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Full Length Research Article

Estimation of Biomass and Carbon Stocks in Mangrove Forests Dominated by *Nypa fruticans* Wurmb in the Nagari Mandeh Area, West Sumatra, Indonesia

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ABSTRACT

Ecosystem condition, biomass, and carbon storage in mangrove forests are highly dependent on the presence of mangrove species in coastal ecosystems. Conversely, the presence of a dominant species alters ecosystem mechanisms; for example, *Nypa fruticans* Wurmb. Biomass, carbon storage, and potential carbon sequestration were estimated in a coastal area dominated by *N. fruticans*. Sampling was conducted by laying out multi-level plots along transect lines representing different vegetation types. Biomass on the ground surface was calculated by applying species-specific allometric equations to convert biomass to carbon and CO_2 equivalents, and then computing the total carbon stocks. Biomass was calculated at 140.21 tons/ha, with a carbon stock of 66.11 tons/ha, yielding a carbon sequestration potential of 241.82 tons/ha. It is obvious that *N. fruticans*, the dominant species as the biggest carbon store, is accompanied by low diversity of native mangrove species. Ecological imbalance between *N. fruticans* and other species persists despite increased total carbon storage. Management efforts must be implemented to support biodiversity and carbon sequestration in coastal mangrove forests.

1. Introduction

The term "blue carbon" is often associated with mangrove forests because of their ability to store and absorb carbon. Mangroves, as part of the blue carbon ecosystem, capture and store carbon effectively through plant biomass and soil. Because of this, Indonesia, with the largest mangrove forest area, is the world's largest carbon sink, making it a crucial region for global carbon storage (Choudhary et al. 2024; Rawena et al. 2020). In addition to their ability to store carbon, mangrove forests can also prevent coastal erosion and provide habitats for marine organisms such as fish. Mangrove forests support fish habitats and various other coastal organisms (Sunkur et al. 2023).

Some mangrove species, such as *N. fruticans*, can negatively impact the structure of mangrove forests. *N. fruticans* can dominate an ecosystem and replace native mangroves, which is a negative impact. *N. fruticans* is a species that can grow and develop rapidly (Numbere 2018). The diversity of mangrove forests can be disrupted and depleted by the dominance of a single species, which inhibits the growth of others. This can affect the ecosystem's carbon balance (Barenblitt et al. 2023; Miniat et al. 2021; Ratul et al. 2022).

In the mangrove forest area of Nagari Mandeh, West Sumatra, there is a healthy ecosystem that is considered a high carbon sink. *N. fruticans* is now found covering large areas, raising concerns about its effects on native species and carbon sequestration capacity. There has been very little research on biomass and carbon reserves in mangrove forests dominated by *N. fruticans*. Therefore, research in the mangrove forests of the Nagari Mandeh area is needed to achieve objectives, including estimating biomass content, carbon reserves, and the potential for carbon storage. This research will also examine the relationship between species dominance and the particular ecology so that the results can support management and conservation plans for these mangrove forests.

2. Materials and Methods

2.1. Study Area

The study was conducted in the mangrove forest of Nagari Mandeh, XI Koto Tarusan Subdistrict, Pesisir Selatan Regency, West Sumatra, Indonesia. The research was conducted in an area covering 325 ha (**Fig. 1**). The mangrove forest in the Nagari Mandeh area is geographically located at coordinates 1°11'33" S, 100°25'45" E.

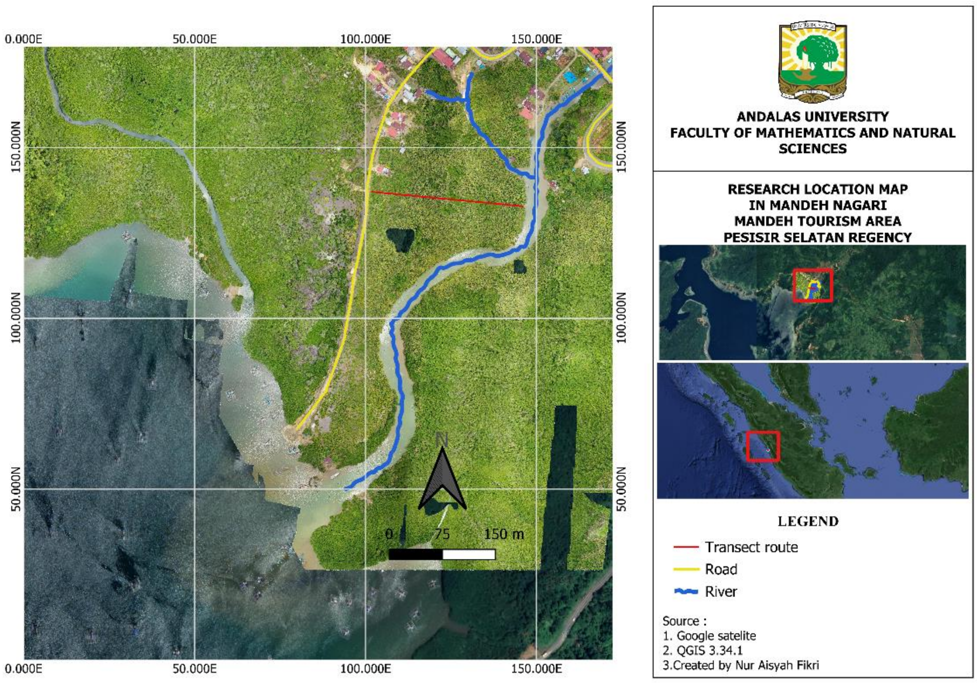

Fig. 1. The location of the Nagari Mandeh area shows the location of transect placement and sampling.

2.2. Sampling Design and Layout

Vegetation data were collected by conducting surveys using a multi-level plot system arranged along a transect line running from the coast to inland areas. This was carried out to account for differences in mangrove vegetation along the transect. This transect was 200 m long and included 20 plots. These plots varied in size based on vegetation density, with larger plots for more vegetation, measuring 10 m × 10 m for tree vegetation with a DBH of 5 cm or more, and 5 m × 5 m for seedlings with a DBH of less than 5 cm. Data for each plot required for this study were collected, including species, number of plants, DBH, and vegetation height, determined by direct observation. All of this was carried out without causing damage to the vegetation, in accordance with non-destructive study principles for mangroves, and data on environmental factors were collected at the study site (FAO 2018; Komiyama et al. 2008).

2.3. Data Analysis

The biomass of vegetation was calculated using Equation 1 (Chave et al. 2014).

$$AGB_{est} = 0.0673 \times (pD^2H)^{0,976} \quad (1)$$

where *AGB* is the above-ground biomass (kg), *D* is the tree diameter (cm), *p* is the specific gravity of wood (g/cm^3), and *H* is the tree height (m).

The biomass of Nypa species was calculated using Equation 2 (Matsui et al. 2014).

$$AGBest = 0.85 \; Log \; D2L + 1.54 \quad (2)$$

where *AGB* is the above-ground biomass (kg), *D* is the midrib diameter (cm), and *L* is the frond length (m).

Carbon stocks of vegetation are calculated using Equation 3 (Standar Nasional Indonesia 2011).

$$Cb = B \times \%C \; organic \quad (3)$$

where *Cb* is the carbon content of biomass (kg), *B* is the total biomass (kg), and *%C organic* is the percentage of carbon content (0.47).

Carbon absorption of vegetation is calculated using Equation 4 (Kauffman and Donato 2012).

$$WCO_2 = Carbon \; Reserve \times 3.67 \quad (4)$$

where WCO_2 is the carbon dioxide absorption, and *3.67* is the equivalent number or conversion of element C to CO_2.

Environmental measurements were conducted in each plot, including soil pH, salinity, soil and air temperature, and substrate characteristics. This data was collected to describe the conditions of the research site's ecosystem that could potentially influence the distribution of mangrove species. The relationship between vegetation patterns and environmental variables was then analyzed using canonical correspondence analysis (CCA), as described by Leaw et al. (2020) and applied by Zereen and Sardar (2018).

3. Results and Discussion

3.1. Composition of Mangrove Vegetation Species

Species classification is crucial for understanding ecosystem conditions, especially in coastal areas that face environmental challenges such as species invasion. This is because species dominance is critical for understanding interactive behaviors, such as community dynamics, spatial relationships, and vegetation in the given ecosystem. Environmental functionality or stability varies with the dominance of particular individual species within a scope that influences other individuals in the ecosystem. Hence, understanding vegetation diversity is crucial for understanding individual elements and for laying a foundation for understanding carbon stocks and the environmental functions of mangroves in a given ecosystem. More detailed information is provided in **Table 1**.

Table 1. Composition of mangrove vegetation species in the Nagari Mandeh area

No	Family	Species	Number of individuals
1	Arecaceae	*Nypa fruticans* Wurmb	613
2	Malvaceae	*Heritiera littoralis* Aiton	4
		Hibiscus tiliaceus L.	4
3	Meliaceae	*Xylocarpus granatum* J.Koenig	42
4	Rhizophoraceae	*Rhizophora apiculata* Blume	84
5	Rubiaceae	*Scyphiphora hydrophylacea* C.F.Gaertn.	33
	Total		780

Table 1 shows the plant composition at the research site. It is suspected that the large number of *N. fruticans* may be due to the muddy tidal area of the study site, where strong river flow leads to a high intake of freshwater. In accordance with the statement by Nugroho et al. (2020), *N. fruticans* typically occurs in wetlands with low salinity, especially along riverbanks, in ponds, or in swampy areas, and is highly influenced by the seawater tidal process.

The dominance of *N. fruticans* indicates that this species is well adapted to low-salinity conditions and muddy substrate. This result is similar to that of Nugroho et al. (2020), who reported that Nypa palms tend to grow better in estuarine areas that receive freshwater inputs. This tree produces high biomass but spreads rapidly, thereby hindering the natural regeneration of true mangrove trees (Barenblitt et al. 2023; Numbere and Camilo 2016; Ratul et al. 2022). Similar conditions were recorded along the coastlines of Malaysia and the Philippines, where *N. fruticans* forms dense stands that can limit the growth of *Rhizophora* and *Sonneratia* species within the vegetation (Wimmler et al. 2021; Sitoy and Buenavista, 2024). This may also be the cause of reduced species diversity and changes in ecosystem structure.

Another species is *R. apiculata* (**Table 1**). *R. apiculata* is a species of mangrove that lives on muddy soil and is flooded at low tide. *R. apiculata* is a coastal mangrove species that has high adaptability to the environment influenced by the mixing of seawater and freshwater. Its life success is influenced by various abiotic factors, such as temperature, pH, and especially water salinity (Aljahdali et al. 2021). According to **Table 1**, the least found species are *H. littoralis* and *H. tiliaceus*, with 4 individuals found. The small number of individuals found at the study site is thought to be due to the plants' incompatibility with the environment, which prevents them from living and thriving. This is in accordance with the statement of Akhmadi (2023) that mangrove forests are environments with extreme conditions and numerous limiting factors for plants, allowing only plant species that can adapt and tolerate specific environmental conditions to survive, grow, and reproduce. The environment in which to live is one of the important factors for every species to grow and develop properly (Solfiyeni et al. 2016).

The structural features of mangrove vegetation also play an important role in estimating the biomass and carbon stock. The mean diameter at breast height of true mangrove species such as *R. apiculata* and *S. hydrophylacea* ranged between 8.2 and 13.6 cm, while the basal area ranged between 4.21 and 3.67 m^2/ha, respectively. These features are usually used as an indicator of stand maturity and productivity (Alongi 2014; Indriyani et al. 2020). Biomass estimation for *N. fruticans* involved morphological variables of frond diameter (D) and frond length (L). The average frond diameter was 4.5 ± 0.9 cm, while the mean frond length reached 5.8 ± 0.7 m. Similar findings were also reported by Matsui et al. (2014) and Barenblitt et al. (2023), who reported comparable values in *N. fruticans*-dominated mangrove forests in Thailand and West Sumatra.

3.2. Plant Biomass

The study's findings indicate that 140.21 tons of biomass are stored per hectare. There are various biomass types and levels at the Nagari Mandeh research site (**Table 2**).

Table 2. Plant biomass in the Nagari Mandeh area

	Species Name	**Number of Individuals**	**Biomass (ton/ha)**	**Total Biomass (ton/ha)**
Tree	*R. apiculata*	54	27.44	28.39
	H. littoralis	1	0.34	
	S. hydrophylacea	3	0.61	
Sapling	*R. apiculata*	30	5.51	14.21
	H. littoralis	3	0.55	
	S. hydrophylacea	30	3.29	
	X. granatum	42	4.63	
	H. tiliaceus	4	0.23	
Palm	*N. fruticans*	613	97.61	97.61
Total		780	140.21	140.21

From **Table 2**, it can be seen that the mangrove species with the highest total biomass at the tree level is *R. apiculata* (27.44 tons/ha). On the other hand, the minimum biomass contributor at the tree level is *H. littoralis,* which produced 0.34 tons/ha. Differences in biomass will also contribute to differences in carbon stocks, driven by factors such as climate and land type, crop species, and planting age (Ruslono 2015). Above-ground biomass within an area is an important factor in determining carbon storage. So, different parameters can produce abundance levels at any given site, depending on species composition and tree density, branch width, which branches die off in the thicket, and individual diameter (Chave et al. 2014; Indriyani et al. 2020). The greater number of individuals in *R. apiculata* than in other tree species is assumed to be the cause of the higher biomass contribution. This has been reported by Obonyo et al. (2023), who note that an increase in tree density in an ecosystem may lead to higher carbon stocks through increased biomass.

At the sapling level, the species that contributed most to biomass was *R. apiculata*, with a total contribution of 5.51 tons/ha. On the other hand, the minimum of *H. tiliaceus* is 0.23 tons/ha. Variation in biomass storage across sapling species is likely related to diameter, density, and canopy cover (Sione et al. 2023). This is in accordance with the data of Vonderach et al. (2023), which examined the relationship between a tree's diameter and height and its biomass. The greater the diameter and height of a tree, the greater its biomass. Furthermore, the more trees stand, the greater the biomass and carbon stock increase, as CO_2 is captured from the atmosphere through photosynthesis. The resulting biomass is then partitioned among all plant compartments.

The biomass of *N. fruticans* was 97.61 tons/ha in the study results. This is believed to be due to the study site being dominated by *N. fruticans* (n = 613). The substantial biomass contribution made by *N. fruticans* is mainly due to its high density in the study region. Nevertheless, despite its high biomass, the wood density of *N. fruticans* is comparably low to that of woody mangrove species (Alongi 2014; Indriyani et al. 2020; Matsui et al. 2014). This indicates that *N. fruticans* stores less carbon per unit of biomass compared with species such as *Rhizophora* or *Xylocarpus*.

3.3. Carbon Stock and Carbon Sequestration of Plants

Based on the study's results on carbon stocks and carbon absorption in tree vegetation, the total carbon stock in the tree strata was found to be 13.55 tons/ha, and the total carbon absorption was 48.97 tons/ha (**Table 3**). The results show that *N. fruticans* contributed about 69% of the total carbon stock in this area. This supports the idea that high plant density plays a big role in determining total carbon content (Obonyo et al. 2023). Still, the presence of this species may not guarantee long-term carbon stability as its plant parts decompose more rapidly than those of woody mangroves (Miniat et al. 2021).

Table 3. Carbon stock and carbon absorption of plants in the Nagari Mandeh area

	Species Name	Carbon stock (ton/ha)	Carbon absorption (ton/ha)	Carbon stock (ton/ha)	Carbon absorption (ton/ha)
Tree	*R. apiculata*	12.9	47.33	13.55	48.97
	H. littoralis	0.16	0.59		
	S. hydrophylacea	0.29	1.05		
Sapling	*R. apiculata*	2.59	9.511	6.69	24.53
	H. littoralis	0.26	0.951		
	S. hydrophylacea	1.55	5.68		
	X. granatum	2.18	7.991		
	H. tiliaceus	0.11	0.401		
Palm	*N. fruticans*	45.87	168.33	45.87	168.33
Total		66.11	241.82	66.11	241.82

Based on **Table 3**, the total carbon stock in the Nagari Mandeh mangrove forest is 66.11 tons/ha, while the total carbon absorption is 241.82 tons/ha. The stored carbon stock is influenced by the size of the biomass owned, which affects the biomass at the research site, namely diameter, vegetation height, number of stands and standing age. In contrast, factors that affect carbon absorption include environmental factors related to photosynthesis or carbon dioxide absorption (Indriyani et al. 2020).

Carbon stocks and biomass are closely linked because some biomass is part of the carbon stock, and biomass content in vegetation is influenced by factors such as size, height, and the number of individual stands within the research plot (Obonyo et al. 2023). The age of the stand also affects the biomass and carbon stocks it stores (Indriyani et al. 2020). Carbon sequestered in vegetation is associated with the carbon stock that vegetation holds. This is in line with the findings of Rudianto et al. (2020), who reported that the carbon sequestration capacity of a stand can be represented by the carbon content stock stored, that is, the pastoral ability to absorb, as better described by the amount of carbon storage it has. The carbon sequestration potential of a plant species is another factor that can influence its role in carbon sequestration, as suggested by Peng et al. (2020), who noted that each plant has a different capacity for carbon absorption.

3.4. Comparison of Biomass and Carbon Stock Values

A comparison with results from earlier studies was conducted to understand better the significance of the biomass and carbon stock values obtained in this study (**Table 4**). This comparison sheds light on how sampling techniques, vegetation composition, and site features might affect the observed variations.

Table 4. Environmental factors in the Nagari Mandeh area

No	Study Location	Biomass (ton/ha)	Carbon Stock (ton/ha)	Reference
1	Nagari Mandeh, West Sumatra	140.21	66.11	This study
2	Segara Anakan Area, Cilacap	59.1	25.4	Isnaeni et al. 2019
3	Thailand	83	-	Matsui et al. 2014

According to **Table 4**, the Nagari Mandeh mangrove forest has a total biomass of 140.21 tons/ha and carbon stocks of 66.11 tons/ha. Although dominated by *N. fruticans*, these values are much higher than those reported by Isnaeni et al. (2019) in Segara Anakan, Cilacap, which recorded a biomass of 59.1 tons/ha and a carbon stock of 25.4 tons/ha. On the other hand, Matsui et al. (2014) found that *N. fruticans* had a biomass of 83 tons/ha in Thailand, supporting the idea that this species can contribute significantly to carbon storage. Although *N. fruticans* is important for biomass accumulation and carbon storage, its dominance raises ecological concerns because it may reduce the diversity of native mangrove species. These findings emphasize the importance of integrating carbon stock management with biodiversity conservation strategies in mangrove ecosystems.

3.5. Environmental Factors

The results of the analysis of environmental factors in mangrove forests in Nagari Mandeh, namely, the determination of abiotic factors that affect the continuity and sustainability of mangrove forests (**Table 5**). The results show that soil temperature at the research site ranges from 30 to 31 °C. Mean air temperature at the study site ranged from 31 to 31.6 °C. The soil pH at the research site ranged from 4 to 5.5, indicating an acidic soil. All results obtained on the surrounding environmental factors were then analyzed for their relationships with carbon stock.

Table 5. Environmental factors in the Nagari Mandeh area

Environmental Parameters	Measurement Results
Soil temperature	30–31˚C
Air temperature	31–31.6˚C
Soil pH	4–5.5
Salinity	18–24 ppt
Substrat	Muddy

The relationship between mangrove species and environmental factors measured during the study was evaluated using canonical correspondence analysis (CCA). Based on **Fig. 2**, X. granatum was mainly found in areas with higher air temperatures, while *S. hydrophylacea* was associated with higher salinity levels. Meanwhile, *R. apiculata* and *N. fruticans* were observed in various environmental conditions. These results are consistent with the findings of Alongi (2014) and Wimmler (2021), who stated that salinity and air temperature appear to have the greatest impact on distribution patterns. Based on the CCA results in **Table 5** and **Fig. 2**, the analysis shows that each mangrove species responds ecologically differently to environmental factors; salinity and air temperature appear to have the greatest impact on distribution patterns, as evidenced by their longer vector lengths compared to other variables; these findings reflect varying habitat preferences and levels of adaptability to abiotic conditions among species in mangrove ecosystems.

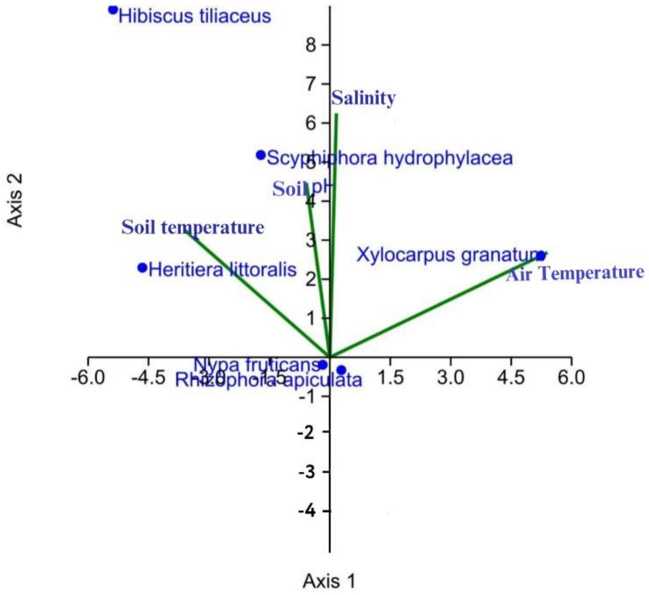

Fig. 2. Results of canonical correspondence analysis (CCA) on the relationship between environmental factors and carbon stock of mangrove vegetation.

Carbon stock in the forest is divided into three categories: low, medium, and high. Carbon stock is categorized as low when the total is below 35 tons/ha. Carbon stocks are labeled medium (between 35 and 100 tons/ha) and high (over 100 tons/ha) (BAPENNAS 2010). According to the criteria, the carbon stock in this study around Nagari Mandeh is classified as medium. This study thus concludes that the dominance of *N. fruticans* in the mangrove forest of Nagari Mandeh indicates a sudden change in vegetation structure, which may, in the long run, lower the diversity of native species and the carbon storage capacity.

This finding highlights that the ecological importance of mangrove forests cannot be estimated solely by their carbon storage. Even though *N. fruticans* contributed the most to total biomass, and maintaining species diversity remains an essential strategy for the long-term resilience and sustainability of mangrove ecosystems. Community involvement in mangrove conservation in West Sumatra and other parts of Indonesia should consider integrating carbon management and biodiversity protection into future activities.

4. Conclusions

The results of this study show that the mangrove forest in Nagari Mandeh has a total biomass of 140.21 tons/ha, a carbon stock of 66.11 tons/ha, and a carbon sequestration potential of 241.82 tons/ha. The species *N. fruticans* made the largest contribution to both biomass and carbon stocks due to its high density in the area. However, its dominance also reduced the number of native mangrove species and changed the natural structure of the forest. In general, these findings suggest that while *N. fruticans* can increase the total carbon stored in mangrove ecosystems; its continuous expansion could harm biodiversity in the long term. For that reason, effective management is needed to maintain a balance between carbon storage and ecological stability. Controlling *N. fruticans* populations and restoring native mangrove species will be important steps for the sustainability of the mangrove forest in Nagari Mandeh.

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Author Contributions

N.A.F.: Conceptualization, Methodology, Data Curation, Writing – Original Draft Preparation, Writing – Review & Editing; S.: Conceptualization, Methodology, Data Curation, Writing – Original Draft Preparation, Writing – Review & Editing; T.M.: Conceptualization, Methodology, Data Curation, Writing – Original Draft Preparation, Writing – Review & Editing; M.A.R.: Conceptualization, Methodology, Data Curation, Writing – Original Draft Preparation, Writing – Review & Editing.

Conflict of Interest

The authors declare no conflict of interest.

Declaration of Generative AI And AI-Assisted Technologies in the Manuscript Preparation

Not applicable.

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