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Species Diversity and Estimation of Aboveground Carbon Stocks in the Coastal Forest of Negeri Hatusua, Maluku, Indonesia

Keanekaragaman Jenis dan Pendugaan Cadangan Karbon Atas Permukaan di Hutan Pantai, Negeri Hatusua, Maluku, Indonesia

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ABSTRAK

Hutan pantai memiliki peran ekologis yang penting dalam menjaga keseimbangan ekosistem pesisir, termasuk dalam menyerap karbon dan mendukung keanekaragaman hayati. Penelitian ini bertujuan untuk menganalisis keanekaragaman jenis pada berbagai tingkat pertumbuhan vegetasi dan menduga cadangan karbon di atas permukaan di hutan pantai Negeri Hatusua, Kecamatan Kairatu, Kabupaten Seram Bagian Barat, Maluku. Analisis keanekaragaman menggunakan indeks Shannon-Wiener, dan pendugaan cadangan karbon dilakukan dengan metode non-destruktif dan destruktif, yang mencakup pohon, nekromas, tumbuhan bawah, dan serasah. Hasil penelitian menunjukkan bahwa tingkat semai memiliki nilai keanekaragaman tertinggi (H' = 2,48), diikuti oleh pancang (H' = 2,18), pohon (H' = 1,59), dan tiang (H' = 1,22). Kerapatan vegetasi mencerminkan pola regenerasi alami hutan, dengan tingkat semai mencapai 130.500 individu/ha, namun mengalami penurunan signifikan pada tingkat pancang (1.920 individu/ha), tiang (460 individu/ha), dan pohon (100 individu/ha). Total cadangan karbon di atas permukaan mencapai 89,41 ton/ha, dengan pohon sebagai penyimpan karbon terbesar (83,87 ton/ha atau 93,81% dari total karbon), dan serapan ekuivalen karbon dioksida mencapai 327,83 ton/ha.

Kata Kunci: Hutan pantai, keanekaragaman hayati, cadangan karbon, vegetasi, indeks Shannon-Wiener

ABSTRACT

Coastal forests play a crucial ecological role in maintaining the balance of coastal ecosystems, particularly in carbon sequestration and supporting biodiversity. This study aims to assess species diversity at various growth stages of vegetation and estimate the aboveground carbon reserves in the coastal forest of Negeri Hatusua, Kairatu District, West Seram Regency, Maluku. Species diversity was evaluated using the Shannon-Wiener index (H'), while carbon stocks were estimated through non-destructive and destructive methods, encompassing trees, necromass, understory vegetation, and litter. The results revealed that the seedling stage exhibited the highest species diversity (H' = 2.48), followed by the sapling stage (H' = 2.18), tree stage (H' = 1.59), and pole stage (H' = 1.22). Vegetation density analysis reflected the forest's natural regeneration pattern, with seedling density reaching 130,500 individuals/ha. A significant decrease in density was observed at the sapling stage (1,920 individuals/ha), pole stage (460 individuals/ha), and tree stage (100 individuals/ha). The total aboveground carbon reserves were estimated at 89.41 tons/ha, with trees serving as the primary carbon reservoir (83.87 tons/ha or 93.81% of the total carbon). Carbon dioxide equivalent sequestration was calculated at 327.83 tons/ha.

***Keyword**: Coastal forest, biodiversity, carbon reserves, vegetation, Shannon-Wiener index*

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INTRODUCTION

Climate change is one of the most significant challenges of this century, primarily driven by greenhouse gas (GHG) emissions. According to the latest IPCC Report, global warming now affects every continent with visible impacts, such as sea level rise, intensification of extreme weather events, and loss of biodiversity. Deforestation and forest degradation continue to make the forestry sector, and other land uses in Indonesia major contributors to GHG emissions (Houghton et al., 2017).

As an archipelagic nation, Indonesia possesses unique coastal ecosystems, including coastal forests. These ecosystems serve as natural barriers against coastal erosion and storms and as significant carbon sinks. Negeri Hatusua's beach forests, like other coastal areas in Indonesia, play an important role in storing organic carbon, supporting biodiversity, and increasing climate resilience (Lowitt *et al.*, 2015).

However, these ecosystems are under pressure from resource exploitation, land use change, and rising sea-level threats. Measuring forest carbon stocks, as conducted in Negeri Hatusua, is a crucial step in supporting climate change mitigation through sustainable forest management. These carbon estimates are also relevant in the context of implementing global policies such as REDD+ and carbon credits, which aim to reward forest conservation as one solution to mitigating emissions (Nahib & Suwarno, 2017).

This research reinforces the understanding of coastal forests as carbon sinks and underscores the necessity of management strategies informed by research data to ensure the sustainability of this ecosystem. In addition, the carbon stock data produced can be the basis for fighting for carbon-based funding, supporting conservation, and strengthening the environmental resilience of Hatusua Village in the face of global climate change.

RESEARCH METHODS

Time and Study Site

The research on carbon reserve estimation was conducted in Negeri Hatusua, Kairatu District, West Seram Regency, Maluku Province. The study spanned a period of five months, from June 2024 to October 2024. The research site was the Negeri Hatusua Coastal Forest, located in Kairatu District, West Seram Regency, as illustrated in Figure 1.

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Figure 1. Location Map of Negeri Hatusua Coastal Forest Research Site

Research Tools and Object

Research Tools

This study utilized various tools for field data collection, sample testing, and data analysis. Field data collection utilized tools such as a phiband, measuring tape, caliper, Haga Meter, clinometer, 50 kg hanging scale, thermometer, compass, GPS, and digital camera. Sample testing involved a digital scale (0.5% accuracy), an oven, a digital camera, and data recording instruments. Data analysis was performed using a computer system equipped with Microsoft Excel software.

Research Object

The objects of this study include land cover vegetation (trees, poles, saplings, seedlings, and understory plants), necromass (fallen trees/large necromass and dead wood/small necromass), and litter.

Research Methods

This study involved direct field measurements of carbon stocks across various carbon pools, including aboveground biomass (trees), understory vegetation, litter, dead trees, and necromass. Both non-destructive and destructive biomass estimation techniques were employed within the sampling plots. The non-destructive method was used for measuring aboveground biomass, specifically trees, while the destructive method was applied to understory plants, litter, and small necromass. Carbon reserves were quantified in living trees, necromass, and destructive samples by determining dry weight and biomass. Aboveground carbon reserve measurements were conducted for trees and understory plants, litter, and necromass (Penman et al., 2003).

Sample Plot Shape and Size

In the coastal forest, tree-level measurements were conducted using square plots (20x20 m), with five contiguous plots forming a 20 x 100 m transect. For pole-level measurements, the sample plots measured 10 x 10 m, with 5 plots covering a total area of 500 m². Sapling-level plots were sized 5 x 5 m, with 5 plots encompassing a total area of 125 m². Seedling-level plots were 2 x 2 m, with 5 plots covering a total area of 20 m². The configuration and dimensions of the sample plots are depicted in Figure 2.

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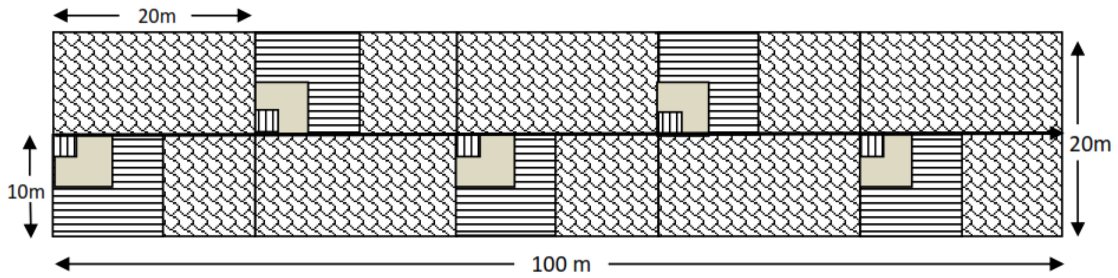

Keterangan:

(vertical lines)	:	2m x 2m	petak semai ukuran Ø < 2 cm s.d. tinggi 150 cm
(plain)	:	5m x 5m	petak pancang ukuran Ø ≥ 2 cm s.d. Ø < 10 cm)
(horizontal lines)	:	10m x 10m	petak tiang ukuran Ø ≥ 10 cm s.d. Ø < 20 cm)
(cross-hatched)	:	20m x 20m	petak pohon ukuran Ø ≥ 20 cm.

Figure 2. Configuration and dimensions of vegetation sample plots

Litter and understory plant samples were collected from 2 x 2 m plots, with 3 plots located along the research transect, representing different densities (high, moderate, and low). Necromass (fallen trees) was sampled along the research transect, covering an area of 20 x 100 m, using a geometrical method for calculations. Small necromass was collected from 5 x 5 m plots within the transect. Samples were weighed in the field, with a 300 g portion taken from each, and then dried in an oven at 80°C to determine their dry weight.

Vegetation Analysis

The field data on vegetation measurements and observations were subsequently analyzed to determine the values of density, dominance, and frequency using the formulas outlined by Mueller-Dombois & Ellenberg (2016), as follows:

$$\text{Density (D)} = \frac{\text{Individual density}}{\text{Sample plot area}}$$

$$\text{Dominansi (Do)} = \frac{\text{Basal Area (BA)}}{\text{Sample plot area}}$$

$$\text{Frequency (F)} = \frac{\text{Number of plots where a species was found}}{\text{Total number of plots}}$$

$$\text{BA} = 0.25\,\pi\,(DBH)^2$$

Note:

Dbh = Diameter at breast height

π = 3.1428

DBH measurements were conducted for trees, poles, and saplings to calculate the basal area. For seedlings, only the count and species identification were recorded for each sample plot.

Species Diversity Analysis

Species diversity and community stability at each growth stage were assessed using the Shannon-Wiener index (Omayio et al., 2019), which can be calculated using the following equation:

$$H' = -\sum_{i=1}^{s} (pi) \text{ Ln } pi$$

Note:

H' = Species diversity index
pi = ni / N
ni = Number of individuals of species i
N = Total number of individuals across all species

A higher H' value indicates greater community stability within the ecosystem. H' = 0 when only one species is present; H' increases as the number of individuals is more evenly distributed across species. Thus, diversity is considered low when H' < 1, moderate when 1 < H' < 3, and high when H' > 3.

Measurement Method

Carbon reserves measurements and calculations were carried out following the guidelines of the Indonesian National Standard (SNI) 7724:2019 (BSN, 2019), "Measurement and Calculation of Carbon Reserves - Field Measurements for Estimating Land-Based Carbon Reserves," with specific modifications. This standard refers to the COP-15 Decision on the REDD+ methodology (Dec. 4/CP-15), the IPCC 2006 Guidelines for National Greenhouse Gas Inventories, and the IPCC 2003 Good Practice Guidance for Land Use, Land Use Changes, and Forestry.

Measurement and Calculation of Tree Biomass

Tree biomass measurement involved: identifying tree species, measuring diameter at breast height (Dbh), recording Dbh data and species names, and calculating tree biomass.

Tree biomass measurements are taken for tree life forms starting from the sapling stage (Ø ≥ 2 to < 10 cm), pole stage (Ø ≥ 10 to < 20 cm), and tree stage (Ø ≥ 20 cm), with species and Dbh recorded (Manuri et al., 2011). Tree biomass calculation is done using allometric equations that take Dbh into account (Brown, 1997).

$$W = 0.118 * D^{253}$$

Where:
W : Tree biomass (ton/ha)
D : Diameter at breast height

Biomass Calculation for Understory Plants, Litter, and Small Necromass

The biomass calculation for understory plants, litter, and necromass was conducted after obtaining the dry weight data from samples dried in an oven at the Silviculture Laboratory of Universitas Pattimura.

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$$\text{Botb} = \frac{\text{Bks x Bbt}}{\text{Bbs}}$$

Note:

Botb = total biomass of understory plants/litter/necromass (kg);
Bks = dry weight of sample (kg);
Bbt = total wet weight (kg);
Bbs = wet weight of sample (kg).

RESULTS AND DISCUSSION

The natural forests of Negeri Hatusua encompass various forest types, each with unique characteristics. The coastal forest, a specific formation along the shoreline, is characterized by sandy soils and direct exposure to coastal winds. The vegetation within these coastal forests is typically divided into two primary formations: the *Ipomoea pes-caprae* formation and the *Barringtonia* formation. The *Ipomoea pes-caprae* formation, located closest to the coastline, is composed of pioneer species such as *Ipomoea pes-caprae*, *Spinifex littoreus*, and *Canavalia maritima*. In contrast, the *Barringtonia* formation is found further inland and consists of several characteristic species, including *Barringtonia asiatica* (keben), *Terminalia catappa* (ketapang), *Hibiscus tiliaceus* (waru laut), and *Casuarina equisetifolia* (cemara laut). These species are recognized for their strong root systems, which enable them to grow successfully in sandy soils (Gusti et al., 2024).

Structure and Composition of the Coastal Forests of Negeri Hatusua

The coastal forest of Negeri Hatusua is characterized by the presence of tree species tolerant of strong winds and sandy soils, such as *Ceriops tagal*, *Pongamia pinnata*, *Ficus benjamina*, *Intsia bijuga*, *Adenanthera pavonina*, *Calophyllum inophyllum*, and *Hernandia nymphaeifolia*. This forest serves as a natural barrier against erosion and a windbreak, and plays a crucial role in maintaining the sustainability of the coastal ecosystem by providing shelter and breeding grounds for local fauna. The number of families, species, and the local names of these species in the coastal forest of Negeri Hatusua are presented in Table 1.

Table 1. Number of Families and Species in the Coastal Forest of Negeri Hatusua

No	Family	Scientific Name	Local Name
1	*Anacardiaceae*	*Koordersiodendron pinnatum*	Kayu Buaya
		Gluta renghas	Lenat
2	*Apocynaceae*	*Cebera manghas*	Mangga Berabu
3	*Boraginaceae*	*Cordia subcordata*	Salimuli
4	*Calophyllaceae*	*Calophyllum inophyllum*	Bintanggur Pantai
5	*Combretaceae*	*Terminalia cattapa*	Ketapang
6	*Euphorbiaceae*	*Mallotus paniculatus*	Kayu Kumang
7	*Fabaceae*	*Intsia bijuga*	Kayu Besi
		Pongamia pinnata	Kayu Besi Pantai

No	Family	Scientific Name	Local Name
		Adenanthera pavonina	Saga Pantai
8	*Goodeniaceae*	*Scaevola taccada*	Papaceda
9	*Hernandiaceae*	*Hernandia nymphaeifolia*	Kayu Mata Ikan
10	*Lamiaceae*	*Clerodendrum minahassae*	Matel Hutan
11	*Lecythidaceae*	*Barringtonia asiatica*	Hutung
12	*Malvaceae*	*Thespesia populnea*	Waru Pantai
13	*Moraceae*	*Ficus benjamina*	Beringin

Based on the results of the study, the data presented in Table 1 indicate that the coastal forest of Negeri Hatusua exhibits significant species diversity, consisting of 13 plant families and 15 vegetation species. The plant families identified in the coastal forest of Negeri Hatusua include Anacardiaceae, Apocynaceae, Boraginaceae, Calophyllaceae, Combretaceae, Euphorbiaceae, Fabaceae, Goodeniaceae, Hernandiaceae, Lamiaceae, Lecythidaceae, Malvaceae, and Moraceae.

The Anacardiaceae family includes species such as *Koordersiodendron pinnatum* (Kayu Buaya) and *Gluta renghas* (Lenat). The Fabaceae family is represented by three species: *Intsia bijuga* (Kayu Besi), *Pongamia pinnata* (Kayu Besi Pantai), and *Adenanthera pavonina* (Saga Pantai). Other families are represented by individual species, including *Terminalia catappa* (Ketapang), *Calophyllum inophyllum* (Bintanggur Pantai), *Thespesia populnea* (Waru Pantai), and *Ficus benjamina* (Beringin).

The Fabaceae family is particularly noteworthy in the coastal forests of Negeri Hatusua due to its ability to form symbiotic relationships with nitrogen-fixing bacteria in the roots (Zhao et al., 2021). This relationship enhances the nitrogen content in the soil, thus contributing to soil fertility, a critical factor in the generally nutrient-poor coastal ecosystem.

The vegetation species within the coastal forest of Negeri Hatusua are categorized based on their growth stages, which include tree, pole, sapling, and seedling stages. For a more detailed analysis, the tree-level vegetation of the coastal forest in Negeri Hatusua is presented in Table 2.

Table 2. Tree Level Vegetation Analysis of the Coastal Forest

No	Local Name	Scientific Name	D	RD	F	RF	D_O	RD_o	IVI	H'
1	Mangga Berabu	*Cebera manghas L*	45	45	80	28.57	5.15	43.32	116.89	0.36
2	Kayu Besi Pantai	*Pongamia pinnata*	20	20	60	21.43	2.68	22.53	63.96	0.32
3	Beringin	*Ficus benjamina*	10	10	40	14.29	0.68	5.68	29.97	0.23
4	Kayu Besi	*Intsia bijuga*	10	10	40	14.29	1.34	11.23	35.52	0.23
5	Saga Pantai	*Adenanthera pavonina*	5	5	20	7.14	0.30	2.50	14.64	0.15
6	Bintanggur Pantai	*Calophyllum inophyllum*	5	5	20	7.14	0.85	7.14	19.28	0.15
7	Kayu Mata Ikan	*Hernandia nymphaeifolia*	5	5	20	7.14	0.90	7.60	19.75	0.15
Total			**100**	**100**	**280**	**100.00**	**11.89**	**100.00**	**300.00**	**1.59**

Note: D = Density (N/Ha), RD = Relative Density, F = Frequency (%), RF = Relative Frequency, D_o = Dominance (m^2/ha), RD_o= Relative Dominance, IVI = Importance Value Index, H' = Shannon Index.

The tree level vegetation structure in the coastal forest of Negeri Hatusua reveals that the species with the highest density is *Cebera manghas* (Mangga Berabu), with a density of 45 trees per hectare, accounting for 45% of the total density. Other species exhibit lower densities, with *Adenanthera pavonina* (Saga Pantai) contributing only 5% to the total density.

Cebera manghas also exhibits the highest frequency (80%), indicating a relatively uniform distribution across the area. The lowest frequency (20%) is observed in four species (*Adenanthera pavonina*, *Calophyllum inophyllum*, *Hernandia nymphaeifolia*, and others), suggesting a more restricted distribution. The highest dominance is observed in *Cebera manghas* (5.15 m²/ha), while species such as *Ficus benjamina* and *Adenanthera pavonina* demonstrate significantly lower relative dominance values, at 0.85 m²/ha and 0.90 m²/ha, respectively.

The Importance Value Index (IVI) reflects the overall ecological influence of a species within the community. *Cebera manghas* records the highest IVI (116.89), indicating its significant ecological dominance. In contrast, species such as *Adenanthera pavonina* have a lower IVI of 14.64, suggesting a more minor ecological role.

Species diversity at the tree level in the coastal forest of Negeri Hatusua is assessed using the Shannon Index (H'). The H' value of 1.59 suggests a moderate level of species diversity, which is influenced by the dominance of certain species, particularly *Cebera manghas*.

At the pole stage, *Cebera manghas* again emerges as the dominant species, with a density of 260 trees per hectare (56.52% of the total density). The species exhibiting the lowest density is *Pongamia pinnata* (Kayu Besi Pantai), with 20 trees per hectare (4.35%). A comprehensive analysis of the pole-level vegetation in the coastal forest of Negeri Hatusua is presented in Table 3.

Table 3. Vegetation Analysis at the Pole Stage in the Coastal Forest of Negeri Hatusua

No	Local Name	Scientific Name	D	RD	F	RF	D_O	RD_o	IVI	H'
1	Mangga Berabu	*Cebera manghas*	260	56.52	1.00	41.67	4.89	54.61	152.80	0.32
2	Bintanggur Pantai	*Calophyllum inophyllum*	100	21.74	0.60	25.00	1.58	17.63	64.37	0.33
3	Ketapang	*Terminalia cattapa*	40	8.70	0.40	16.67	1.13	12.67	38.04	0.21
4	Beringin	*Ficus benjamina*	40	8.70	0.20	8.33	1.10	12.34	29.37	0.21
5	Kayu Besi Pantai	*Pongamia pinnata*	20	4.35	0.20	8.33	0.25	2.74	15.42	0.14
		Total	460	100.00	2.40	100.00	8.95	100.00	300.00	1.22

Note: D = Density (N/Ha), RD = Relative Density, F = Frequency (%), RF = Relative Frequency, D_o = Dominance (m²/ha), RD_o= Relative Dominance, IVI = Importance Value Index, H' = Shannon Index.

The highest density at the pole stage is dominated by *Cebera manghas* (260 saplings/ha or 56.52%), indicating its significant dominance at this stage. Other species, such as *Calophyllum inophyllum* and *Terminalia catappa*, contribute 21.74% and 8.70%, respectively, to the total density. The highest frequency is observed in *Cebera manghas*, with a frequency of 100%, indicating a uniform distribution across the study area.

Conversely, the lowest frequency is recorded in *Pongamia pinnata* and *Ficus benjamina* (20%).

Cebera manghas also exhibits the highest dominance at the pole stage, with a dominance value (D) of 4.89 m²/ha, accounting for 54.61% of the total dominance. In contrast, *Pongamia pinnata* has the lowest dominance, with a value of 0.25 m²/ha (2.74%). The species with the highest IVI is *Cebera manghas* (152.80), far surpassing other species, underscoring its primary ecological role within the community. The lowest IVI is recorded for *Pongamia pinnata* (15.42), indicating its relatively minor ecological contribution. Species diversity at the pole stage is measured using the Shannon Index (H'), yielding a value of 1.22, which categorizes the diversity as moderate.

At the sapling stage in the coastal forest of Negeri Hatusua, the total density is 1920 individuals/ha, with *Cebera manghas* (Mangga Berabu) being the dominant species, accounting for a density of 400 individuals/ha or 20.83% of the total. Other species, such as *Gluta renghas* (Lenat), *Clerodendrum minahassae* (Matel Hutan), and *Barringtonia asiatica* (Hutung), exhibit the lowest densities, each contributing 80 individuals/ha or 4.17% to the total density. For a more detailed analysis of the sapling stage vegetation, refer to Table 4.

Table 4. Vegetation Analysis at the Sapling Stage in the Coastal Forest

No	Local Name	Scientific Name	D	RD	F	RF	D_O	RD	IVI	H'
1	Mangga Berabu	*Cebera manghas*	400	20.83	80	18.18	1.42	39.11	78.13	0.35
2	Kayu Mata Ikan	*Hernandia nymphaeifolia*	160	8.33	40	9.09	0.77	21.20	38.62	0.26
3	Salimuli	*Cordia subcordata*	320	16.67	60	13.64	0.20	5.49	35.79	0.25
4	Papaceda	*Scaevola taccada*	240	12.50	60	13.64	0.29	7.85	33.99	0.25
5	Kayu Besi Pantai	*Pongamia pinnata*	160	8.33	40	9.09	0.54	14.94	32.36	0.24
6	Waru Pantai	*Thespesia populnea*	160	8.33	40	9.09	0.12	3.28	20.71	0.18
7	Kayu Kumang	*Mallotus paniculatus*	160	8.33	40	9.09	0.07	1.99	19.42	0.18
8	Kayu Buaya	*Koordersiodendron pinnatum*	80	4.17	20	4.55	0.13	3.50	12.21	0.13
9	Hutung	*Barringtonia asiatica*	80	4.17	20	4.55	0.04	1.17	9.88	0.11
10	Matel Hutan	*Clerodendrum minahassae*	80	4.17	20	4.55	0.04	1.08	9.79	0.11
11	Lenat	*Gluta renghas*	80	4.17	20	4.55	0.01	0.39	9.10	0.11
		Total	1920	100.00	440	100.00	3.64	100.00	300.00	2.18

Note: D = Density (N/Ha), RD = Relative Density, F = Frequency (%), RF = Relative Frequency, D_o = Dominance (m²/ha), RD = Relative Dominance, IVI = Importance Value Index, H' = Shannon Index.

The highest frequency at the sapling stage in the coastal forest of Negeri Hatusua is recorded for *Cebera manghas* (80%), indicating a widespread distribution across the study area. In contrast, species such as *Gluta renghas* and *Clerodendrum minahassae* exhibit a frequency of only 20%, indicating a more limited distribution. The total dominance at this stage is 3.64 m²/ha, with *Cebera manghas* dominating at 1.42 m²/ha (39.11%). The lowest dominance is recorded for *Gluta renghas* (0.01 m²/ha or 0.39%), indicating its minimal contribution to the canopy area.

Cebera manghas also records the highest Importance Value Index (IVI) of 78.13, signifying its significant ecological dominance. On the other hand, species such as *Gluta renghas* show the lowest IVI (9.10), highlighting their relatively minor role in the community structure. Species diversity at the sapling stage is quantified using the Shannon Index (H'), which yields a value of 2.18, indicating moderate diversity with a clear dominance of certain species, notably *Cebera manghas*.

The coastal forest of Negeri Hatusua also exhibits a diverse structure and composition at the seedling stage. The vegetation analysis reveals a total of 16 species, and the Shannon Index (H') is 2.48, reflecting moderate diversity. A more detailed analysis of vegetation at the seedling stage in the coastal forest of Negeri Hatusua can be found in Table 5.

Table 5. Vegetation Analysis at the Seedling Stage in the Coastal Forest

No	Local Name	Scientific Name	D	RD	F	RF	IVI	H'
1	Mangga Berabu	*Cebera manghas*	22,000	16.86	100	13.89	30.75	0.3
2	Salimuli	*Cordia subcordata*	16,500	12.64	80	11.11	23.75	0.26
3	Kayu Besi Pantai	*Pongamia pinnata*	19,000	14.56	60	8.33	22.89	0.28
4	Bintanggur Pantai	*Calophyllum inophyllum*	12,500	9.58	40	5.56	15.13	0.22
5	Papaceda	*Scaevola taccada*	8,000	6.13	60	8.33	14.46	0.17
6	Beringin	*Ficus benjamina*	7,500	5.75	60	8.33	14.08	0.16
7	Kayu Mata Ikan	*Hernandia nymphaeifolia*	7,000	5.36	60	8.33	13.7	0.16
8	Ketapang	*Terminalia cattapa*	10,500	8.05	40	5.56	13.6	0.2
9	Kayu Besi	*Intsia bijuga*	7,500	5.75	40	5.56	11.3	0.16
10	Kayu Kumang	*Mallotus paniculatus*	5,500	4.21	40	5.56	9.77	0.13
11	Waru Pantai	*Thespesia populnea*	5,500	4.21	40	5.56	9.77	0.13
12	Hutung	*Barringtonia asiatica*	3,000	2.3	20	2.78	5.08	0.09
13	Lenat	*Gluta renghas*	2,000	1.53	20	2.78	4.31	0.06
14	Kayu Buaya	*Cordia subcordata*	1,500	1.15	20	2.78	3.93	0.05
15	Saga Pantai	*Adenanthera pavonina*	1,500	1.15	20	2.78	3.93	0.05
16	Matel Hutan	*Clerodendrum minahassae*	1,000	0.77	20	2.78	3.54	0.04
		Total	**130,500**	**100**	**720**	**100**	**200**	**2.48**

Note: D = Density (N/Ha), RD = Relative Density, F = Frequency (%), RF = Relative Frequency, IVI = Importance Value Index, H' = Shannon Index.

The species dominating the seedling stage is *Cebera manghas* (Mangga Berabu), with the highest density recorded at 22,000 seedlings/ha, followed by *Cordia subcordata* (Salimuli) with a density of 16,500 seedlings/ha. These two species contribute significantly to the structure of the seedling stage in the coastal forest. Additionally, the highest frequency is also observed in *Cebera manghas*, with a value of 100%, followed by *Cordia subcordata* at 80%. This indicates that these species have a more uniform distribution compared to others. In contrast, species such as *Clerodendrum minahassae* (Matel Hutan) and *Gluta renghas* (Lenat) have lower frequencies (20%), indicating a more restricted distribution.

The species diversity, measured by an H' value of 2.48, indicates moderate diversity, suggesting a relatively even distribution of individuals across species. However, dominant species such as *Cebera manghas* and *Cordia subcordata* still influence the overall pattern, while minor species contribute minimally to the total composition.

Comparison of Structure and Composition at Each Growth Stage in the Coastal Forest of Negeri Hatusua

The coastal forest of Negeri Hatusua exhibits diverse vegetation structure across each growth stage (seedling, sapling, pole, and tree). The analyzed data reveals distinct patterns of distribution, dominance, and diversity at each stage, with certain species playing varying key roles. At the seedling stage, the density is notably high, reaching 130,500 seedlings per hectare, indicating that many seeds successfully germinate and grow into small seedlings. However, in this phase, competition for resources such as sunlight, water, and nutrients is intense. Not all seedlings will survive to the next growth stage, as they must adapt to often unstable environmental conditions (Adnan and Purnomo, 2023). For a more detailed view, the growth stage density can be shown in Figure 3.

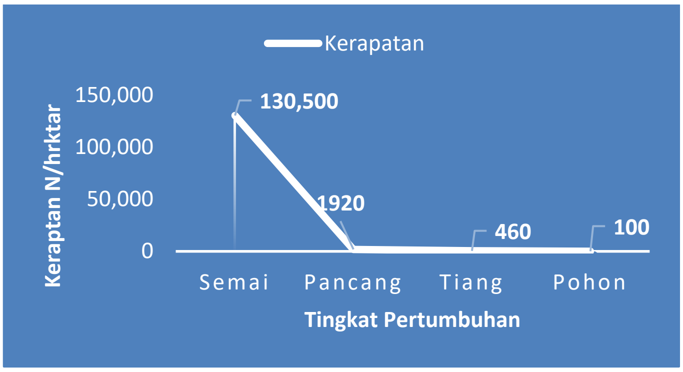

Figure 3. Growth Stage Density Graph

The seedling density in the coastal forest of Negeri Hatusua reaches 130,500 individuals per hectare, which is significantly higher when compared to a study in the Pananjung Pangandaran Nature Reserve coastal forest, which recorded a seedling density of 42,434 individuals per hectare (Susanto et al., 2019). The density at the sapling stage, referring to individuals larger than seedlings, is 1,920 individuals per hectare. This figure is much lower than at the seedling stage, reflecting a natural selection process. Only those seedlings that can compete for resources such as light, water, and nutrients will grow into saplings. The sapling stage plays a crucial role in the transition of regeneration towards larger, stronger individuals. In comparison, a study in the Pananjung Pangandaran Nature Reserve found that the vegetation density at the sapling stage reached 2,873 individuals per hectare (Susanto et al., 2019). Meanwhile, in the Batu Angus area, North Sulawesi, *Guettarda speciosa* had a density of 185 individuals per hectare at the sapling phase (Gusti et al., 2024). Therefore, the 1,920 individuals per hectare at the sapling stage in the coastal forest of Negeri Hatusua fall within the range commonly found in other locations.

At the pole stage, the density decreases to 460 individuals per hectare. This decline indicates that competition becomes more intense as individuals grow. Some comparisons of pole stage density in other coastal forests include Cipatujah, West Java, where it is around 280 individuals per hectare (Hilwan and Irfani, 2018), and *Terminalia catappa* coastal forest on Marsegu Island, which has a density of approximately 410 individuals per hectare (Irwanto et al., 2024).

The tree stage density in the coastal forest of Negeri Hatusua is 100 individuals per hectare, lower than the tree stage density in the coastal forest of *Terminalia catappa* on Marsegu Island, which has 110 trees per hectare (Irwanto et al., 2024). This difference could be attributed to various factors, such as soil conditions, human disturbance levels, natural regeneration, and species composition at each location. The lower density in Negeri Hatusua may be due to human exploitation pressures near settlements and other environmental disturbances that hinder tree growth.

Species diversity of the coastal forest in Negeri Hatusua at various growth stages

The species diversity of the coastal forest in Negeri Hatusua can be analyzed using the Shannon-Wiener diversity index (H') at each growth stage. The species diversity index across all growth stages falls within the 'moderate' category, though there is a noticeable trend of decline from the seedling stage to the tree stage, as depicted in Figure 4.

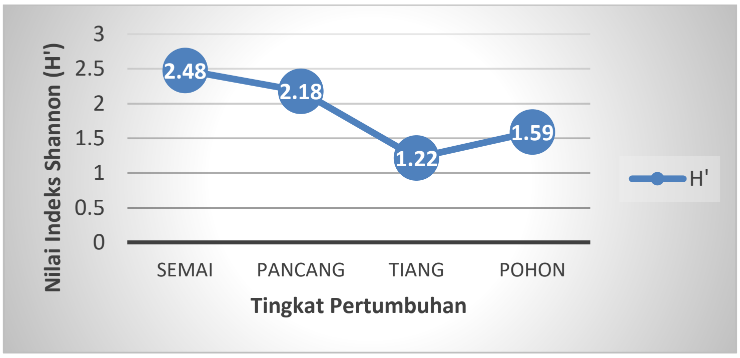

Figure 4. Species diversity index at each growth stage graph

Figure 4 shows that the seedling stage of the coastal forest in Negeri Hatusua has the highest diversity index, at 2.48. This indicates that many species have successfully germinated and persisted, suggesting that the regeneration potential of the coastal forest in Negeri Hatusua is still quite good. At the sapling stage, the diversity index decreases to 2.18, indicating that several species are able to survive and grow evenly, supported by diverse seed sources and favorable environmental conditions. Diversity further declines at the pole stage, with an index of 1.22, suggesting that the number of species that persist decreases due to increased competition or less favorable environmental conditions. At the tree stage, the diversity index of 1.59 reflects moderate diversity, where although there are variations in species, the dominance of certain species results in a lower diversity compared to the previous stages.

Carbon Reserves of Trees in the Coastal Forest of Negeri Hatusua

The calculation of carbon from biomass, in accordance with SNI 7724-2019, is performed by converting the vegetation biomass into carbon using a standard carbon fraction of 0.47 (BSN, 2019). Biomass is estimated using field data such as stem diameter, which is processed with allometric equations to calculate the dry biomass weight. After determining the total biomass, the subsequent step is to compute its carbon content. The carbon reserves on the surface of each species at various stages of tree growth in the coastal forest of Negeri Hatusua are presented in Table 6.

Table 6. Carbon Reserves on the Surface of Each Species at Various Growth Stages of Trees in the Coastal Forest of Negeri Hatusua

No	Scientific Name	Tree	Pole	Sapling	Biomass/Ha	Carbon/Ha
1	*Cebera manghas*	36,683.97	32,333.20	6,161.37	75,178.55	35,333.92
2	*Ficus benjamina*	24,178.83	7,848.46		32,027.30	15,052.83
3	*Pongamia pinnata*	26,599.35	1,406.35	2,249.66	30,255.36	14,220.02
4	*Intsia bijuga*	12,029.91			12,029.91	5,654.06
5	*Calophyllum inophyllum*	1,386.50	10,119.33		11,505.84	5,407.74
6	*Terminalia cattapa*		8,124.01		8,124.01	3,818.28
7	*Hernandia nymphaeifolia*	1,386.50		3,580.89	4,967.40	2,334.68
8	*Adenanthera pavonina*	1,736.42			1,736.42	816.12
9	*Scaevola taccada*			890.08	890.08	418.34
10	*Cordia subcordata*			582.73	582.73	273.88
11	*Koordersiodendron pinnatum*			424.23	424.23	199.39
12	*Thespesia populnea*			330.52	330.52	155.34
13	*Mallotus paniculatus*			173.54	173.54	81.56
14	*Barringtonia asiatica*			105.89	105.89	49.77
15	*Clerodendrum minahassae*			95.89	95.89	45.07
16	*Gluta renghas*			26.33	26.33	12.38
17	**Total**	**104,001.49**	**59,831.36**	**14,621.13**	**178,453.98**	**83,873.37**

Based on the data in Table 6, it can be explained that *Cebera manghas* has the highest total carbon reserve, at 35,333.92 kg/ha, with the majority of the contribution coming from the tree growth stage. *Ficus benjamina* also shows a significant carbon reserve of 15,052.83 kg/ha, mainly from the tree stage with a small contribution from the pole stage. Meanwhile, *Pongamia pinnata* records a carbon reserve of 14,220.02 kg/ha, with a minor contribution from the sapling stage. *Intsia bijuga* contributes 5,654.06 kg/ha, all of which comes from the tree stage. Additionally, *Calophyllum inophyllum* and *Terminalia cattapa* make moderate contributions to carbon reserves, mainly from the pole stage. Some other species, such as *Scaevola taccada* and *Adenanthera pavonina*, show smaller carbon reserves, with a total below 1,000 kg/ha. These differences in carbon reserves reflect variations in growth stages, tree structure, and ecological roles. The comparison of carbon reserves across all growth stages (tree, pole, sapling), without distinguishing tree species, is shown in Figure 5.

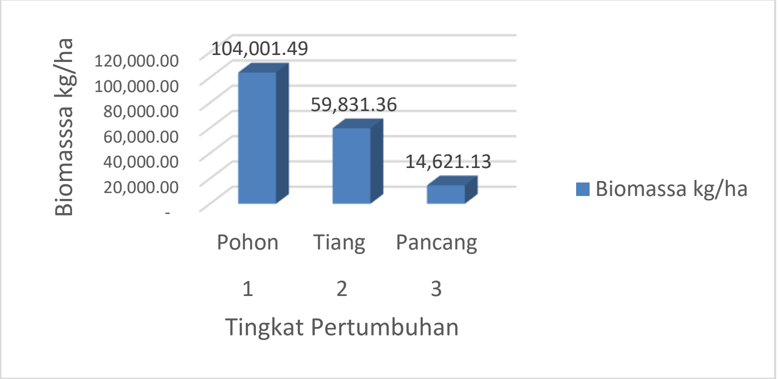

Figure 5. Carbon reserves comparison across different growth stages

Figure 5 shows that the tree stage is the primary contributor to the total carbon reserves in the coastal forest of Negeri Hatusua. With a total of 104,001.49 kg/Ha, the tree stage contributes approximately 58.3% of the overall carbon reserves. Meanwhile, the pole stage contributes 59,831.36 kg/Ha, or about 33.5% of the total carbon reserves. The smallest contribution comes from the sapling stage, with carbon reserves of 14,621.13 kg/Ha, or 8.2% of the total carbon. The growth of trees from the early stages forms the foundation for the long-term sustainability of carbon stocks in the ecosystem, ensuring a continuous increase in carbon reserves as the vegetation develops.

Carbon reserves on the surface of necromass, understory vegetation, and litter

Necromass is classified into two categories: large necromass (fallen trees) and small necromass (branches and twigs). Within the coastal forest transect, two fallen trees were identified. The first tree had a basal diameter of 15 cm, a tip diameter of 12 cm, and a length of 17 m, while the second tree had a basal diameter of 25 cm, a tip diameter of 20 cm, and a length of 12 m, with approximately 10% decay. The biomass calculation for these fallen trees yielded 1,478.59 kg/ha, corresponding to a carbon reserve of 694.94 kg/ha.

Carbon reserves in small necromass, understory vegetation, and litter were assessed through field measurements. The samples were then dried in an oven to remove moisture content. The calculated carbon reserves for each sample plot are shown in Tables 7 and 8.

Table 7. Small necromass biomass calculation

Carbon pool	Field Weight (gr)	Wet Weight (gr)	Dry Weight (gr)	Biomass (gr)	Sample Area	Biomass (kg/ha)	Carbon Reserves kg/ha
Small necromass	6,680	300	203	4.52	0.0025	1,808.05	849.79

The measurement results in Table 7 indicate a field weight of 6,680 grams, with a wet weight of 300 grams and a dry weight of 203 grams. With a sample area of 0.0025 ha, the biomass of small necromass was calculated to be 1,808.05 kg/ha, and the corresponding carbon reserve amounted to 849.79 kg/ha. Both large and small necromass contribute to carbon sequestration in the coastal forest ecosystem. The biomass derived from both forms of necromass demonstrates significant potential for carbon storage. Therefore, understanding necromass is crucial for forest conservation and climate change mitigation, as dead organic material continues to play a vital role in the carbon cycle and the overall functioning of the forest ecosystem.

Table 8. Biomass calculation of understory vegetation and litter

No	Carbon pool	Biomass kg			Biomass kg/ha			Biomass kg/ha	Carbon Reserves kg/ha
		P1	P2	P3	P1	P2	P3		
1	Understory plant	1.61	1.16	0.49	4,028.17	2,894.60	1,225.65	2,716.14	1,276.59
2	Litter	2.21	2.49	2.23	5,524.75	6,230.78	5,565.61	5,773.71	2,713.64

Note: P1 = Dense, P2 = Moderate, P3 = Sparse

Understory vegetation consists of various types of herbs, shrubs, and grasses that grow on the forest floor, while litter refers to the layer of dead organic material, such as leaves, small branches, and other plant residues. Both components play a significant role in the carbon reserves on the soil surface. This study aims to estimate the carbon reserves in the understory vegetation and litter of the coastal forest in Negeri Hatusua, based on field biomass measurements.

The data shown in Table 8 indicates that the biomass of understory vegetation varies depending on vegetation density. In areas with dense vegetation (P1), the biomass reaches 4,028.17 kg/ha, while in moderately dense areas (P2), it is 2,894.60 kg/ha, and in sparsely vegetated areas (P3), it is 1,225.65 kg/ha. From these data, the average carbon reserve stored in the understory vegetation is 2,716.14 kg/ha, with the largest contribution coming from areas with dense vegetation.

Litter also plays an important role in carbon storage within the coastal forest ecosystem. Measurements at three locations with varying vegetation densities show that the biomass of litter in dense areas (P1) reaches 5,524.75 kg/ha, in moderately dense areas (P2) is 6,230.78 kg/ha, and in sparse areas (P3) is 5,565.61 kg/ha. Therefore, the average carbon reserve stored in the litter is 5,773.71 kg/ha, indicating that litter stores more carbon than understory vegetation.

Both the understory vegetation and litter contribute to the carbon reserves on the soil surface in the coastal forest ecosystem. Litter has a higher carbon storage capacity compared to understory vegetation, suggesting that the decomposition process of dead organic material plays a significant role in the carbon cycle. Therefore, sustainable management of coastal forests is essential for maintaining ecosystem balance and optimizing carbon sequestration and storage capacity.

Carbon Reserves on the Surface of the Coastal Forest in Negeri Hatusua

The coastal forest plays a vital role in carbon sequestration on the soil surface through its various ecosystem components. Carbon storage occurs across several key carbon pools, including trees, large necromass, small necromass, understory vegetation, and litter. Each of these carbon pools contributes to the carbon cycle, with differing capacities for carbon storage as shown in Table 9.

Table 9. Carbon Reserves on the Soil Surface of the Coastal Forest in Negeri Hatusua

No	Carbon Pool	Carbon reserves (ton/ha)	Persentase (%)
1	Trees	83.87	93.81%
2	Necromass	0.69	0.78%
3	Small Necromas	0.85	0.95%
4	Understory plant	1.28	1.43%
5	Litter	2.71	3.04%
	Total	89.41	100.00%

Table 9 presents the carbon pools with the largest carbon reserves in the coastal forest of Negeri Hatusua. The trees are the dominant contributor, holding 93.81% of the total carbon reserves. Trees store carbon in their trunks, branches, leaves, and roots, making them the primary component for carbon storage in the coastal forest ecosystem. The larger and denser the tree stands, the greater the carbon storage capacity it can generate (Brown, 1997).

The second largest contributor, at 3.04%, is litter, which consists of fallen leaves, small branches, and other organic material that decomposes and returns nutrients to the soil. Litter holds a carbon reserve of 2.71 tons/ha. This component plays an important role in maintaining ecosystem balance by acting as a source of organic matter that decomposes, enriching the soil and sustaining nutrient cycles.

The third contributor is the understory vegetation, including small plants such as shrubs and grasses, which account for 1.28 tons/ha or 1.43% of the carbon reserves. While not as significant as the trees, understory vegetation is still crucial in the carbon cycle, particularly through photosynthesis, which helps absorb carbon dioxide from the atmosphere.

The fourth pool is small necromass, consisting of dead branches and twigs, with a carbon reserve of 0.85 tons/ha or 0.95%. Although smaller than large necromass, small necromass remains an important component in the carbon storage and release process, especially as it decomposes and contributes to the soil.

The smallest contribution comes from large necromass, which includes dead wood or fallen trees. The carbon reserve in large necromass is recorded at 0.69 tons/ha or 0.78%. This material can store carbon for an extended period before naturally decomposing.

The total carbon stock on the surface of the coastal forest in Negeri Hatusua is 83.87 tons/ha, which is higher than in degraded ecosystems such as those on Marsegu Island, Maluku. According to Irwanto et al. (2024), carbon stock in *Imperata cylindrica* grasslands is only 3.428 tons/ha, in rehabilitation areas 10.925 tons/ha, and in *Terminalia catappa* coastal forests 33.796 tons/ha. When compared to studies in Yap Island and Palau (Donato et al., 2012), the carbon stock in the coastal forest of Negeri Hatusua is lower than in mangrove forests (101–249 tons/ha) and coastal forests (145–216 tons/ha), but significantly higher than in savannas (5.1–9.9 tons/ha). This indicates that ecosystems like the one in Hatusua have significant potential for carbon storage, though improvements can still be made.

Carbon Dioxide Equivalent Sequestration in the Coastal Forest of Negeri Hatusua

The sequestration of carbon dioxide (CO_2) from carbon (C) can be calculated by converting the amount of carbon present into carbon dioxide. This conversion is carried out using a factor of 3.67, which is based on the molar mass ratio of carbon (12 g/mol) to carbon dioxide (44 g/mol). This factor reflects that for every unit of carbon mass sequestered in the biomass, it is equivalent to 3.67 times the mass of carbon dioxide. The carbon dioxide sequestration on the soil surface of various types of natural forests in Negeri Hatusua is presented in Table 10.

Table 10. Carbon Dioxide Equivalent Sequestration in Different Carbon Pools of the Coastal Forest in Negeri Hatusua

No	Carbon pool type	CO_2 equivalent sequestration (ton/ha)
1	Pohon	307.54
2	Necromass	2.55
3	Small necromass	3.12
4	Understory plant	4.68
5	Litter	9.95
	Total	327.83

Based on the data presented in Table 10, the total carbon dioxide equivalent sequestration in the coastal forest of Negeri Hatusua is estimated at 327.83 tons/ha. This sequestration is derived from various ecosystem components, including trees, necromass (dead biomass), understory plants, and litter. Among these components, trees contribute the largest share, accounting for 307.54 tons/ha, indicating the dominant role of large vegetation in carbon storage within this ecosystem.

Each ecosystem contributes differently to carbon storage. In addition to trees, necromass contributes 2.55 tons/ha, small necromass contributes 3.12 tons/ha, understory plants contribute 4.68 tons/ha, and litter contributes 9.95 tons/ha. Although the carbon stored in litter and understory plants is relatively small compared to that in trees, these components still play a crucial role in maintaining a healthy carbon cycle within the ecosystem. Furthermore, dead biomass, such as necromass, is important for enriching the soil with organic material during decomposition, contributing to the long-term carbon balance.

In the context of carbon trading, the carbon sequestration value can be monetized through carbon market mechanisms. Carbon trading allows entities with high emissions to purchase carbon credits from areas or ecosystems that are capable of absorbing significant amounts of carbon. Assuming a carbon price of US$5 per ton of CO_2 in the global market, each hectare of the coastal forest in Negeri Hatusua holds an estimated economic value of approximately US$1,639.15 per hectare. The coastal forest area in Negeri Hatusua spans 4,874 meters, and according to Goltenboth et al. (2006), the boundary of coastal forest zoning is set at 50 meters, resulting in an estimated area of 24.37 hectares. Therefore, the total economic value is approximately US$39,946.15.

When converted using the exchange rate of US$1 to IDR 16,000, this amounts to approximately IDR 639,138,365.99.

The carbon trading mechanism presents an opportunity for sustainable forest management and serves as an alternative source of income for local communities and regional governments. By maintaining forests in a pristine condition and enhancing their carbon sequestration capacity, regions can derive economic benefits while avoiding excessive exploitation of natural resources. In addition, coastal forests provide various ecological functions, such as protecting coastlines from erosion, conserving biodiversity, and serving as habitats for numerous plant and animal species.

The data on carbon stock and sequestration in the coastal forest of Negeri Hatusua demonstrates the ecosystem's significant potential in mitigating climate change through carbon sequestration. When harnessed through appropriate carbon trading schemes, this potential can yield substantial economic benefits while simultaneously promoting environmental conservation. A sustainable approach to coastal forest management can provide not only effective carbon sink but also long term ecological and economic advantages for future generations.

CONCLUSIONS

The coastal forest of Negeri Hatusua plays an essential role in sustaining the balance of the coastal ecosystem, serving as both a significant carbon sequestration site and a vital habitat for a diverse array of plant species. Analyzing species diversity using the Shannon-Wiener index categorizes all growth stages within the "moderate" diversity range. Among these stages, the seedling stage exhibits the highest diversity (H' = 2.48), followed by the sapling stage (H' = 2.18), the tree stage (H' = 1.59), and the pole stage (H' = 1.22). These findings indicate that natural regeneration processes are operating effectively, despite a decrease in species diversity at higher growth stages, likely due to natural selection and competition for resources.

The vegetation structure of the coastal forest in Negeri Hatusua consists of 13 families, with various species contributing significantly to the ecosystem's function. Cebera manghas (Mangga Berabu) dominates across nearly all growth stages, while species such as Pongamia pinnata (Kayu Besi Pantai), Intsia bijuga (Kayu Besi), and Calophyllum inophyllum (Bintanggur Pantai) play a crucial role in maintaining ecological stability. The vegetation density reflects the natural regeneration pattern of the forest, with the seedling stage hosting 130,500 individuals/ha. However, a considerable decline is observed at the sapling (1,920 individuals/ha), pole (460 individuals/ha), and tree (100 individuals/ha) stages.

Estimates of carbon reserves indicate that the total carbon stored above the forest floor is 89.41 tons/ha, with trees contributing the most substantial portion of this storage (83.87 tons/ha, or 93.81% of the total carbon). In addition to trees, necromass, understory plants, and litter also contribute to carbon sequestration, with a combined total of 5.54 tons/ha. The overall carbon dioxide equivalent sequestration in the coastal forest of Negeri Hatusua is estimated to be 327.83 tons/ha.

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