Mangrove structure, carbon stock, and socio-economics in Kapitu, North Sulawesi, Indonesia

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Abstract. Mangrove ecosystems in the Wallacea region, particularly in North Sulawesi, play a crucial role as coastal life support systems, blue carbon sinks, and livelihood supporters for local communities. However, anthropogenic pressures and land-use changes threaten the sustainability of these ecological functions. This study presents a comprehensive analysis of vegetation community structure, above-ground biomass (AGB) and carbon stock estimation, and socio-economic dimensions of the mangrove ecosystem in Kapitu Village, located in the ecologically critical Amurang Bay, South Minahasa Regency, Indonesia. Using the Line Transect Plot method across three observation stations representing a sea-to-land zonation gradient, three main mangrove species were identified: *Sonneratia alba*, *Avicennia marina*, and *Rhizophora apiculata*. Vegetation analysis showed that Transect 1 had the highest carbon stock at 22.89 megagrams of carbon per hectare (Mg C ha^{-1}), dominated by mature *S. alba* trees contributing 20.52 Mg C ha^{-1}. In contrast, Transects 2 and 3 represented younger or recovering stands with carbon stocks of 4.58 Mg C ha^{-1} and 0.153 Mg C ha^{-1}, respectively. The very low carbon value in Transect 3, despite the high seedling density of *R. apiculata* (up to 63 individuals per regeneration plot), indicates that this area is in an early stage of rehabilitation initiated by community groups and a local non-government organization since 2015-2018. A socio-economic survey of 51 respondents revealed high social capital for conservation: 100% of respondents acknowledged the protective function of mangroves against waves, and 83.3% expressed willingness to reprimand illegal loggers. These findings indicate that the Kapitu mangrove ecosystem is in a critical recovery phase, supported by strong social awareness, and requires long-term management strategies to optimize its carbon storage potential towards levels typical of primary mangrove forests in the Indo-Pacific region.

Key Words: Amurang Bay, *Avicennia marina*, blue carbon, community-based conservation, *Sonneratia alba*.

Introduction. Mangroves are among the most productive ecosystems in intertidal zones and provide essential services for marine biodiversity and coastal communities. They function as highly efficient ”blue carbon” sinks, storing large quantities of carbon in biomass and sediments, often exceeding the carbon density of many terrestrial forests (Donato et al 2011; Alongi 2012). If undisturbed, this carbon can remain sequestered for long periods (Murdiyarso et al 2015). At the same time, mangroves protect shorelines from waves and abrasion, trap sediments, and support fisheries and other livelihoods (Lee et al 2014).

Indonesia holds approximately 23% of the world’s mangrove area and therefore plays a strategic role in meeting its Nationally Determined Contributions (NDCs) for climate change mitigation (Giri et al 2011; Murdiyarso et al 2015). However, widespread conversion to aquaculture, coastal infrastructure development, and other land-use changes continue to reduce mangrove extent and condition (Ilman et al 2016; Richards & Friess 2016). The loss and degradation of mangroves diminish their capacity to store carbon, release previously stored carbon to the atmosphere, and weaken their physical coastal protection functions.

The North Sulawesi region, situated within the Coral Triangle, features close ecological linkages between mangroves, seagrass beds, and coral reefs (Wagey et al 2020). Previous studies have focused mainly on areas such as Bunaken National Park and North Minahasa, documenting mangrove flora, community structure, and habitat characteristics (Djamaluddin 2018; Opa et al 2019; Oroh et al 2024). In contrast, the southern coast of North Sulawesi, including Amurang Bay, has received far less attention. Amurang Bay is an ecologically important semi-enclosed bay that is also highly vulnerable to coastal abrasion and human impacts (Patty & Huwae 2023; Lumingas et al 2024), yet its mangrove ecosystems remain poorly quantified, particularly in terms of carbon stocks.

A specific knowledge gap exists regarding the structure and carbon dynamics of recovering and restored mangrove stands in Amurang Bay. While nearby systems such as Bunaken have been studied in detail, including their blue carbon potential (Murdiyarso et al 2015), there is a lack of quantitative data on above-ground biomass (AGB), carbon stock, and community structure in secondary and actively rehabilitated mangroves in Amurang Bay. This is critical because the bay is both exposed to abrasion and the focus of community-based restoration initiatives. Without site-specific ecological and socio-economic information, it is difficult to evaluate the effectiveness of these restoration efforts or to design appropriate management interventions.

Kapitu Village, located on the coast of Amurang Bay, illustrates these challenges. The area has experienced historical pressures from destructive fishing and land conversion, which have reduced mangrove cover. In response, local communities and partner institutions have carried out mangrove rehabilitation since around 2015, intensifying from 2018 onward. These activities have created a mosaic of remnant natural stands and replanted areas with different species compositions and age structures. Pioneer species such as *Avicennia marina* and *Sonneratia alba* differ in growth and biomass allocation from *Rhizophora apiculata*, which is widely used in restoration (Komiyama et al 2008), so evaluating restoration success requires quantitative information on vegetation structure and biomass, not just seedling counts.

The long-term sustainability of mangrove conservation in Kapitu also depends on the human dimension. Community-Based Ecological Mangrove Restoration (CBEMR) emphasizes local communities as resource managers rather than only as planting labor (Brown et al 2014; Damastuti & de Groot 2017). In Kapitu, the establishment of Tourism Awareness Groups (Pokdarwis) and mangrove nursery groups reflects efforts to build social capital that supports collective action. Perceptions of ecological functions (such as abrasion protection) and the economic benefits of mangrove ecosystem services influence community behavior and willingness to participate in conservation (Malik et al 2015).

Therefore, this research aims to: (1) analyze the mangrove community structure in Kapitu Village, Amurang Bay, including species composition, density, frequency, dominance, and Importance Value Index (IVI); (2) estimate AGB and carbon stock using appropriate allometric equations; (3) assess the socio-economic profile and community perceptions of mangrove functions and conservation; and (4) formulate management recommendations that integrate ecological and social information to support sustainable, community-based rehabilitation of mangroves in this priority coastal area.

Material and Method

Study site. This research was conducted in the coastal area of Kapitu Village, West Amurang District, South Minahasa Regency, North Sulawesi Province, Indonesia. The site is situated along the coastline of Amurang Bay, a semi-enclosed body of water known for its high biodiversity potential but susceptible to physical abrasion. Geographically, the study site is located at coordinates 1°11′16″N-1°11′55″N and 124°30′59″E-124°31′10″E. The region has a tropical monsoon climate, with an average annual rainfall of approximately 2,361 mm and daily air temperatures ranging between 26 and 27°C. Hydro-oceanographic conditions at the study site indicate estuarine characteristics supporting mangrove growth, with water temperatures between 28.8 and 31.4°C, salinity ranging from 33 to 33.2 ppt, and neutral to slightly acidic pH (pH 6). The substrate varies from sandy mud in open areas to deep mud in protected areas.

Three stations were established using purposive sampling to capture the heterogeneity of the mangrove ecosystem (Figure 1). The selection criteria for each station were based on natural zonation patterns, the degree of degradation, and restoration history as follows: Station 1 (Remnant Natural Forest): selected to represent the mature forest zone with high structural complexity. This station is characterized by the presence of large *Sonneratia alba* parent trees, indicating a remnant area that has survived past degradation and serves as a natural reference. Station 2 (Pioneer Zone): selected to represent the seaward pioneer zone dominated by *Avicennia marina*. This area reflects the natural zonation capability of mangroves in colonizing sediment-rich substrates typical of the bay's edge. Station 3 (Restoration Zone): selected to represent the recovering ecosystem with a specific history of active rehabilitation initiated by community groups and NGOs since 2015. This station represents the regeneration phase, characterized by lower tree density but a high abundance of *Rhizophora apiculata* seedlings.

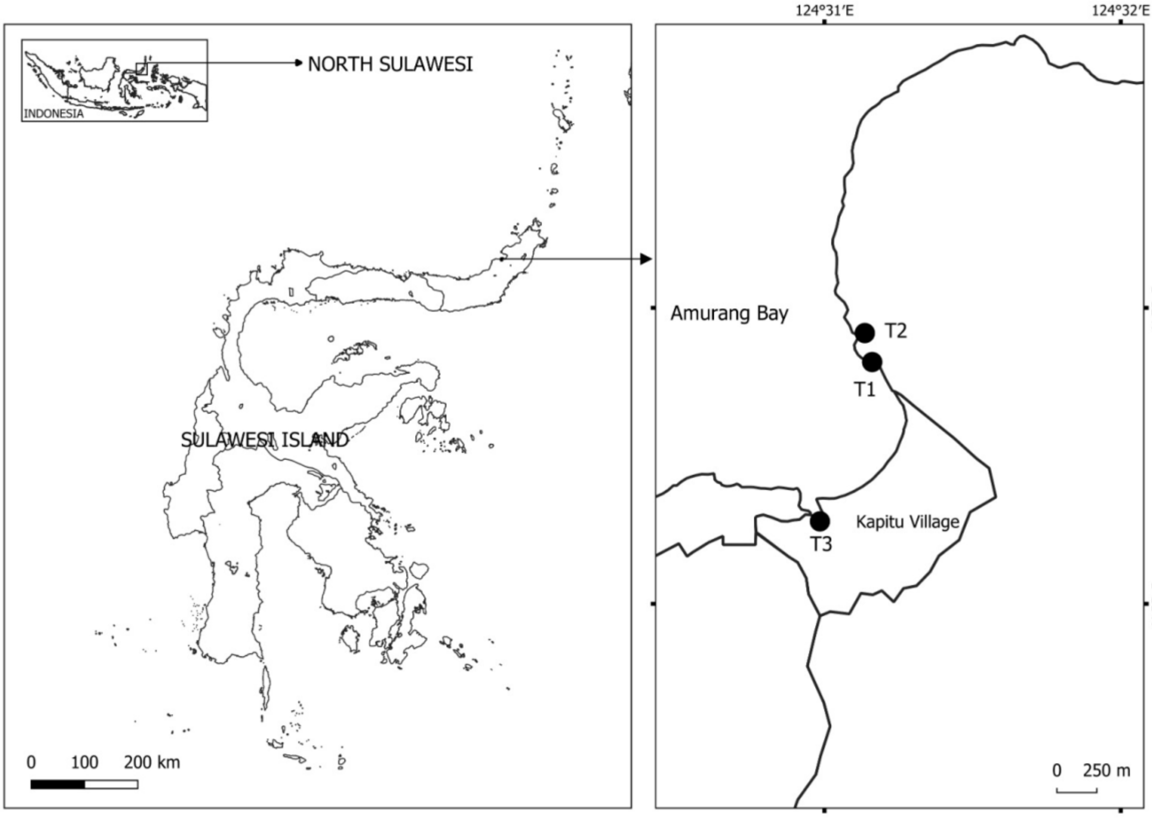

Figure 1. Study site.

Vegetation data collection. The vegetation analysis utilized the Line Transect Plot Method (English et al 1997; Lintong et al 2023). Three line transects were drawn perpendicular to the coastline towards the land at locations representing the condition of the mangrove forest in Kapitu. On each transect, we established 5 square observation plots measuring 10 m × 10 m (100 m²) for trees, resulting in a total sampled area of 500 m² (0.05 ha) per transect. Within each 10 m × 10 m plot, all trees with diameter at breast height (DBH) ≥ 5 cm and height ≥ 1.5 m were identified to species level (Noor et al 2006) and measured for circumference at breast height (CBH) at 1.3 m above ground (or above prop roots for *Rhizophora*), total height, and canopy cover percentage. CBH (cm) was converted to DBH (cm) using the formula:

$$DBH = CBH/\pi$$

Where:
DBH = the diameter at breast height (cm);
CBH = the circumference at breast height (cm);
π = 3.14159.

Subsequently, the basal area (BA) of each tree was calculated using the formula:

$$BA = \pi(DBH/2)^2$$

Where:
BA = the basal area (cm^2);
DBH = the diameter at breast height (cm);
π = 3.14159.

Seedlings and saplings (height < 1.5 m and/or DBH < 5 cm) were recorded separately in 1 m × 1 m regeneration subplots placed within the tree plots.

Transect 1: (1°11’54.88”N; 124°31’8.15”E). Represents an area with mixed stands and large parent trees.

Transect 2: (1°11’49.00”N; 124°31’9.64”E). Represents an area dominated by *Avicennia marina*.

Transect 3: (1°11’16.70”N; 124°30’59.05”E). Represents a regeneration area or new planting results with lower tree density but abundant seedlings.

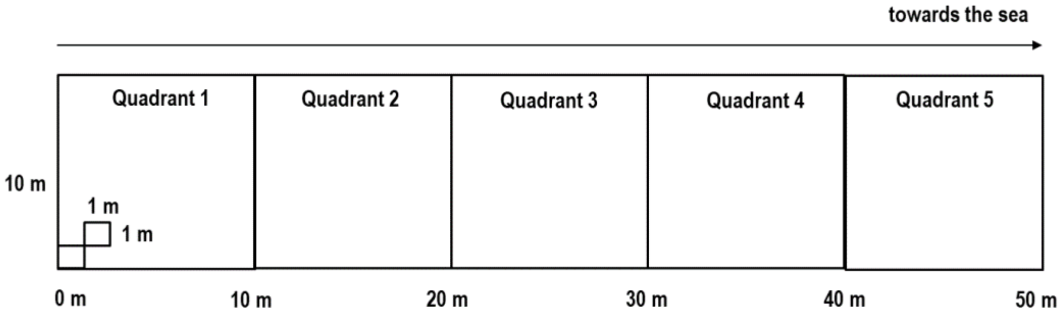

Figure 2. Line Transect Plot Method with square observation plots measuring 10 m x 10.m

Community structure analysis. Collected vegetation data were analyzed to obtain quantitative ecological indices (Krebs 1999; Magurran 2004) as follows:

1. Species Density (*Di*): Number of individuals of species *i* per unit area (ind ha^{-1}).
2. Relative Density (*RDi*): Percentage of species density to total density.
3. Species Frequency (*Fi*): Probability of finding species *i* in sample plots.
4. Relative Frequency (*RFi*): Percentage of species frequency to total frequency.
5. Species Dominance (*Doi*): Total Basal Area (BA) of species *i* per unit area (ha^{-1}).
6. Relative Dominance (*RDoi*): Percentage of species dominance to total dominance.
7. Importance Value Index (IVI): IVI = *RDi* + *RFi* + *RDoi* (Range 0-300).
8. Shannon-Wiener Diversity Index (H'): $H' = -\Sigma(Pi \ln Pi)$ where *Pi* is the proportion of individuals of a species *i*. Criteria: $H' < 1$ (Low), $1 < H' < 3$ (Moderate), $H' > 3$ (High).

Biomass and carbon stock estimation. Carbon stock estimation focused on AGB using non-destructive methods with allometric equations (Kauffman & Donato 2012). This study adopted equations from Komiyama et al (2005; 2008) developed for Southeast Asian mangroves, incorporating wood density (ρ) to improve accuracy:

$$W_{top} = 0.251\rho D^{2.46}$$

Where:
W_{top} = the Above-Ground Biomass (kg);
ρ = the wood density (g cm^{-3});
D = the Diameter at Breast Height (cm).

Biomass and carbon stock estimations were calculated only for trees in the tree layer (DBH ≥ 5 cm and height ≥ 1.5 m). Seedlings and saplings with DBH < 5 cm were not included in the biomass and carbon calculations because their individual contribution to stand biomass is minimal and their survival and growth are uncertain. Instead, seedling and sapling data are reported separately as indicators of regeneration status.
Wood density (ρ) values used were: *Avicennia marina* $\rho \approx 0.65$ - 0.85 g cm^{-3}, *Rhizophora apiculata* $\rho \approx 0.77$ g cm^{-3}, and *Sonneratia alba* $\rho \approx 0.475$ g cm^{-3}) (Komiyama et al 2005; 2008). Total biomass was converted to carbon stock (C) using the standard conversion factor recommended by IPCC (2006) and BSN (2011): Carbon Stock (C) = Biomassa (AGB) x 0.47. Carbon stock results are presented as megagrams of carbon per hectare (Mg C ha^{-1}; Mg = 10^6 g), and AGB as ton ha^{-1}.

Socio-economic survey. Socio-economic data were collected to understand how the Kapitu community interacts with, benefits from, and contributes to the mangrove ecosystem. Data collection was conducted in December 2025, using guided interviews based on a structured questionnaire. A purposive sampling approach was applied to select 51 adult respondents representing the main stakeholder groups in the village, including village officials, fishermen, entrepreneurs, and housewives. According to 2023 village statistics, Kapitu has a total population of 2,452 residents (1,173 males and 1,279 females), so the survey was designed as a stakeholder-focused, village-scale assessment rather than a full-population census. The sample size was chosen to ensure adequate representation of the key social groups directly involved in or affected by mangrove use and conservation, while remaining feasible for in-depth, face-to-face interviews. The questionnaire covered demographic characteristics, involvement in mangrove-related activities (nurseries, planting, Tourism Awareness Groups/Pokdarwis), perceptions of ecological functions (e.g., abrasion protection and habitat provision), economic benefits associated with mangroves, and willingness to participate in or support conservation actions.

Data analysis. The collected vegetation data were processed and analyzed using Microsoft Excel 2021 to determine the quantitative ecological indices and carbon stock estimations. The analysis was divided into three main components: 1) Community Structure Analysis: Vegetation parameters, including Species Density (Di), Relative Density (RDi), Species Frequency (Fi), Relative Frequency (RFi), Species Dominance (Doi), and Relative Dominance ($RDoi$), were calculated to obtain the IVI. The diversity level was assessed using the Shannon-Wiener Diversity Index (H'). 2) Carbon Stock Estimation: AGB was calculated for each tree using species-specific allometric equations that incorporate tree diameter (DBH) and wood density (ρ). Total biomass was then converted to carbon stock (C) using the standard IPCC conversion factor of 0.47. 3) Socio-Economic Data: Data obtained from the 51 respondents were analyzed using a descriptive-quantitative approach. Frequency distribution and percentage analysis were applied to evaluate community perceptions, environmental awareness, and economic dependencies on the mangrove ecosystem.

Results

Mangrove community structure. Three true mangrove species were identified across the three transects in Kapitu, Amurang Bay: *Avicennia marina* (Forssk.) Vierh., *Rhizophora apiculata* Blume, and *Sonneratia alba* J. Smith. The composition and vegetation structure showed significant spatial variation between transects, as shown in Table 1.

Table 1

Vegetation community structure of mangroves in Kapitu, Amurang Bay

Station / Species	*Density (ind ha^{-1})*	*Relative density (%)*	*Frequency*	*Relative frequency (%)*	*Dominance (m^2 ha^{-1})*	*Relative dominance (%)*	*IVI*
Transect 1							
Sonneratia alba J. Smith	360	31.58	0.8	32.44	14.12	77.56	142.47
Avicennia marina (Forssk.) Vierh.	360	31.58	0.6	24.33	4.68	25.74	81.65
Rhizophora apiculata Blume	420	36.84	0.6	24.33	2.67	14.71	75.88
Transect 2							
Avicennia marina (Forssk.) Vierh.	1	76.92	0.8	66.67	5.82	62.62	206.21
Sonneratia alba J. Smith	300	23.08	0.4	33.33	3.47	37.38	93.79
Transect 3							
Sonneratia alba J. Smith	500	55.56	0.6	60.00	1.22	49.51	165.07
Avicennia marina (Forssk.) Vierh.	200	22.22	0.2	20.00	0.85	34.55	76.77
Rhizophora apiculata Blume	200	22.22	0.2	20.00	0.39	15.94	58.16

Transect 1: Mixed forest with Sonneratia alba biomass dominance. Represented a zone with high structural complexity and the presence of large trees. A total of 57 individuals were found in a 500 m^2 area. *R. apiculata* had the highest abundance (36.84%), followed by *A. marina* (31.58%) and *S. alba* (31.58%). The total stand density was 1,140 trees ha^{-1}. All stand densities are expressed per hectare (trees ha^{-1}), calculated by scaling the number of individuals recorded in the 500 m^2 sampled area of each transect to a 1 ha basis. Although *R. apiculata* was numerically abundant, *S. alba* was ecologically dominant with an IVI of 142.47. This high IVI was driven by its Relative Dominance of 77.56%, attributed to the presence of large *S. alba* trees with CBH reaching 288 cm and 320 cm. These "giant" trees contributed the most to the stand's Basal Area. *A. marina* (IVI = 81.65) and *R. apiculata* (IVI = 75.88) acted as co-dominants. The diversity index (H') was recorded at 3.30, indicating a high level of diversity and evenness.

Transect 2: Avicennia marina dominance zone. Exhibited characteristics of a pioneer zone or area with high sedimentation. Only two species were found: *A. marina* (10 individuals) and *S. alba* (3 individuals). The total density was 1,300 trees ha^{-1}, with *A. marina* dominating (1,000 ind ha^{-1}). The IVI analysis showed *A. marina* dominance (IVI = 206.21), controlling more than two-thirds of the community's importance value, while *S. alba* (IVI = 93.79) acted as an associate species. The diversity index (H') was 1.73 (moderate category).

Transect 3: Regeneration and recovery zone. It had unique characteristics with lower tree density but high regeneration potential. Composition consisted of *S. alba* (5 ind), *A. marina* (2 ind), and *R. apiculata* (2 ind). The total tree density was 900 trees ha^{-1}, the lowest among the three transects. *S. alba* dominated with an IVI of 165.07. The most significant finding in Transect 3 was the abundance of seedlings; 63 individuals of *R. apiculata* seedlings were recorded in the regeneration plot, compared with only 2 adult *R. apiculata* trees. This indicates a strong dominance of the regeneration stage relative to the current adult tree layer.

Biomass and carbon stock estimation. Biomass analysis revealed drastic differences between transects correlated with stand age structure and tree size (Table 2).

Table 2
Biomass and carbon stock estimation of the mangrove forest in Kapitu, Amurang Bay

Species	*Transect 1 (Mg C ha^{-1})*	*Transect 2 (Mg C ha^{-1})*	*Transect 3 (Mg C ha^{-1})*
Avicennia marina	1.94	3.47	0.016
Rhizophora apiculata	0.43	-	0.001
Sonneratia alba	20.52	1.11	0.136
Total carbon stock	22.89	4.58	0.153
Biomass (AGB) (Ton ha^{-1})	48.70	9.72	0.333

Note: Carbon stock and AGB were calculated only for trees with DBH ≥ 5 cm; seedlings and saplings (DBH < 5 cm) were excluded from these calculations.

Transect 1 (22.89 Mg C ha^{-1}) held the highest carbon reserves. Notably, 89.6% of the total carbon in this transect was contributed by *Sonneratia alba* (20.52 Mg C ha^{-1}), underscoring the crucial role of old *Sonneratia* trees as the primary "carbon warehouse" in Kapitu. Transect 2 (4.58 Mg C ha^{-1}) had significantly lower reserves, dominated by *Avicennia marina*, indicating younger stands or smaller average tree sizes. Transect 3 had the lowest tree biomass carbon stock, at only 0.153 Mg C ha^{-1}, corresponding to an AGB of 0.333 ton ha^{-1}. This reflects the very early successional status of this restoration area, where only a few small trees currently contribute to biomass. Although 63 *Rhizophora apiculata* seedlings were recorded in the regeneration plots, these individuals are not included in the biomass and carbon calculations because their DBH is < 5 cm; instead, they indicate a strong potential for future carbon accumulation as the stand matures.

Socio-economic profile and community perception. The survey of 51 respondents provided an overview of the human–mangrove relationship in Kapitu (Table 3). Respondents were dominated by the productive age group (31–40 years; 50%), and livelihoods were diverse, with only 13.7% identifying as full-time fishermen, indicating that direct economic dependence on mangrove resource extraction is relatively limited. Environmental awareness was very high: 100% of respondents stated that mangroves protect their homes and boats from wave damage, and 83.3% strongly agreed that mangroves are important for preventing coastal abrasion. Participation in organized conservation initiatives was also notable, with 33.3% involved in Tourism Awareness Groups (Pokdarwis) and 16.7% active in mangrove nursery groups. Informal social control appeared strong, as 83.3% of respondents expressed willingness to reprimand individuals cutting mangrove trees indiscriminately. In terms of economic benefits, none of the respondents reported additional income from catching fish, shellfish, or crabs within the mangrove itself, whereas 83.3% reported small additional income (less than USD 32) derived from conservation-related activities such as planting and nursery work facilitated by external programs.

Table 3

Summary of socio-economic characteristics and perceptions of respondents in Kapitu Village (n = 51)

Variable	*Category / indicator*	*Percentage (%)*
Age structure	31–40 years (productive age group)	50.0
Main occupation	Full-time fishermen	13.7
Perception of protection	Mangroves protect homes and boats from wave damage (agree)	100
Perception of abrasion control	"Strongly agree" that mangroves are important to prevent abrasion	83.3
Conservation participation	Member of Tourism Awareness Group (Pokdarwis)	33.3
Conservation participation	Active in mangrove nursery group	16.7
Informal social control	Willing to reprimand illegal mangrove cutters	83.3
Income from extractive use	Additional income from fishing/shellfish/crabs in mangroves	0
Income from conservation work	Additional income (< USD 32 month^{-1}) from conservation activities	83.3

Discussion. The mangrove community structure in Kapitu reflects a natural zonation pattern interrupted by recovery activities. The dominance of Sonneratia alba and Avicennia marina in Transects 1 and 2 is consistent with the ecological characteristics of pioneer species in the Indo-Pacific region capable of colonizing sandy-mud substrates at the seaward edge (Giri et al 2011; Djamaluddin 2018). The presence of Sonneratia alba trees with gigantic sizes (CBH > 200-300 cm) in Transect 1 is a significant ecological finding. These trees are likely remnants of a forest that survived past degradation. Ecologically, these parent trees function as natural seed banks and physical protectors, facilitating sediment deposition, allowing other species like Rhizophora apiculata to grow under their canopy, as seen in the seedling composition of Transect 1. On the other hand, Transect 3, with the dominance of Rhizophora apiculata seedlings (63 individuals) represents the early success of active restoration efforts. Rhizophora apiculata is the most common species used in rehabilitation programs in Indonesia due to abundant propagule availability and ease of planting (Kusmana 2013). The high seedling density suggests that planting and early establishment have been successful, but that continued protection and post-planting care will be crucial to translate this regeneration into substantial biomass and carbon gains over time.

The total carbon stock in Kapitu (maximum 22.89 Mg C ha^{-1} in Transect 1) is low compared with values reported for primary mangrove forests in Indonesia, which often exceed 100 Mg C ha^{-1}, and may reach around 300 Mg C ha^{-1} for AGB in locations such as Kalimantan or Papua (Donato et al 2011; Murdiyarso et al 2015). A nearby study in Bunaken National Park, for example, recorded carbon stocks of about 103.6 Mg C ha^{-1} (Murdiyarso et al 2015). The relatively low values in Kapitu can be explained by stand age and successional stage: most mangrove areas are secondary forests or the result of rehabilitation efforts initiated in 2015–2018, so many trees are still young and have not yet accumulated substantial wood biomass. This is especially evident in Transect 3, where tree carbon stock is only 0.153 Mg C ha^{-1}, and AGB is 0.333 ton ha^{-1}, while seedling density is high. In this context, the role of *Sonneratia* is critical; conserving a few large *S. alba* trees in Transect 1 has a carbon impact equivalent to planting hundreds of new seedlings. In our data, *S. alba* contributed nearly 90% of the total carbon in Transect 1, indicating that strict protection of remaining old-growth individuals must be a priority alongside new planting.

The pattern observed in Transect 3 illustrates both the opportunities and limitations of early-stage restoration. Tree biomass and carbon stock are currently very low (0.153 Mg C ha^{-1} and 0.333 ton ha^{-1} AGB), reflecting the small size and limited number of adult trees. At the same time, the high density of *R. apiculata* seedlings (63 individuals recorded in the regeneration plots) indicates that planting and natural establishment have been successful in initiating a new cohort. This combination suggests that restoration efforts in Kapitu have effectively reintroduced mangrove propagules and promoted seedling establishment, but that appreciable carbon gains will only occur over longer time scales as these cohorts grow and survive. Similar time lags between planting and substantial biomass accumulation have been reported for other restored mangrove sites, where AGB stocks in the first decade typically remain well below those of mature reference forests (Nam et al 2016).

Conversely, the dominance of a few large *S. alba* trees in Transect 1 highlights the disproportionate contribution of mature individuals to stand-level blue carbon storage. Although *R. apiculata* is numerically abundant in this transect, nearly 90% of the total AGB is stored in *S. alba*, demonstrating that conserving remnant old-growth trees can yield much higher immediate carbon benefits than planting many small seedlings. This finding supports a dual strategy for blue carbon management in recovering landscapes such as Kapitu: (1) strict protection of existing large trees and remnant mature stands as "carbon reservoirs" and seed sources, and (2) targeted restoration in degraded areas to build future carbon stocks and ecosystem functions. Focusing solely on reforestation without safeguarding remaining mature trees could result in net carbon losses if old-growth individuals are removed faster than restored stands can accumulate biomass.

Socio-economic findings highlight the success of the conservation model applied by Manengkel Solidaritas. The high willingness of the community to reprimand illegal loggers (83.3%) is a strong indicator of the formation of informal social control. In common-pool resource management theory, monitoring by local users is often more effective and cheaper than government patrol (Ostrom 1990). Interestingly, conservation motivation in Kapitu seems driven by risk perception (fear of abrasion) and program incentives (project wages), rather than extractive economic benefits. This model has strengths (low pressure on wood extraction) but also weaknesses (dependence on external funding/projects). Therefore, livelihood diversification strategies towards more independent models, such as ecotourism development initiated by Pokdarwis, are crucial for the resilience of this conservation model (Kontu et al 2025).

Conclusions*.* The mangrove ecosystem in Kapitu Village, Amurang Bay, is an actively recovering system with marked spatial heterogeneity in structure and function. Transect 1 represents a remnant, structurally complex stand dominated by large *Sonneratia alba* trees, Transect 2 represents a pioneer zone dominated by *Avicennia marina* on recently accreted sediments, and Transect 3 represents a restoration/regeneration zone characterized by low adult tree density but high *Rhizophora apiculata* seedling abundance.

AGB stocks in Kapitu are currently low compared with primary mangrove forests elsewhere in Indonesia, with a maximum of 22.89 Mg C ha^{-1} in Transect 1 and only 0.153 Mg C ha^{-1} in the restored Transect 3. This pattern reflects the dominance of secondary and restored stands at early successional stages, where only a few large **S. Alba** trees in Transect 1 act as major carbon reservoirs, while most planted and naturally regenerating trees have not yet accumulated substantial biomass.

From a social perspective, the Kapitu community shows high awareness of the protective functions of mangroves, strong informal social control against illegal cutting, and active participation in conservation groups. However, direct income from extractive use of mangrove resources is low, and most additional income is currently linked to project-based conservation activities, indicating both an opportunity for and a need to develop more sustainable livelihood options tied to long-term mangrove stewardship.

Management recommendations. Based on the ecological and socio-economic findings of this study, several strategic recommendations are proposed to enhance the sustainability of the mangrove ecosystem in Kapitu Village:

1. Zonasi and Protection of High-Carbon Stocks: Given the significant carbon sequestration potential identified at Station 1, the local government of South

Minahasa should establish this area as a "Priority Conservation Zone." Strict regulations against land conversion and mangrove cutting must be enforced to maintain the existing blue carbon reservoir.

2. Community-Based Restoration: For areas with lower density and biomass (e.g., Station 3), restoration efforts should prioritize the planting of Sonneratia alba and Avicennia marina, which showed high adaptation in the local environment. These programs should involve the Kapitu community through "Cash for Work" or local conservation groups to foster a sense of ownership.
3. Eco-Tourism Development: The high community awareness and positive perception towards mangroves identified in this study suggest a potential for sustainable ecotourism. Developing educational boardwalks or bird-watching tracks could provide an alternative livelihood for residents while minimizing anthropogenic pressure on the forest.
4. Integration into Local Policy: It is recommended that the findings of this study be integrated into the Village Development Plan (Rencana Pembangunan Desa) and the Regional Coastal Management Plan (RZWP3K) of North Sulawesi. This ensures that the ecological value of blue carbon is recognized as a regional asset in climate change mitigation strategies.

Conflict of interest. The authors declare that there is no conflict of interest.

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