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Mangrove community structure, aboveground biomass, and carbon sequestration in the unprotected coastal areas of Sta. Cruz, Davao del Sur, Philippines

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Abstract. *Sante GLC, Ubat DE, Pendon MM, Pucot JR. 2026. Mangrove community structure, aboveground biomass, and carbon sequestration in the unprotected coastal areas of Sta. Cruz, Davao del Sur, Philippines. Biodiversitas 27 (5): d270507. https://doi.org/10.13057/biodiv/d270507.* Mangrove ecosystems are vital for carbon sequestration and climate change mitigation, yet their ecological functions within fragmented, unprotected margins remain understudied. This study provides the first integrated evaluation of mangrove community structure, aboveground biomass (AGB), and carbon stocks in the unprotected coastal zones of Sta. Cruz, Davao del Sur, Philippines. A total of 36 plots (10×10 m) were established across four barangays for vegetation assessment. Five mangrove species from three families were recorded, indicating substantially lower species richness compared to nearby protected areas. The community was numerically dominated by *Avicennia marina* (67.80% relative abundance), while *Sonneratia alba*, despite its low abundance, contributed the highest aboveground biomass (217.15 Mg/ha) and carbon stock (104.23 MgC/ha). Total estimated stand aboveground biomass and carbon stock were 519.33±75.57 Mg/ha and 249.27±36.28 MgC/ha, respectively. Diversity was highest in Brgy. Tuban (H′: 1.04, J′: 0.94), reflecting a relatively balanced species distribution despite low overall richness. Crucially, while the area retains significant blue carbon capacity driven by mature legacy trees, it suffers from structural imbalance and depleted biodiversity. This underscores the urgent need for strategic conservation interventions, including mixed-species restoration and the strict protection of mature stands, and their integration into local coastal management frameworks to enhance both biodiversity and climate mitigation functions.

Keywords: *Avicennia marina*, carbon sequestration, coastal conservation, *Sonneratia alba*, Philippines

INTRODUCTION

Mangroves thrive in intertidal zones, where they are repeatedly exposed to fluctuating salinity, waterlogging, unstable substrates, tidal inundation, and other extreme environmental conditions. Their ability to persist in such stressful habitats is largely attributed to unique morphological and physiological adaptations that distinguish them from most terrestrial plant communities (Sharma 2018). Mangroves are particularly recognized for their diverse root systems and specialized structures, including aerial roots, prop roots, and pneumatophores, which contrast strongly with the rooting patterns of typical terrestrial vegetation (Takarina 2020). These adaptations enhance anchorage, gas exchange, and survival in oxygen-poor soils, enabling different mangrove species to tolerate a broad range of substrate and tidal conditions. Some species are more resilient in sandy soils and high tidal zones (Abrogueña et al. 2022), whereas others are better adapted to muddy, soft, and frequently inundated substrates (Yoslianto et al. 2023). This ecological flexibility allows mangroves to form distinct zonation patterns and maintain productivity in coastal environments that are otherwise unsuitable for many plant species.

Mangrove ecosystems are globally distributed across tropical and subtropical coastlines, with Southeast Asia hosting the largest and most diverse mangrove stands (Gerona-Daga and Salmo 2022). These coastal forests have exhibited remarkable resilience, allowing certain pioneer species to colonize, thrive, and multiply in otherwise hostile intertidal environments (Alongi 2015; Etongo et al. 2022). Despite this inherent adaptability, global mangrove extents are increasingly threatened by both natural and anthropogenic pressures (Ahmed et al. 2022; Singh et al. 2024; Candraningtyas et al. 2025). Their baseline ecosystem resilience is currently being severely degraded by the compounding effects of a drier climate, increased inundation, sedimentation, rapid sea-level rise, and escalating human influences (Ellison 2021). In the Philippines, these human-induced threats are further intensified by limited public awareness of the ecological importance of mangroves. Although some coastal communities recognize their value for shoreline protection, fisheries support, and livelihood security, comprehensive conservation education remains inadequate in many regions, thereby contributing to continued habitat degradation and loss (Alimbon and Manseguiao 2021).

Amidst escalating climate change impacts, recent research has increasingly emphasized the critical role of mangroves in capturing atmospheric carbon dioxide (CO_2) and storing carbon in woody biomass and sediments (Yu et al. 2021; Quitain 2022). Several studies have also highlighted the vast carbon sequestration potential of Philippine coastal ecosystems, underscoring their importance for climate change mitigation and nature-based conservation strategies (Romañach et al. 2018; Decena et al. 2023). While ecological assessments are gradually expanding across Mindanao and the broader Davao region (Pototan et al. 2017; Agduma and Cao 2023; Pacyao and Llameg 2024), granular data on mangrove carbon dynamics remain highly limited. In Davao del Sur, particularly within the Municipality of Sta. Cruz, previous investigations have been restricted almost exclusively to taxonomic diversity and species occurrence (Jumawan et al. 2015; Cardillo and Novero 2018; Baylon et al. 2025). Consequently, baseline documentation of mangrove community structure, aboveground biomass, and carbon stocks has remained largely unquantified, especially within highly vulnerable and unprotected coastal margins where degradation pressures are often more pronounced.

Despite local ordinances aimed at protecting marine sanctuaries, Sta. Cruz continues to face anthropogenic pressures, including pollution, habitat degradation, resource extraction, and overexploitation (Baylon et al. 2025). These issues persist largely because conservation frameworks lack empirical data regarding the localized ecological value of these forests, particularly their biomass and carbon storage functions. To address this critical knowledge gap, this study assesses the community structure, aboveground biomass, and carbon stocks of highly vulnerable, unprotected mangrove patches in Sta. Cruz, Davao del Sur. It is hypothesized that mangrove stands outside protected areas exhibit lower species richness and higher single-species dominance, resulting in structurally imbalanced communities where carbon storage is disproportionately driven by a limited number of large individuals. Consequently, we investigate how species composition and stand structure influence biomass and carbon distribution across these degraded zones. As the first study to establish these baseline parameters in the municipality, our findings provide a crucial quantitative foundation for ecological restoration and the drafting of conservation policies tailored to the unique environmental conditions of Sta. Cruz, Davao del Sur, Philippines.

MATERIALS AND METHODS

Study area

This study was conducted in the coastal areas of Sta. Cruz, Davao del Sur, Philippines (6˚50' North and 125˚25' East). The study's sampling sites include: Barangay (Brgy.) Bato, Brgy. Tuban, Brgy. Zone II, and Brgy. Astorga (Figure 1). The study area focused specifically on the unprotected mangrove patches outside the formal boundaries of the protected areas.

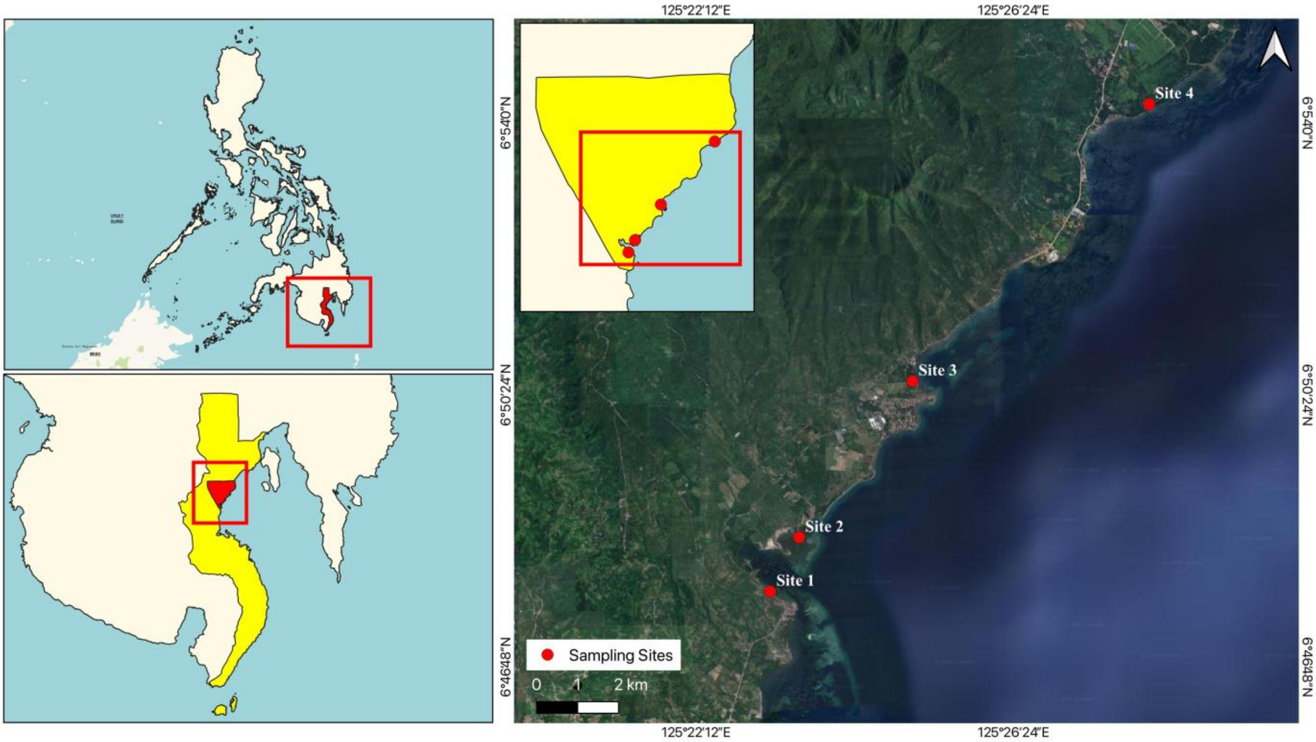

Figure 1. Map of Sta. Cruz, Davao del Sur, Philippines, showing the four (4) mangrove sampling sites of this study. Site 1: Brgy. Bato, Site 2: Brgy. Tuban, Site 3: Brgy. Zone II, Site 4: Brgy. Astorga

Data collection

A preliminary visit was conducted twice to ensure that the chosen sites were adequate for providing a comprehensive understanding of the mangrove community structure, aboveground biomass, and carbon stock. Fieldwork was conducted in September-December 2024, following the methodology of Alimbon and Manseguiao (2021). We first delineated our study zones by identifying the formal boundaries of the protected areas, guided by local officials, to ensure all sampling occurred strictly within unprotected areas. We then randomly selected three 100-meter transects that were placed perpendicular to the shore, spaced 50 meters apart. Along each transect, three 10×10-meter plots were established, spaced 30 meters apart. In total, 36 plots were surveyed. Fiberglass tape, bamboo stakes, and polyethylene nylon rope were used to demarcate the plots (Figure 2).

The Diameter at Breast Height (DBH) was measured at 1.3 meters above the ground, with adjustments for forking trees following the method described by Howard et al. (2014). Mangrove saplings, seedlings, and trees with a DBH less than 4 cm were only recorded for species identification and abundance and were excluded from carbon stock estimation. This threshold is a standard convention in similar studies, ensuring a consistent baseline for data comparison across various sites and ecosystems. Further, the aboveground biomass of individual trees was estimated using an allometric equation developed by Komiyama et al. (2005). As suggested by Kauffman and Donato (2012), a conversion factor of 0.48 was applied to determine the carbon content of the aboveground biomass.

This research focused only on aboveground biomass and did not include soil and belowground carbon pools. Also, environmental covariates such as salinity and sediment type were not measured. Further, the geographic scope was limited to four barangays, offering only a partial view of mangrove conditions within the municipality.

Identification of species

A preliminary identification of mangrove species was conducted on-site using the Field Guide to the Philippines Mangroves by Primavera (2009), a widely used reference in mangrove research. Photographic documentation and specimens were collected to support accurate species identification. Voice recordings and field notes were also gathered to capture verbal observations and ensure no data were lost during fieldwork. Key morphological traits of leaves, flowers, and propagules were carefully recorded to aid in species confirmation. The identification was then confirmed and certified by a botanist from the University of Southern Mindanao (USM), Philippines.

Data analysis

Various diversity indices were used to assess the diversity, composition, and abundance of mangrove communities across sampling sites. The key indices included Proportion of Species, Species Richness, Shannon-Weiner Index of Diversity, Pielou's Evenness Index, Simpson's Dominance Index, Species Density, and Relative Abundance. Community structure, aboveground biomass, and other statistical analyses were also calculated.

Proportion of species (p)

$$p = (n/N) \times 100$$

Where, p: Proportion of species (%), n: Number of individuals of a specific species, N: Signifies the total number of individuals across all species.

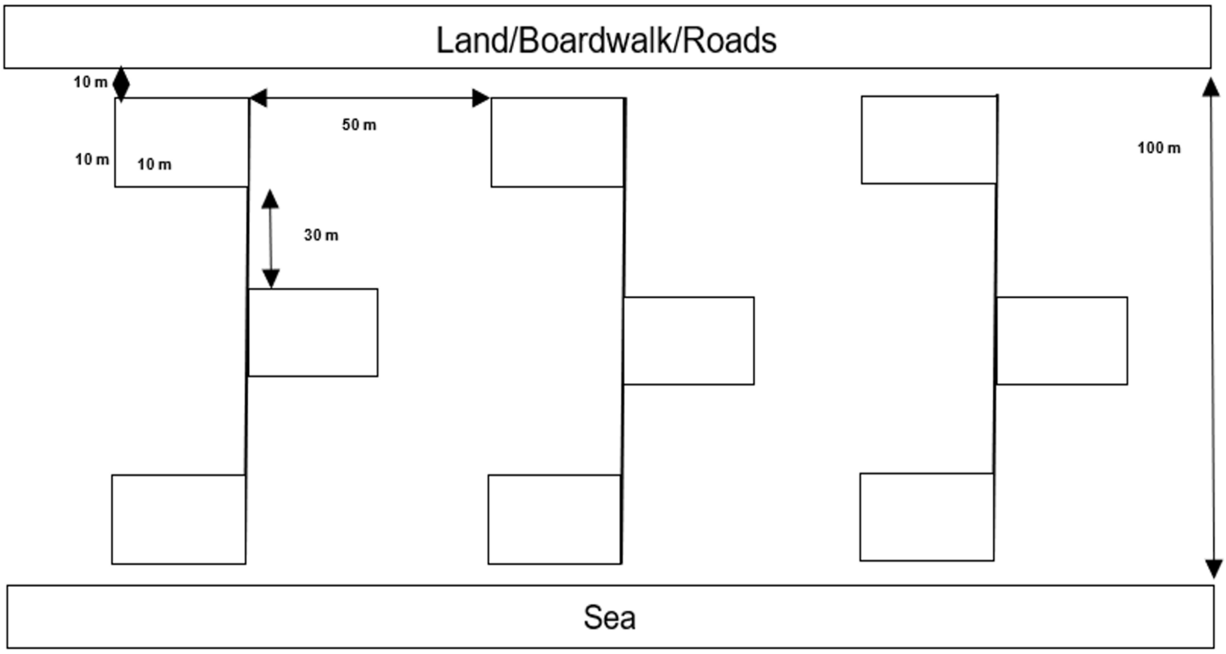

Figure 2. The field survey design using the transect line plots method of Alimbon and Manseguiao (2021)

Species richness (S)

S: Number of distinct species found in the study area

Shannon-Weiner Index of diversity (H')

$$H = -\Sigma pi * \ln(pi)$$

Where, Σ: A Greek symbol that means "sum,", ln: Natural log, pi: Proportion of the entire community made up of species *i.*

Pielou's Evenness Index (J')

$$J' = H'/\ln(S)$$

Where, H': Shannon Weiner diversity, ln: Natural log, S: Total number of species in a sample.

The diversity and evenness indices were calculated separately for each sampling site to compare patterns across sites and interpreted according to the biodiversity and evenness scale (Table 1) (Gevaña and Pampolina 2009).

Simpson's Dominance Index (D)

$$D = \Sigma ni(ni-1) / N(N-1)$$

Where, Σni: The sum of the number of organisms that belong to species i, N: The total number of organisms. As D approaches 1, it signifies lower diversity due to the overwhelming dominance of a single species.

Species density (SD)

$$SD = N/At,$$

Where, SD: Species Density (individuals per hectare), N: Total number of individuals of a species, At: Indicates the total sampled area (hectares).

Community structure

Community structure was determined by applying the formulae provided by English et al. (1997), and these are as follows:

$$\text{Basal area per tree } (\text{cm}^2) = \frac{\pi \text{DBH}^2}{4}$$

$$\text{Stand basal area } (\text{m}^2\ \text{ha}^{-1}) = \frac{\text{sum of basal areas}}{\text{area of the plot}}$$

$$\text{Stands Density } (\text{stems ha}^{-1}) = \frac{\text{no.of living stems in a plot x 10,000}}{\text{area of the plot}}$$

$$\text{Relative density } = \frac{\text{no.of individuals of a species}}{\text{total no.of individuals of all species}}\ x\ 100$$

$$\text{Relative dominance } = \frac{\text{total basal area of a species}}{\text{basal area of all species}}\ x\ 100$$

$$\text{Relative frequency} = \frac{\text{frequency of species}}{\text{total frequency of all species in different plots}}\ x\ 100$$

$$\text{Relative abundance } = \frac{\text{total number of individuals per species}}{\text{total number of individuals}}\ x\ 100$$

Importance Value (IV) = Relative density + relative frequency + relative dominance

The aboveground biomass of mangroves was quantified using an allometric equation derived by Komiyama et al. (2005):

$$AGB = 0.251 \times p \times D^{2.46}$$

Where, AGB: Aboveground biomass (kg), p: Wood density (g/cm³), D: Diameter at breast height (cm).

Species-specific wood density (p) values utilized for the aboveground biomass calculations were sourced from Malabrigo et al. (2017) (Table 2).

Total and mean aboveground biomass

Plot-level biomass was calculated by summing the AGB of all individual trees within a plot. To determine the mean aboveground biomass in standard units of Megagrams per hectare (Mg/ha), the total kg per plot was divided by 1,000 to convert to Mg and then divided by the plot area (in hectares) to scale it to a per-hectare basis. These standardized plot values were then categorized by species and averaged across the sampled area to report mean species-specific and total site biomass using descriptive statistics.

Carbon stock estimation

The conversion factor of 0.48 from Kauffman and Donato (2012) was utilized to estimate the carbon storage in mangrove ecosystems:

$$\text{Carbon Stock} = AGB \times 0.48$$

Where, AGB is the standardized aboveground biomass of the stand (Mg/ha), and 0.48 is the carbon fraction of the biomass. Mean carbon stock (Mg C/ha) was subsequently calculated using the same plot-level scaling and averaging framework applied to the biomass data.

Table 1. Biodiversity and evenness scale

Relative interpretation	Shannon-Wiener (H')	Evenness Index (J')
Very high	>3.5	0.75-1.00
High	3.00-3.49	0.50-0.74
Moderate	2.50-2.99	0.25-0.49
Low	2.00-2.49	0.15-0.24
Very low	<1.99	0.05-0.14

Table 2. Wood density values for each identified mangrove species in the unprotected areas of Sta. Cruz, Davao del Sur, Philippines

Mangrove species	Wood density (p)
Avicennia marina	0.650
Avicennia officinalis	0.720
Rhizophora apiculata	0.850
Rhizophora mucronata	0.820
Sonneratia alba	0.510

Permits and ethical considerations

Prior to conducting the study, permission was obtained from the relevant local government units and communities, i.e., the captains of the four barangays, and coordination with the local communities was established. A permit from the Mayor of the municipality of Sta. Cruz was also obtained. Further, the Wildlife Gratuitous Permit (WGP No. XI-2024-68) was also secured from the Department of Environment and Natural Resources (DENR) Region XI.

RESULTS AND DISCUSSION

Species composition

A total of 3,444 mangrove individuals were recorded across 36 sampling plots in the four study sites. Five true mangrove species belonging to three families were identified: *Avicennia marina* and *Avicennia officinalis* (Acanthaceae); *Rhizophora apiculata* and *Rhizophora mucronata* (Rhizophoraceae); and *Sonneratia alba* (Lythraceae) (Figure 3). Although these species are currently classified as "Least Concern" on the IUCN Red List (IUCN 2021) and are absent from the national list of threatened Philippine plants (DAO 2007-01 and 2017-11), global populations of these species are reportedly experiencing steady declines due to compounding environmental stressors (Singh et al. 2024)

The species assemblage observed here largely aligns with the mangrove diversity assessment by Cardillo and Novero (2018) in Sta. Cruz, who similarly recorded *A. marina*, *R. apiculata*, *R. mucronata*, and *S. alba* within the Marine Protected Areas (MPAs) of Brgy. Bato, Tagabuli, and Tuban, as well as in Miranda, Brgy. Zone III. Notably, *A. officinalis* was documented exclusively in Brgy. Astorga, a site not included in the earlier survey, which likely explains its absence from the previous species list (Table 3).

Overall, this study recorded a lower species richness compared to the findings of Baylon et al. (2025), despite sharing three of the same sampling sites (Brgy. Bato, Tuban, and Astorga). This disparity is primarily driven by the deliberate exclusion of MPAs in the current study. Because MPAs intrinsically support higher species richness due to targeted conservation efforts and the active mitigation of anthropogenic disturbances, strictly sampling outside of these boundaries provides a critical, realistic baseline of the biodiversity and ecological conditions prevailing in these highly vulnerable, unmanaged mangrove patches.

Figure 3. Mangrove species found in the unprotected coastal areas of Sta. Cruz, Davao del Sur, Philippines. A. *Avicennia marina*, B. *Avicennia officinalis*, C. *Rhizophora apiculata*, D. *Rhizophora mucronata*, E. *Sonneratia alba*

Table 3. Comparison of mangrove species occurrence in Sta. Cruz, Davao del Sur, Philippines, across three surveys (2018-2026). (Cardillo and Novero 2018; Baylon et al. 2025) and the present survey (this study)

Mangrove species	Sta. Cruz mangrove studies		
	Cardillo and Novero (2018)	Baylon et al. (2025)	This study (2026)
Acanthus ebracteatus Vahl.	✓	X	X
Aegiceras floridum Roem. and Schult.	X	✓	X
Aegiceras corniculatum (L.) Blanco	✓	X	X
Avicennia alba Blume	X	✓	X
Avicennia marina (Forssk.) Vierh.	✓	✓	✓
Avicennia officinalis L.	X	✓	✓
Avicennia rumphiana Hallier f.	✓	✓	X
Barringtonia asiatica (L.) Kurz	✓	X	X
Bruguiera cylindrica (L.) Blume	X	✓	X
Bruguiera gymnorrhiza (L.) Lam.	X	✓	X
Bruguiera parviflora (Roxb.) Wight & Arn. ex Griff.	X	✓	X
Ceriops tagal (Perr.) C.B.Rob.	✓	✓	X
Dolichandrone spathacea (L.f.) Baill. ex K.Schum.	✓	X	X
Excoecaria agallocha L.	X	✓	X
Heritiera littoralis Dryand. ex Aiton	X	✓	X
Hibiscus tiliaceus L.	✓	X	X
Lumnitzera racemosa Willd.	✓	✓	X
Nypa fruticans Wurmb	✓	✓	X
Rhizophora apiculata Blume	✓	✓	✓
Rhizophora mucronata Poir.	✓	✓	✓
Rhizophora stylosa Griff.	✓	✓	X
Sonneratia alba Sm.	✓	✓	✓
Sonneratia caseolaris (L.) Engl.	✓	✓	X
Xylocarpus granatum J.König.	✓	✓	X
Xylocarpus moluccensis (Lam.) M.Roem.	✓	✓	X

Remarks: ✓: Present, X: Absent

Mangrove geographic distribution

Species distribution and population sizes varied considerably across the sampling sites, likely driven by specific micro-habitat preferences. For instance, species such as *A. marina* are known to proliferate in sandy substrates and high-intertidal zones (Abrogueña et al. 2022), which is consistent with the results of this study. Consequently*, A. marina* heavily dominated the surveyed stands, accounting for 67.80% of the total population with 2,335 individuals documented in Brgy. Zone II and Brgy. Astorga.

Rhizophora apiculata formed the second most abundant population (15.13%), comprising 521 individuals widely distributed across all sampling sites. *S. alba* ranked third (6.91%), with 238 individuals recorded in Brgy. Zone II, Bato, and Tuban. Closely following was *R. mucronata* (6.68%; 230 individuals), which exhibited a notably lower proportion compared to *R. apiculata* despite both species being distributed throughout the study area. Finally, *A. officinalis* recorded the lowest population size, with only 120 individuals (3.48%), and was observed exclusively in Brgy. Astorga (Table 4).

The observed prevalence of Rhizophoraceae across all sampling sites in this study is consistent with that reported by Baylon et al. (2025). Together, these studies suggest that the high proportion of *Rhizophora* saplings is likely the result of replanting efforts rather than natural regeneration. However, because the substrate types in some of these specific areas do not inherently promote their growth (Pacyao and Llameg 2024), this artificial dominance raises critical concerns about potential disruptions to the species' natural ecological functions and interactions (Van Bijsterveldt et al. 2022), as well as the long-term viability of these Rhizophora stands.

Additionally, although *S. alba* was limited in number (6.91%), it was represented primarily by large, mature individuals (mean DBH of 34.44 cm; Table 7) thriving in the muddy substrates of Brgy. Bato and Tuban are habitats to which the species is well adapted. Conversely, *A. officinalis* exhibited the lowest population proportion (3.48%). Data also suggest that this species is limited to Brgy. Astorga, which indicates that certain environmental conditions in other barangays may fall outside the species' optimal tolerance range. Interestingly, the findings of Alam et al. (2020) in the Sundarbans of Bangladesh indicate that *A. officinalis* is present across varying salinity zones and displays significant genetic diversity. The species has developed multiple ecotypes in that region, enhancing its adaptability. The restricted occurrence in Brgy. Astorga may reflect a localized population with reduced genetic variation or exposure to unique stressors. This highlights the importance of assessing both local environmental factors and genetic diversity in shaping effective conservation and management strategies.

Furthermore, the documentation of only five true mangrove species across four distinct sampling sites represents a markedly low observed species richness when compared to adjacent protected or rehabilitated areas. For context, recent surveys within municipal protected zones recorded 20 species (Baylon et al. 2025), while regional mangrove reserves in Carmen, Tagum, Panabo, and Davao City host varying richness, ranging from 11 to 34 species (Pototan et al. 2017; Seniel et al. 2024). Baseline biodiversity data for coastal margins outside of these designated protected networks remain conspicuously scarce. This sharp disparity highlights a critical bias in regional monitoring efforts and underscores the necessity of expanding comprehensive mangrove assessments into unprotected, potentially degraded zones to accurately capture regional biodiversity baselines and inform more inclusive conservation strategies.

Diversity analysis

Evenness was highly variable across sites in Sta. Cruz, Davao del Sur (J': 0.42 to 0.94) (Table 5). Among the four barangays surveyed, Brgy. Tuban exhibited the highest diversity index (H′: 1.04, J': 0.94, D: 0.37), a pattern consistent with the findings of Baylon et al. (2025). Interestingly, this high diversity was recorded despite Brgy. Tuban has a lower species richness (S: 3) than Brgy. Zone II and Brgy. Astorga (S: 4). This is driven entirely by species evenness and dominance. Brgy. Zone II exhibited the lowest evenness (J': 0.42) and highest dominance (D: 0.69) because the ecosystem is heavily skewed by the overwhelming proliferation of a single pioneer species, *A. marina*. However, a critical contextual distinction must be acknowledged: the current study was conducted outside of the protected area of the municipality. Further, Brgy. Zone II, a sampling site in the present study, was not included in Baylon et al. (2025), while Brgy. Tagabuli, a site assessed in Baylon et al.'s work, is not included in the current dataset. This variation in sampling locations limits the direct comparability of the two studies and underscores the importance of site-specific ecological contexts.

Importantly, while diversity indices offer insight into species distribution and evenness, they do not fully capture the ecosystem's overall resilience or ecological stability. Parameters such as genetic diversity, adaptive capacity of species, and functional redundancy are not reflected in Shannon (H′), evenness (J'), or dominance (D) metrics alone. As Kiernan (2024) argues, ecological systems, particularly mangroves, are inherently dynamic, and species diversity can fluctuate in response to environmental variables, anthropogenic pressures, and natural disturbances. Therefore, the observed diversity in Brgy. Tuban, while informative, should not be interpreted in isolation as a definitive indicator of ecosystem health or long-term sustainability.

Overall, the low species richness (S: 3-4), coupled with high dominance in heavily disturbed zones, suggests a simplified and highly stressed community structure. This vulnerability is directly exacerbated by the presence of residential waste and the expansion of local aquaculture activities within the unprotected areas, contributing to pollution, contamination, and habitat degradation.

This low diversity finding is consistent with reports from neighboring areas such as Banay-Banay, Davao Oriental (Pototan et al. 2020), Davao City (Seniel et al. 2024), and Brgy. Camudmud MPA in the Island Garden City of Samal, Davao del Norte (Agua and Wong 2023). These similarities indicate that mangrove stands in the study area are ecologically compromised and require targeted interventions, including habitat restoration, enhancement of environmental quality, and measures to prevent overexploitation.

Table 4. Species composition and distribution of mangroves in the unprotected areas of Sta. Cruz, Davao del Sur, Philippines

Mangrove Species	**No. of individuals**				**Total**	**Proportion of species (P_s) (%)**
	Brgy. Bato	**Brgy. Tuban**	**Brgy. Zone II**	**Brgy. Astorga**		
Avicennia marina	0	0	1,063	1,272	2,335	67.80
Avicennia officinalis	0	0	0	120	120	3.48
Rhizophora apiculata	64	123	176	158	521	15.13
Rhizophora mucronata	35	102	3	90	230	6.68
Sonneratia alba	137	49	52	0	238	6.91
Total no. of individuals	236	274	1,294	1,640	3,444	100

Table 5. Diversity indices of mangrove ecosystems in the unprotected coastal areas of Sta. Cruz, Davao del Sur, Philippines

Diversity indices	**Brgy. Bato**	**Brgy. Tuban**	**Brgy. Zone II**	**Brgy. Astorga**
S	3	3	4	4
H'	0.95	1.04	0.58	0.77
J'	0.87	0.94	0.42	0.56
D	0.43	0.37	0.69	0.62

Notes: S: Species richness, H': Shannon-Wiener Index of diversity, J': Pielou's Evenness Index, D: Simpson's Dominance Index

Species abundance

The ecological dominance of mangrove species in the sampling area, as shown in Table 6, revealed that *A. marina* is the most abundant species, with the highest species density (6,486.11 ind/ha) and relative abundance (67.80%). This was followed by *R. apiculata*, which exhibited moderate values of species density (1,447.22 ind/ha) and relative abundance (15.13%), while *S. alba* (661.11 ind/ha, 6.91%) and *R. mucronata* (638.89 ind/ha, 6.68%) had comparatively lower values. In contrast, *A. officinalis* had the lowest recorded species density (333.33 ind/ha) and relative abundance (3.48%). Furthermore, an analysis of the Importance Value Index (IVI) reveals a structural contrast between *S. alba* and *R. apiculata*. While *R. apiculata* was more numerous (SD: 1,447.22 ind/ha), *S. alba* held a higher Importance Value (IVI: 79.17 vs 61.26).

The high density and relative abundance of *A. marina* indicate its successful adaptation and dominance in the mangrove ecosystem of Brgy. Zone II and Brgy. Astorga. While the discrepancy of the IVI between *S. alba* and *R. apiculata* is explained by the fact that the *S. alba* population consists of larger, more mature individuals with greater basal area (Mean SBA of 117.51±39.25 m^2/ha; Table 7), whereas the *R. apiculata* population, though dense, likely comprises smaller individuals (Mean SBA of 64.50±26.98 m^2/ha). These findings are consistent with those of Jumawan et al. (2015), who also reported the dominance of *A. marina* in the protected landscape of Hagonoy, Davao del Sur. In their study, *A. marina* was also identified as the most influential species within the area.

Stand characteristics

Mangrove stand analysis highlights the ecological contribution and role of each species in shaping the structure and functionality of the mangrove ecosystem in the unprotected areas of Sta. Cruz. *S. alba* demonstrated a substantial contribution to the mangrove stands primarily due to its large diameter at breast height (mean DBH: 34.44±1.83 cm) and stand basal area (mean SBA: 117.51±39.25 m^2/ha), despite its relatively low species density (mean SD: 661.11±198.38 ind/ha).

In contrast, *A. marina* exhibited a high-density, small-stature growth form, characterized by the lowest mean DBH (8.87±0.35 cm) but the highest species density (6,486.11±2,140.67 ind/ha). Despite lacking large-diameter trunks, its overwhelming numerical presence allowed it to generate the highest mean stand basal area in the study site (122.84±40.68 m^2/ha).

The substantial contribution of *S. alb*a to stand basal area aligns with prior studies reporting that it consistently exhibits a comparatively large basal area across various mangrove ecosystems in the Philippines, including Puerto Princesa Bay, Palawan Island (Dangan-Galon et al. 2016), and Maasim, Sarangani Province (Bigsang et al. 2016). Meanwhile, the high-density, small-stature growth of *A. marina* is consistent with its role as a pioneer species capable of enduring extreme environmental conditions (Sreekanth 2017). Its comparatively higher growth rate and resilience suggest that *A. marina* should be considered in mangrove restoration efforts, as it improves ecosystem stability and resilience against environmental change and human disturbances (Etongo et al. 2022).

Quantification of aboveground biomass and carbon stock

The total estimated aboveground biomass (AGB) within the surveyed unprotected areas of Sta. Cruz reached 519.33±75.57 Mg/ha, with a total carbon stock of 249.27±36.28 MgC/ha (Table 8). Spatially, biomass distribution across sites was highly heterogeneous, with Barangay Bato and Barangay Tuban exhibiting the most structurally mature stands, largely influenced by the presence of large *S. alba* individuals. In contrast, other barangays showed lower and more fragmented aboveground biomass pools. Among the recorded species, *S. alba* was the dominant contributor to the ecosystem's carbon pool, yielding a mean AGB of 217.15 Mg/ha and a carbon stock of 104.23 MgC/ha. The *Rhizophora* species (*R. apiculata* and *R. mucronata*) also contributed substantially, collectively accounting for over 224 Mg/ha of biomass. Meanwhile, *A. officinalis* yielded a relatively low mean AGB of 23.88 Mg/ha and carbon stock of 11.46 MgC/ha. Similarly, *A. marina*, despite its high species density, recorded a comparatively low mean AGB of 53.41 Mg/ha and carbon stock of 25.64 MgC/ha.

The results demonstrate that biomass and carbon storage in the study area are strongly influenced by stand structure, particularly the presence of mature and large-diameter trees. The dominance of *S. alba* in terms of biomass contribution underscores the ecological importance of fewer, larger individuals for carbon sequestration. Likewise, *Rhizophora* species significantly enhance biomass accumulation due to their substantial trunk diameters and extensive root architectures (Figure 4).

In contrast, the relatively low biomass contribution of both *Avicennia* species, despite the high density of *A. marina*, suggests that these species are generally composed of smaller or younger individuals, limiting their role in carbon storage. This pattern emphasizes that species density alone does not directly translate to higher biomass or carbon stock, as tree size and maturity are more critical determinants.

Table 6. Mangrove composition and density in the unprotected coastal areas of Sta. Cruz, Davao del Sur, Philippines

Mangrove species	Species Density (SD) (ind/ha)	Relative Abundance (RA) (%)	Importance Value Index (IVI)
Avicennia marina	6,486.11±2,140.67	67.80	114.77
Avicennia officinalis	333.33±249.79	3.48	11.72
Rhizophora apiculata	1,447.22±372.07	15.13	61.26
Rhizophora mucronata	638.89±279.24	6.68	33.08
Sonneratia alba	661.11±198.38	6.91	79.17

Table 7. Structural size and basal area characteristics of mangrove species in the unprotected coastal areas of Sta. Cruz, Davao del Sur, Philippines

Mangrove species	Mean individual DBH (cm)	Mean stand basal area (m^2/ha)
Avicennia marina	8.87±0.35	122.84±40.68
Avicennia officinalis	15.69±1.88	29.81±28.39
Rhizophora apiculata	16.49±1.27	64.50±26.98
Rhizophora mucronata	20.37±1.82	54.78±24.80
Sonneratia alba	34.44±1.83	117.51±39.25
Total	--	389.44±53.12

Table 8. Estimated Aboveground Biomass (AGB) and carbon stock of mangroves in the unprotected coastal areas of Sta. Cruz, Davao del Sur, Philippines

Mangrove species	Mean AGB (Mg/ha)	Mean C Stock (MgC/ha)
Avicennia marina	53.41±13.49	25.64±6.48
Avicennia officinalis	23.88±21.33	11.46±10.24
Rhizophora apiculata	113.41±46.41	54.43±22.28
Rhizophora mucronata	111.48±52.17	53.51±25.04
Sonneratia alba	217.15±53.06	104.23±25.47
Total study area average	519.33±75.57	249.27±36.28

Figure 4. *Rhizophora apiculata* and *Rhizophora mucronata* in Sta. Cruz, Davao del Sur, Philippines. Brgy. Tuban (A), along with *S. alba* in Brgy. Bato (B), exhibiting massive trunks that contribute to the overall aboveground biomass of the studied mangrove stands in Sta. Cruz, Davao del Sur, Philippines

Linking mangrove community dynamics to aboveground biomass and carbon sequestration

To synthesize the relationship between species dominance, physical structure, and climate mitigation potential, an integrative analysis of the core ecological parameters was conducted (Table 9). In low-biodiversity mangrove ecosystems, aboveground biomass and carbon storage are often concentrated in a single, dominant species with large individuals, such as *S. alba* (Alimbon and Manseguiao 2021). Our findings strongly align with this dynamic. We observed that *S. alba* functionally anchored specific locations, namely, Brgy. Bato and Brgy. Tuban, resulting in a disproportionately high AGB (217.15±53.06 Mg/ha) and carbon storage capacity (104.23±25.47 MgC/ha) despite its lower population counts.

The density of mangrove species is another key factor influencing carbon storage, though not always positively. For example, *A. marina* dominated the areas in terms of species density (6,486.11±2,140.67 ind/ha) but primarily consisted of small-diameter trees. Consequently, its carbon sequestration potential (25.64±6.48 MgC/ha) was drastically lower than that of species with larger individual structures, such as *S. alba*.

This highlights a critical ecological distinction: carbon sequestration capacity is driven by stand biomass rather than numerical abundance. As demonstrated in the sampled unprotected areas of the Municipality of Sta. Cruz stands dominated by high-density, small-stature trees may appear thriving, but contribute less to the aboveground carbon pools than mature, low-density stands of *S. alba*. This observation aligns with findings in Brgy. Camudmud MPA, Samal, where the community was similarly dominated by high-density species with relatively low individual biomass (Agua and Wong 2023).

A higher IVI typically indicates a species' greater ecological importance within a stand (Ismail et al. 2021). However, as shown in this study, an IVI driven primarily by extreme relative density (such as in *A. marina*) does not equate to high climate mitigation value. In terms of carbon sequestration, individual tree biomass and structural maturity prove to be much more reliable indicators of ecosystem services than species abundance (Ucat and Tampus 2024).

Citizen science, community engagement, and institutional support in sustaining mangrove ecosystem conservation

The current study underscores the potential and critical importance of citizen science as a complementary strategy in mangrove ecosystem management, monitoring, and sustainability. Translating these findings into action, community-centered initiatives were conducted in February and April 2025. These included a symposium for local stakeholders, comprising policymakers, youth leaders, and educators, designed to foster environmental literacy and catalyze dialogue around the local conservation priorities identified in this study.

Table 9. Integrative synthesis of mangrove structural parameters, relative abundance, and carbon storage capacities in the unprotected coastal areas of Sta. Cruz, Davao del Sur, Philippines

Species	Mean density (ind/ha)	Relative abundance (%)	IVI	Mean DBH (cm)	Mean basal area (m^2/ha)	Mean AGB (Mg/ha)	Mean carbon (MgC/ha)
Avicennia marina	6,486.11±2,140.67	67.80	114.77	8.87±0.35	122.84±40.68	53.41±13.49	25.64±6.48
Avicennia officinalis	333.33±249.79	3.48	11.72	15.69±1.88	29.81±28.39	23.88±21.33	11.46±10.24
Rhizophora apiculata	1,447.22±372.07	15.13	61.26	16.49±1.27	64.50±26.98	113.41±46.41	54.43±22.28
Rhizophora mucronata	638.89±279.24	6.68	33.08	20.37±1.82	54.78±24.80	111.48±52.17	53.51±25.04
Sonneratia alba	661.11±198.38	6.91	79.17	34.44±1.83	117.51±39.25	217.15±53.06	104.23±25.47

Note: Data aggregated from Tables 5, 6, and 7

By presenting site-specific biomass data to local leaders, the symposium moved beyond generalities to address the specific vulnerabilities of unmanaged patches in Sta. Cruz. This approach aligns with recent frameworks (Kiruba-Sankar and Barman 2024; Song et al. 2025), which emphasize the necessity of community participation in environmental stewardship. Such community-driven efforts not only support the physical conservation of mangrove ecosystems but also bridge critical knowledge gaps by facilitating the active exchange of Scientific, Local, and Traditional Ecological Knowledge (SEK, LEK, and TEK) (Marquez and Olavides 2024).

The long-term success of community-based programs, however, relies heavily on institutional support and the sustained collaboration of key stakeholders. Marquez and Olavides (2024) highlight that in the Philippines, continuous conservation efforts must be anchored by three key actors: national NGOs, people's organizations, and Local Government Units (LGUs). Effective knowledge transfer among these entities is critical for both the initial implementation and the long-term viability of mangrove restoration projects. Empowering local communities through shared capacity-building fosters a sense of ownership and drives sustainable local economies. Furthermore, in areas where Traditional Ecological Knowledge (TEK) may be eroded or absent, continuous and robust support from LGUs becomes essential. Local governments must institutionalize environmental education, secure long-term funding, and ensure the longevity of conservation efforts, an imperative made all the more urgent as the increasing frequency of typhoons serves as a constant reminder of the mangroves' indispensable protective role.

In conclusion, the sampled mangrove stands in the unprotected coastal areas of Sta. Cruz, Davao del Sur, are characterized by low species richness (3-4 species per site) and strong dominance by *A. marina* (67.80% relative abundance; 6,486.11 ind/ha), yet their carbon storage is disproportionately driven by a limited number of large *S. alba* individuals. Despite its low abundance (6.91%), *S. alba* contributed the highest aboveground biomass (217.15 Mg/ha) and carbon stock (104.23 MgC/ha), supporting a total stand average of 519.33 Mg/ha biomass and 249.27 MgC/ha carbon. Furthermore, the restricted distribution of other species, such as *A. officinalis* and *R. mucronata*, exacerbates the low overall species richness, affecting biodiversity maintenance and ecosystem resilience. This indicates a structurally imbalanced system in which ecosystem function is concentrated in a small fraction of mature trees, while overall biodiversity and resilience remain limited.

Several limitations should be considered. The study focused only on aboveground biomass and excluded belowground and soil carbon pools, potentially underestimating total carbon stocks. Environmental drivers (e.g., salinity, sediment type) were not quantified, and sampling was restricted to four barangays, limiting broader spatial inference. In addition, the analysis was primarily descriptive, with no statistical or multivariate testing to quantify relationships among diversity, structure, and biomass. Future research should prioritize conducting carbon baseline studies within formally designated Marine Protected Areas (MPAs) to serve as ecological reference points. Comparing these protected benchmarks against adjacent, unprotected mangrove systems will provide the critical comparative data necessary to inform comprehensive, municipal-wide conservation and climate mitigation strategies. Additionally, expanding to belowground carbon assessments, integrating environmental variables, and applying multivariate analyses (e.g., correlation, PCA) will be essential to better understand ecosystem functioning and to support evidence-based coastal management and blue carbon strategies.

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