

Ecological restoration efficacy: Comparative carbon stock assessment and economic valuation of natural and rehabilitated mangroves in Surigao del Sur

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ABSTRACT

Mangrove ecosystems are critical blue carbon sinks, yet site-specific data on their functional capacity remain limited in the Philippines. This study quantified the biomass, soil organic carbon (SOC), and total ecosystem carbon stock of natural (Aras-Asan) and rehabilitated (Poblacion) mangrove stands in Cagwait, Surigao del Sur. Using a stratified random sampling design, forest inventories, species-specific allometric equations, and spectrophotometric soil analysis (100 cm depth), the study assessed ecosystem carbon allocation. Results revealed that the rehabilitated stand exhibited significantly higher total vegetative biomass (71.38 ± 3.85 t/ha) and vegetative carbon stock (35.69 ± 1.93 t C/ha) compared to the natural stand (59.44 ± 5.32 t/ha and 29.72 ± 2.66 t C/ha, respectively; $p < .001$). However, the natural stand contained a greater total ecosystem carbon volume (984.44 t C/ha versus 952.97 t C/ha) due to immense subterranean reserves. Strikingly, SOC averaged 845 t C/ha across both sites, constituting an overwhelming 96.62% of the total ecosystem carbon stock. The total carbon dioxide equivalent (CO₂e) sequestered averaged 3,555.17 t CO₂e/ha, presenting a potential high-end voluntary carbon market valuation exceeding \$250,000 per hectare. These findings validate the rapid vegetative sequestration efficacy of active mangrove rehabilitation while emphatically highlighting that the strict preservation of undisturbed anaerobic substrate is paramount for preventing catastrophic greenhouse gas emissions. Ultimately, this data provides a robust quantitative baseline to integrate localized coastal wetlands into broader climate finance mechanisms.

Keywords: mangrove ecosystem, biomass estimation, carbon stock, allometric equations, soil organic carbon, coastal conservation.

INTRODUCTION

The rising concentration of atmospheric carbon dioxide (CO₂), a direct consequence of human activities, has led to unprecedented global climate change, necessitating immediate and effective mitigation strategies (Nunes, 2023). Scientific attention has shifted to the role of natural ecosystems as carbon sinks, particularly “blue carbon” habitats like mangroves, seagrass meadows, and tidal salt marshes. Despite covering a small portion of the Earth’s surface, these coastal ecosystems are highly efficient at sequestering atmospheric carbon, storing it in their biomass and anoxic soils for long periods (Primavera et al., 2018).

Mangroves, also known as coastal woodlands or intertidal forests, are unique ecosystems at the land-sea interface (Primavera et al., 2016). Physiological and ecological adaptations drive their remarkable carbon sequestration to harsh conditions such as high salinity, extreme tides, and anaerobic soils (Choudhary et al., 2024). These adaptations boost primary productivity, while anaerobic soils slow microbial decomposition, accumulating vast carbon reservoirs over centuries (Choudhary et al., 2024; Decena et al., 2024). Studies show mangroves can sequester carbon four times faster than terrestrial rainforests, making them carbon supersinks (Sanderman et al., 2018; Ali et al., 2025).

The Asia-Pacific region, particularly the Philippine archipelago, is a global hotspot for mangrove biodiversity. The Philippines is one of the top 15 most mangrove-rich countries, harboring 50% of the world's known mangrove species, including many endemic, threatened, and vulnerable ones (Garcia et al., 2013). These forests provide essential ecosystem services, such as coastal protection, nursery grounds for fisheries, and livelihoods for millions of coastal inhabitants (Primavera et al., 2018)

The Philippines' critical natural heritage, mangroves, faces severe threats. Over the past century, it has lost over half its original cover due to anthropogenic pressures (Ong et al., 2002; Agduma and Cao, 2023), primarily the conversion of mangrove forests into aquaculture ponds for fish and shrimp farming (Garcia et al., 2013; Tahiluddin et al., 2025). Coastal development, over-exploitation for timber and fuel, and pollution exacerbate this degradation (Akram et al., 2023). It diminishes biodiversity, coastal resilience, and transforms vital carbon sinks into greenhouse gas sources (Garcia et al., 2013; Akram et al., 2023).

The province of Surigao del Sur, located in the Caraga Region of northeastern Mindanao, boasts an extensive coastline and historically vast mangrove forests (Uy et al., 2018). Regional assessments document their floral diversity, but site-specific data on their functional capacity, especially carbon storage, are lacking. Current national-level estimates might over- or underestimate the local sequestration capacity. While the mangrove systems along Cagwait's coastline contribute significantly to the regional carbon budget but remain unquantified, this research addresses that need, thereby filling a local knowledge gap with global implications.

The objective is to estimate the total ecosystem carbon stock of the mangrove forests along Cagwait, Surigao del Sur, by quantifying the carbon stored in living biomass and soil pools. This involves conducting a floristic survey to determine the species composition, diversity (Shannon-Wiener Index), and tree density of the mangrove community; estimating the above-ground and below-ground biomass, and total biomass of the mangrove stands using species-appropriate allometric equations; quantifying the carbon stock within the AGB and BGB pools using established carbon fraction conversion factors; determining the soil organic carbon (SOC) among selected coastal barangays in Cagwait;

identifying significant differences between natural and rehabilitated mangrove areas in terms of biomass and vegetative carbon stock; and determining the total carbon and the carbon market value available for trading.

METHODOLOGY

Research design and locale research design

This study uses a quantitative, field-based research design. A stratified random sampling approach was utilized, with the strata being the different coastal barangays within the municipality of Cagwait. This design allows for both an overall estimation of the ecosystem's carbon stock for the entire municipality and a robust statistical comparison of carbon storage among different administrative units, providing valuable data for localized management.

Research locale

The study was conducted in mangrove forests along the coastline of Cagwait, Surigao del Sur, Philippines (8.8757°N, 126.2414°E). Cagwait is a coastal municipality that shares the resources of Lianga Bay and is known to have extensive mangrove forests (Uy et al., 2018). A preliminary site selection process was undertaken using satellite imagery to identify potential study areas within key coastal communities. This is followed by a ground-truthing survey to finalize the selection of two representative mangrove sites: the natural mangrove area in Aras-Asan and the rehabilitated mangrove area in Poblacion. Criteria for site selection included accessibility, the presence of a well-defined mangrove stand - indicating the presence of a clearly recognizable, mature, or established group of mangrove trees, and the obtaining of necessary permits from the LGU of Cagwait and the MENRO. A detailed map of Cagwait with selected study sites and sampling transects is included in Figure 1.

FIELD SAMPLING PROTOCOL

At each of the three selected mangrove sites, a systematic sampling framework was established. Three parallel transects, each 100 meters long, were laid out perpendicular to the shoreline,

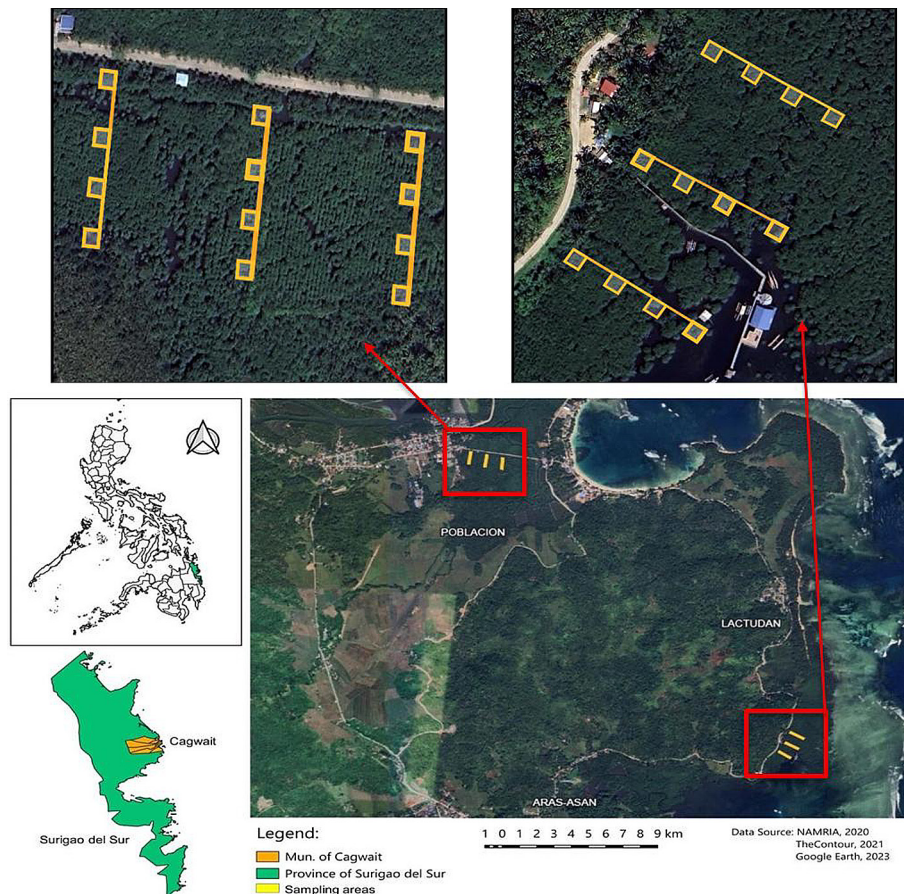


Figure 1. Research area of the study: Poblacion and Aras-Asan, Cagwait, Surigao del Sur

extending from the seaward edge inland. The starting points of each transect were at least 50 meters apart to ensure spatial independence (FMB, 2014). Within each transect, four (4) 10×10 m sampling quadrats were established with 20 m intervals to capture the variability within the site. This resulted in a total of 12 quadrats per mangrove site.

At each of the four quadrats, a single soil core was extracted using an auger to a uniform depth of 100 cm. Instead of analyzing these four cores individually, they were combined into a single composite bag for each transect, also known as composite sampling. This sampling effectively averages the organic matter concentrations across the four sampling points (Ackerson, 2018).

Vegetation assessment and ecological data calculation

Within each 10×10 m quadrat, a 100% inventory of mangrove trees was conducted. All living mangrove trees with a DBH of 4 cm or

greater were included, representing the primary structural component contributing to AGB, since those 4 cm below are considered as sapling (Macintosh and Ashton, 2023). For each qualifying tree, species identification was conducted *in situ* using established field guides for Philippine mangroves (Primavera et al., 2004; Quevedo and Ruaza, 2021). The trunk diameter was measured at 1.3 m from the ground, or 30 cm above the highest stilt root for species with prominent stilt roots, as per standard protocol (FMB, 2014; Avila-Acosta et al., 2024).

The raw data from the vegetation assessment were used to calculate key ecological metrics for the mangrove community. For each species and stand within each area, calculations included: (1) density, defined as individual trees per unit area (indi. ha^{-1}); and (2) species diversity, assessed through the Shannon-wiener diversity index (H') to quantify density (Shannon, 1948) and importance value index (IVI) to quantify the ecological significance of the mangrove community and determining which species control the structure of the ecosystem.

Estimation of soil organic carbon stocks

The fused soil samples per transect were submitted to the Regional Soils Laboratory for routine analysis. The lab utilized the Walkley & Black Spectrophotometric Method to determine the organic matter percentage. This specific method involves the chemical oxidation of organic carbon in the soil, which is then measured to calculate the total percentage of organic matter present in the bulked profile, suitable for the rapid assessment required for local management (Walkley and Black, 1934; Hossain et al., 2023).

Quantification of total ecosystem biomass

The total ecosystem biomass was quantified by calculating the sum of the total living vegetative biomass (AGB + BGB) and the total soil organic matter (SOM). SOM was estimated from the calculated SOC stock using the van Bemmelen factor of 1.724 (SOM = SOC × 1.724) (Minasny et al., 2020). The final value will be expressed in Mg C ha⁻¹.

Determination of carbon market value

The potential market value of the stored carbon was determined by, first, the total ecosystem carbon stock (vegetative carbon + soil carbon) in

Mg C ha⁻¹ was converted to its carbon dioxide equivalent by multiplying the value by 3.67. This provides the total number of potential carbon credits per hectare. This value was then multiplied by a range of current market prices for blue carbon credits to provide low, medium, and high-end economic valuations. The price range was derived from recent market reports and studies, such as \$27.80/ton (Lawson et. al., 2023), \$35/ton (Lelis, 2025), and up to \$80/ton for premium credits (FairAtmos, 2025).

Estimation of vegetative carbon stocks (AGB & BGB) biomass calculation

The DBH data for each tree were utilized to estimate AGB and BGB using appropriate, published allometric equations. Species-specific equations for Philippine mangroves are prioritized, and a robust general equation is used for other species. Table 1 lists the specific equations and parameters.

Carbon stock calculation

The AGB and BGB of each tree were calculated in kilograms. These values were summed for all trees in a quadrat to get the total plot-level biomass. This plot-level value was extrapolated to a per-hectare basis and converted to megagrams

Table 1. Allometric equations and parameters for biomass estimation of target mangrove species

Species	Biomass pool	Allometric equation	Wood density (ρ) (g cm ⁻³)	Source citation
<i>Aegiceras corniculatum</i>	ABG	$0.251 \rho D^{2.46}$	0.506	Komiyama et al. (2005)
	BGB	$0.199 \rho^{0.899} D^{2.22}$	0.506	Komiyama et al. (2005)
<i>Avicennia marina</i>	ABG	$0.1848 D^{2.3524}$	0.732	Dharmawan and Siregar (2008)
	BGB	$1.28 D^{1.17}$	0.732	Komiyama et al. (2008)
<i>Avicennia rumphiana</i>	ABG	$0.251 \rho D^{2.46}$	0.430	Komiyama et al. (2005)
	BGB	$0.199 \rho^{0.899} D^{2.22}$	0.430	Komiyama et al. (2005)
<i>Rhizophora mucronata</i>	ABG	$0.128 \rho D^{26}$	0.848	Fromard et al. (1998)
	BGB	$0.199 \rho^{0.899} D^{2.22}$	0.848	Komiyama et al. (2005)
<i>Rhizophora apiculata</i>	ABG	$0.38363 D^{2.2348}$	0.881	Bersaldo (2023)
	BGB	$0.199 \rho^{0.899} D^{2.22}$	0.770	Komiyama et al. (2008)
<i>Rhizophora stylosa</i>	ABG	$0.105 D^{2.68}$	0.940	Clough and Scott (1989)
	BGB	$0.134 D^{2.40}$	0.940	Clough and Scott (1989)
<i>Sonneratia alba</i>	ABG	$0.251 \rho D^{2.46}$	0.580	Komiyama et al. (2005)
	BGB	$0.3841 \rho D^{2.101}$	0.580	Kauffman and Cole (2010)
<i>Xylocarpus granatum</i>	ABG	$0.1832 D^{2.2}$	0.6271	Tarlan (2008)
	BGB	$0.199 \rho^{0.899} D^{2.22}$	0.6271	Komiyama et al. (2005)

Note: In the equations, represents the Diameter at breast height in cm, and represents the species-specific wood density.

(Mg ha⁻¹). Finally, biomass estimates were converted to carbon stock estimates using established carbon fraction conversion factors. AGB and BGB were both converted with a factor of 0.5 (50%), consistent with literature recommendations for mangrove ecosystems (Komiya et al., 2005; Price et al., 2024).

Data analysis

The data analysis process involved assessing mangrove community structure using descriptive statistics (Mean ± SD) for tree metrics and the Shannon-Wiener index for species diversity. The IVI, which reflects the contribution of each mangrove species to the stand in terms of density, basal area (dominance), and probability of occurrence across the plots (frequency), were calculated based on the formula adopted from English et al. (1994) and Odum and Barret (2005) as described in the following parameters:

$$\text{Relative density} = \frac{\text{No. of individuals of a species}}{\text{Total of no. individuals (all Species)}} \times 100 \quad (1)$$

$$\text{Relative frequency} = \frac{\text{frequency of a species}}{\sum \text{frequency of a species}} \times 100 \quad (2)$$

$$\text{Relative dominance} = \frac{\text{total basal area of species}}{\text{basal area of all species}} \times 100 \quad (3)$$

The IVI is the sum of relative density, relative frequency, and relative dominance, with values ranging from 0 to 300. The species with the highest importance value is considered the most significant in the community (Cañeda et al., 2022). An independent-samples T-test was used to determine the significance of differences between the

two sites. Data management, diversity indices, carbon stock summaries, and significant differences were processed using Microsoft Excel and the Paleontological Statistics Software (PAST 4.03). To determine whether the vegetative carbon stock differed significantly, an independent-samples T-test was conducted using PAST.

RESULTS AND DISCUSSION

Natural and rehabilitated mangrove stands

The floristic inventory of the Cagwait mangrove ecosystem, detailed in Table 2, reveals a community structure that challenges some conventional assumptions regarding natural versus rehabilitated stands. A total of 533 individual mangroves were found in all observation plots, with eight (8) true mangrove species under 5 families identified across the sampling network. This includes *A. corniculatum* (saging-saging), *A. marina* and *A. rumphiana* (bungalon, api-api, piapi), *R. apiculata* (bakhaw lalaki), *R. mucronata* (bakhaw babae), *R. stylosa* (bakhaw bato), *S. alba* (pagatpat), *X. granatum* (tabigi). However, only four (4) species were commonly found in Aras-Asan and Poblacion sites, namely, *R. apiculata*, *R. mucronata*, *S. alba*, and *X. granatum*.

The Shannon-wiener diversity index (H') is notably low for both sites ($H' < 1.5$), classifying them as very low diversity according to Fernando's scale (Fernando, 1998). However, the finding that the rehabilitated site in Poblacion ($H' = 1.00$) has higher diversity than the natural site in Aras-Asan ($H' = 0.66$) is a significant anomaly that requires physiological and ecological dissection.

Table 2. Diversity, density, importance value index, and trunk diameter range of the mangrove ecosystem in Cagwait, Surigao del Sur

Mangrove species	Aras-Asan	Poblacion	DBH range (cm)	DBH mean (cm)
<i>A. corniculatum</i>	-	+	5.73-15.95	9.37 ± 4.66
<i>A. marina</i>	-	+	8.08-8.09	8.09 ± 0
<i>A. rumphiana</i>	-	+	5.06-6.68	5.87 ± 0.81
<i>R. apiculata</i>	+	+	5.00-10.66	5.99 ± 1.14
<i>R. mucronata</i>	+	+	5.00-14.29	7.26 ± 2.04
<i>R. stylosa</i>	+	-	5.00-8.75	6.16 ± 1.41
<i>S. alba</i>	+	+	5.00-21.96	7.41 ± 5.9
<i>X. granatum</i>	+	+	8.44-16.07	10.98 ± 3.60
Diversity Index	0.66	1.00		
Tree density (tree ha ⁻¹)	2057.51	2382.38		

Note: (+) = was found; (-) = not found.

Typically, natural mangrove forests in the Philippines exhibit higher heterogeneity due to niche differentiation over long time scales. The low diversity in Aras-Asan may indicate that the sampling plots were located within a competitive-exclusion zone, likely a *Rhizophora* or *Sonneratia* consociation in which one species physiologically dominates due to optimal tidal positioning. *Rhizophora* species, with their interlocking prop roots, often create monospecific stands in the mid-intertidal zone, effectively shading out competitors (Hugo et al., 2025).

The higher diversity observed in Poblacion suggests that this rehabilitated system may have resulted from several factors. One possibility is assisted natural regeneration (ANR), where planting efforts were complemented by the natural recruitment of pioneer species such as *Avicennia* and *Sonneratia* from nearby propagule sources (World Economic Forum, 2021).

Another factor could be multi-species planting efforts, indicating a deliberate initiative by the local government unit (LGU) or non-governmental organizations (NGOs) to move beyond monoculture practices (Oceanus Conservation, 2024). Additionally, edge effects might have contributed to this diversity, as the presence of landward species like *X. granatum* and *A. corniculatum* suggests that the site may be adjacent to terrestrial or riverine environments. This proximity allows for a wider variety of species that are tolerant to lower salinity levels (Raganas and Magcale-Macandog, 2020).

Table 3 showed that *R. apiculata* is the most dominant species in the study area, with the highest IVI (183.54%), relative density (68.48%), frequency (44.44%), and dominance (65.61%). This indicates that the species strongly influences the overall structure and composition of

the mangrove community. The dominance of *R. apiculata* is consistent with its adaptability and widespread use in mangrove rehabilitation programs (Primavera, 2000) which often leads to monospecific stands. In contrast, *S. alba* ranked second (IVI = 45.17), indicating moderate ecological importance, particularly in terms of its contribution to stand structure. This species is commonly associated with seaward zones and reflects natural zonation patterns in mangrove ecosystems (Duke et al., 1998). Other species such as *R. stylosa* (24.60) and *R. mucronata* (17.11) showed lower contributions, suggesting they play secondary roles in the community.

The remaining species exhibited low IVI values, indicating limited abundance and distribution. The strong dominance of a single species suggests a simplified community structure with low species evenness or reduced diversity, which is often associated with disturbed or replanted mangrove ecosystems (Alongi, 2009). This highlights the need for more diverse mangrove rehabilitation strategies that incorporate multiple native species to enhance ecosystem reliance and biodiversity.

As illustrated in Figure 2, *R. apiculata* is the most dominant species in the overall composition of 69.79%. This aligns with regional observations by Saro et al. (2025), who noted that *Rhizophoraceae* often dominate the floral landscape of Surigao del Sur. The lower diversity in the natural stand (Aras-Asan) mirrors findings from Hugo et al. (2025) in Surigao City, where natural stands were found to have low diversity due to the overwhelming dominance of a single species, specifically *R. apiculata*.

The stand structure data provides insight into the age and health of the forest. The tree density values, 2,057 indi./ha⁻¹ for Aras-Asan and 2,382 indi./ha⁻¹ for Poblacion, are indicative of young

Table 3. Importance value index (%) of mangrove species in Cagwait, Surigao del Sur

Mangrove species	Total individuals	No. of plots present	Relative (%)			IVI (%)
			Density	Frequency	Dominance	
<i>A. corniculatum</i>	13	4	1.50	8.89	1.80	12.30
<i>A. marina</i>	1	1	0.12	2.22	0.28	2.63
<i>A. rumphiana</i>	6	3	0.69	6.67	0.52	7.93
<i>R. apiculata</i>	593	20	68.48	44.44	65.61	183.54
<i>R. mucronata</i>	29	3	3.35	6.67	6.85	17.11
<i>R. stylosa</i>	62	5	7.16	11.11	5.81	24.60
<i>S. alba</i>	99	7	11.43	15.56	17.35	45.17
<i>X. granatum</i>	4	2	0.46	4.44	1.77	6.71

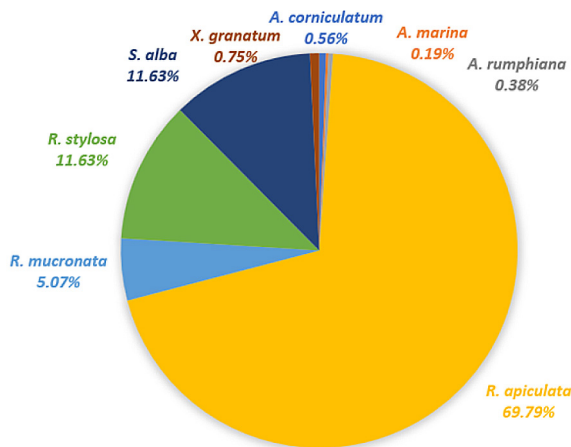


Figure 2. Composition of mangrove species in the study area

to intermediate-aged forests. Mature, old-growth mangrove forests in the Philippines typically exhibit lower densities (e.g., 600–900 indi./ha¹) as large trees outcompete smaller ones for light and canopy space (De Quiroz et al., 2025).

The mean diameter at breast height (DBH) values further support this observation. In Aras-Asan, the presence of *S. alba*, with a DBH range reaching up to 21.96 cm, indicates the persistence of some older mother trees. As a pioneer species, *S. alba* exhibits high photosynthetic rates and rapid radial growth (Decena et al., 2024), serving as the frontline defense against wave energy. Its physiological resilience to high salinity and prolonged inundation underscores its critical role as a structural component in the ecosystem.

In Poblacion, the DBH range is relatively narrow, mostly between 5–10 cm, observed across species such as *R. apiculata* (5.99 ± 1.14 cm) and *R. mucronata* (7.26 ± 2.04 cm). This uniformity in DBH is indicative of an even-aged plantation, likely established around 10–15 years ago. The combination of high tree density and small diameters signifies anthropogenic reforestation efforts, which often involve close spacing, initially planting between 4,000 to 10,000 seedlings per hectare, to compensate for expected mortality rates.

The presence of *A. rumphiana* in Poblacion is physiologically notable. This species is classified as Vulnerable (IUCN, 2021) and is typically a riverine/landward species that favors lower salinity (Agduma and Kao, 2023). Its absence in the Aras-Asan plots might suggest that the Aras-Asan site is more exposed (seaward) or lacks the freshwater inputs necessary for *A. rumphiana* to thrive competitively against halophytes like *Sonneratia* (Jeffrey et al., 2024).

Table 4. Average of above- and below-ground mangrove biomass in each study site

Sites	AGB (t/ha)	BGB (t/ha)	Total biomass (t/ha)
Aras-Asan	39.59 ± 3.54	19.85 ± 1.77	59.44 ± 5.32
Poblacion	48.76 ± 2.63	22.62 ± 1.22	71.38 ± 3.85
Average	44.18 ± 3.42	21.24 ± 1.41	65.41 ± 4.85

Above- and below-ground biomass

Table 4 details the above-ground biomass (AGB) and below-ground biomass (BGB) of the surveyed mangrove stands. The results indicate a notable difference in vegetative accumulation between the sites, with the rehabilitated stand in Poblacion recording a higher total biomass (71.38 ± 3.85 t/ha) compared to the natural stand in Aras-Asan (59.44 ± 5.32 t/ha). Across both areas, the combined average total vegetative biomass reached 65.41 ± 4.85 t/ha, with the above-ground components (average 44.18 ± 3.42 t/ha) consistently accounting for roughly double the mass of the below-ground root structures (average 21.24 ± 1.41 t/ha). This spatial variation underscores the heterogeneity often observed in mangrove community structures, which can fluctuate significantly even within localized areas due to varying environmental factors and anthropogenic pressures (Obsina, 2022; Choudhary et al., 2024; Tahiluddin et al., 2025).

Despite these site-specific structural differences, the substantial biomass recorded across both locations highlights the functional efficiency of these intertidal forests as carbon sinks. The unique physiological adaptations of mangroves enable rapid photosynthesis, allowing them to effectively capture atmospheric carbon and convert it into extensive organic biomass within their trunks, branches, and root systems. However, as emphasized by Primavera et al. (2018), while the living trees in these ecosystems store significant amounts of carbon, the most critical and long-term carbon sequestration actually occurs below the surface. Therefore, the robust above-ground and below-ground biomass pools quantified in these Cagwait stands not only represent significant immediate carbon stocks but also serve as vital precursors to the waterlogged, anaerobic soils that preserve the vast majority of the ecosystem's long-term carbon wealth.

Figure 3 reveals that *R. apiculata* overwhelmingly drives vegetative carbon storage in both the

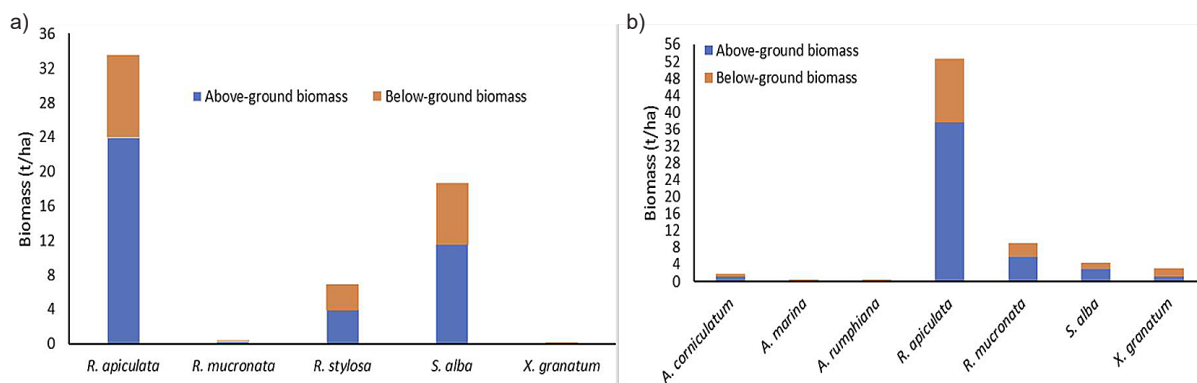


Figure 3. Comparison of above and below-ground biomass in: (a) Aras-Asan, Cagwait, Surigao del Sur, (b) Poblacion, Cagwait, Surigao del Sur

natural stand of Aras-Asan and the rehabilitated stand of Poblacion, aligning with observations that the Rhizophoraceae family frequently dominates Philippine mangrove ecosystems (Primavera et al., 2018). While the planted Poblacion site exhibits a broader representation of species, including minor biomass contributions from *Avicennia* and *Aegiceras*, the sheer structural bulk in both locales relies heavily on *R. apiculata*, a pattern consistent with localized studies in the Surigao region that report low-diversity stands heavily dominated by this single species (Hugo et al., 2025). This spatial heterogeneity in community structure is heavily influenced by specific local environmental factors and anthropogenic pressures (Choudhary et al., 2024; Tahiluddin et al., 2025). Finally, across all documented species in both sites, the above-ground biomass consistently comprises a substantially larger proportion of the total vegetative mass compared to the below-ground root structures; yet, it remains vital to recognize that while these living trees store significant immediate carbon, the ecosystem’s most critical, long-term sequestration capacity ultimately lies within the anaerobic soils beneath them (Primavera et al., 2018).

Carbon stock estimates from mangrove biomass

The quantified vegetative carbon stock and its corresponding carbon dioxide sequestration

equivalent demonstrate the robust capacity of the surveyed mangrove stands to act as vital carbon sinks. Consistent with higher biomass accumulation, the rehabilitated stand in Poblacion exhibited a greater vegetative carbon stock of $35.69 \pm 1.93 \text{ t C/ha}$ and a sequestration potential of $130.88 \pm 7.07 \text{ t CO}_2\text{e/ha}$, compared to the natural stand in Aras-Asan, which recorded $29.72 \pm 2.66 \text{ t C/ha}$ and $108.99 \pm 9.75 \text{ t CO}_2\text{e/ha}$. This higher accumulation in the planted site aligns seamlessly with other local Philippine contexts; for instance, Camacho et al. (2011) similarly found that mature, community-managed rehabilitated mangrove plantations in Bohol stored significantly more carbon than the area’s natural stands, proving that local reforestation efforts can yield superior carbon sinks. This spatial variation reflects the inherent structural heterogeneity often driven by varying local environmental conditions, historical anthropogenic pressures, and successful localized management (Tahiluddin et al., 2025). Furthermore, the structural bulk in both locales relies heavily on *R. apiculata*, a pattern consistent with localized studies in the Surigao region that report low-diversity stands heavily dominated by this single species (Hugo et al., 2025) (Table 5).

Despite these site-specific differences, the substantial volume of atmospheric carbon captured within the living biomass underscores the efficiency of these coastal ecosystems, which are highly proficient at sequestering carbon due to unique physiological adaptations that boost

Table 5. Average carbon stock estimates and sequestration (CO₂ equivalent) calculated from mangrove biomass

Sites	Carbon stock (t C ha ⁻¹)	CO ₂ equivalent (t CO ₂ e ha ⁻¹)
Aras-Asan	29.72 ± 2.66	108.99 ± 9.75
Poblacion	35.69 ± 1.93	130.88 ± 7.07
Average	32.71 ± 2.19	119.94 ± 8.03

primary productivity (Choudhary et al., 2024). On a broader scale, a comprehensive global analysis of four decades of data confirms that planted mangroves are highly effective at sequestering carbon, capable of accumulating up to 75% of the carbon stocks found in intact, mature natural stands over time, proving their viability as carbon supersinks (Bourgeois et al., 2024; Ali et al., 2025). Quantifying this vegetative carbon provides a critical baseline for integrating local conservation efforts into broader mitigation strategies necessitated by unprecedented global climate change (Nunes, 2023). While this living organic matter represents a substantial ecological service, it primarily serves as a precursor to the massive, long-term carbon reservoirs stored within the anaerobic soils below (Primavera et al., 2018). Documenting these high-quality „blue carbon” reserves is imperative, as they are increasingly valued in carbon markets for their exceptional sequestration rates and co-benefits (Macreadie et al., 2022), thereby justifying stringent protection and supporting the ecosystem’s potential inclusion in climate finance mechanisms.

Further addressing the quantification of vegetative carbon stocks, Figure 4 delineates specific species contributions, revealing that *R. apiculata* overwhelmingly drives carbon storage in both the natural stand of Aras-Asan (16.76 t C/ha) and the rehabilitated stand of Poblacion (26.32 t C/ha). This heavy structural reliance on *R. apiculata* aligns with regional literature confirming that the Rhizophoraceae family frequently dominates Philippine mangrove ecosystems (Primavera et al., 2018), and specifically mirrors localized observations in Surigao City, where low-diversity stands were heavily dominated by this exact species (Hugo et al., 2025). Furthermore, while the planted Poblacion site exhibits a broader

representation of contributing species, including *R. mucronata* (4.50 t C/ha), which is also noted as highly abundant in Surigao del Sur (Saro et al., 2025), the pronounced structural concentration within a single dominant species across both locales underscores the spatial heterogeneity of mangrove communities. Such distinct variations in community structure and localized carbon accumulation are widely understood to be driven by specific local environmental factors and varying anthropogenic pressures (Agduma and Cao, 2023; Choudhary et al., 2024; Tahiluddin et al., 2025). Ultimately, while these diverse species actively sequester significant atmospheric carbon into their living biomass, it remains imperative to recognize that this vegetative storage is merely a precursor to the ecosystem’s most massive, long-term carbon reservoirs located in the anaerobic soils beneath them (Primavera et al., 2018).

Soil organic carbon of mangrove stands

Table 6 details the SOC estimates, directly addressing the fourth objective by revealing substantial carbon stocks in both the natural stand of Aras-Asan (954.72 ± 66.53 t C/ha) and the rehabilitated stand of Poblacion (917.28 ± 67.82 t C/ha), which yields an impressive average of 936.00 ± 67.18 t C/ha across the top 100 cm of substrate. This immense subterranean pool completely dwarfs the previously estimated vegetative biomass, confirming that while living trees store significant carbon, the most critical and long-term sequestration undeniably occurs within the soil (Primavera et al., 2018). The waterlogged, anaerobic conditions characteristic of mangrove sediments significantly slow microbial decomposition, enabling these undisturbed ecosystems to accumulate vast carbon reservoirs over centuries

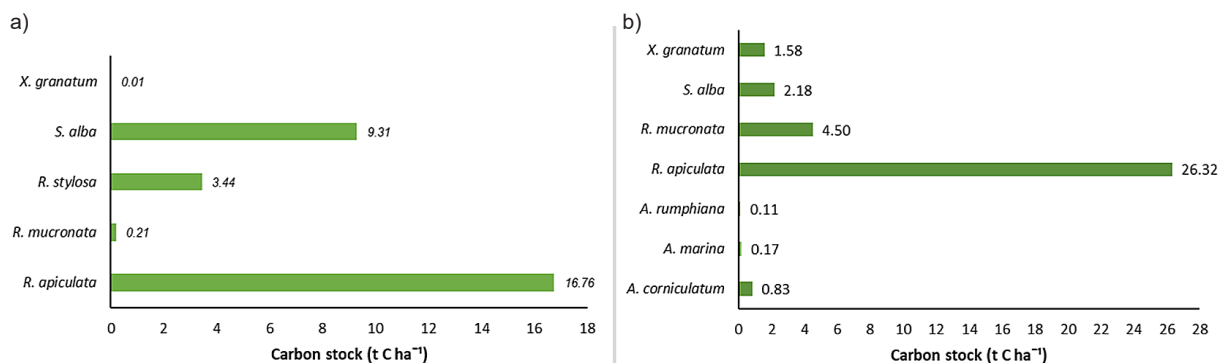


Figure 4. Mangrove species contribution to carbon stock in: (a) Aras-Asan, Cagwait, Surigao del Sur, (b) Poblacion, Cagwait, Surigao del Sur

Table 6. Soil organic carbon (SOC) of mangrove forest in Cagwait, Surigao del Sur

Location	% Organic carbon (Mean)	Bulk density (g cm ⁻³) - Standard	Soil depth (cm)	Area (m ²)	SOC (t C ha ⁻¹)	SOC in 300 m ² (t C)
Aras-asan	13.26 ± 0.92	0.72	100	300	954.72 ± 66.53	28.64 ± 2.00
Poblacion	12.74 ± 0.94	0.72	100	300	917.28 ± 67.82	27.52 ± 2.03
Average	13.00 ± 0.93				936.00 ± 67.18	28.08 ± 2.02

(Choudhary et al., 2024). These high localized SOC values in Cagwait align seamlessly with broader Philippine assessments, which consistently demonstrate that soil carbon constitutes the vast majority of total ecosystem wealth, such as the 53% reported in Carigara Bay, Leyte (Decena et al., 2024), and the 40% to 90% observed in Macajalar Bay, Misamis Oriental (Lomoljo-Bantayan et al., 2023).

The profound magnitude of these below-ground reservoirs necessitates a fundamental shift in the conservation paradigm, moving beyond the mere protection of above-ground vegetation to rigorously preserving the entire wetland system and its soil integrity (Duncan et al., 2022). While the planted Poblacion site successfully regenerated a robust living biomass structure, the historically undisturbed natural substrate in Aras-Asan remains the more potent carbon sink, highlighting the catastrophic environmental risks associated with substrate disturbance. Anthropogenic activities that drain and excavate these habitats, particularly aquaculture pond construction, expose these carbon-rich sediments to oxygen, triggering rapid microbial decomposition and transforming functional supersinks into massive sources of greenhouse gas emissions (Tahiluddin et al., 2025). Consequently, the 845 t C/ha average quantified in this study represents a massive volume of avoidable emissions, providing a compelling, data-driven argument for the strict protection of Surigao del Sur’s intact coastal habitats to secure their invaluable climate regulation services.

Test of significance between mangrove stands and total ecosystem carbon stocks

The comparative analysis of vegetative biomass and carbon stock between the natural mangrove stand (Aras-Asan) and the rehabilitated stand (Poblacion) in Cagwait reveals a statistically significant difference across all measured parameters. The rehabilitated stand exhibited significantly higher above-ground biomass (48.76 ± 2.63 t/ha), below-ground biomass (22.62 ± 1.22 t/ha), and overall vegetative carbon stock (35.69 ± 1.93 t C/ha) compared to the natural stand (p <.001 for all). These findings indicate that the rehabilitation efforts in Poblacion have successfully established a mangrove stand that currently outperforms the local natural stand in terms of rapid vegetative carbon accumulation (Table 7).

The superior biomass observed in the Poblacion stand aligns with current literature regarding the efficacy of active coastal restoration during early-to-mid successional stages. While intact, mature natural mangroves typically possess larger overall ecosystem carbon reservoirs due to centuries of soil carbon storage, planted stands are highly efficient at rapid vegetative carbon sequestration (Bourgeois et al., 2024). Rehabilitated stands in the Philippines are often established using fast-growing pioneer species planted at optimal, high-density spacing, which accelerates canopy closure and maximizes rapid above-ground biomass production by minimizing initial competition (Kang et al., 2024).

Table 7. Test of significance on natural and rehabilitated mangrove stands – biomass and vegetative carbon stock

Variable	Aras-asan	Poblacion	t-value	df	p-value	Decision
AGB (t/ha)	39.59 ± 3.54	48.76 ± 2.63	-7.20	22	3.4 × 10 ⁻⁷	Reject H ₀
BGB (t/ha)	19.85 ± 1.77	22.62 ± 1.22	-4.46	22	1.93 × 10 ⁻⁴	Reject H ₀
Total biomass (t/ha)	59.44 ± 5.32	71.38 ± 3.85	-6.29	22	2.5 × 10 ⁻⁶	Reject H ₀
Vegetative carbon stock (Mean ± SD)	29.72 ± 2.66	35.69 ± 1.93	-6.29	22	2.5 × 10 ⁻⁶	Reject H ₀

Note: Values are presented as Mean ± Standard Deviation. Sample size is n = 12 quadrants per site. An independent-samples t-test was used to determine the significance of differences between the two sites.

Conversely, the comparatively lower biomass in the natural Aras-Asan stand may reflect environmental stressors or anthropogenic pressures, as natural stands in Southeast Asia frequently experience unmonitored extraction for fuelwood that continuously depletes standing above-ground biomass (Qur'ani et al., 2023). Additionally, natural stands possess varied structural complexity, including senescing trees and canopy gaps, resulting in lower average biomass per hectare compared to the uniform, vigorous growth of successfully managed, age-controlled rehabilitated plots (Salmo et al., 2024). Ultimately, these findings underscore the value of localized mangrove rehabilitation; when properly managed, these restored habitats act as aggressive carbon sinks that can rival or exceed the vegetative growth rates of adjacent natural stands.

Table 8 synthesizes the total ecosystem carbon stock, revealing an impressive regional average of 877.71 t C/ha and directly addressing the objective to compare natural and rehabilitated mangrove areas. Although the planted stand in Poblacion accumulated slightly more vegetative carbon (35.69 t C/ha), the natural stand in Aras-Asan harbored a higher total carbon volume (984.44 t C/ha versus 952.97 t C/ha) due to its massive subterranean reserves. Most strikingly, soil organic carbon accounts for an overwhelming 96.62% of the total ecosystem carbon across both sites, 96.62% in Aras-Asan and 96.25% in Poblacion. This massive below-ground allocation confirms the fundamental ecological principle that while living trees store significant amounts of carbon, the most critical and long-term carbon sequestration in these coastal ecosystems actually occurs within the soil (Primavera et al., 2018). The waterlogged, anaerobic conditions of these mangrove sediments drastically slow microbial decomposition, allowing them to accumulate and securely lock away vast carbon wealth over centuries (Choudhary et al., 2024). Furthermore, this staggering ~96% soil contribution in Cagwait aligns with and exceeds previous

Philippine assessments that consistently identify sediments as the largest ecosystem reservoirs, such as the 53% soil carbon fraction observed in Carigara Bay (Decena et al., 2024) and the 40% to 90% range reported in Macajalar Bay (Lomoljo-Bantayan et al., 2023).

The profound concentration of carbon within the substrate necessitates a critical shift in local environmental management and conservation strategies. Acknowledging that the vast majority of the ecosystem's carbon wealth is stored below ground shifts the conservation paradigm from merely protecting the standing, above-ground biomass to rigorously preserving the entire wetland system and its soil integrity (Duncan et al., 2022). While deforestation is detrimental, the physical disturbance of the substrate represents the most catastrophic event for carbon emissions; activities such as aquaculture pond construction, draining, and excavating the soil, exposing these incredibly carbon-rich sediments to oxygen and triggering rapid, massive microbial decomposition (Tahiluddin et al., 2025). Therefore, the substantial total carbon stock quantified here provides a data-driven argument for preventing further substrate disturbance. By officially accounting for these high-quality „blue carbon” reserves, local stakeholders can better advocate for their protection and potentially integrate these ecosystems into lucrative climate finance mechanisms, as these credits are considered premium products in carbon markets due to their exceptional sequestration rates and ecological co-benefits (Macreadie et al., 2022).

Economic valuation of mangrove stands

Table 9 presents the ecological data in financial terms by converting the total carbon stock into CO₂ equivalent (CO₂e) and applying current carbon market prices. The findings reveal a transformative increase in the ecosystem's assessed value when soil carbon is considered. On average, the total potential CO₂e

Table 8. Total ecosystem carbon stock of mangrove forests in Cagwait, Surigao del Sur (vegetative + soil)

Study site	Vegetative carbon (AGB + BGB) (t C/ha)	Soil organic carbon (SOC) Stock (t C/ha)	Total ecosystem carbon Stock (t C/ha)	% Contribution of soil to total carbon
Aras-asan	29.72	954.72	984.44	96.62
Poblacion	35.69	917.28	952.97	96.25
Average	32.71	936.00	968.71	96.62

Table 9. Total economic valuation of CO₂ equivalent (vegetative + soil) of Aras-Asan and Poblacion mangrove stands

Sites	Total carbon stock (t C/ha)	Total CO ₂ equivalent (t CO ₂ e/ha)	Low economic valuation (\$27.80/ton)	Medium economic valuation (\$35/ton)	High economic valuation (\$80/ton)
Aras-Asan	984.44	3, 612.89	\$100,438.34	\$126,451.15	\$289,031.00
Poblacion	952.97	3, 497.40	\$92,227.72	\$122, 409.00	\$279,792.00
Average	968.71	3, 555.17	\$98,833.73	\$124,430.95	\$284,413.60

sequestered is 3,555.17 t CO₂e per hectare. When valued at a high-end estimate of \$80 per ton, which is feasible for high-quality blue carbon credits with biodiversity co-benefits, the Aras-Asan natural stand is valued at approximately \$289,031.00 per hectare, while the Poblacion rehabilitated stand is valued at approximately \$279,792.00 per hectare. Even with a conservative low-end valuation of \$27.80 per ton, the average value per hectare remains significant. This valuation underscores the substantial avoided cost associated with degradation. If these mangrove areas were converted for aquaculture or development, the release of stored carbon could lead to severe economic and environmental losses.

According to FairAtmos (2025), the Philippines is positioning itself to leverage such assets through the voluntary carbon market (VCM), with data from Table 8 indicating that the Cagwait mangroves are premium assets for these markets. Moreover, the minimal economic difference, approximately \$10,000 per hectare in high-end valuation, between the natural and rehabilitated sites is a critical policy insight. It strongly supports the financial justification for the ongoing maintenance and protection of reforested areas like Poblacion. This data validates investments in reforestation, emphasizing that the value of invisible soil carbon far surpasses the visible value of young trees, as highlighted by Macreadie et al. (2022).

CONCLUSIONS

The mangrove ecosystem along the coastline of Cagwait, Surigao del Sur, functions as a highly efficient and invaluable blue carbon sink. The comprehensive assessment of these coastal woodlands reveals that while the living vegetative structures sequester a significant volume of atmospheric carbon, the true carbon wealth of this ecosystem resides beneath

the surface. Specifically, SOC accounts for an overwhelming average of 96.27% of the total ecosystem carbon across both study sites, completely dwarfing the vegetative biomass pools.

The comparative analysis demonstrates distinct, statistically significant functional differences between natural and rehabilitated stands. The rehabilitated mangrove stand in Poblacion currently outperforms the natural stand in Aras-Asan regarding rapid vegetative carbon accumulation, exhibiting significantly higher above-ground and below-ground biomass. However, due to centuries of uninterrupted soil carbon storage in its waterlogged, anaerobic substrate, the natural stand in Aras-Asan retains a higher total ecosystem carbon volume. Despite variations in structure and a generally low species diversity heavily dominated by *R. apiculata* across both sites, the overarching ecosystem stores an impressive regional average of 877.71 t C/ha.

Economically, this stored ecosystem carbon translates to a staggering 3,221.20 t CO₂e per hectare on average, representing a premium asset in the voluntary carbon market (VCM) with a potential high-end valuation exceeding \$250,000 per hectare. Ultimately, this study proves that local mangrove rehabilitation is a highly effective climate mitigation tool, while simultaneously underscoring that the preservation of undisturbed natural substrate is the single most critical factor in preventing massive greenhouse gas emissions.

Acknowledgements

The authors extend their sincere gratitude to the North Eastern Mindanao State University for its unwavering support in approving the conduct of this research study. Additionally, they express their deepest appreciation to the Municipal Environment and Natural Office – Cagwait, Surigao del Sur, for granting permission to conduct the study in the designated locale.

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