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(Research Article)

Species diversity and total carbon inventory in mangrove forests of Teluk Kimi District, Nabire Regency

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Abstract

Teluk Kimi District, a coastal location in Nabire Regency with a mangrove forest, has degraded due to many destructive activities. The study seeks fundamental data on species diversity (H', richness, E) and carbon stock potential. Basic random sampling is used. Square plots are used for sampling, with a 10 m × 10 m plot for tree observation, a 5 m × 5 m plot for saplings, and a 2 m × 2 m plot for seedlings, litter, and soil. Carbon stocks are assessed using allometric equations for biomass and destructive sampling for understorey, litter, necromass, and soil. The Taman Wisata Alam (TWA) Nabire species richness was 1.62 and 18. Pantai Pelangi has a 2.11 H' value and 17 richness. Muara Air Mandidi has a 1.15 H' value and 8 richness. TWA Nabire and Pantai Pelangi have moderate to high biodiversity and balanced species richness. Monodominance is shown in Muara Air Mandidi's low species richness and H' value. Pantai Pelangi has a community structure with an evenness above 0.6. TWA Nabire's uniformity approaches ecological stability. Muara Air Mandidi is moderately uneven and dominated by *Rhizophora mucronata*. TWA Nabire, Pantai Pelangi, and Muara Air Mandidi have carbon stocks of 592.46, 383.47, and 331.67 tC/ha. The moderate carbon stock in TWA Nabire (>500 tC/ha) is suitable for blue carbon conservation. Pantai Pelangi and Muara Air Mandidi are low-class coastal transitions and degraded ecosystems. The second implication concerns the eventual location of community-based rehabilitation.

Keywords: Species Diversity; Carbon Stock Potential; Allometric Equation; Destructive Sampling; Blue Carbon; Restoration

1. Introduction

The Papuan mangrove forest is one of Indonesia's most ecologically diverse and expansive coastal ecosystems. This region, which comprises approximately 10% of the national mangrove forest area, is crucial for climate change mitigation and biodiversity preservation through blue carbon sequestration [1,2,3,4]. Papua exhibits a significant diversity of mangrove species, predominantly including *Rhizophora apiculata*, *Rhizophora mucronata*, and *Bruguiera gymnorrhiza*. This diversity enhances a multifaceted community structure and elevates environmental productivity. Research in the East Sorong District of Sorong City has identified a total biomass of 666.29 t/ha and a carbon content of 313.13 tC/ha, demonstrating significant capacity for carbon sequestration [5]. Mangrove ecosystems in Demta Bay, Papua have been estimated to store an average above-ground biomass (AGB) of 117.6 t/ha and below-ground biomass (BGB) of 56.6 t/ha, resulting in a total biomass of approximately 174.2 t/ha or 87.1 tC/ha [6]. However, studies in undisturbed mangrove ecosystems in West Papua report much higher carbon stocks, reaching an average total ecosystem carbon stock (TECS) of 1,087 ± 584 tC/ha, making these areas some of the most carbon-rich mangrove ecosystems globally [7].

Age, species composition, management practices, and growth will affect carbon sequestration in a forest type. In a particular kind of forest, the amount of carbon stored will be affected by factors such as age, type, forest usage, growth

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rate, and substrate quality. Therefore, the carbon accumulation stored in a site needs to be calculated by calculating carbon reserves. This is necessary to determine an ecosystem's capacity to absorb carbon and identify the extent to which it contributes to lowering the concentration of greenhouse gases in the atmosphere [8,9,10].

The mangrove forests of Teluk Kimi District are biologically distinctive and significant ecosystems. The mangrove ecosystem in this region protects against coastal erosion, mitigates the impacts of waves and storms, and reduces the risk of flooding in coastal zones. Mangrove forests play a significant role in stabilizing coastlines and riverbanks, thereby protecting them from erosion and abrasion. Furthermore, mangrove forests contribute to land expansion by assimilating sediment deposits [11,12]. Mangrove trees, with their robust and salt-tolerant roots, contribute to soil stability along the shoreline and provide a habitat for a diverse and unique array of flora and fauna. Mangrove forests in the Teluk Kimi District offer economic and social advantages to local populations. Mangroves are a sustainable natural resource, providing firewood, traditional construction materials, and handicraft supplies. In the Teluk Kimi District, mangrove forests are utilized for multiple purposes, including providing firewood, harvesting mangrove crabs, catching fish, and extracting shellfish [13,14].

In any case, the present state of Teluk Kimi District, a coastal region in Nabire Regency characterized by mangroves along its shoreline, has declined. This region exhibits activities that result in forest degradation, including illegal harvesting for construction materials, the development of tourist attractions, the conversion of forest land to industrial use, and pollution from industrial operations. The collective operations in Papua would undoubtedly diminish the density of mangrove trees, thereby reducing their capacity to absorb carbon [15,16,17].

Substantial management efforts are necessary to prevent further significant destruction of mangrove ecosystems. Data concerning the variety of forms and the quantity of carbon that mangrove forests in the region can sequester and absorb remains unacquired [18,19]. Consequently, it is imperative to research the assessment of carbon sequestration in mangrove forests within the Teluk Kimi District of Nabire Regency. The objective of this study is to analyze the diversity of mangrove varieties and evaluate the potential TECS in the mangrove areas of Teluk Kimi District, Nabire Regency.

2. Material and methods

2.1. Study area

The data inventory of biodiversity and total carbon stock was performed in the mangrove region of TWA Nabire, Pantai Pelangi, and Muara Air Mandidi in Teluk Kimi District, Nabire Regency, Central Papua Province. The Teluk Kimi District is situated between the coordinates 135032.29'E, 3023.05'S and 135042.43'E, 3009.93'S, with its northern boundary next to Cendrawasih Bay, the southern boundary bordering Uwapa District, the eastern boundary neighboring Makimi District, and the western boundary abutting Nabire District.

The information was collected by establishing a 200 m transect with two lines at the TWA Nabire. The overall area of the plot is 40 square meters, with dimensions of 10 m x 10m. Pantai Pelangi features a transect length of 100 meters, with 3 lines yielding 30 plots, while Muara Air Mandidi exhibits conditions analogous to those at Pantai Pelangi (Figure 1).

The selection of these locations was intended to illustrate varying levels of human disturbance within the TWA Nabire. The first site represents an area that remains relatively undisturbed by the activities of surrounding communities, providing an example of intact natural conditions. The second site is at Pantai Pelangi, which, in contrast to the first location, has experienced deforestation and environmental degradation, likely due to increased human activity. The third site is at Muara Air Mandidi, an area cleared for agricultural activities and residential development. This location also corresponds to the area described previously, highlighting land conversion and its impacts on the natural landscape.

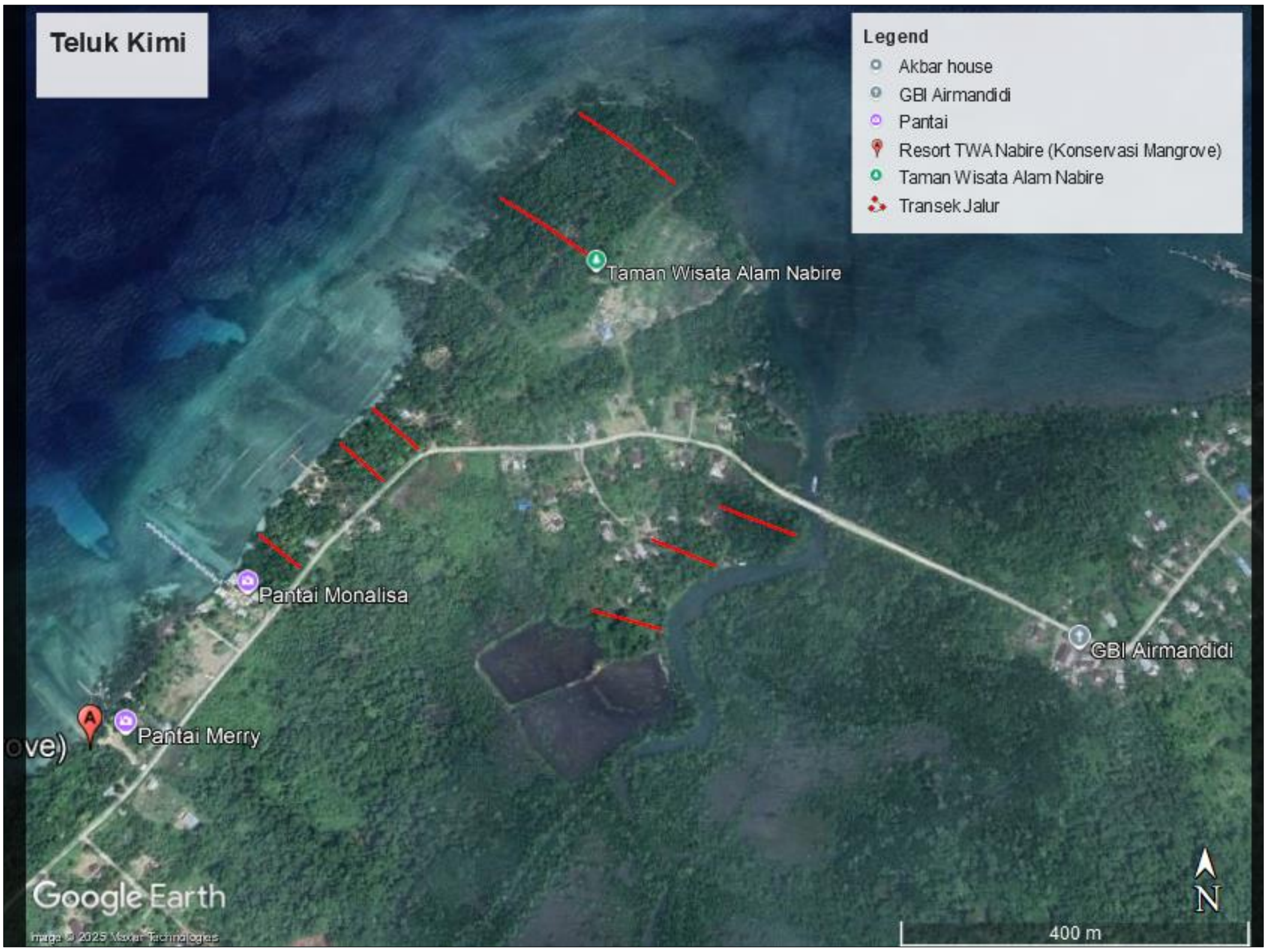

Figure 1 Transect data collection map (red line)

2.2. Method of data analysis

This study employed a purposive sample strategy to assess species diversity and carbon stocks in the mangrove region of Teluk Kimi District, Nabire Regency, Central Papua Province. The employed sample approach was simple random sampling. Quadratic plot measurements were utilized as a sampling technique, using a 10 m × 10 m plot for tree observation, a 5 m × 5 m plot for saplings, and a 2 m × 2 m plot for seedlings, litter, understorey, and soil [20,21] (Figure 2).

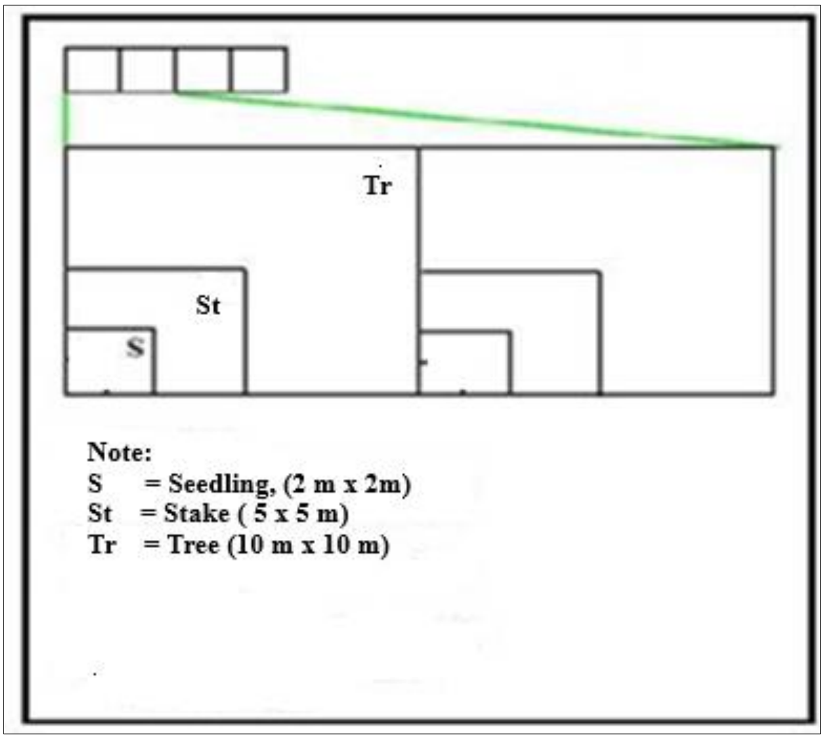

Figure 2 Nested plot belt transect design

2.3. Species Diversity

Biodiversity analysis uses the species diversity index (H' value) to assess the distribution patterns of various abundance measurements among species [22]. The species diversity index is computed with Shannon's Wiener formula [23]

$$H' = \sum (pi \times \ln pi) \ldots \ldots \ldots 1$$

H represents the species diversity index, ∑ which is the total number of species inside the community, and Pi signifies the proportion of species i relative to the overall number of individual species in the community (N). The requirements for the H-index value are categorized as follows: high (> 2.0), medium (1.6 < x < 2.0), low (1.0 < x < 1.6), and very low (< 1.0) [24].

Species richness refers to the total number of species present within a community or ecosystem, regardless of the population size of any individual species. [25] asserts that this is a crucial indicator of biodiversity, particularly in terms of the species composition within a designated area. The discovery of additional species in a region enhances its richness value. Assessment criteria: high category (3) for more than 100 species; medium category (2) for 30 to 100 species; and low category (1) for less than 10 species.

Evenness relates to the extent of uniformity in the distribution of individual species within a community. The evenness rating reflects the uniformity of individual distribution among all existing species. If all species possess approximately equal populations, the evenness score will tend towards 1 (maximum). If one or more species exhibit considerable dominance, the evenness value will tend towards 0 (minimum) [26,27]. The equation for Evenness (E) is presented below.

$$E = \frac{H'}{\ln S} \ldots \ldots \ldots 2$$

where E represents the Evenness value, H' denotes the Shannon-Wiener diversity index, and S indicates the number of species. The E value criteria are as follows: <0.25 is very low, 0.26-0.50 is low, 0.51-0.75 is moderate, and 0.76-1.0 is high [28].

2.4. Total Ecosystem Carbon Stock (TECS) Analysis

2.4.1. Aboveground Biomass (AGB)

The carbon computation from AGB was produced by combining the allometric formula for calculating leaves and stems with the equation proposed by [29], which can be summarised as follows

$$W = 10^{(-1.8571+2.1072*LOG(DBH))} \ldots\ldots\ldots 3$$

$$W = \rho * (0.0000695DBH^{2,64)} \ldots\ldots..4$$

where W describes the biomass of leaves and stems (kg), ρ represents the specific gravity of the plant (kg/m^3), and DBH indicates the diameter at breast height (cm).

2.4.2. Belowground Biomass (BGB)

The allometric formula was used in conjunction with the equation provided by [29] to arrive at the following computation for the amount of BGB carbon that was produced by this activity:

$$W = 0.199 * \rho^{0.899} * DBH^{2,22} \ldots\ldots\ldots 5$$

where W measures the amount of biomass (kg), ρ reflects the density of the plant (kg/m^3), and DBH pertains to the diameter at breast height (cm).

2.4.3. Understorey

To conduct understorey carbon sampling, a 2 m x 2 m plot was randomly selected, with an odd number of plots on each transect path representing each path. The following equation illustrates the calculation of carbon from understorey plants [30]

$$B = \mathrm{B(u). A. cf} \ldots\ldots\ldots 6$$

where B reflect the estimated understorey carbon (tC/ha), B(u) describe the dry weight of understorey plants (t/m^2), A refer to the area (m^2/ha), and cf indicate the non-dimensional conversion factor from biomass to carbon [31], valued at 0.5).

2.4.4. Litter

Carbon sampling for litter is conducted inside a 1 m x 1 m subplot, in conjunction with the undergrowth. The carbon calculations for litter comprising leaves, branches, and small branchers correspond to the subsequent equation.

$$\mathrm{L} = \mathrm{L(u). A. cf} \ldots\ldots\ldots 7$$

Where L is the estimated carbon from litter, branches, and twigs (tC/ha), L(u) denotes the dry weight of litter, branches, and twigs (t/m^2), A signifies the area (m^2/ha), and cf is the non-dimensional conversion factor from biomass to carbon [31], with a value of 0.5.

In the meantime, for deceased and decomposing trees, employ the following equation:

$$V_{km} = 0.25\pi(\frac{(d_p + d_u)}{2x100})^2 . p \ldots\ldots\ldots$$

$$\mathrm{B}_{Km=} V_{Km} \times \rho \ldots\ldots\ldots 9$$

Vkm defines the volume of dead wood (m^3), dp represents the diameter at the base of the dead wood (cm), du indicates the diameter at the tip of the dead wood (cm), p represents the length of the dead wood (m), Bkm refers to the biomass of dead wood (kg), and ρ is the specific gravity of dead wood (kg/m^3) [31].

2.4.5. Soil

Soil carbon sampling was conducted in a 1 m × 1 m subplot; fortunately, the generally uniform soil sample can be reflected by the sampling plot position. The following equation represents the calculation of soil carbon:

$$S = C_f \rho_s . 100 \ldots\ldots\ldots 10$$

where S represent soil carbon (t/ha), ρs denote soil density (g/cm^3), cf identify the non-dimensional conversion factor from biomass to carbon (IPCC, 2013, equivalent to 0.5), d indicate the vertical distance beneath the ground surface (cm), and 100 serve as the conversion factor [31].

3. Results and discussion

3.1. Species Diversity

Table 1 presents the results obtained regarding the variety of mangrove species in the Teluk Kimi region. These results were achieved by observing Shannon's Wiener index (H'), the number of species (richness), and the evenness (E) at three different locations.

Table 1 Species diversity in Teluk Kimi

Species Diversity	H'	Richness	E
TWA Nabire			
Line 1	1.62	18	0.56
Line 2	1.61	17	0.57
Pantai Pelangi			
Line 1	2.17	15	0.80
Line 2	2.08	18	0.72
Line 3	2.07	19	0.7
Muara Air Mandidi			
Line 1	0.94	8	0.45
Line 2	1.22	9	0.53
Line 3	1.29	6	0.72

TWA Nabire along transect line 1 recorded an H' value of 1.62, categorizing it as moderate with significant dominance, although indicating the presence of many species; the community is beginning to diversify. The other site on transect line 2 recorded an H' value of 1.61, indicating a modest level of diversity with significant dominance by multiple species, suggesting the community is beginning to diversify.

Pantai Pelangi transect line 1 has a medium-high H' value of 2.17, indicating high variety, even species distribution, and a stable ecosystem with the dominant species. Transect line 2 has a medium-high H' value of 2.08, indicating high variety, even species distribution, and a stable ecosystem. Transect line 3 has a medium-high H' value of 2.07, indicating high variety, even species distribution, and a stable ecosystem.

Transect line 1 of Muara Air Mandidi has a low H' value of 0.94, indicating a fragile ecosystem with one or a few dominant species. The dominant species was *R. mucronata*. Estuaries with harsh tidal conditions, muddy soil, and high salinity have this makeup. This community is ecologically fragile and susceptible to biotic and abiotic perturbations. Transect line 2 had a medium-low H' value of 1.22, indicating high dominance, but more than one species and community diversification. Additional species, including *Aegiceras, Bruguiera*, and *Tracheophyta*, raised the H' value. Although still dominated by *R. mucronata*, the community structure became more diverse. This may indicate natural regeneration or recovery. Transect line 3 had a medium-low H' value of 1.29, indicating high dominance but more than one species and community diversification. The community is more diverse than the preceding transects. *Nypa* and *Acrostichum* suggest a watery impact zone and protective habitat for understorey species. This transect has more natural recovery potential, as shown by the higher H' value.

An H' index ranging from 0.62 to 1.19 is a relatively prevalent value in the coastal regions of Papua, as observed in the research conducted by [32] on mangrove vegetation in the Mimika District. Investigations in the Raja Ampat mangrove region revealed an H' value ranging from 1.60 to 1.75 for communities predominantly composed of *Avicennia marina*, where regenerative patterns persist without considerable human interference [33]. [34] A study was conducted in the Sulawesi mangrove protected area, revealing an H' of approximately 1.7 in an ecosystem increasingly subjected to human pressures, including logging and land conversion.

The species composition of the three locations in the Teluk Kimi District is shown in Figure 3. TWA Nabire primarily comprises *Syzygium pycnanthum* (50%) and *Pandanus tectorius* (20%). Variations persist among other species, signifying moderate diversity circumstances. Pantai Pelangi exhibits a more balanced species composition, featuring three predominant species, while others constitute 40% of the total. This indicates a varied and comparatively stable community. Muara Air Mandidi has a near-monodominant composition of *Rhizophora mucronata*, comprising 70% of the total. Minimal contributions from other species result in poor diversity and increased vulnerability.

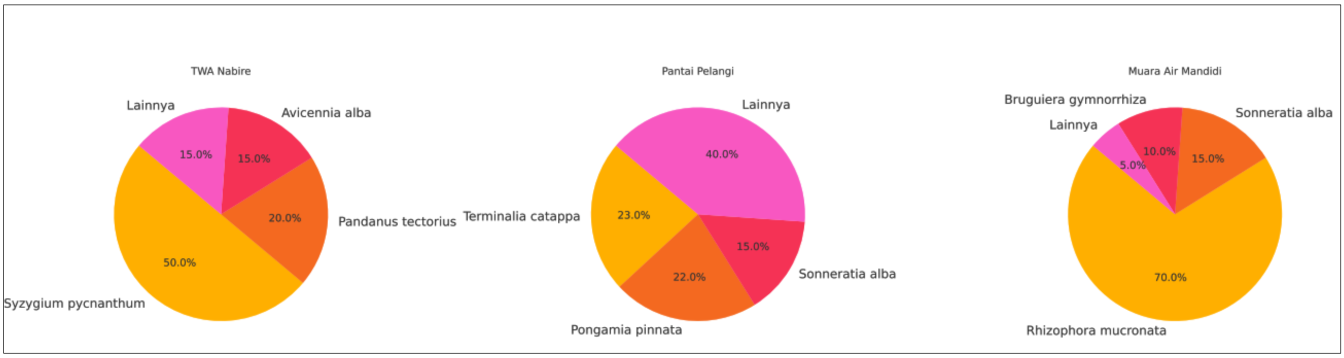

Figure 3 Composition of mangrove species in Teluk Kimi District

Species richness is a crucial structural element of biodiversity. The richness category is not absolute; it must be interpreted within the context of the environment. In the mangrove ecosystem, 10-15 species are deemed diverse due to the specialized adaptations required for survival in tidal settings. Conversely, in tropical rainforests, this figure is relatively low. Pantai Pelangi and TWA Nabire exhibit a medium-high richness classification, signifying substantial potential for ecological stability and ecosystem functions, including carbon sequestration and coastal protection. Muara Air Mandidi, particularly Transect 1, falls within the low-to-moderate richness group due to the predominance of Rhizophora mucronata. This region is susceptible and is recommended for recovery treatments involving mixed species. This pattern corroborates the assertions of [35] and [36] that mangrove ecosystems with more than 10 species can be deemed structurally robust; however, the H' and evenness values must also be considered.

The evenness (E) value quantifies the distribution of individuals among species, specifically indicating the uniformity of species dominance within the community. An E value approaching 1 suggests that all species have the exact population sizes, resulting in an equitable community. E <0.6 signifies substantial dominance by one or many species, indicating an uneven community structure. Pantai Pelangi (lines 1–3) exhibits an evenness greater than 0.6, signifying a comparatively balanced community structure (Figure 4). TWA Nabire exhibits uniformity that approaches or somewhat exceeds the threshold of ecological stability. Research from various locations indicates a range of E values, from low to high. In Bangkalan, East Java, the E value ranges from 0.23 to 0.78; in Sentebang Village, West Kalimantan, it ranges from 0.50 to 0.75, exhibiting a relatively uniform distribution. The E values for Bali mangrove ecotourism range from 0.61 to 0.67, distributed evenly, while Boroko, North Sulawesi, exhibits E values from 0.68 to 0.71, maintaining a consistent distribution [37, 38, 39, 40].

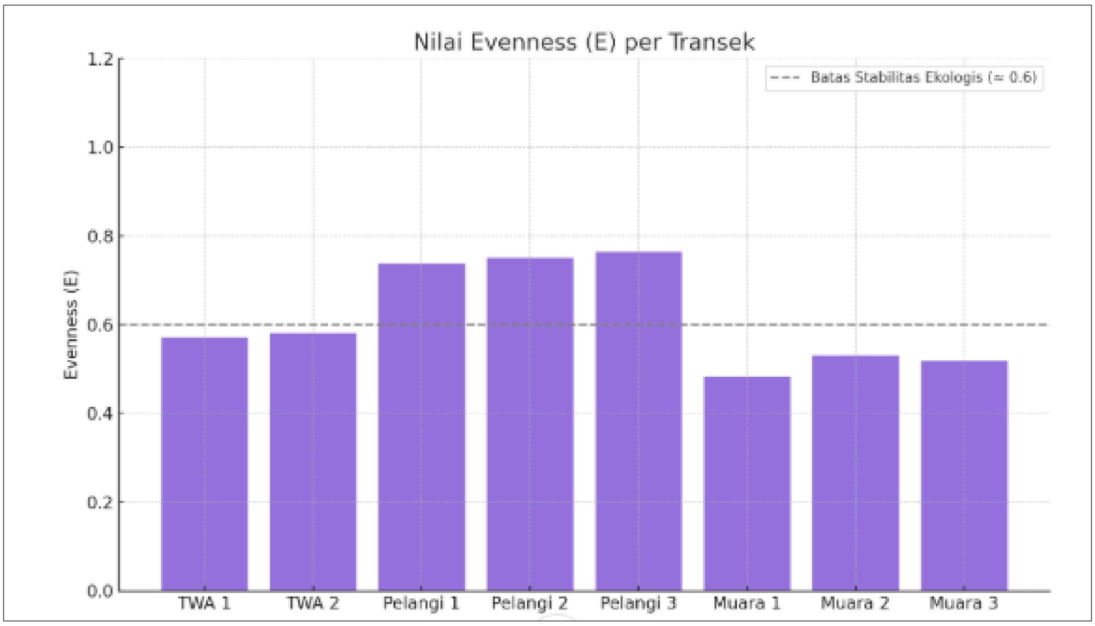

Figure 4 Eveness Value (E) in Teluk Kimi District

3.2. Total Ecosystem Cabon Stok (TECS)

3.2.1. Total Biomass

TWA Nabire exhibited substantial total biomass carbon stock storage, with 197.76 tC/ha measurements at transect line 1 and 186.13 tC/ha at transect line 2, respectively (Figure 5). These values are analogous to those of primary mangrove forests in Papua, specifically Bintuni Bay, which have been documented to range from 190 to 280 tC/ha [41, 42]. The primary contribution originated from mature species, such as *Syzygium pycnanthum*, *Avicennia alba*, and *Terminalia catappa*, indicating that the region is ecologically sound and architecturally intricate. The ratio of BGB to AGB at the sapling stage was minimal compared to the pole and tree stages. The typical stem diameter at the seedling stage is 5 cm. The mean diameter was determined to be 24 cm at the pole and tree levels.

The conservation status of the TWA Nabire site, as identified on transect line 1, categorized the dominating species as being of least concern, with their natural populations being stable, unknown, or declining. Additionally, one species, *Anisoptera marginata*, has been identified as vulnerable, with a declining presence in its natural habitat [43]. The TWA Nabire transect line 2 identified the dominating species, classified as least concern, which exhibit stable, unknown, and declining populations in their natural habitat. Other species were identified as near threatened due to diminishing availability in their natural habitats (*Intsia palembanica, Artocarpus odoratissimus*) and vulnerable with declining and uncertain conditions in the wild (*Anisoptera marginata, Phoebe angustifolia*).

TWA Nabire transect line 2 identified the dominating species as those classified as least concern, with their populations in nature being constant, unknown, or decreasing. Additional species were identified as near threatened due to diminishing availability in their natural habitats (*Intsia palembanica, Artocarpus odoratissimus*) and vulnerable with declining and uncertain conditions in the wild (*Anisoptera marginata, Phoebe angustifolia*).

The ecological assessment of the mangrove ecosystem in TWA Nabire reveals the attributes of primary or highly mature mangrove forests, characterized by robust and dense stand structures, moderate to high tree variety, and an absence of observable anthropogenic alteration or degradation. Consequently, the mangrove ecosystem is a significant carbon sink, with a carbon stock value approaching the national threshold (~200 tC/ha), thereby playing a crucial role in mitigating climate change. Moreover, it serves as a coastline guardian, with substantial biomass that aids in absorbing wave energy and mitigating erosion. Another role is serving as a biodiversity habitat, with particular protected species, where mature stands provide habitat for aquatic birds, monkeys, and soil organisms [44, 45, 46].

Carbon stocks in Pantai Pelangi ranged from 53.08 to 86.69 tC/ha, indicating a moderate capacity for carbon storage (Figure 5). These values are below the national mangrove average (~150 AGB + 50 BGB = 200 tC/ha) but constitute a viable carbon reservoir. All transects exhibit below-ground biomass (BGB) of less than 30 tC/ha, significantly lower than the national norm of approximately 50 tC/ha. This can be understood as sandy or gravelly soil substrates that fail to facilitate the growth of lateral and respiratory roots, the absence of aerial root species like *Rhizophora*, which typically generate substantial root biomass, and the influence of anthropogenic disturbances or recent sediment deposition.

The conservation status of Pantai Pelangi (transect lines 1-3) is primarily characterized by species of low concern, whose populations are stable. Still, their status is unknown, and some have started to decline. Transect 1 also revealed species with varying conservation statuses, including those nearing threatened status due to diminishing natural availability (*Intsia palembanica, Artocarpus odoratissimus*) and those classified as vulnerable with declining availability in nature (*Anisoptera marginata*). Transect 2 identified species with statuses nearing threatened due to diminishing natural availability (*Artocarpus odoratissimus, Intsia bijuga, Canarium luzonicum*) and vulnerable species with indeterminate natural availability that have commenced a decrease (*Phoebe chekiangensis, Hopea odorata*). Transect 3 identified species with statuses nearing threatened due to diminishing natural availability (*Intsia palembanica, Intsia bijuga, Artocarpus odoratissimus*) and vulnerable species with uncertain natural availability (*Phoebe angustifolia*).

Pantai Pelangi has potential for carbon sequestration if enriched with productive mangrove species, such as *Rhizophora apiculata* or *Avicennia marina*, and utilized as an educational area for coastal transition ecosystems. Several low BGB issues can indicate soil structure instability, which increases the danger of erosion and abrasion. It is also aware of the key sources of human pressure (such as wood use or land clearing) that have increased, resulting in a severe decline in carbon stock content, AGB [47,48]. The technical recommendations for Pantai Pelangi [49,50] include vegetative rehabilitation using local species with high salinity tolerance, area zoning to identify core conservation zones versus limited-use zones, and periodic monitoring of biomass and soil quality.

Muara Air Mandidi had the lowest biomass carbon stock values (9.66-32.28 tC/ha), with transect line 2 having the lowest (Figure 5). This suggests significant anthropogenic disturbance, limited recovery, and early successional or scant canopy cover. The average AGB value was ~18.9 tC/ha, well below the national standard (150 tC/ha). This means the vegetation is in an early growth stage or undergoing post-disturbance regeneration. Seedlings and non-woody plants predominate, with few mature *Rhizophora* or *Bruguiera* specimens. Other degraded mangrove zones in Java, such as Muara Gembong, have carbon stocks below 70 tC/ha [51].

Conservation status in Muara Air Mandidi on transect lines 1-3 for dominating species and others with minimal concern, whose natural availability is largely declining, stable, or unknown. Nothing approaching threatened or vulnerable was discovered. Ecological conditions in threatened areas with young species or saplings and few trees with large DBH indicate anthropogenic pressure, including tree felling for firewood, land conversion for ponds or settlements, and natural disturbances like high sedimentation or extreme salinity [52,53].

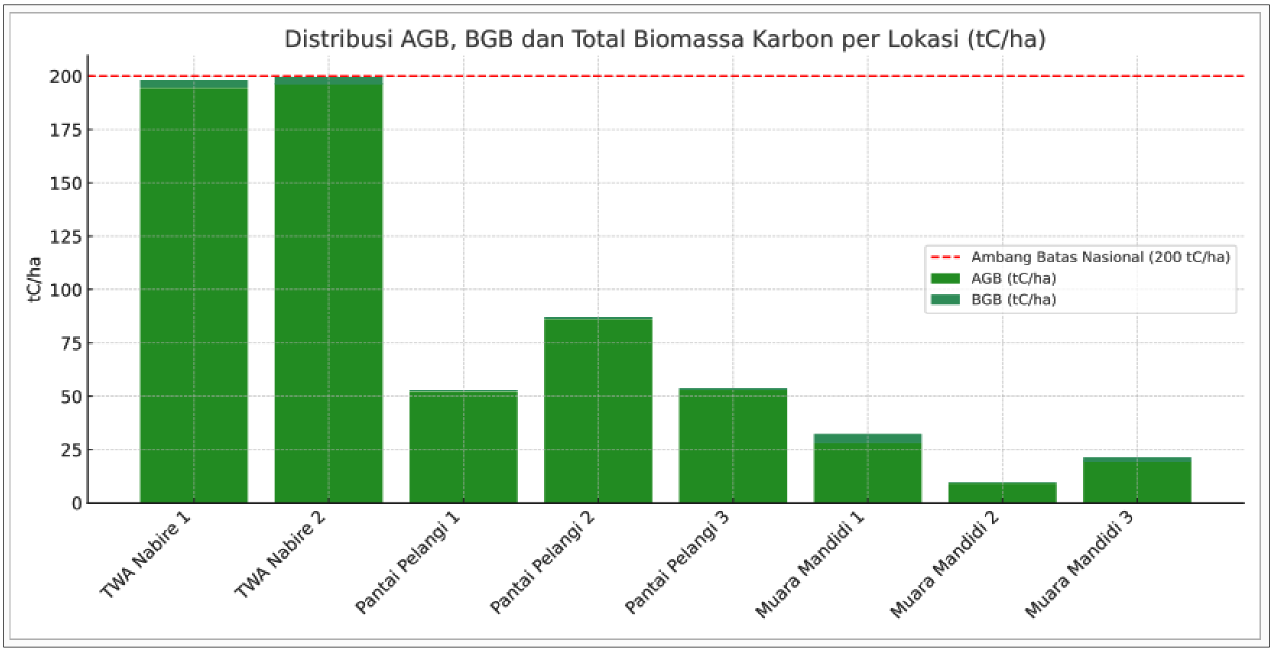

Figure 5 Total biomass carbon stock in Teluk Kimi District

3.2.2. Understorey

For real mangroves, *Avicennia alba* and *Bruguiera gymnorhiza* dominate the seedling phase at TWA Nabire, which calculates carbon stores in understorey plants. *Syzygium pycnanthum, Pandanus tectorius, Terminalia catappa*, and *Calophyllum inophyllum* dominate the mangrove relationship. For real mangroves, *Sonneratia alba* and *Bruguiera gymnorhiza* dominate Pantai Pelangi. *Syzygium pycnanthum, Terminalia catappa, Pongamia pinnata, Pometia pinnata,* and *Intsia bijuga* dominate the mangrove association. True mangroves, *Rhizophora mucronata*, *Soneratia alba*, and *Rhizophora apiculata*, dominate Muara Air Mandidi. *Pandanus tectorius, Pongamia pinata, Nypa fruticans*, and *Pometia pinnata* dominate mangrove associations.

A destructive sample was taken from a 2 m × 2 m plot in several selected plots, and the wet weight was calculated. The sample was then dried for three days at 80 °C in the Forestry Laboratory at the University of Papua (UNIPA) to determine the understorey carbon. The carbon content of the dry weight was estimated using equation 6. The understorey carbon in the TWA Nabire, Pantai Pelangi, and Muara Air Mandidi locations was 0.70, 0.46, and 0.88 tC/ha, respectively (Figure 6). Under the primary forest canopy, shrubs, herbs, grasses, ferns, and tree regeneration can collect or absorb carbon. This category has high, medium, or low carbon absorption and biomass [54,55,56]. TWA Nabire and Pantai Pelangi have low forest floor carbon potentials of less than 1.5 tC/ha. Disturbed forests hinder the regeneration of trees, plants, herbs, and grasses, which raises concerns about seedling establishment. Note: high criteria (> 5 tC/ha) and medium criteria (1.5 – 5 tC/ha).

3.2.3. Litter

The carbon supply in litter was assessed by examining the decomposition of leaves, branches, and twigs from the juvenile, pole, and mature tree stages. Furthermore, destructive sampling was conducted to collect litter of decomposing material inside 2 m x 2 m plots across several meticulously chosen locations.

Litter is frequently located in regions with decomposing wood, such as TWA Nabire. The trash was desiccated at the Forestry Laboratory UNIPA for three days at a temperature of 80°C. The total carbon stock of litter in TWA Nabire, Pantai Pelangi, and Muara Air Mandidi was 4.02, 1.41, and 1.26 tC/ha, respectively (Figure 6). The litter carbon potential readings at Pantai Pelangi and Muara Air Mandidi were classified as low, with carbon levels below 2 tC/ha. This signifies that the state of the forest is frequently disrupted [57,58]. Note: high criteria (> 5 tC/ha) and moderate criteria (2-5 tC/ha).

3.2.4. Necromass

The necromass of decaying wood in TWA Nabire is characterized by the collapse of numerous substantial trees, alongside the identification of around 8 large logs (diameter 30-50 cm and height 10 m) and 15 medium logs (diameter 12-20 cm and height 5 m), with an estimated wood density of 0.5 for decaying mangrove wood.

Sampling was conducted non-destructively by measuring the diameter of the rotting wood's tip, base, and length. Subsequently, calculations were performed using equations 8 and 9 to determine the potential carbon value of necromass. The necromass carbon findings in TWA Nabire, Pantai Pelangi, and Muara Air Mandidi were 10.23, 1.26, and 0.48 tC/ha, respectively (Figure 6). The total carbon potential from undergrowth, litter, and necromass for each location—TWA Nabire, Pantai Pelangi, and Muara Air Mandidi—was 14.95, 3.13, and 2.62 tC/ha, respectively. The overall carbon stock of understorey and decomposing vegetation in TWA Nabire is within the global range for tropical forests, specifically 14 to 138 tC/ha [59].

The potential carbon necromass results in TWA Nabire are classified as high, with a value exceeding 7.5 tC/ha. This is attributable to the substantial quantity of fallen trees, sizable dead trunks, branches, and the gradual decomposition process. This value is also present in multiple primary tropical forests across various locations in Indonesia, including Papua [60,61]. Currently, Pantai Pelangi is classified as moderate, whereas Muara Air Mandidi is categorized as low. Note: moderate criteria: 2.5 - 7.5 tC/ha and low criteria: less than 2.5 tC/ha.

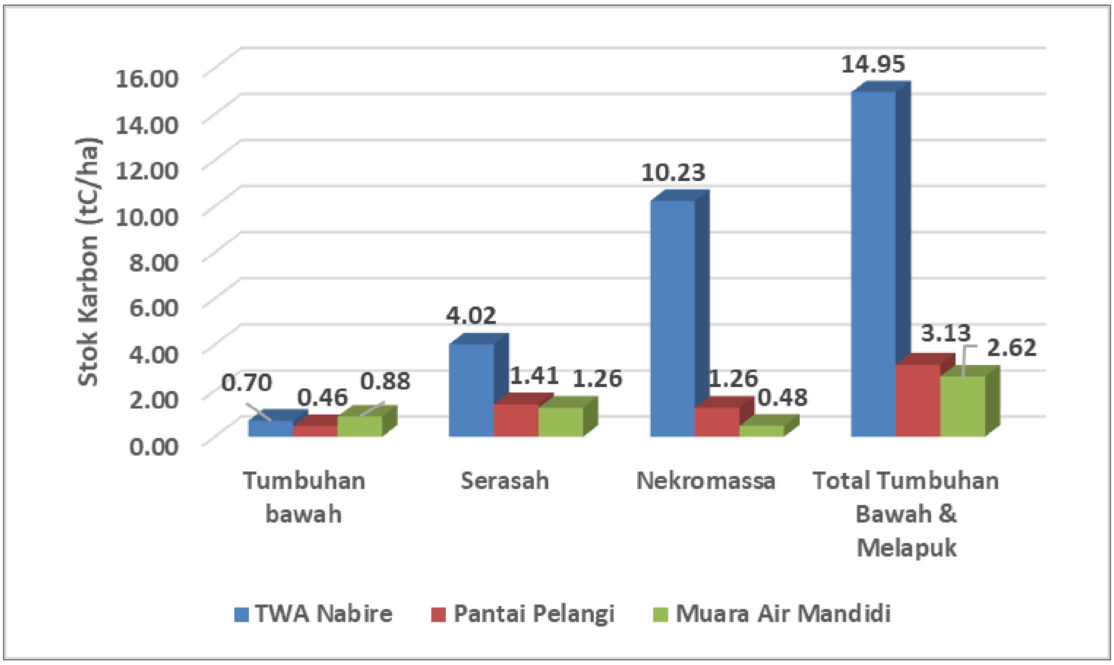

Figure 6 Understorey and decaying carbon stocks in Teluk Kimi District

3.2.5. Soil

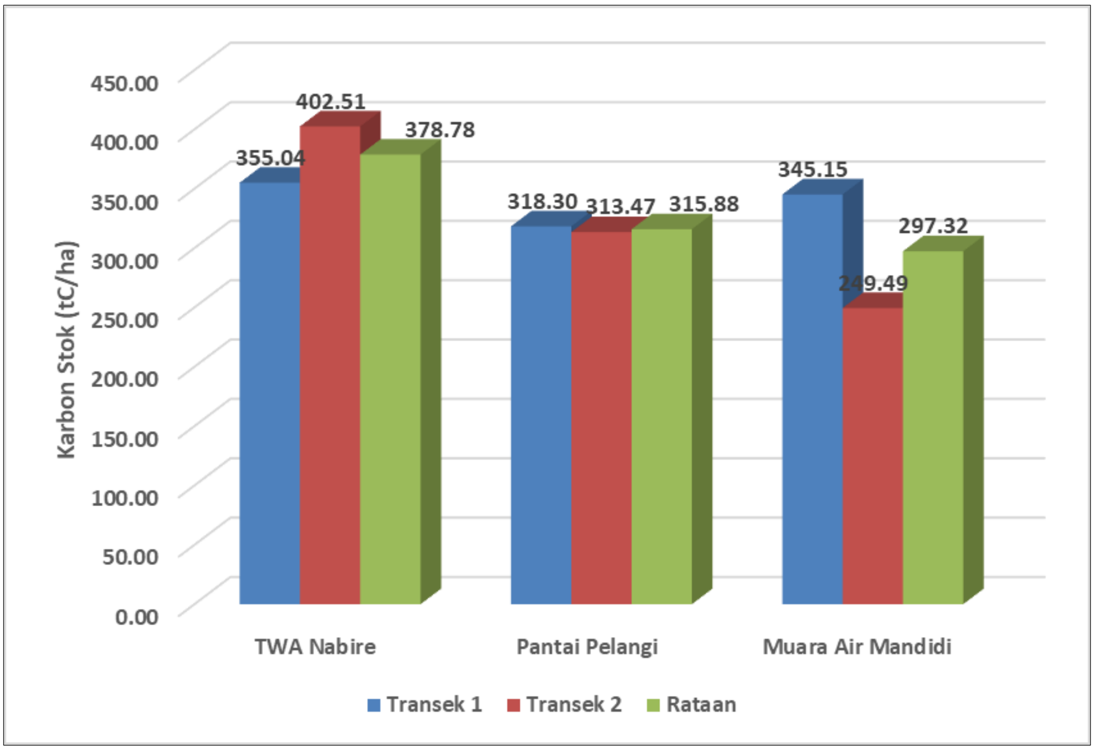

Figure 7 Soil carbon stocks in Teluk Kimi District

TWA Nabire, Pantai Pelangi, and Muara Air Mandidi have average C-organic soil values of 4.66%, 4.66%, and 5.26%. Sample data were collected from plots 10 and 5 in the middle of TWA Nabire and Pantai Pelangi Transects 1 and 2, and plot 1 at the start of Muara Air Mandidi transects 1 and 2. A 1-m-deep soil profile was taken on a 1 m x 1 m plot in the designated plot for this destructive sampling. Additionally, soil was gathered from each color layer, averaging 4 levels. Carbon content was taken from the University of Papua Forestry Laboratory, and soil carbon potential was calculated using equation 9. The calculation also takes soil density from lab data, which averages 0.69 gr/cm3, and each %C content per layer of soil depth calculates the carbon potential of the TWA Nabire, Pantai Pelangi, and Muara Air Mandidi as 378.78, 315.88, and 297.32 tC / ha (Figure 7).

Massively decomposing litter in fields allows carbon to enter the soil, resulting in a high carbon content. Mangrove soil carbon can reach 1,000 tC / ha in layers up to 1 meter, supplying 75% of the mangrove ecosystem's carbon. Papuan mangroves (Teluk Bintuni, Sorong, Mimika) have 700 tC/ha of soil carbon and a depth of 1.5–2 m with a high C-organic content [62]. Moderate soil carbon potential values (> 300 tC/ha) were found at depths of 1 m in TWA Nabire and Pantai Pelangi. In Muara Air Mandidi, values are low at <300 tC/ha. In Papua, this value is also found in mangrove habitats, where there is a significant accumulation of organic matter and slow breakdown [63, 64, 65]. Note: intermediate criteria (300-600 tC/ha) and low criteria (<300 tC/ha).

3.2.6. Total Ecosystem Carbon Stock (TECS)

The cumulative TECS potential at the TWA Nabire, Pantai Pelangi, and Muara Air Mandidi sites, derived from total biomass, understory vegetation, litter, necromass, and soil, was 718.45 tC/ha (Figure 8). The highest percentage of carbon was derived from total biomass and soil, with values of 19.97% and 78.65%, respectively. The residual carbon percentages were identified in necromass, litter, and understory plants at 0.73%, 0.48%, and 0.17%, respectively. The ratio of carbon above the surface to below the surface is 20% to 80%.

Research in Indonesia indicates that mangrove ecosystems allocate roughly 32% of their total carbon to above-ground biomass and around 68% to below-ground biomass and soil, which corresponds closely with the often-referenced worldwide ratio of 20% above and 80% below. Research in Eastern Sumatra revealed above-ground carbon stores ranging from 96 to 356 Mg C/ha and below-ground stocks from 28 to 153 Mg C/ha, demonstrating considerable diversity yet a pronounced predominance of carbon in below-ground and soil reservoirs [66]. Research conducted on Gili Petagan, Lombok Timur, revealed 161.8 t C/ha above ground and 112.0 t C/ha below ground, indicating that about 40% of carbon is sequestered above ground and 60% below ground [67].

Globally, average mangrove forests sequester from 12.0 to 150.2 Mg C/ha in above-ground carbon and 46.6 to 388.6 Mg C/ha in below-ground carbon, indicating that 69–91% of the entire carbon stock resides below ground, with a root: shoot ratio varying from 1.3 to over 4 [68]. A separate global evaluation found that around 78–96% of total ecosystem carbon in mangroves is contained in the soil and below-ground biomass, contingent on mangrove height, thereby corroborating the widely recognized 20:80 above-to-below carbon allocation ratio [69].

The total carbon potential results in the TWA Nabire are classified as moderate, with a value over 500 tC/ha. The total carbon at Pantai Pelangi and Muara Air Mandidi, valued at <500 tC/ha, is classified as low. This value is also present in several locations within the mangrove environment of Papua. Criteria for medium (500 – 900 tC/ha) and low (< 500 tC/ha).

Research in Southeast Asia and Oceania indicates elevated average TECS values—1,016 t C/ha in Southeast Asia and 1,141 t C/ha in Oceania—compared to the global average of roughly 856 t C/ha. This suggests that the carbon storage in Nabire's mangroves is comparable, albeit marginally lower, than the global mean [70].

In Indonesia, average TECS values are often elevated due to the presence of substantial peat and mangrove ecosystems. Worldwide meta-analyses indicate that the total global mangrove carbon stock averages 629 ± 448 Mg C/ha, with soils accounting for approximately 63% of that total [71]. The TECS in Nabire corresponds with global norms but is inferior to intact systems in West Papua, where undisturbed mangroves, such as those in Bintuni Bay, exceed 1,000 tC/ha [72].

Globally, TECS varies significantly from 79 to 2,208 Mg C/ha, with tropical regions averaging between 800 and 960 Mg C/ha. Soil carbon typically constitutes 60–70% of the entire store [73]. In Lamu, Kenya, the total carbon storage in the mangrove ecosystem was quantified at 560 ± 64 Mg C/ha, with soils accounting for 70% and biomass contributing less, mirroring global trends of soil predominance (Frontiers in Lamu).

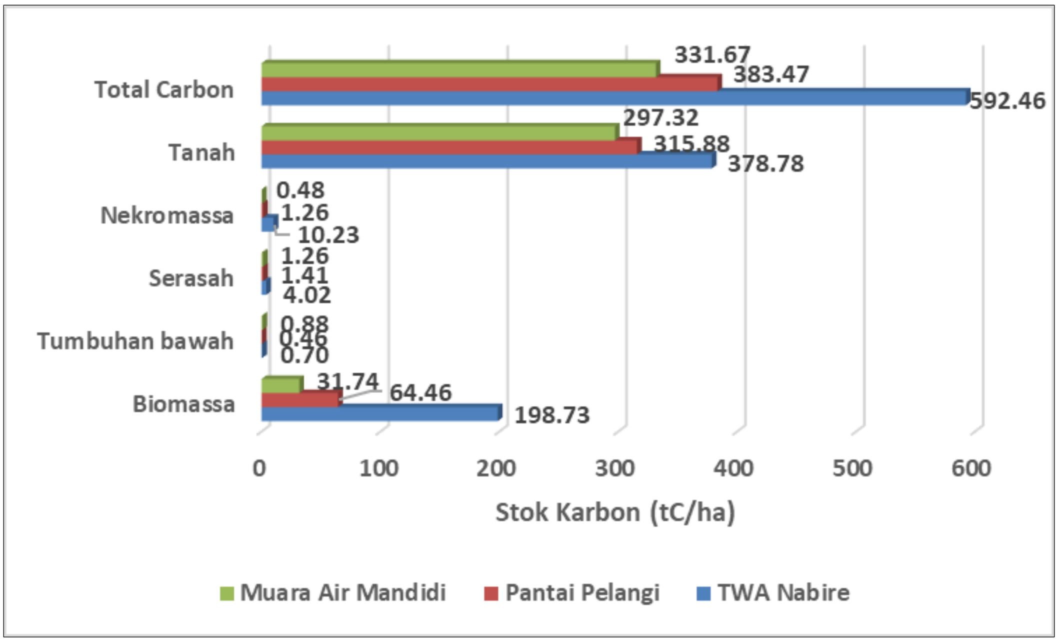

Figure 8 TECS in Teluk Kimi District

4. Conclusion

The H values and species richness at TWA Nabire (transect lines 1 and 2) were recorded as 1.62 and 1.61, respectively, with 18 and 17 species. The H' and richness values for Pantai Pelagi (transect lines 1-3) were recorded as 2.17, 2.08, 2.07, and 15, 18, 19, respectively. The H' and richness values for Muara Air Mandidi were recorded as 0.94, 1.22, 1.29, and 8, 9, 6, respectively. Pantai Pelangi and TWA Nabire exhibited comparatively high and equitable species richness and H'. Concurrently, Muara Air Mandidi, particularly transect line 1, exhibited low species richness and low H', signifying a pronounced domination by a single species (monodominance). Pantai Pelangi exhibited an evenness greater than 0.6, indicating a relatively balanced community structure. TWA Nabire exhibits uniformity that approaches or somewhat exceeds the threshold of ecological stability. Muara Air Mandidi, particularly transect line 1, exhibits moderate and uneven evenness due to the pronounced dominance of Rhizophora mucronata.

The average total biomass carbon stocks in TWA Nabire, Pantai Pelangi, and Muara Air Mandidi were recorded at 198.73, 64.46, and 31.74 tC/ha, respectively. The total carbon stock of understory vegetation in TWA Nabire, Pantai Pelangi, and Muara Air Mandidi was 0.70, 0.46, and 0.88 tC/ha, respectively. The total carbon stock of litter in TWA Nabire, Pantai Pelangi, and Muara Air Mandidi was 4.02, 1.41, and 1.26 tC/ha, respectively. The total carbon stock of necromass in TWA Nabire, Pantai Pelangi, and Muara Air Mandidi was 10.23, 1.26, and 0.48 tC/ha, respectively. The total carbon stock of soil in TWA Nabire, Pantai Pelangi, and Muara Air Mandidi was recorded at 378.38, 315.88, and 297.32 tC/ha, respectively. The TECS at the TWA Nabire, Pantai Pelangi, and Muara Air Mandidi locations were measured at 592.46, 383.47, and 331.67 tC/ha, respectively. The overall carbon stock at the TWA Nabire is classified as moderate (exceeding 500 tC/ha) and is suitable for blue carbon conservation. Pantai Pelangi and Muara Air Mandidi are classified as low, falling under the coastal transition ecosystem and degraded ecosystem classifications. The remaining two places aim to implement restoration under indigenous populations.

Compliance with ethical standards

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Disclosure of conflict of interest

There is no conflict of interest.

Statement of ethical approval

Ethical approval for field data collection is consistent with the Manual for Measuring Blue Carbon in Mangroves published by the Ministry of Environment and Forestry in October 2024.

Statement of informed consent

Informed consent was obtained from all individual participants included in the study.

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