of nipa palm populations and the implications of their dominance, management and restoration of mangrove ecosystems, ecological risk assessment, and development of conservation policies.

MATERIALS AND METHODS

Study site description

This research was conducted in the Air Telang Protected Forest (ATPF), a mangrove forest area located in Banyuasin District, South Sumatra Province, Indonesia, covering approximately 12,660.87 hectares (Figure 1). The eastern part of this area borders Muara Telang Sub-district and Banyuasin II Sub-district, while the western boundary is the Banyuasin River. The northern boundary is the Bangka Strait and the Banyuasin River, while the southern boundary is Muara Telang Sub-district. Most of this area has experienced degradation and land conversion into plantations, agricultural lands, settlements, and ponds. As of 2023, only about 26% of the area remains as primary forest (Eddy et al. 2023a). Two ports have been operational in this area since 2013: a sea terminal for goods transport and a ferry terminal for passenger transport, both situated near the research area, specifically on the Banyuasin River in Tanjung Api-Api. The government is currently constructing a new sea terminal at Tanjung Carat (north of ATPF).

Nipah invasion is prevalent in degraded mangrove forest areas in South Sumatra Province, including ATPF (Eddy et al. 2024). Nearly all areas, from tidal coastal zones to the mainland, have been invaded by nipah (Eddy and Basyuni 2020). Nipah's high adaptability, combined with its prolific fruit production and the ability of its fruits to be easily dispersed by tidal currents, facilitates its invasion of this area.

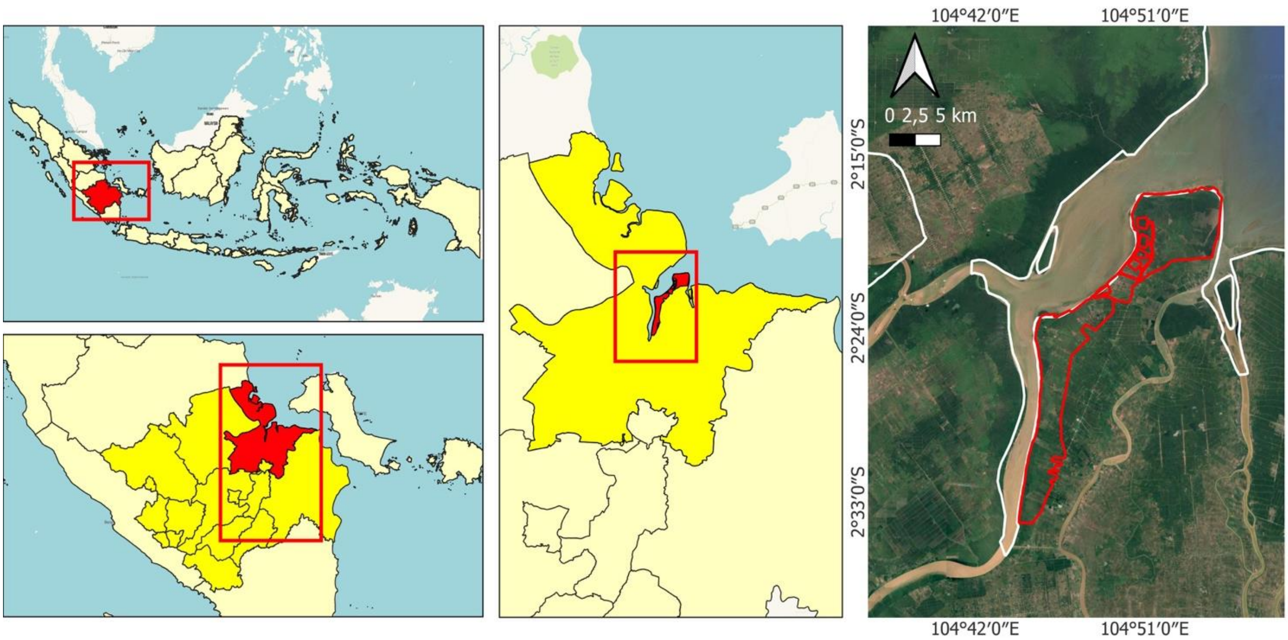

Figure 1. Location of the study area in the Air Telang Protected Forest (ATPF), Banyuasin District, South Sumatra, Indonesia

This research utilized Landsat 9 image data for ATPF land cover in 2024, sourced from https://earthexplorer.usgs.gov. The downloaded Landsat 9 image data has a multi-spectral band with a resolution of 30 meters, acquired on May 25, 2024. Image sharpening was performed by adding band 8 as panchromatic data with a resolution of 15 meters. The coordinate system used is the UTM (Universal Transverse Mercator) Zone 48 coordinate system. Identification of ATPF mangrove forests in Landsat 9 imagery was conducted using the Normalized Difference Vegetation Index (NDVI). The research location was selected through purposive sampling, and verification of land cover types and location boundaries was conducted via field surveys. Each sampling point's coordinates were marked using the Geographical Positioning System (GPS) and identified according to the land cover classification (Table 1).

Vegetation data collection

Vegetation sampling was conducted using a purposive sampling method at the sampling points listed in Table 1 from May to June 2024. Vegetation samples were collected based on their association with nipah, with a maximum distance of 10 meters for trees and 5 meters for shrubs. The selected nipah specimens were tree life forms with a diameter at breast height (DBH) of ≥10 cm. All plants collected were identified in the plant taxonomy laboratory of Universitas PGRI Palembang, South Sumatra, Indonesia. Identified species were assigned local names, species types, and habitat types, which were then tabulated in a matrix.

We also documented the distribution of nipah through aerial photography using drones. The drone model used was the DJI Mini 3, equipped with a 48 MP image sensor capable of capturing images from a maximum height of 500 meters. Nipah stand samples were photographed in various locations, including primary forests, secondary forests, shrubs, and open areas. Drone photography was conducted at various heights to ensure representative positions for each type of vegetation.

Data analysis

Landsat data analysis

Land cover changes in ATPF were analyzed and classified using Geographic Information System (GIS) software, specifically ArcGIS Desktop 10.8. The classification of land cover was based on plant canopy density and land use types, which included primary forest, secondary forest, open area (shrubs), and plantation (coconut and oil palm). The GIS analysis followed four steps: pre-processing, processing, image classification, and field survey (Eddy et al. 2017). We employed a supervised classification maximum likelihood analysis method (visual interpretation) to classify the image data (Ghebrezgabher et al. 2016).

Analysis of nipah association and distribution patterns with other plants

All species associated with nipah were identified and grouped based on their location-primary forest, secondary forest, and shrubs-and tabulated as shown in Table 2; meanwhile, in plantation areas, nipah were not found, and in open areas, only nipah were found without any association with other plant species. Additionally, we categorized the identified plant species into two groups, namely true mangroves and mangrove associates. We also identified the local names of each species based on information from the local community. The analysis of Nipah Distribution Patterns involved identifying nipah growth locations and predicting the distribution process. We documented nipah growing in four locations: open areas, shrubs, secondary forests, and primary forests. The distribution pattern of nipah was analyzed based on observations and compared with relevant literature, presented in matrix form in Table 3. Furthermore, we illustrated the results in a flowchart to predict the distribution patterns of nipah-both solitary and colonial-in association with other plants or independently.

Table 1. Coordinates of sampling points for each study site along with their existing conditions

Study sites	UTM coordinate		Existing condition
	X	Y	
Muara Sungsang Village	490551	9745431	Shrub/open area
Marga Sungsang Village	483657	9740547	Shrub/open area
Karang Anyar Village	474117	9720844	Shrub/open area
Muara Sungsang Village	477330	9735590	Shrub/open area
Muara Sungsang Village	478669	9737374	Shrub/open area
Teluk Payo Village	475174	9728896	Coconut plantation
Muara Sungsang Village	474822	9723408	Coconut plantation
Teluk Payo Village	478382	9734814	Coconut plantation
Muara Sungsang Village	480975	9737571	Oil palm plantation
Karang Anyar Village	475226	9722737	Oil palm plantation
Muara Sungsang Village	473358	9735873	Secondary mangrove forest
Sungsang 4 Village	487653	9747706	Secondary mangrove forest
Muara Sungsang Village	475962	9736329	Secondary mangrove forest
Marga Sungsang Village	482488	9744194	Secondary mangrove forest
Marga Sungsang Village	482739	9743193	Secondary mangrove forest
Sungsang 1 Village	482257	9745317	Secondary mangrove forest
Muara Sungsang Village	485396	9747147	Primary mangrove forest
Marga Sungsang Village	482327	9741753	Primary mangrove forest
Marga Sungsang Village	483231	9742249	Primary mangrove forest

RESULTS AND DISCUSSION

Land cover changes in ATPF

Interpretation of Landsat image data from 2024 (Figure 2) classified ATPF into four land cover types: primary forest, secondary forest, open area, and plantation. Our survey revealed additional land cover types, such as settlements and ponds, but their extent was minimal and insignificant. Plantations in ATPF were categorized into two groups: coconut and oil palm, with coconut plantations occupying a larger area than oil palm plantations (Eddy et al. 2017; Eddy et al. 2021a,b; Eddy et al. 2022). The largest land cover type in ATPF in 2024 was open areas, covering 34% (4,296.51 ha), followed by plantations with 30% (3,797.67 ha). Primary forests and secondary forests accounted for approximately 23% (2,961.75 ha) and 13% (1,604.94 ha), respectively.

The map resulting from our image interpretation indicates the presence of coastal zones classified as land areas but not included in the ATPF area. This discrepancy may arise from two possibilities: either the image data was collected during low tide, or there has been an increase in land area due to intensive sedimentation along the banks of the Banyuasin River. Our previous research indicated significant sedimentation in the downstream Banyuasin River, attributed to reduced forest cover upstream, leading to the formation of new land areas downstream (Eddy et al. 2017).

Association of nipah with other plants

Our study identified 29 plant species belonging to 17 families associated with nipah in ATPF, including 22 species in shrub vegetation, 18 species in secondary forest vegetation, and 8 species in primary forest vegetation (Table 2). The Fabaceae and Poaceae families had the highest number of species, with four species each, followed by the Acanthaceae and Asteraceae families, which had three species each. We categorized the identified plants into two groups: true mangroves and mangrove associates, with 9 true mangrove species and 20 mangrove associate species. Local names for each species were obtained from the local community.

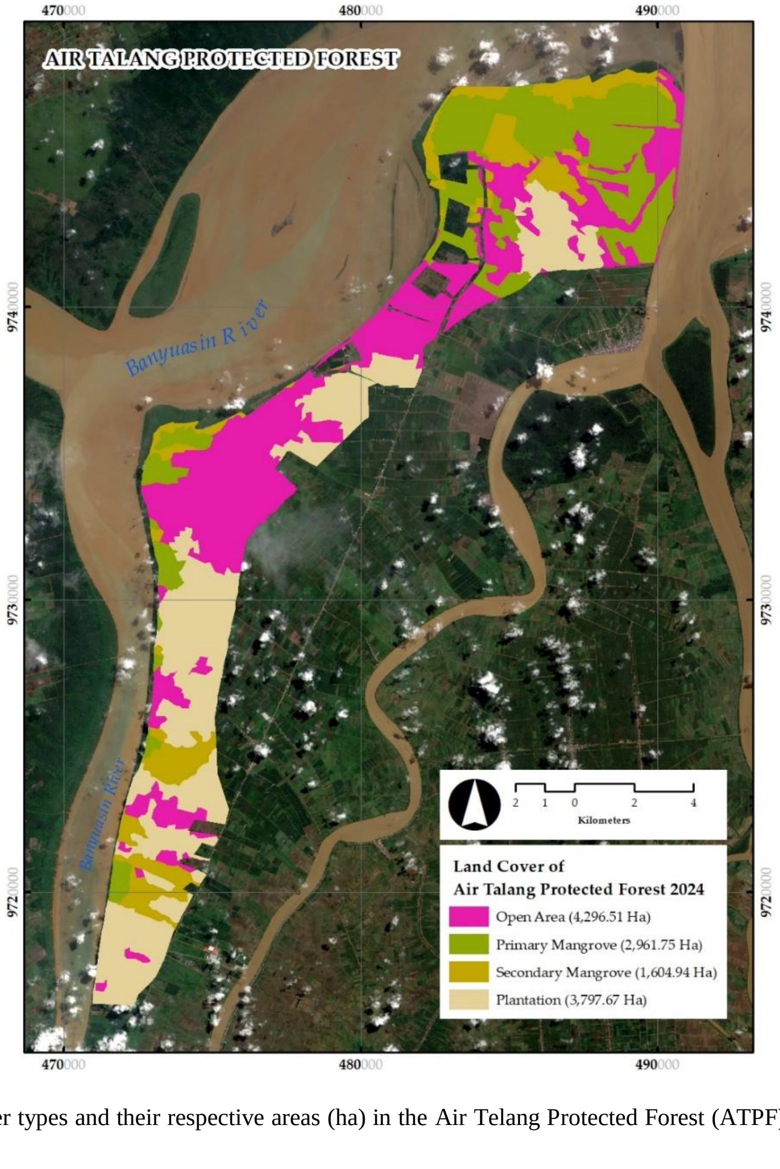

Figure 2. Map of land cover types and their respective areas (ha) in the Air Telang Protected Forest (ATPF), Banyuasin District, South Sumatra, Indonesia, 2024

Analysis of nipah distribution patterns

We observed nipah growing in several habitats: open areas, shrubs, secondary forests, and primary forests. The distribution pattern of nipah is detailed in Table 3 and Figure 6 based on the results of data analysis and various theories of vegetation succession (Clements 1916; Egler 1954; Connell and Slatyer 1977). Nipah in open areas acts as a pioneer plant, growing either solitarily or in colonies (Figure 3) and not associated with other plants, with seed distribution facilitated by tidal currents. Nipah in shrub vegetation creates a favorable microclimate for the growth of associated cover plants. The distribution of nipah in shrub vegetation (Figure 4) can result from nipah growing in open areas that provide suitable microclimate, nutrients, and water for various cover plants and seedlings (Table 3, option 1A). Additionally, seeds may be carried by tidal currents to shrub areas, where they germinate due to favorable conditions (Table 3, option 2A).

Table 2. Diversity of plant species associated with nipah in three types of vegetation in Air Telang Protected Forest (ATPF), Banyuasin District, South Sumatra, Indonesia

Species	Family	Local name	Species type	Vegetation type		
				A	B	C
Acacia mangium	Fabaceae	*Akasia*	Mangrove associate	√	-	-
Acanthus ilicifolius	Acanthaceae	*Jeruju*	True mangrove	-	√	√
Acrostichum aureum	Pteridaceae	*Paku laut*	True mangrove	√	√	√
Asystasia gangetica	Acanthaceae	*Ara sungsang*	Mangrove associate	√	√	-
Avicennia alba	Acanthaceae	*Api-api*	True mangrove	-	√	√
Bruguiera cylindrica	Rhizophoraceae	*Tomok*	True mangrove	-	√	√
Calamus sp.	Arecaceae	*Rotan*	Mangrove associate	-	√	-
Chloris barbata	Poaceae	*Jejarongan*	Mangrove associate	√	√	-
Clerodendrum inerme	Verbenaceae	*Pacar laut*	Mangrove associate	√	√	-
Cyperus rotundus	Cyperaceae	*Rumput teki*	Mangrove associate	√	-	-
Derris trifoliata	Fabaceae	*Tuba laut*	Mangrove associate	√	√	√
Desmodium heterocarpon	Fabaceae	*Katepan*	Mangrove associate	√	-	-
Eleusine indica	Poaceae	*Rumput Belulang*	Mangrove associate	√	-	-
Eragrostis sp.	Poaceae	*Rumput jarum*	Mangrove associate	√	√	-
Excoecaria agallocha	Euphorbiaceae	*Buta-buta*	True mangrove	√	√	√
Imperata cylindrica	Poaceae	*Alang-alang*	Mangrove associate	√	-	-
Melastoma candidum	Melastomataceae	*Senduduk*	Mangrove associate	√	-	-
Mikania micrantha	Asteraceae	*Sambung rambut*	Mangrove associate	√	-	-
Mimosa pudica	Mimosaceae	*Putri malu*	Mangrove associate	√	-	-
Nephrolepis sp.	Dryopteridaceae	*Pakis Gunung*	Mangrove associate	√	√	-
Oncosperma tigillarium	Arecaceae	*Nibung*	Mangrove associate	-	√	-
Pluchea indica	Asteraceae	*Beluntas*	Mangrove associate	√	√	-
Rhynchosia minima	Fabaceae	*Kacang moncong*	Mangrove associate	√	-	-
Rhizophora apiculata	Rhizophoraceae	*Bakau*	True mangrove	√	√	√
Sarcolobus globosa	Apocynaceae	*(None)*	True mangrove	√	√	-
Sonneratia alba	Lythraceae	*Pedada/perepat*	True mangrove	-	√	-
Stenochlaena palustris	Polypodiaceae	*Pakis udang*	Mangrove associate	√	-	-
Synedrella nodiflora	Asteraceae	*Jotang kuda*	Mangrove associate	√	-	-
Xylocarpus granatum	Meliaceae	*Boli*	True mangrove	-	√	√
			Total	22	18	8

Note: √: found; (-): not found. A. Shrub; B. Secondary forest; C. Primary forest

Figure 3. Nipah growing in open areas in Air Telang Protected Forest (ATPF), Banyuasin District, South Sumatra, Indonesia. A-B. Both solitarily; C-D. In colonies, as observed in ATPF

Table 3. Description of predicted nipah distribution patterns in open areas, shrubs, secondary forests, and primary forests in Air Telang Protected Forest (ATPF), Banyuasin District, South Sumatra, Indonesia based on our findings and references to the theory of succession mechanisms according to Clements (1916), Egler (1954) and Connell and Slatyer (1977)

Natural forms of association	Location found	Description of distribution pattern prediction	
		Option 1	**Option 2**
Solitary in open areas (no association/ pioneer)	In open areas of land and coast	Ripe nipah fruit floats on water and is dispersed by tidal currents, settling solitarily on muddy substrates in open areas. The seed germinates due to sufficient nutrients and water, leading to solitary nipah seedlings that are not associated with other plants.	(none)
Colony in open areas (no association/ pioneer)	In open areas of land and coast	A group of ripe nipah fruits floats on water and is dispersed by tidal currents, settling in colonies on muddy substrates in open areas. The seeds germinate and grow into clustered seedlings due to the availability of sufficient nutrients, water, and environmental conditions suitable for their growth. Furthermore, these seedlings develop into nipah palms that remain grouped but are not associated with other plants.	(none)
Association in the shrubs	In shrub areas of land and coast	Option 1A: Nipah colonies create a microclimate conducive to the growth of cover plants or shrubs whose seeds are dispersed by water currents, wind, or animals (e.g., birds). Open areas provide nutrients, water, and favorable conditions for these plants, leading to diverse shrub growth associated with nipah.	Option 2A: Ripe nipah fruit is carried by tidal currents to shrub areas where it germinates under favorable conditions, developing into solitary or colonial nipah palms found in association with other plants. This process can occur during high tides, which do not hinder the fruit's movement.
Association in secondary forests	In secondary forest areas of land and coast	Option 1B: Woody plant seeds dispersed by water or animals also develop in open areas alongside shrubs and nipah, supported by favorable conditions, leading to the formation of secondary forests.	Option 2B: Ripe nipah fruit is carried by tidal currents to secondary forest areas, where it germinates and develops into seedlings. These seedlings may develop into solitary or colonial nipah trees, often associated with woody plants and shrubs. This process can occur during high tides, which do not hinder the movement of the nipah fruit.
Association in primary forests	In primary forest areas of land and coast	Option 1C: True mangroves and nipah in secondary forests grow rapidly, creating a canopy cover that inhibits sunlight penetration into the forest floor and hinders cover plant growth. This leads to the formation of primary forests with true mangroves, nipah, and a few shrubs.	Option 2C: Nipah fruits are carried by tidal currents to primary forest areas, where they germinate due to the availability of sufficient water and nutrients. Nipah will develop into seedlings, which in turn grow into solitary or colonial nipah palms, found in association with true mangrove trees and a few shrubs. This process can occur during high tides, which do not hinder the movement of the nipah fruit.

Figure 4. Nipah in association with shrubs, as observed in Air Telang Protected Forest (ATPF), Banyuasin District, South Sumatra, Indonesia

The distribution of nipah in secondary forest vegetation (Figures 5.A and 5.B) is a process that begins with the dispersion of woody plant seeds. These seeds are carried by tidal currents or animals, highlighting the crucial role of animals in the seed dispersion process. The seeds develop in open areas alongside shrubs and nipah, and their growth is significantly influenced by supportive environmental conditions such as nutrients, water, and microclimate. This understanding of the interconnectedness of forest ecosystems is crucial for comprehending the formation of secondary forests (Table 3, option 1B). Alternatively, ripe nipah fruits may be carried by tidal currents to secondary forest areas, where they grow as solitary or colonial trees due to favorable conditions (Table 3, option 2B).

Nipah in primary forest vegetation (Figures 5.C and 5.D) has a distribution pattern that starts with the formation of a secondary forest, where nipah associates with other woody plants and shrubs. These woody plants, including nipah, exhibit remarkable resilience and rapid growth, leading to the formation of primary forests (Table 3, option 1C). Additionally, the distribution of nipah can occur when the nipah fruit is carried by tidal currents to primary forest areas, where it grows due to favorable conditions (Table 3, option 2C).

We predict that nipah populations in ATPF (Figure 6) may begin with nipah invasion in open areas (i.e., as pioneers), either solitary or colonial, subsequently developing into shrub vegetation. Shrubs will evolve into secondary forest vegetation, which will subsequently transition into primary forest vegetation. The availability of nutrients, water, and a conducive microclimate supports nipah's adaptability across all vegetation types.

Figure 5. Nipah in association with A-B. Secondary forest; C-D. Primary forest, as observed in Air Telang Protected Forest (ATPF), Banyuasin District, South Sumatra, Indonesia

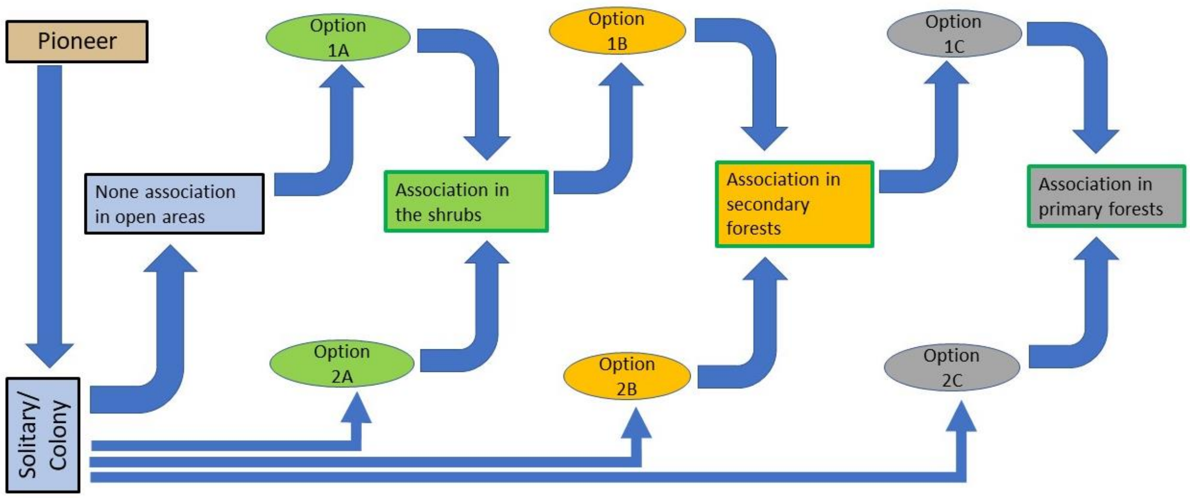

Figure 6. Analysis of the predicted distribution pattern of the nipah population in Air Telang Protected Forest (ATPF), Banyuasin District, South Sumatra, Indonesia, ranging from open areas to shrubs, secondary forests, and primary forests, as described in Table 3

Discussion

In comparing land cover in 2023 (Eddy et al. 2023a) and 2024, open areas decreased from 6,588.34 ha to 4,296.51 ha, representing a reduction of approximately 2,291.83 ha (18.10% of ATPF's total area). Similarly, primary forests decreased from 3,370.50 ha to 2,961.75 ha, a reduction of about 408.75 ha (3.23% of ATPF's total area). In contrast, secondary forests increased from 1,244.91 ha to 1,604.94 ha, an increase of approximately 360.03 ha (2.84% of ATPF's total area). Plantations also increased significantly from 1,197.37 ha to 3,797.67 ha, an increase of about 2,600.30 ha (20.54% of ATPF's total area).

The substantial increase in plantation land from 2023 to 2024-approximately 20.54% of ATPF's total area-is noteworthy. The primary plantation types are coconut and oil palm. Coconut plantations in ATPF were initiated by farmers from Sulawesi, specifically the Bugis tribe, in 1972. Currently, coconut plantations are the largest in ATPF, surpassing oil palm plantations, which began in 1989 (Eddy et al. 2017). Both have significantly contributed to the loss of mangrove forests in ATPF (Eddy et al. 2021a). This pattern is also observed in other Southeast Asian regions, where certain mangrove habitats in the Philippines have been replaced by coconut plantations, significantly affecting carbon stocks (Castillo et al. 2017a; Castillo et al. 2017b).

The largest area identified in this research is open areas, which account for 34% of ATPF's total area. The emergence of these open areas is due to land clearing by the community for various purposes, particularly for plantations. Our previous research in 2023 identified open areas covering 6,588.34 ha, accounting for more than half of ATPF's total area (Eddy et al. 2023a). Open areas are particularly vulnerable to nipah invasion because they lack physical barriers, such as mangrove roots, that could otherwise impede the spread of nipah fruit by tidal currents. Nipah seeds migrate more readily in open regions, especially when mangrove forests are degraded and tree numbers decline. Initially, these seeds form small colonies before establishing permanent populations (Eddy et al. 2024). The distribution of plant species, including nipah, is largely influenced by seed availability and dispersal mechanisms such as wind and water currents (Eddy et al. 2024).

Illegal logging and land conversion for plantations have greatly contributed to the decline of primary forests and open areas in ATPF from 2023 to 2024. The community's utilization of wood from primary forests has reduced tree stands, leading to a decrease in primary forests and an increase in secondary forests due to the degradation of the former. Open areas identified in 2023 have been converted to plantations by 2024, resulting in a significant increase in plantation areas. We combined the land cover classification for open areas and shrubs into a single category termed 'open areas' due to the complexities of distinguishing between the two in Landsat imagery interpretation. However, in the field, we observed nipah growing in both areas. This differentiation was further clarified in aerial photo interpretations using drones, as shown in Figures 3 and 4.

We identified 29 plant species associated with nipah, comprising 9 true mangroves and 20 mangrove associates. Species diversity in ATPF is relatively low, particularly in primary forests. This low diversity is most likely caused by only a few species that can survive in the very dynamic mangrove forest habitat, despite the importance of plant species in providing ecosystem services. According to du Toita et al. (2018), ecosystem services encompass goods and services provided by ecosystems to people, such as provisioning, regulating, cultural, and supporting/habitat services. The diversity of plant species in the area enables numerous ecosystem services, such as natural disaster protection, oxygen supply, aesthetic value, climate change mitigation, and provision of food, medicine, and building materials (Eddy et al. 2023b,c). Each plant species contributes significantly to these services, offering various products to nearby communities (Panyadee et al. 2022). Furthermore, wild plant products containing beneficial chemical compounds are a significant source of income and livelihood for people in developing countries (Smith 2018; Shafi et al. 2021).

Based on our observations along the east coast of Sumatra, particularly in South Sumatra Province, we witnessed the extraordinary adaptability of nipah. Most mangrove forests, including ATPF, have been invaded by nipah, a species whose seeds tend to thrive in shallow inland areas (Widodo et al. 2020). Nipah's ability to invade nearly the entire east coast of Sumatra across all land cover types (open areas, shrubs, secondary forests, and primary forests) is attributed to its adaptability to coastal environments, both on land and in flooded areas. Several factors support its high adaptability, including tolerance to high salinity, growth in muddy substrates, efficient reproduction through abundant seed production, and resilience to dynamic environmental changes like sea level and tidal fluctuations. Additionally, nipah possesses lenticels at the base of the leaves that aids in oxygen acquisition in muddy or flooded environments, which often lack oxygen (Björn et al. 2022). According to Numbere and Mason (2019), floating nipah seeds invade mangrove forests and degraded areas due to their rapid growth patterns and ability to survive in conditions that are inhospitable for other mangrove plants. Urbanization also contributes significantly to nipah invasion, as anthropogenic activities degrade ecosystem quality and create opportunities for nipah encroachment (Obayelu 2018).

Based on the predicted distribution of nipah populations in Figure 6, we anticipate that nipah will dominate nearly all degraded areas of ATPF. The mangrove forest succession process could be accelerated through community intervention aimed at rehabilitating degraded forests and controlling nipah distribution. However, without proper management, the succession process will be obstructed, allowing nipah to replace mangrove forests. Nipah invasion can impede water movement, leading to increased sedimentation and decreased waste circulation, which in turn lowers substrate quality (Eddy et al. 2024). Nipah is often found as a pioneer species that develops alongside sediment accumulation, ultimately invading the area (Moudingo et al. 2020). Nipah invasion in mangrove forest ecosystems is closely linked to the loss of mangrove forests (Nwobi et al. 2020; Barenblitt et al. 2024).

The reduction of mangrove stands due to nipah invasion has broader implications for disrupting ecosystem balance. This decline not only affects the quality and quantity of vegetation but also impacts aquatic biota, such as fish and shrimp. Mangrove forest degradation disrupts the spawning processes of aquatic biota, reducing fisheries productivity and leading to ecological challenges (Numbere 2019). Additionally, harm to mangrove forests can diminish species richness among flora and fauna, reduce carbon storage, and increase greenhouse gas emissions (Eddy et al. 2021a,b; Basyuni et al. 2021; Basyuni et al. 2023).

Nipah is a palm plant classified as a monocotyledon with fibrous roots. Generally, the ability of monocotyledonous plant roots to withstand soil erosion is weaker than that of dicotyledonous plants, such as *R. apiculata*, *S. alba,* and *A. alba,* which possess taproots and root structures adapted for growth in muddy substrates. Nipah roots do not penetrate deeply into the soil, limiting their reach. While this root system effectively absorbs water and nutrients from the topsoil, it is less effective in stabilizing soil structure at greater depths. Consequently, monocotyledonous plants, including nipah, are less capable of resisting erosion in unstable soils, such as muddy coastal areas.

This research successfully mapped several land cover types in ATPF in 2024, including primary forests, secondary forests, open areas (shrubs), and plantations. We identified 29 plant species associated with nipah in primary forests, secondary forests, and shrubs. The distribution of nipah seeds, primarily dispersed by tidal currents, has spread across various land cover types through several mechanisms, leading to its dominance. These findings of this study will improve our understanding of competition dynamics and interactions between plant species, the implications of nipah's dominance, and strategies to control its invasion. More broadly, the results are crucial for conserving mangrove forests, not only in ATPF but also in other regions worldwide affected by nipah invasion.

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REFERENCES

Almond REA, Grooten M, Peterson T. 2020. Living Planet Report 2020 - Bending the Curve of Biodiversity Loss. World Wildlife Fund, Switzerland.

Barenblitt A, Fatoyinbo L, Thomas N, Stovall A, de Sousa C, Nwobi C, Duncanson L. 2024. Invasion in the Niger Delta: Remote sensing of mangrove conversion to invasive *Nypa fruticans* from 2015 to 2020. Remote Sens Ecol Conserv 10 (1): 5-23. DOI: 10.1002/rse2.353.

Basyuni M, Gultom K, Fitri A, Susetya IE, Wati R, Slamet B, Sulistiyono N, Yusriani E, Balke T, Bunting P. 2018. Diversity and habitat characteristics of macrozoobenthos in the mangrove forest of Lubuk Kertang Village, North Sumatra, Indonesia. Biodiversitas 19 (1): 311-317. DOI: 10.13057/biodiv/d190142.

Basyuni M, Sasmito SD, Analuddin K, Ulqodry TZ, Saragi-Sasmito MF, Eddy S, Milantara N. 2022. Mangrove biodiversity, conservation and roles for livelihoods in Indonesia. In: Das SC, Pullaiah, Ashton EC (eds). Mangroves: Biodiversity, Livelihoods and Conservation. Springer, Singapore. DOI: 10.1007/978-981-19-0519-3_16.

Basyuni M, Simanjutak EO, Eddy S, Amelia R. 2021. Carbon stock and vegetation estimation the abandoned pond, Pulau Sembilan, North Sumatra, Indonesia. IOP Conf Ser: Earth Environ Sci 912: 012006. DOI: 10.1088/1755-1315/912/1/012006.

Basyuni M, Wirasatriya A, Iryanthony SB, Amelia R, Slamet B, Sulistiyono N, Pribadi R, Sumarga E, Eddy S, Al Mustaniroh SS, Sasmito SD, Sidik F, Kajita T, Ali HM, Macklin PA, Arifanti VB. 2023. Aboveground biomass and carbon stock estimation using UAV photogrammetry in Indonesian mangroves and other competing land uses. Ecol Inform 77: 102227. DOI: 10.1016/j.ecoinf.2023.102227.

Björn LO, Middleton BA, Germ M, Gaberšˇcik A. 2022. Ventilation systems in wetland plant species. Divers 14: 517. DOI: 10.3390/d14070517.

Castillo JAA, Apan AA, Maraseni TN, Salmo SG. 2017a. Estimation and mapping of above-ground biomass of mangrove forests and their replacement land uses in the Philippines using Sentinel imagery. ISPRS J Photogramm Remote Sens 134: 70-85. DOI: 10.1016/j.isprsjprs.2017.10.016.

Castillo JAA, Apan AA, Maraseni TN, Salmo SG. 2017b. Soil C quantities of mangrove forests, their competing land uses, and their spatial distribution in the coast of Honda Bay, Philippines. Geoderma 293: 82-90. DOI: 10.1016/j.geoderma.2017.01.025.

Chowdhury A, Naz A, Maiti SK. 2023. Variations in soil blue carbon sequestration between natural mangrove metapopulations and a mixed mangrove plantation: A case study from the world's largest contiguous mangrove forest. Life 13: 271. DOI: 10.3390/life13020271.

Clements FE. 1916. Plant Succession: An Analysis of Vegetaion. Carnegie Institution, Wahsington DC. DOI: 10.5962/bhl.title.56234.

Connel JH, Slatyer RO. 1977. Mechanisms of succession in natural communities an their role in communiry stability. Am Nat 111: 1119-1144. DOI: 10.1086/283241.

Cooley SR, Schoeman DS, Bopp L, Boyd P, Donner S, Ito S, Kiessling W, Martinetto P, Ojea E, Racault MF. 2022. Oceans and Coastal Ecosystems And Their Services. Cambridge University Press, Great Britain.

Cui L, DeAngelis DL, Berger U, Cao M, Zhang Y, Zhang X, Jiang J. 2024. Global potential distribution of mangroves: Taking into account salt marsh interactions along latitudinal gradients. J Environ Manag 351: 119892. DOI: 10.1016/j.jenvman.2023.119892.

du Toita MJ, Cilliersa SS, Dallimerb M, Goddardb M, Guenatb S, Corneliusa SF. 2018. Urban green infrastructure and ecosystem services in sub-Saharan Africa. Landsc Urban Plan 180: 249-261. DOI: 10.1016/j.landurbplan.2018.06.001.

Ebana RUB, Etoc CA, Edet UO. 2015. Phytochemical screening and antimicrobial activity of *Nypa fruticans* harvested from Oporo River in the Niger Delta region of Nigeria. J Sci Res 10: 1120-1124.

Eddy S, Basyuni M. 2020. Short Communication: The phenomenon of nipah (*Nypa fruticans*) invasion in the Air Telang Protected Forest, Banyuasin District, South Sumatra, Indonesia. Biodiversitas 21 (11): 5114-5118. DOI: 10.13057/biodiv/d211116.

Eddy S, Dahlianah I, Mashito C, Oktavia M, Utomo B. 2022. Anthropogenic implications for land cover changes and vegetation structure in coastal protected forest. Biodiversitas 23 (9): 4473-4481. DOI: 10.13057/biodiv/d230913.

Eddy S, Iskandar I, Ridho MR, Mulyana A. 2017. Land cover changes in the air telang protected forest, South Sumatra, Indonesia (1989-2013). Biodiversitas 18 (4): 1538-1545. DOI: 10.13057/biodiv/d180432.

Eddy S, Milantara N, Basyuni M. 2021b. Carbon emissions as impact of mangrove degradation: A case study on the Air Telang Protected Forest, South Sumatra, Indonesia (2000-2020). Biodiversitas 22 (4): 2142-2149. DOI: 10.13057/biodiv/d220464.

Eddy S, Milantara N, Sasmito SD, Kajita T, Basyuni M. 2021a. Anthropogenic drivers of mangrove loss and associated carbon emissions in South Sumatra, Indonesia. Forest 12 (2): 187. DOI: 10.3390/f12020187.

Eddy S, Mutiara D, Mediswati RYT, Rahman RG, Milantara N, Basyuni M. 2021c. Short Communication: Diversity of bird species in Air Telang Protected Forest, South Sumatra, Indonesia. Biodiversitas 22 (12): 5274-5279. DOI: 10.13057/biodiv/d221206.

Eddy S, Ridho MR, Iskandar I, Mulyana A. 2019. Species composition and structure of degraded mangrove vegetation in the Air Telang

Protected Forest, South Sumatra, Indonesia. Biodiversitas 20 (8): 2119-2127. DOI: 10.13057/biodiv/d200804.

Eddy S, Rizal S, Kartika T, Sari KJ. 2023c. Vegetation analysis and ethnobotanical study of rubber agroforests in South Sumatra, Indonesia. Biodiversitas 24 (4): 2276-2283. DOI: 10.13057/biodiv/d240441.

Eddy S, Setiawan AA, Taufik M, Oktavia M, Utomo B, Milantara N. 2023a. Loss of carbon stock as an impact of anthropogenic activities in a protected mangrove forest. Biodiversitas 24 (12): 6493-6501. DOI: 10.13057/biodiv/d241211.

Eddy S, Setiawan AA, Zaharaini, Utomo B, Oktavia M. 2023b. Nipah (*Nypa fruticans*): Can it be a renewable alternative energy source?. IOP Conf Ser: Earth Environ Sci 1180 (1): 012042. DOI: 10.1088/1755-1315/1180/1/012042.

Eddy S, Taufik M, Setiawan AA, Utomo B, Oktavia M. 2024. Study of population distribution and benefits of Nipah (*Nypa fruticans*). E3S Web Conf 475: 02007. DOI: 10.1051/e3sconf/202447502007.

Egler FE. 1954. Vegetation science concept I. Initial florostic composition. A factor in old field vegetation development. Vegetatio 4: 412-417.

Friess DA, Rogers K, Lovelock CE, Krauss KW, Hamilton SE, Lee SY, Lucas R, Primavera J, Rajkaran A, Shi S. 2019. The state of the world's mangrove forests: Past, present, and future. Annu Rev Environ Resour 44 (1): 89-115. DOI: 10.1146/ANNUREV-ENVIRON-101718-033302.

Gallardo B, Bacher S, Barbosa AM, Gallien L, González-Moreno P, Martínez-Bolea V, Sorte C, Vimercati G, Vilà M. 2024. Risks posed by invasive species to the provision of ecosystem services in Europe. Nat Commun 15 (1): 2631. DOI: 10.1038/s41467-024-46818-3.

Ghebrezgabher MG, Yang T, Yang X, Wang X, Khan M. 2016. Extracting and analyzing forest and woodland cover change in Eritrea based on landsat data using supervised classification. Egypt J Remote Sens Space Sci 19 (1): 37-47. DOI: 10.1016/j.ejrs.2015.09.002.

Heringer G, Fernandez RD, Bang A, Cordonnier M, Novoa A, Lenzner B, Capinha C, Renault D, Roiz D, Moodley D, Tricarico E, Holenstein K, Kourantidou M, Kirichenko NI, Adelino JRP, Dimarco RD, Bodey TW, Watari Y, Courchamp F. 2024. Economic costs of invasive non-native species in urban areas: An underexplored financial drain. Sci Tot Environ 917: 170336. DOI: 10.1016/j.scitotenv.2024.170336.

Hochard JP, Hamilton S, Barbier EB. 2019. Mangroves shelter coastal economic activity from cyclones. Proc Nat Acad Sci USA 116 (25): 12232-12237. DOI: 10.1073/pnas.1820067116.

Kusmana C, Hidayat T, Hikmah WF. 2019. Above-ground biomass and carbon stock of Ciletuh Mangrove Forest, West Java, Indonesia. IOP Conf Ser: Earth Environ Sci 394 (1): 012005. DOI: 10.1088/17551315/394/1/012005.

Liu C, Wolter C, Xian W, Jeschke JM. 2020. Species distribution models have limited spatial transferability for invasive species. Ecol Lett 23 (11): 1682-1692. DOI: 10.1111/ele.13577.

Mai NTH, Tan NQ, Linh NHK. 2019. Understanding the status and challenges of mangrove conservation in central Vietnam: Case study in Duy Xuyen District, Quang Nam Province. Hue Univ J Sci: Agric Rural Dev 128 (3B): 71-83. DOI: 10.26459/hueunijard.v128i3b.5361.

Moudingo JH, Gordon A, Dibong D, Tomedi M. 2020. Distribution, devastating effect, and drivers of the exotic mangrove *Nypa fruticans* Van Wurmb (Arecaceae) on the mangroves of West and Central Africa. In: Patra JK, Mishra RR, Thatoi (eds). Biotechnological Utilization of Mangrove Resources. Academic Press, Cambridge. DOI: 10.1016/B978-0-12-819532-1.00003-2.

Myint SW, Giri CP, Wang L, Zhu Z, Gillete SC. 2008. Identifying mangrove species and their surrounding land use and land cover classes using object-oriented approach with a lacunarity spatial measure. GIScience Remote Sens 45 (2): 188-208. DOI: 10.2747/1548-1603.45.2.188.

Numbere AO, Mason M. 2019. Mapping of nypa palm invasion of mangrove forest using low-cost and high resolution UAV digital imagery in The Niger Delta, Nigeria. Curr Trends For Res 6: 1-8. DOI: 10.29011/2638-0013.101031.

Numbere AO, Moudingo JHE. 2023. Scenarios of *Nypa fruticans* invasion: Impacts and management strategies in West and Central Africa. J Coast Res 39 (1): 114-128. DOI: 10.2112/JCOASTRES-D-22A-00012.1.

Numbere AO. 2019. Impact of invasive nypa palm (*Nypa fruticans*) on mangroves in coastal areas of the Niger Delta Region, Nigeria. In Makowski C, Finkl CW (eds). Impacts of Invasive Species on Coastal Environments. Springer International Publishing, New York. DOI: 10.1007/978-3-319-91382-7_13.

Nwobi C, Williams M, Mitchard ET. 2020. Rapid mangrove forest loss and nipa palm (*Nypa fruticans*) expansion in the Niger Delta, 2007-2017. Remote Sens 12 (14): 2007-2017. DOI: 10.3390/rs12142344.

Obayelu AE. 2018. Assessment of land use dynamics and the status of biodiversity exploitation and preservation in Nigeria. J Adv Dev Econ 3: 32-47. DOI: 10.13014/k25x273x.

Ouyang X, Lee SY, Connolly RM, Kainz MJ. 2018. Spatially-explicit valuation of coastal wetlands for cyclone mitigation in Australia and China. Sci Rep 8 (1): 30-35. DOI: 10.1038/s41598-018-21217-z.

Panyadee P, Meunrew J, Balslev H, Inta A. 2022. Ethnobotany and ecosystem services in a tidal forest in Thailand. Sustain 14: 6322. DOI: 10.3390/ su14106322.

Rahman KS, Rahman MM, Dana NH, Adib A, Al-Masud A, Hossain MdT, Rakkibu MdG, Adhikary N, Debrot AO, Islam MdN. 2024. *Nypa*-based land uses and ecosystem services in the tropics: A review. Ecol Indic 159: 111613. DOI: 10.1016/j.ecolind.2024.111613.

Sasmito SD, Basyuni M, Kridalaksana A, Saragi-Sasmito MF, Lovelock CE, Murdiyarso D. 2023. Challenges and opportunities for achieving Sustainable Development Goals through restoration of Indonesia's mangroves. Nat Ecol Evol 7 (1): 62-70. DOI: 10.1038/s41559-022-01926-5.

Shafi A, Hassan F, Zahoor I, Majeed U, Khanday FA. 2021. Biodiversity, Management and Sustainable Use of Medicinal and Aromatic Plant Resources. In: Aftab T, Hakeem KR (eds). Medicinal and Aromatic Plants. Springer, Cham. DOI: 10.1007/978-3-030-58975-2_3.

Smith P. 2018. The Book of Seeds: A Life-Size Guide to Six Hundred Species from Around the World. University of Chicago Press, Chicago. DOI: 10.7208/chicago/9780226362373.001.0001.

Widodo P, Herawati W, Hidayah HA, Chasanah T, Proklamasiningsih E. 2020. Distribution and characteristics of nypa palm (*Nypa fruticans* Wurmb.) in Southern Part of Cilacap Regency. IOP Conf Ser: Earth Environ Sci 550: 012010. DOI: 10.1088/1755-1315/550/1/012010.

Wijana S, Setyawan HY, Wan Z, Zhu M, Pranowo D, Dewi IA, Nareswari MP. 2023. The potential of *Nypa frutican* as an energy source in Indonesia: A review. Adv Food Sci Sustain Agric Agroind Eng 6 (1): 88-96. DOI: 10.21776/ub.afssaae.2023.006.01.8.