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Original Article

Estimation of carbon stocks of mangrove forests along the Carigara Bay in Leyte, Philippines

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ABSTRACT

Mangrove forest ecosystems are known to sequester large quantities of carbon, becoming a significant carbon source when disturbed. This paper presents a quantification in aboveground (standing trees, palm, shrub, standing dead trees, downed wood and litter), belowground (root and soil) and ecosystem carbon stocks in mangrove forests along the Carigara Bay in Leyte, Philippines. The carbon stocks in the different mangrove forest types (fringe and riverine) and zones (landward, middleward, and seaward/along water) were compared. Further, the relationship between environmental factors (eg, interstitial soil salinity, soil water content and soil depth) and ecosystem carbon stocks was examined. The study yielded an ecosystem carbon stock of 558.02±51.13Mg ha^{-1}, partitioned into aboveground and belowground carbon stocks of 251.96±31.08 and 306.06±28.50Mg ha^{-1}, respectively. The ecosystem carbon stocks of the riverine (805.89±80.57Mg ha^{-1}) greatly exceeded that of the fringe mangrove forests (310.15±24.59Mg ha^{-1}). In general, biomass and soil both store a similar proportion of carbon, corresponding to 57% and 43%, respectively. In addition, regression analysis revealed that soil depth was a reasonable predictor of ecosystem carbon stocks, whereby increasing ecosystem carbon stocks were associated with deeper soil deposits. Overall, the study's results highlight the exceptionally high amount of carbon stored in the mangrove ecosystems,

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indicating their potential role in climate change mitigation.

Keywords: Biomass, climate change mitigation, fringe, riverine, sequestration

INTRODUCTION

Mangrove forests are considered among those vital ecosystems in tropical countries (Dangan-Galon et al 2016) that are characterized by their highly specialized vegetation (salt-tolerant trees and shrubs) thriving under a limiting environment (Walsh 1974). These complex and productive ecosystems are situated between 32°N and 38°S latitudes along the tropical coast of Africa, Australia, Asia, and the Americas (Md Isa and Suratman 2021). As productive coastal ecosystems, they provide various goods and ecosystem services, including shoreline stabilization and protection against calamities, habitat and spawning areas, fisheries, forest products and food (Petrosian et al 2016, Singh 2020, Trettin et al 2021). Most importantly, biogeochemical cycling (eg, carbon storage) has been regarded as one of mangrove forests' most important environmental services (Sitoe et al 2014).

Mangrove forests are recognized for their essential role in the carbon cycle (Suratman 2008). Specifically, these ecosystems act as a carbon stock reservoir, as they can sequester and store carbon (Vinod et al 2019). Mangrove ecosystems' exceptionally high carbon sequestration capacity accounts for 3–4% of global carbon sequestration by the total tropical forest (Bhomia et al 2016, Alongi et al 2020). Plant communities of mangrove forests remove atmospheric carbon dioxide (CO_2) through sequestration during photosynthesis (Sahu et al 2016). Then, the sequestered carbon is stored in various pools in biomass (aboveground, belowground, litter, wood) and most importantly, enormous proportions are kept in soils (Sahu et al 2016, Aye et al 2022).

The soils from mangrove ecosystems sequester large amounts of carbon (Sasmito et al 2020a) with a global soil carbon sequestration rate of 210g/cm^2/yr, higher than terrestrial forests (10g/cm^2/yr) (Chmura et al 2003, Clark and York 2005). The mangrove soils appear to be an effective carbon sink with their ability to bury and preserve carbon for long periods (Kristensen et al 2008). Deposition and accumulation of organic carbon in mangrove soils occur under waterlogged and anoxic conditions, which can inhibit or slow down the microbial breakdown of organic matter (MacKenzie et al 2021). Predominantly, the carbon stored in mangrove soils and sediments is derived from roots (Ezcurra et al 2016), but the deposition of sediments from rivers/streams serve as an essential source (Wendling et al 2005). Therefore, these equate to a greater amount of carbon being stored in soil than in biomass, which can constitute more than two-thirds of the total mangrove ecosystem carbon stocks (Sasmito et al 2020a). For example, Kauffman et al (2011) found that soils in Micronesian mangrove forests contained ~70% of the ecosystem's carbon stocks.

Since mangrove ecosystems, particularly biomass and soils, are important carbon sinks, they play a significant role in climate change mitigation (Camacho et al 2011, Sahu et al 2016). In developing countries, there has been a growing interest in including mangrove ecosystems in national climate change mitigation strategies, involving them in incentive programs for climate change mitigation (Stringer et al 2015). Specifically, the strategy consists of the reduction of carbon emissions through the reduction of deforestation (Kauffman et al 2011). Mangrove ecosystems warrant preservation and restoration because they capture and preserve significant amounts of carbon; otherwise, they become substantial sources of greenhouse gases when disturbed (eg, land-use change) (Kauffman et al 2020). Therefore, policy and decision-makers should consider the balance between the ecological significance of mangroves as carbon sinks and other economic activities.

As an archipelagic country with an extensive coastline, the Philippines is considered one of the most mangrove-rich countries in the world (Giri et al 2011). Consequently, a large part of the country's population depends on ecosystem services provided by these mangrove ecosystems (Garcia et al 2014). More than half of the country's 1,500 towns and 42,000 villages derive benefits from these marine habitats for food and other goods and services (Primavera 2000). However, anthropogenic pressures have resulted in the degradation and contraction of the country's mangrove forests over the past century (Long and Giri 2011). The total mangrove area has decreased by almost half (Field et al 1998), from an estimated 400,000 to 500,000ha in 1920 (Buitre et al 2019). Of the remaining mangrove forests in the Philippines (256,185ha), only a small proportion (19% or 49,363ha) is located within existing protected area networks (Long and Giri 2011). Specifically, the deforestation of mangrove forests in the Philippines has been attributed to coastal dwellers' overexploitation and conversion to aquaculture, salt ponds and settlements, as well as government sanctioned reclamation and industrial developments (Melana et al 2000, Primavera 2000, Richards and Friess 2016). Thus, the historical removal of the mangrove forests must have negatively impacted its various ecological functions, including as a carbon sink.

Mangrove forests store large quantities of carbon; thereby, their quantification is essential in determining the long-term dynamics associated with climate change or land management (Kauffman and Donato 2012). However, in the Philippines, the majority of the studies on carbon stock measurements/estimations in mangrove forests have mainly focused on biomass carbon stocks (Gevaña et al 2008, Camacho et al 2011, Castillo et al 2018, Alimbon and Manseguiao 2021, Nesperos et al 2021), with limited studies on the determination of ecosystem carbon stocks by considering the soil component (Salmo III and Gianan 2019). To the authors' knowledge, no previous studies in the Philippines have been conducted to directly assess the carbon storage relative to the mangrove forest types, where carbon storage distribution or variability has been observed to be influenced by mangrove forest formations or geomorphic settings (Kauffman et al 2020). There have been no previous studies on carbon stocks on Leyte Island, particularly in the area of interest, even though the island or the province ranked 11th out of 66 provinces in terms of mangrove forest cover (5,807.07ha) in the country (Long and Giri 2011). Therefore, the current study was conducted to address the above-mentioned gaps in knowledge. The objectives of the study were (a) to quantify and determine any difference in aboveground carbon stocks (live trees, palm, shrubs, standing dead trees, downed wood and litter), belowground (root, soil), and ecosystem carbon stocks between forest types (fringe and riverine) and zones (landward, middleward, and seaward/along the water) of mangrove forests along the Carigara Bay, and (b) to examine the interrelationship between environmental factors with carbon stocks. Furthermore, in this study, we hypothesize that (a) mangrove forest ecosystems along the Carigara Bay are significant carbon sinks, (b) greater carbon stocks are found in riverine than in fringe mangrove forests, (c) most of the carbon of the mangrove forests is stored in the soil, and (d) soil depth affects carbon storage.

MATERIALS AND METHODS

Study Area and Sites

The present study on the carbon stocks estimation was conducted on the mangrove forest ecosystems along Carigara Bay in Leyte Island (Figure 1). Typically, the mangrove forests along the bay are represented by stands of fringe and riverine mangrove forests distributed among the five surrounding coastal municipalities (Capoocan, Carigara, Barugo, San Miguel and Babatngon).

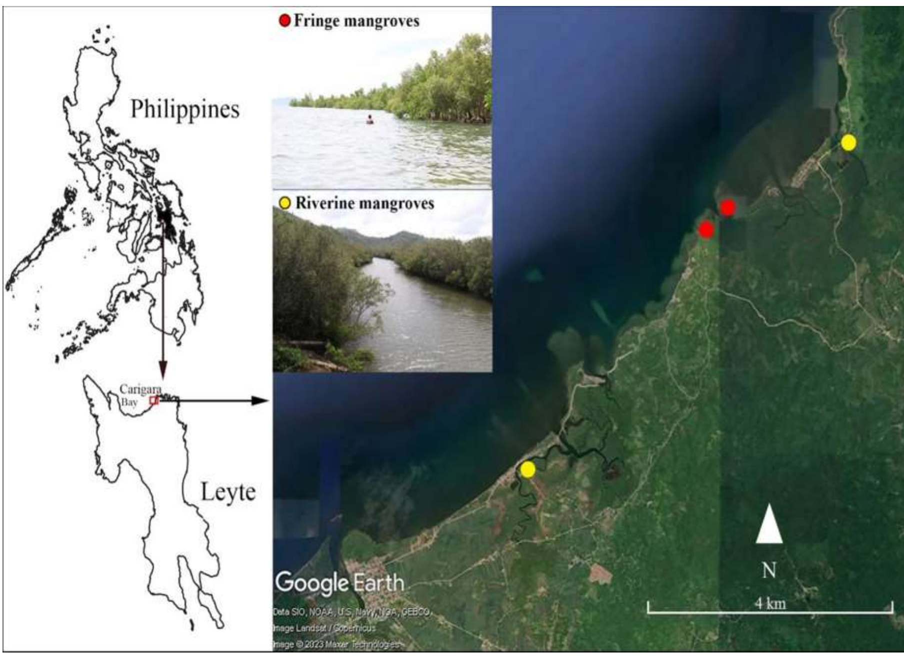


Figure 1. Map of the study area, and study sites (fringe and riverine mangroves) along the Carigara Bay in Leyte, Philippines

The study area experiences an equatorial rainforest-fully humid climate (Kottek et al 2006). It is characterized by the absence of a dry season, but rather with more or less evenly distributed rainfall throughout the year. The warmest month of the year is April, with a mean annual temperature of 27°C, while pronounced wetness is observed in November, December and January, with annual total precipitation of 2293mm (Quiñones and Asio 2015, Marteleira 2019).

The sites in the present study included fringe and riverine mangrove forests along the bay. The fringe mangroves considered were those mangrove forest stands bordering the beach/coastline of the bay, which are constantly subjected to tidal flooding (Ross et al 2006). There were two stands of these mangrove forests sampled, one stand is in Barangay Mawodpawod, and the other one is in Barangay Malpag, both located in the municipality of San Miguel. The two stands are separated by a small stream, and the sampling location from these stands was 500m away from each other. The stands of fringe mangroves sampled were about

60–200m wide from the landward to the seaward zone. The nearest community was about 500m away.

Similarly, two riverine mangrove stands near the estuary from two rivers draining toward Carigara Bay were sampled. Typically, these mangrove stands occupy the floodplain along a river drainage or a tidal creek, which are inundated by most high tides and dry up at most low tides (Cintrón and Shaeffer-Novelli 1984). The first mangrove stand was in Barangay Bagacay of the municipality of San Miguel. The river is approximately 3.2km long and starts flowing from the western side of the Babatngon Range. The sampled mangrove stand was located 200m from the mouth of the river. The other riverine mangrove stand was in Barangay Minuhang of the municipality of Barugo. The mangrove stand was approximately 800m from the estuary, with settlements on the opposite side of the river. The river is approximately 4.4km long and originates from hilly areas in the southern direction of the river system. Both mangrove stands are characterized by large-sized mangrove trees (>100cm DBH).

Plot Establishment and Sampling

Reconnaissance surveys were conducted first to identify the mangrove stands to be sampled. The geographic location of each sampling station was determined using a handheld GPS (Model etrex). All the field samplings were carried out from July 2022 to February 2023. Additionally, the necessary permit for this study (Wildlife Gratuitous Permit DENR-GP No. 2022-39) was obtained from the Department of Environment and Natural Resources (DENR), Region VIII, Tacloban City, Leyte.

Aboveground Carbon Stocks

Standing trees

The method proposed by Kauffman and Donato (2012) was used to sample live mangrove trees. The method employed establishing a 125m long transect line parallel to the coastline in each zone (landward, middleward and seaward) in every site. The transect line in the landward zone was laid 15m from the adjacent terrestrial forest and a transect line at the seaward zone was laid approximately 15m from the ecotone. Along the transect line, a 7m radius circular plot with an area of 154m^2 was demarcated at 25m intervals. In the riverine mangroves, transect lines of the same length were laid at one side of the bank, parallel to the river. Similarly, the riverine mangrove stand was divided into three zones, the landward, which is adjacent to the terrestrial forest or ecosystem, middleward or interior, and along the water close to the bank. The transect lines were also established at the same distance from the ecotones.

In each mangrove forest type (fringe and riverine), 36 circular plots were established, bringing the total number of plots to 72. All the standing trees with a DBH of ≥5cm inside the plot were counted and measured for DBH and height. The height of the tree was visually determined using a 2m long calibrated pole (Madeira et al 2009, Decena et al 2022). Each tree sampled was identified up to the species level using *The Field Guide to Philippine Mangroves* of Primavera (2009) and the *Handbook of Mangroves in the Philippines-Panay* of Primavera et al (2004).

To estimate the aboveground tree biomass (W_{top}), the general allometric equation developed by Komiyama et al (2005) for mangrove trees in Southeast Asia was used. The equation is as follows:

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

where ρ is the wood density of mangrove tree species, and D is the diameter-at-breast height (DBH). The wood density for each of the mangrove tree species was extracted from the wood density database of the International Center for Research in Agroforestry (ICRAF) (2023). The individual tree biomass values were computed using the above biomass allometric equation and were summed to give the total tree biomass stock. The biomass stock was then divided by the area sampled ($154m^2$) to give a value in kg m^{-2}. This value was converted into Mg ha^{-1} by multiplying it by 10. Since the study area belongs to the tropical region, the tree biomass stock was converted to carbon stock density by multiplying it with the default carbon value of 0.47, as recommended by the Intergovernmental Panel on Climate Change (IPCC) (2006).

Palms

The biomass of the non-woody nipa palms (eg, *Nypa fruticans*) was sampled either by non-destructive or destructive methods. The average mass of the palm leaves was determined by harvesting 22 leaves covering varying size distributions. Leaves were cut at ground level and transported to the laboratory for oven drying. However, for the very large nipa leaves (>6m in height), the total fresh weight of the whole leaf was determined in the field using a digital weighing scale. Then, only two subsamples of 300g each were taken from leaflets and rachis for oven-drying. The fresh and oven-dry weights of the sub-samples were subsequently used to compute/adjust the dry biomass of the whole leaf. Also, all the leaves inside the plot were counted. The mass of the nipa leaves was calculated by multiplying the total number of leaves with the average oven-dried/estimated mass of the leaves. Then, to convert leaf mass to carbon mass, a conversion factor of 0.47 was used (Kauffman et al 1998).

Shrub Mangroves

The shrub mangroves (<5cm DBH) were sampled from the nested 2m radius circular plots located at the center of the main plot. The main stem diameter (30cm above the ground) and height were measured for each individual and later used to calculate aboveground biomass. To calculate the aboveground biomass of shrub mangroves, the allometric equation developed in Puerto Rico by Cintrón and Shaeffer-Novelli (1984) was used. The equation is,

$$\text{Biomass (g)}=125.9571 D_{30}^{2} \times H(m)^{0.8557}$$

D_{30} is the diameter 30cm above the ground, and H is the height (m). The biomass of the individuals was computed and summed to give the total shrub biomass stock. The biomass stock was divided by the area sampled ($12.57m^2$) to arrive at a value in g m^{-2}; then, the value was converted to Mg ha^{-1} by dividing it by 100. Lastly, the biomass stock was converted to carbon stock by multiplying it with the conversion factor of 0.47 (Kauffman et al 1998).

Standing Dead Trees

Standing dead trees were also recorded within each main plot. The decay status of each standing dead was further noted as decay status 1, decay status 2 and decay status 3 (Fourqurean et al 2014). Decay status 1 is when the dead tree retains small branches and twigs and resembles a live tree except for the absence of leaves. Decay status 2 characterizes the absence of twigs/small branches and may have lost a portion of large branches. In decay status 3, the dead tree has few or no branches, standing stem only, and the main stem may be broken-topped. The dead tree biomass (decay status 1) was estimated using the live tree estimations but was subtracted by a constant of 2.5% of the live tree biomass estimate. Likewise, the biomass of a dead tree with decay status 2 was estimated by subtracting 10-20% from the live tree biomass estimate. For dead trees with decay status 3, biomass estimation first involves determining volume using an equation for a frustum (truncated cone). The diameter at the base, DBH, and tree height were determined to accomplish this. Eventually, biomass was derived by multiplying the volume by the wood density. Then, the biomass was converted using an acceptable default value of 0.50 based on carbon concentrations of dead wood in tropical forests (Kauffman et al 1995).

Downed Wood

To sample downed wood (≤7.6cm diameter), the planar intercept method (Brown 1974, Waddell 2002) was employed by establishing four 12m transects extending from the center of the circular main plot, oriented at 45° along the transect. The downed wood with a diameter ≤7.6cm was tallied according to size classes along the subsections of the sampling plane: 0.6–2.5cm, 3m plane; 2.5–7.6cm, 10m plane. Downed wood with a diameter of >7.6cm was measured in actual diameter (cm) along a 12m sampling plane and further noted in terms of decay status, whether sound or rotten. The smallest class of downed wood (0–0.6cm) was collected in litter sampling (Kauffman and Donato 2012). Representative samples of each size class were collected and measured for their diameter. As a requirement for computing downed wood volume or carbon stock, quadratic mean diameters (QMD) (Brown and Roussopolous 1974) of the collected samples were determined using the following equation:

$$QMD = \sqrt{\frac{(\sum d_i^2)}{n}}$$

where d_i is the diameter of each sampled piece of wood in the size class, and n is the total number of pieces sampled. Also, the wood-specific gravity (g cm^{-3}) of the collected samples was determined through oven drying (105°C) and then using the water displacement method. Now, the downed wood volume of all the size classes was determined using the equations of van Wagner (1968) and Brown (1971). For fine, small, and medium wood size classes, the equation is,

$$\text{Volume}\left(m^3ha^{-1}\right) = \pi^2 * \left(\frac{N_i * QMDI_i^2}{8 * L}\right)$$

where N_i is the count of intersecting woody debris pieces in size class i, QMD_i is the quadratic mean diameter of size class i (cm) and L is the transect length (m). For the large (>7.6cm diameter) downed wood, the equation is,

$$\text{Volume}\left(m^3ha^{-1}\right) = \pi^2 \left(\frac{d_1^2 + d_2^2 + d_3^2 + ... + d_n^2}{8 * L}\right)$$

where d_1, d_2, etc. is the diameters of intersecting pieces of large dead wood (cm), L is the length of the transect line for large size class (m). Then, the downed wood biomass was derived by multiplying the volume by wood density. Lastly, wood biomass was likewise converted to carbon mass using a conversion factor of 0.05.

Litter

The litter layer was sampled using two microplots with a dimension of 0.50m x 0.50m laid 2m away from the center of the plot. All the litter materials inside the microplot such as fallen leaves, fruits, flowers, seeds, bark fragments, and small woods (<0.6cm in diameter) were collected and placed in labeled ziplock bags. The samples were transported to the laboratory and oven-dried at a temperature of 80°C until the weights of the samples became constant. The oven-dried litter biomass was divided by the area sampled to get a value in g m^{-2}, then the value was divided by 100 to get a value in Mg ha^{-1}. Finally, the litter biomass was multiplied with the recommended conversion factor of 0.45 (Kauffman and Donato 2012) to obtain the carbon content.

Belowground Carbon Stocks

Tree roots

To estimate the root biomass (W_R) of mangrove trees the allometric equation developed by Komiyama et al (2005) was used. The equation is as follows:

$$W_R = 0.199\rho^{0.899}D^{2.22}$$

Similarly to the computations of the aboveground biomass, the belowground biomass for each mangrove tree was computed using the above allometric equation and then summed up to give the total belowground biomass. The same extrapolations were also performed to derive a biomass value in Mg ha^{-1}. Finally, to derive the belowground root carbon stock, the biomass stock was multiplied by a factor of 0.39 (Kauffman and Donato 2012).

Soil

Inside each 7m radius circular plot, an undisturbed soil core sample was collected using a 1m long half-cylindrical steel sampler with an internal diameter of 6cm. For this study, 72 soil core samples were extracted, though sample lengths varied from 10 to >100cm. The core samples were divided into depth intervals of 0–15, 15–30, 30–50, 50–100, and >100cm (Kauffman et al 2020). At the center of each depth layer, a subsample of 5cm depth with 281 soil samples was taken and placed in a properly labeled ziplock bag to avoid moisture loss. The samples were stored at ambient temperature during the field campaign and then were transported to the laboratory for further analysis.

All the soil samples were oven-dried at 105°C for at least 40h until reaching constant weight. The dry bulk density (DBD) of the sample was determined using the equation,

$$DBD(g\ cm^{-3}) = \frac{DOW_{105(g)}}{SV\ (cm^{-3})}$$

where DOW_{105} is the constant weight after drying at 105°C for 40h, and SV is the sample volume. The organic matter (OM) content was determined by the Walkley-Black method in the Central Analytical Services Laboratory (CASL) of PhilRootcrops, Visayas State University. The organic carbon (OC) was obtained by multiplying the OM with a factor of 0.5 (Pribyl 2010). Finally, the soil carbon stock of the mangrove ecosystem was calculated using the equation,

$$SCS\ (Mg\ ha^{-1}) = [DBD\ (g\ cm^{-3}) \times Soil\ layer\ depth\ (cm) \times OC\ (\%)] \times 100$$

The soil carbon stock for each layer with the corresponding bulk density and organic carbon concentration was computed. Then, individual soil layer carbon stocks were added to derive the total carbon stocks for the whole soil profile.

In addition, interstitial soil salinity was measured using a 5mL plastic syringe and a hand-held salt meter (ATAGO). The measurements were performed in three random locations within a 7m radius from the soil sampling point by utilizing the auger boreholes or digging shallow holes using a machete and allowing the soil water to fill the whole for about 5min.

Soil depth was measured in three random locations within the same distance from the soil sampling point. The measurements were done by inserting a 2m long steel rod or using a straight wooden pole in deeper areas until reaching the impenetrable layer such as bedrock or coral fragment deposits.

Ecosystem Carbon Stocks

The ecosystem carbon stocks were derived by summing up the aboveground (standing live trees, palm, shrubs, standing dead trees, downed wood, and litter), and belowground carbon stocks (root and soil).

Data Analysis

The Generalised Linear Models (GLMs) were performed to examine the influence of mangrove forest types (fringe and riverine) and zones (landward, middleward, and seaward/along water) on aboveground carbon stock components (standing trees, palm, shrubs, standing dead tree, litter, downed wood, and total aboveground), belowground (roots, and soils), ecosystem carbon stocks, and soil properties (dry bulk density and soil organic carbon). The GLMs analyses used gamma distribution with a log link function as the analysis involved continuous data. Post-hoc tests were performed using pairwise comparisons whenever significant variations were found at α=0.05. The relationships between environmental factors (interstitial soil salinity, soil water content, soil depth) and ecosystem carbon stocks were examined using regression analysis. The statistical analysis was performed using SPSS 20 for Windows (IBM Corp 2011).

RESULTS AND DISCUSSION

Floristic Composition

The mangrove forest ecosystems along Carigara Bay are home to about 28 mangrove species that belong to 16 families (Table 1). Overall, the dominant mangrove families were Rhizophoraceae with seven species (*Bruguiera cylindrica*, *Bruguiera parviflora*, *Ceriops decandra*, *Ceriops tagal*, *Rhizophora apiculata*, *Rhizophora mucronata*, *Rhizophora stylosa*), and followed by Avicenniaceae with four species (*Avicennia alba*, *Avicennia marina*, *Avicennia officinalis*, *Avicennia rumphiana*). The fringe mangrove forests with high salinity conditions were dominated by *Sonneratia alba*, while riverine mangrove forests were dominated by nipa palm (*N. fruticans*) and *Avicennia rumphiana*. The understorey layer of the mangrove forests was characterized by the presence of shrub, fern, and vine mangroves such as *Acanthus ebracteatus*, *Acanthus ilicifolius*, *Acanthus volubilis*, *Acrostichum speciosum*, *Brownlowia tersa* and *Finlaysonia obovata*. Additionally, several mangrove associates were observed, mainly represented by *Glochidion littorale*, *Hibiscus tiliaceus* and *Terminalia catappa*, which have also been documented in other mangrove forests in the Philippines, such as in Puerto Princesa Bay, Palawan (Dangan-Galon et al 2016), and Camotes Island, Cebu (Lillo et al 2022). These mangrove associates are mostly sub-woody plants that occur in the adjoining tidal periphery of mangrove forests, with most of them either naturally or accidentally dispersed from the adjacent forest types (Md Isa and Suratman 2021).

Table 1. List of mangrove species sampled in the fringe and riverine mangrove ecosystems along the Carigara Bay in Leyte, Philippines. IUCN red list criteria (IUCN 2023), LC least concern, NT near threatened, VU vulnerable, EN endangered

Family	Species	IUCN Red List
Mangrove Trees/Palm		
Arecaceae	*Nypa fruticans* (Thunb.) Wurmb.	LC
Avicenniaceae	*Avicennia alba* Blume	LC
	Avicennia marina (Forsk.) Vierh.	LC
	Avicennia officinalis L.	LC
	Avicennia rumphiana Hall. f.	VU
Bombacaceae	*Camptostemon philippinensis* (Vidal) Becc.	EN
Combretaceae	*Lumnitzera littorea* (Jack) Voigt.	LC
Euphorbiaceae	*Excoecaria agallocha* L.	LC
Meliaceae	*Xylocarpus granatum* Koen.	LC
Myrsinaceae	*Aegiceras corniculatum* (L.) Blanco	LC
	Aegiceras floridum Roem. and Schult.	NT

Table 1. continued

Family	Species	IUCN Red List
Myrtaceae	*Osbornia octodonta* F. Muell.	LC
Rhizophoraceae	*Bruguiera cylindrica* (L.) Blume	LC
	Bruguiera parviflora Wight and Arn. ex Griff.	LC
	Ceriops decandra (Griff.) Ding Hou	NT
	Ceriops tagal (Perr.) C.B. Rob.	LC
	Rhizophora apiculata Blume	LC
	Rhizophora mucronata Lam.	LC
	Rhizophora stylosa Griff. *	LC
Rubiaceae	*Scyphiphora hydrophyllacea* Gaertn.	LC
Sonneratiaceae	*Sonneratia alba* J. Smith	LC
Sterculiaceae	*Heritiera littoralis* Dryand. ex W. Ait.	LC
Understorey		
Acanthaceae	*Acanthus ebracteatus* Vahl	LC
	Acanthus ilicifolius Lour.	LC
	Acanthus volubilis Wall.	LC
Apocynaceae	*Finlaysonia obovata* Wall.	-
Malvaceae	*Brownlowia tersa* (L.) Kosterm.	NT
Pteridaceae	*Acrostichum speciosum* Willd.	LC

Aboveground Carbon Stocks

Mangrove ecosystems have high carbon sequestration capacity, as reflected by their high aboveground biomass (Aye et al 2022). The variations in aboveground carbon stock components in the mangrove ecosystems along Carigara Bay are presented in Figure 2 and Table 2. Importantly, the total aboveground carbon stocks differed significantly between mangrove forest types, where it was observed to be higher in riverine (306.57±58.15) compared to fringe mangrove forests (197.35±19.14), with an average of 251.96±31.08Mg ha^{-1} (Figure 2G). The recorded average total aboveground carbon stocks surpassed those of the carbon estimates for the community-managed mangrove forest in Bohol, Philippines (106.4Mg ha^{-1}, Camacho et al 2011), mangrove forests of Sofala Bay (33.38Mg ha^{-1}, Sitoe et al 2014) and Zambezi River Delta, Mozambique (163.66Mg ha^{-1}, Stringer et al 2015) and Kanhlyashay natural mangrove forest, Myanmar (113.44Mg ha^{-1}, Aye et al 2022). Also, the present value appeared to be comparable to the total aboveground carbon stocks for mangrove ecosystems in Tanga, Tanzania (64.13-301.53Mg ha^{-1}, Alavaisha and Mangora 2016) and Palau (261Mg ha^{-1}, Donato et al 2012). Within the study area, total aboveground carbon stocks varied spatially, comparatively higher in the riverine mangrove forests. This observation corroborated the recent study of Kauffman et al (2020), who recorded higher aboveground carbon stocks in estuarine or riverine areas than in basin or fringe mangrove forests. Similarly, Adame et al (2013) arrived at the highest aboveground carbon stock estimations of the Mexican Caribbean mangrove forests associated with springs and waterways. Such higher carbon stocks in riverine areas or along waterways can be strongly attributed to lower salinities, greater inputs of nutrients, sediment and freshwater, resulting in higher productivity in mangroves (Fatoyinbo et al 2008, Krauss et al 2010).

Table 2. The results of Generalised Linear Models (GLMs) analyses on the carbon stocks of mangrove ecosystems along the Carigara Bay in Leyte, Philippines

Variable	Wald Chi-Square	df	p
Standing tree C (Mg ha^{-1})			
Mangrove forest type	4.61	1	0.032
Zone	1.13	2	0.569
Interaction	0.66	2	0.719
Palm C (Mg ha^{-1})			
Mangrove forest type	0.37	1	0.542
Zone	19.95	2	<0.001
Interaction	-	-	-
Shrub C (Mg ha^{-1})			
Mangrove forest type	0.19	1	0.661
Zone	27.35	2	<0.001
Interaction	8.48	2	0.014
Standing dead tree C (Mg ha^{-1})			
Mangrove forest type	1.69	1	0.194
Zone	0.51	2	0.774
Interaction	6.06	2	0.048
Downed wood C (Mg ha^{-1})			
Mangrove forest type	10.70	1	0.001
Zone	14.23	2	0.001
Interaction	8.21	2	0.017
Litter C (Mg ha^{-1})			
Mangrove forest type	1.11	1	0.292
Zone	4.45	2	0.108
Interaction	2.02	2	0.363
Total aboveground C (Mg ha^{-1})			
Mangrove forest type	4.94	1	0.026
Zone	1.54	2	0.464
Interaction	0.39	2	0.823
Root C (Mg ha^{-1})			
Mangrove forest type	2.08	1	0.149
Zone	0.84	2	0.657
Interaction	0.76	2	0.685
Soil C (Mg ha^{-1})			
Mangrove forest type	424.58	1	<0.001
Zone	23.93	2	<0.001
Interaction	16.02	2	<0.001
Total belowground C (Mg ha^{-1})			
Mangrove forest type	313.23	1	<0.001
Zone	12.45	2	0.002
Interaction	6.09	2	0.048
Ecosystem C (Mg ha^{-1})			
Mangrove forest type	69.45	1	<0.001
Zone	5.10	2	0.078
Interaction	0.96	2	0.618

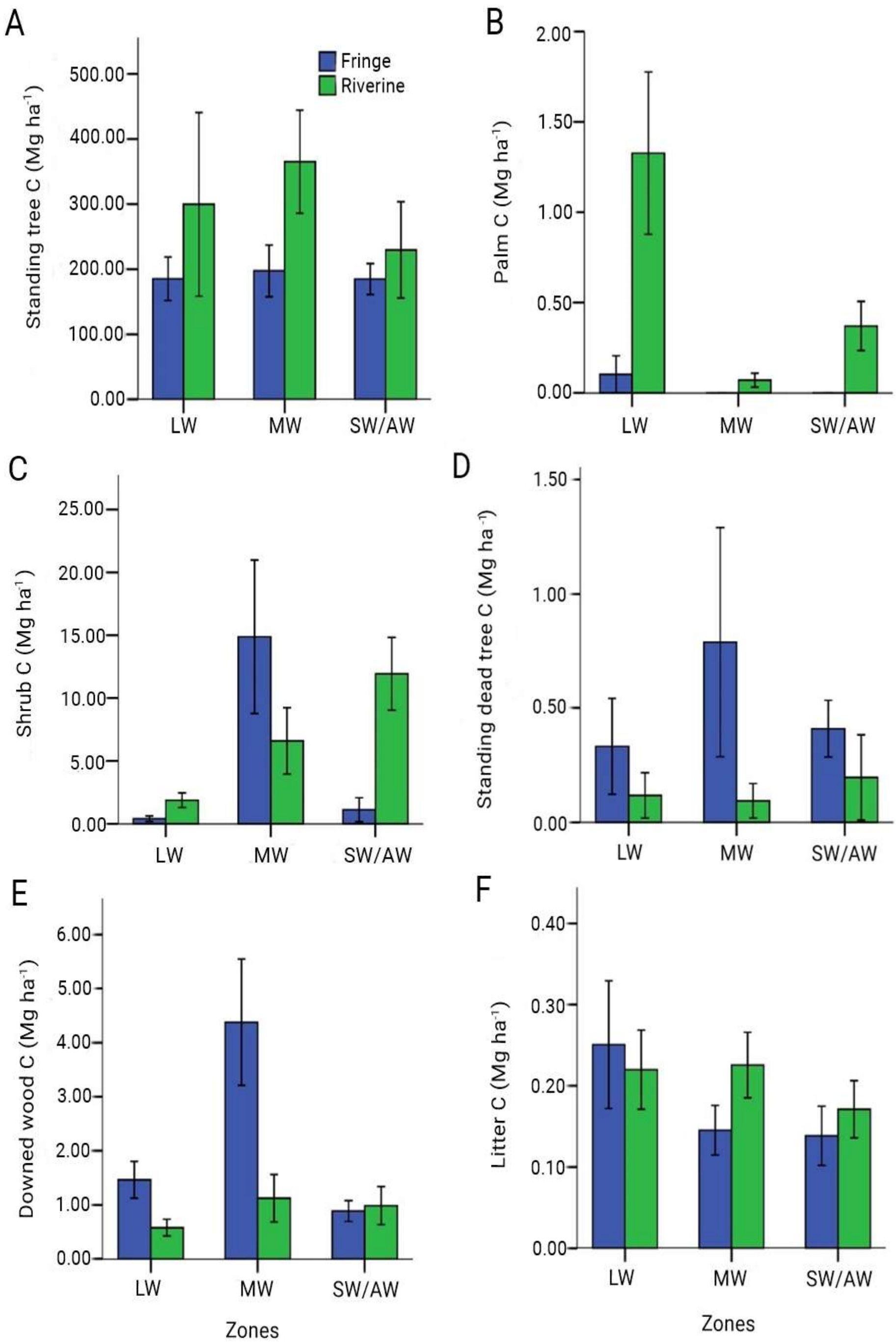


Figure 2. The differences in (A) standing tree, (B) palm, (C) shrub, (D) standing dead tree, (E) downed wood, (F) litter, and (G) total aboveground carbon stocks of mangrove ecosystems along the Carigara Bay in Leyte, Philippines. LW–landward, MW–middleward, SW/AW–seaward/along water

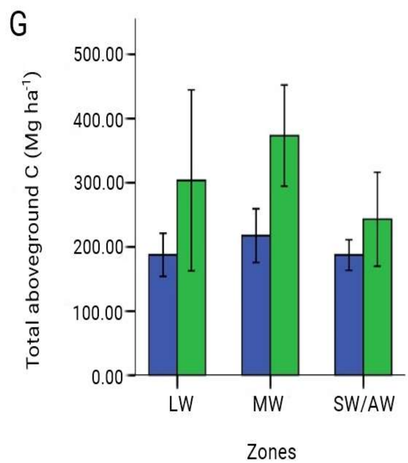


Figure 2. continued

As expected, aboveground carbon stocks are concentrated in standing live trees which accounted for as much as 96.62%, as also observed by other authors (Sitoe et al 2014, Stringer et al 2015). Typically, the higher carbon-storing capacity of mangroves can be directly associated with the increase in biomass (O'Connor 2003), which results from photosynthetic activities and eventually leads to horizontal and vertical growth (Syamani et al 2012). The observed higher standing tree carbon stocks in the riverine compared to the fringe mangrove forests can be associated with favorable environmental conditions (inputs of nutrients in sediments and freshwater) (Fatoyinbo et al 2008), as previously mentioned. This is indicated by huge and adult mangrove trees (>100cm DBH), specifically *A. rumphiana* dominating the riverine mangrove forests. While it appears that the dominance of large trees contributed to large aboveground carbon stocks, other authors reported that stem density was the most important factor in carbon accumulation in biomass (Camacho et al 2011, Harishma et al 2020). Additionally, previous studies also indicated that variation in tree age, tidal and geomorphology influence the on-site carbon stock variability (Bouillon et al 2008, Alongi 2014, Zhang et al 2019). In the present study, geomorphological settings were also likely to have contributed to the variation in carbon stocks, with mangrove forests established at riverine or estuarine areas having higher carbon stocks than those in fringe areas. Such a pattern was likewise observed for carbon stocks of mangrove forests of Bintuni and Kaimana Regencies of West Papua Province, Indonesia (Sasmito et al 2020b).

Species-Wise Contribution to Standing Tree and Root Carbon Stocks

Figure 3A depicts the species-wise contribution of 15 mangrove species to standing tree carbon stocks in fringe mangrove forests. The largest standing tree carbon stocks contribution was from *S. alba* with a value of 116.18±20.68, followed by other two species with larger carbon stocks, such as *A. rumphiana* (37.13±14.92) and *A. marina* (25.14±8.29Mg ha^{-1}). On the other hand, only one out of 19 mangrove species, including mangrove associates, had a greater contribution to standing tree carbon stocks in the riverine mangrove forests, which was the *A. rumphiana* with a value of 259.60±60.82Mg ha^{-1} (Figure 3B). When both mangrove forest types are considered, the mangrove species with the largest standing tree carbon stocks contribution was *A. rumphiana* with a value of 148.37±33.78, followed by other two species such as *S. alba* (60.70±12.33) and *A. marina* (14.41±4.09Mg ha^{-1}) (Figure 3C). For belowground (root) carbon stocks, the pattern of contribution of mangrove species was similar to the standing tree carbon stocks. In the fringe mangrove forests, the largest root carbon stock contribution was still from *S. alba* with a value of 34.69±5.72, followed by *A. rumphiana* and *A. marina* with a value of 9.83±3.78, and 7.09±2.29Mg ha^{-1}, respectively (Figure 4A). Meanwhile, *A. rumphiana* had the most significant root carbon stock contribution (62.29±13.53Mg ha^{-1}) in the riverine mangrove forests (Figure 4B). With fringe and riverine mangrove forests combined, still *A. rumphiana* accounted for the largest root carbon stocks contribution with a value of 36.06±7.34, followed by *S. alba* (18.06±3.49) and *A. marina* (4.56±1.23Mg ha^{-1}) (Figure 4C). Several studies have shown that *A. marina* in the Philippines and India accumulated the largest carbon (aboveground and belowground) where values may range from 71.3-81.09Mg ha^{-1} (Gevaña et al 2008, Harishma et al 2020, Sahu et al 2016, Camacho et al 2011), other authors reported different species such as *A. alba* (80.28Mg ha^{-1}) in Malaysia (Islam et al 2022), and *A. officinalis* (3.92Mg ha^{-1}) in Myanmar (Aye et al 2022). Even in the present study, mangrove species that contributed the largest aboveground and belowground biomass carbon stocks varied between mangrove forest types. For example, *S. alba* contributed the largest aboveground and belowground (root) carbon stocks, a dominant species in the seaward zone of fringe mangrove forests. This mangrove species is intolerant to prolonged periods of freshwater and prefers high salinity (IUCN 2024). Besides tolerance to high salinity conditions, it is regarded as a fast-growing species that prefers the lower intertidal zone, which can be the reason for its ability to accumulate high biomass (carbon) along seaward margins (Banerjee et al 2013, IUCN 2024). Whereas *A. rumphiana* in the riverine mangrove forests contributed the largest aboveground and root carbon stocks, this mangrove is associated with riverine ecosystems with freshwater inputs as indicated by lower soil salinity concentrations in the studied mangrove stands (Decena et al 2024). Typically, this mangrove species prefers higher intertidal regions and downstream estuarine zones and colonizes newly formed mudflats (Robertson and Alongi 1992, Terrados et al 1997). Most importantly, *A. rumphiana* is also regarded as a fast-growing species, forming mono-specific stands of big, old trees (Terrados et al 1997, Primavera et al 2004), eventually accounting for their higher carbon stock contributions in riverine mangrove ecosystems.

Belowground Carbon Stocks

The belowground biomass is regarded as an important component of mangroves as it comprises a relatively high proportion of the mangrove ecosystem than the terrestrial forest ecosystems (Komiyama et al 2008). For root carbon stocks, no significant differences were observed either between mangrove forest types or zones (Figure 5A, Table 2). It appears that in the present study, 18-29% of the total mangrove carbon stocks are accounted for by the root carbon stocks, which is comparable to the previous study by Harishma et al (2020) with 31.51% for the mangrove forests in Kerala, India. The higher allocation of biomass (and therefore carbon) in the belowground root systems in mangroves can be considered a requisite adaptation for mangroves to stand firmly in muddy conditions

(Harishma et al 2020). Moreover, the patterns in belowground carbon are generally similar to any trends exhibited in the aboveground carbon, since the DBH is a factor for both biomass calculations (Stringer et al 2015). Root carbon stocks varied from 56.20±4.62 and 74.26±12.79Mg ha^{-1} for fringe and riverine mangrove forests, where the values were higher compared to the estimated root carbon stocks for Sofala Bay mangrove forests of central Mozambique (25.22Mg ha^{-1}, Sitoe et al 2014), but comparable to the coastal mangroves of the Mexican Caribbean (59.24Mg ha^{-1}, Adame et al 2013). In contrast, measured root carbon stocks for Micronesian mangroves (68-203Mg ha^{-1}, Kauffman et al 2011, Donato et al 2012) were generally higher than in the studied mangroves.

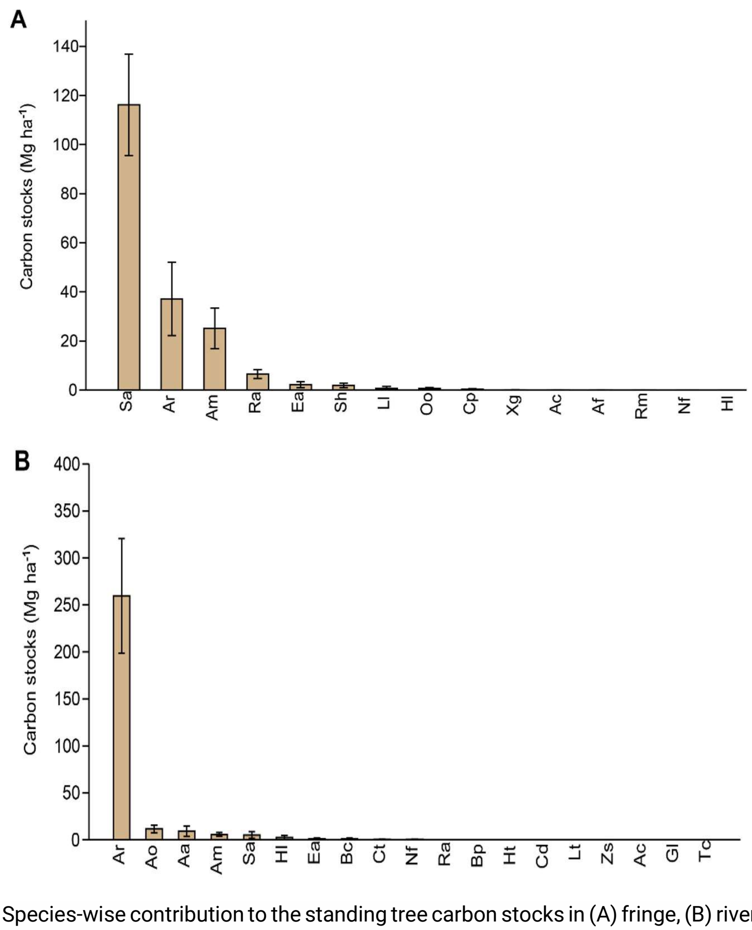
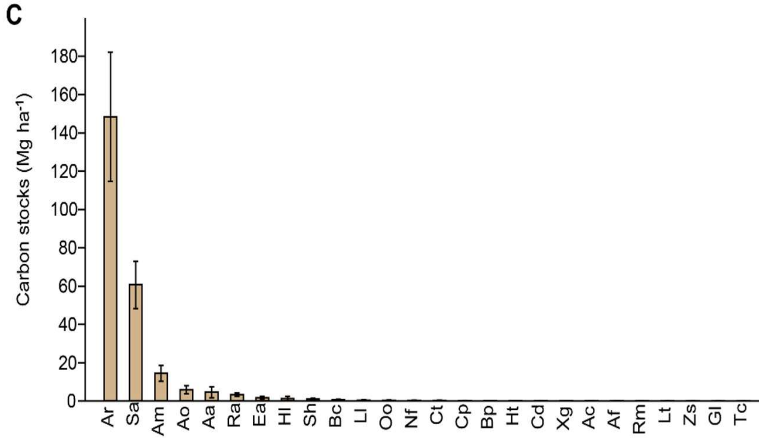


Figure 3. Species-wise contribution to the standing tree carbon stocks in (A) fringe, (B) riverine, and (C) combined mangrove forest types along the Carigara Bay in Leyte, Philippines. Ar–*Avicennia rumphiana*, Sa–*Sonneratia alba*, Am–*Avicennia marina*, Ao–*Avicennia officinalis*, Aa–*Avicennia alba*, Ra–*Rhizophora apiculata*, Ea–*Excoecaria agallocha*, Hl–*Heritiera littoralis*, Sh–*Scyphiphora hydrophyllacea*, Bc–*Bruguiera cylindrica*, Ll–*Lumnitzera littorea*, Oo–*Osbornia octodonta*, Nf–*Nypa fruticans*, Ct–*Ceriops tagal*, Cp–*Camptostemon philippinensis*, Bp–-*Bruguiera parviflora*, Ht–*Hibiscus tiliaceus*, Cd–*Ceriops decandra*, Xg–*Xylocarpus granatum*, Ac–*Aegiceras corniculatum*, Af–*Aegiceras floridum*, Rm–*Rhizophora mucronata*, Lt–*Lepiniopsis cf. ternatensis, Zs–Syzygium* sp., Gl–*Glochidion littorale*, Tc–*Terminalia catappa*



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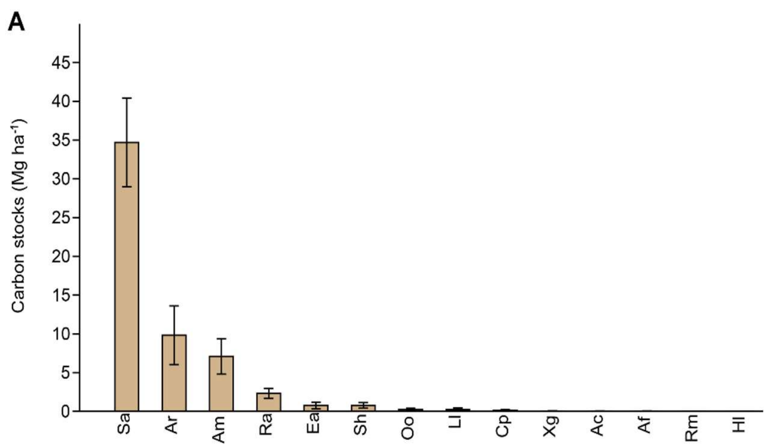
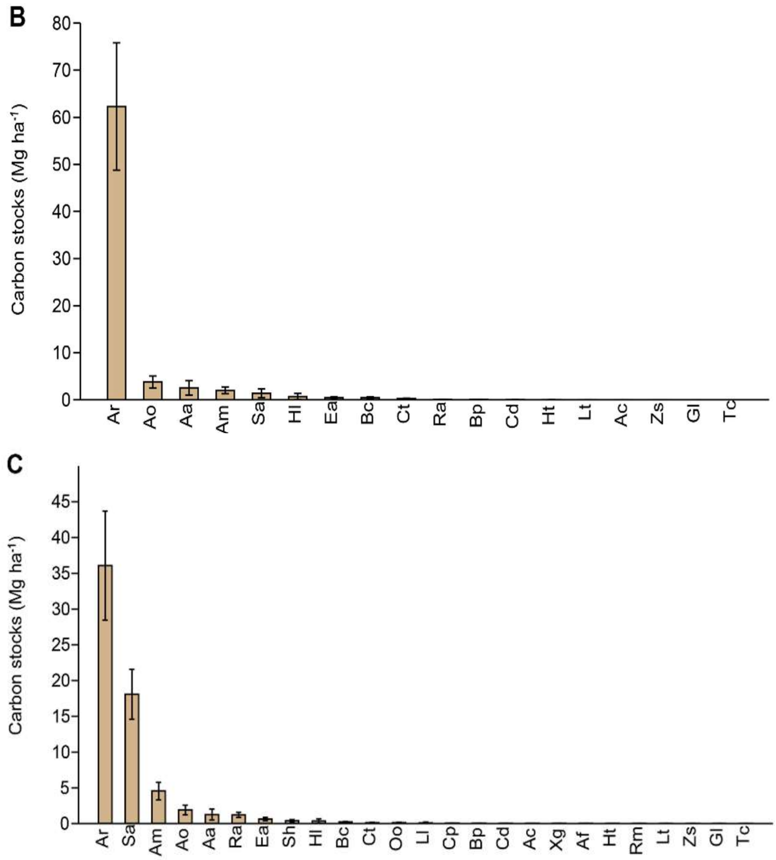


Figure 4. Species-wise contribution to the belowground (root) carbon stocks in (A) fringe, (B) riverine, and (C) combined mangrove forest types along the Carigara Bay in Leyte, Philippines. Ar–*Avicennia rumphiana*, Sa–*Sonneratia alba*, Am–*Avicennia marina*, Ao–*Avicennia officinalis*, Aa–*Avicennia alba*, Ra–*Rhizophora apiculata*, Ea–*Excoecaria agallocha*, Hl–*Heritiera littoralis*, Sh–*Scyphiphora hydrophyllacea*, Bc–*Bruguiera cylindrica*, Ll–*Lumnitzera littorea*, Oo–*Osbornia octodonta*, Ct–*Ceriops tagal*, Cp–*Camptostemon philippinensis*, Bp–-*Bruguiera parviflora*, Ht–*Hibiscus tiliaceus*, Cd–*Ceriops decandra*, Xg–*Xylocarpus granatum*, Ac–*Aegiceras corniculatum*, Af–*Aegiceras floridum*, Rm–*Rhizophora mucronata*, Lt–*Lepiniopsis cf. ternatensis, Zs–Syzygium* sp., Gl–*Glochidion littorale*, Tc–*Terminalia catappa*



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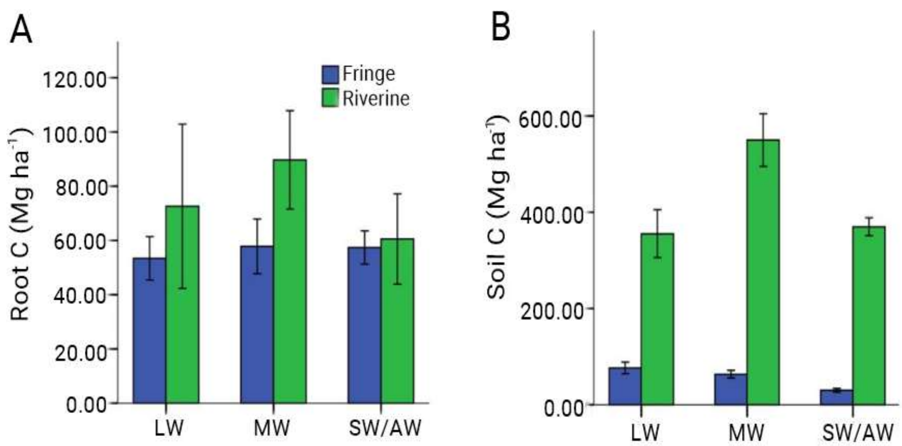
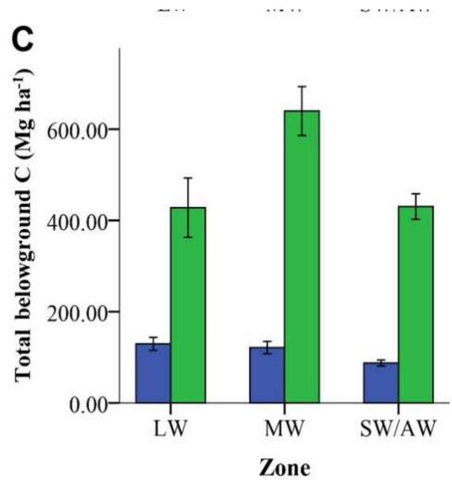


Figure 5. The differences in (A) root, (B) soil, (C) total belowground (soil and roots) carbon stocks of mangrove ecosystems along the Carigara Bay in Leyte, Philippines. LW–landward, MW–middleward, SW/AW–seaward/along water



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The primary elements determining carbon stocks in soils are bulk density, carbon content, and the total depth considered for estimation (Stringer et al 2015, Sasmito et al 2020b). The soil dry bulk density differed significantly among mangrove forest types, zones and interactions (Figure 6A, Table 3). The recorded overall average soil bulk density (0.95±0.04g cm^{-3}) in the mangrove forests of Carigara Bay were comparable to bulk densities (0.7-1.02g cm^{-3}) recorded in some other tropical mangroves such as in northwestern Madagascar (Jones et al 2014), Zambezi River Delta, Mozambique (Stringer et al 2015), and Kerala, India (Harishma et al 2020). Soil bulk densities in the riverine were higher compared to fringe mangrove forests, with an increasing trend with depth, especially where soil depths often exceed 1m, with similar observations by Stringer et al (2015) for mangrove forests of Zambezi River Delta, Mozambique, and Kauffman & Bhomia (2017) in west-central Africa. Soil bulk densities at > 50cm layer were 16-20% higher than the surface layer (0-15cm), indicating increased soil carbon stocks estimation. Similarly, soil organic carbon differed significantly among mangrove forest types, zones, and interactions (Figure 6B, Table 3). The reported average values for other mangrove areas varied from 1.35-1.48% (Sitoe et al 2014, Harishma et al 2020), comparable to the observed value in the study area (1.65±0.04%). However, the current value is lower than that reported by Jones et al (2014) and Donato et al (2012) with 3.17% and 13-15%, respectively. Like the trend of soil bulk density, particularly in riverine sites, soil organic carbon concentrations increased with increasing soil depth. Donato et al (2012) observed consistently high soil organic carbon across soil depth in mangrove soils compared with other ecosystems (eg, savanna and upland forests). Such high organic carbon concentration indicates organic-rich soils (Stringer et al 2015). Lastly, soil depth can also influence soil carbon estimation, as shown in previous studies that have recorded high soil carbon stocks owing to the greater soil depths sampled (Kauffman and Bhomia 2017, Sasmito et al 2020b, Kauffman et al 2020). With the present study, it was expected that the riverine mangrove forests would yield the highest soil organic carbon stock estimates as soil sampling included deeper soil layers (>100cm). Furthermore, Sasmito et al (2020b) noted that sampling deeper soil layers can result in greater precision in soil carbon estimation and understanding carbon stock variability relative to soil depth.

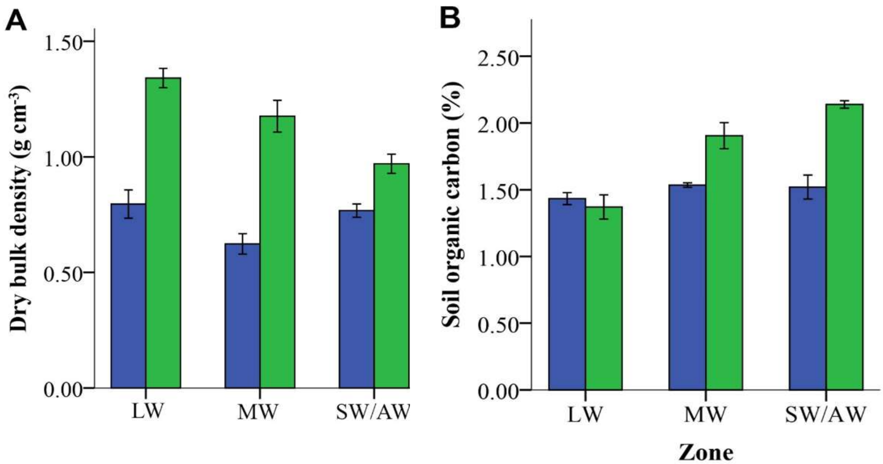

Figure 6. The differences in (A) dry bulk density, and (B) organic carbon of soils in mangrove ecosystems along the Carigara Bay in Leyte, Philippines. LW–landward, MW–middleward, SW/AW–seaward/along water

Table 3. The results of Generalised Linear Models (GLMs) analyses on the dry bulk density and soil organic carbon in mangrove ecosystems along the Carigara Bay in Leyte, Philippines

Variable	Wald Chi-Square	df	p
Dry bulk density (g cm^{-3})			
Mangrove forest type	112.90	1	<0.001
Zone	15.82	2	<0.001
Interaction	14.94	2	0.001
Soil organic carbon (%)			
Mangrove forest type	22.30	1	<0.001
Zone	35.84	2	<0.001
Interaction	19.73	2	<0.001

Mangrove forests store an exceptional amount of carbon in their soils (Atwood et al 2017). In this study, soil was found to be a significant belowground carbon pool, which was three times higher than in roots. Significant variations in soil carbon have been observed among mangrove forest types and zones, as well as with significant interactions (Figure 5B, Table 2). Consistently, soil carbon stocks were higher in the riverine compared to fringe mangrove forests in all the zones, with the highest value of 550.01±54.85Mg ha^{-1} in the middleward. The overall estimated soil carbon stock in the mangrove forests in Carigara Bay was 240.83±26.31Mg ha^{-1}, which was higher than the estimated soil organic carbon stocks of mangrove forests in Kerala, India (81.26±10.16Mg ha^{-1}, Harishma et al 2020), and Sofala Bay, Mozambique (160Mg ha^{-1}, Sitoe et al 2014), and comparable to Zambezi River Delta, Mozambique (286.06Mg ha^{-1}, Stringer et al 2015). However, the soil carbon stocks from this study were much lower compared to those in Brazil's Amazon mangroves (341Mg ha^{-1}, Kauffman et al 2018), and mangrove ecosystems of northwestern Madagascar (429.20Mg ha^{-1}, Jones et al 2014). In the area of interest, the lowest soil carbon stocks have been recorded in fringe mangrove forests where soils or sediments were often found <1m deep. On the other hand, the greatest soil carbon stocks were associated with riverine mangrove forests where maximum soil depth may reach up to 3m, with resulting average soil carbon stocks of 425.06±28.90Mg ha^{-1}. These riverine or estuarine mangroves have higher soil carbon stocks as they are typically supported by extensive allochthonous sediment supply and resulting accommodation space (Sasmito et al 2020b). Additionally, Iimura et al (2019) have found that soil carbon stocks in estuarine subtropical mangroves are positively associated with dead fine roots. The carbon stocks in mangrove ecosystems are concentrated in soils (Sasmito et al 2020b), but this was much more evident in the riverine than in the fringe mangrove forests. It was found that soil organic carbon stocks in the riverine mangrove forests constituted as much as 53% of the ecosystem carbon stocks, which is comparable to other studies where soil carbon comprises around 60-69% of ecosystem carbon stocks (Donato et al 2012, Stringer et al 2015).

The pooled data on root and soil carbon stocks into belowground carbon stocks have varied significantly between mangrove forest types and zones (Figure 5C, Table 2). The pattern of differences was similar to that of soil carbon stocks alone as belowground carbon stocks were predominantly accounted for by soil, which was highest in the riverine mangrove forest (499.32±33.26) and middleward zone (380.50±60.42Mg ha^{-1}). The combined soil and root carbon stocks in riverine were fourfold higher than in fringe mangrove forests, implying that riverine mangrove ecosystems require greater protection as these ecosystems have a higher potential for climate change mitigation (Adame et al 2013). Specifically, minimizing the influence of land use change could be an essential strategy for reducing carbon emissions and sustaining the natural functions of these mangrove forest ecosystems as carbon sinks (Sasmito et al 2020b).

Ecosystem Carbon Stocks

The ecosystem carbon stocks have varied significantly with forest types, being higher in riverine mangrove forests (805.89±80.57Mg ha^{-1}) than in fringe mangrove forests (310.15±24.59Mg ha^{-1}) (Figure 7, Table 2). The overall average ecosystem carbon stock was 558.02 ± 51.13Mg ha^{-1}, which is three to four times higher than the reported mangrove ecosystem carbon stocks of 139.82±10.67Mg ha^{-1} by Harishma et al (2020), 153.64Mg ha^{-1} by Vinod et al (2019) and 218.5Mg ha^{-1} by Sitoe et al (2014), and similar to the reported value of 497.54Mg ha^{-1} by Stringer et al (2015), 511Mg ha^{-1} by Kauffman et al (2018) and 663Mg ha^{-1} by Adame et al (2013). However, the current value was lower than the estimated ecosystem carbon stocks as obtained by other authors ranging from 799-1,087Mg ha^{-1} (Donato et al 2012, Kauffman and Bhomia 2017, Sasmito et al 2020b), and lower than the global average ecosystem carbon stocks of 885Mg ha^{-1} as reported by Kauffman and Bhomia (2017). However, ecosystem carbon stocks were higher in the riverine mangrove with a value of 805.89±80.57Mg ha^{-1}, the same as the previously mentioned global average. These findings of the study of high ecosystem carbon stocks in riverine sites corroborated with the previous study of Sasmito et al (2020b). The distribution of ecosystem carbon stocks at these sites was 47% and

53% for biomass and soil carbon stocks, respectively. Studies have revealed that soil carbon stocks comprise a major proportion of mangrove ecosystem carbon stocks (Kauffman et al 2011), therefore, sample collection at deeper soil layers enhances carbon stocks estimation.

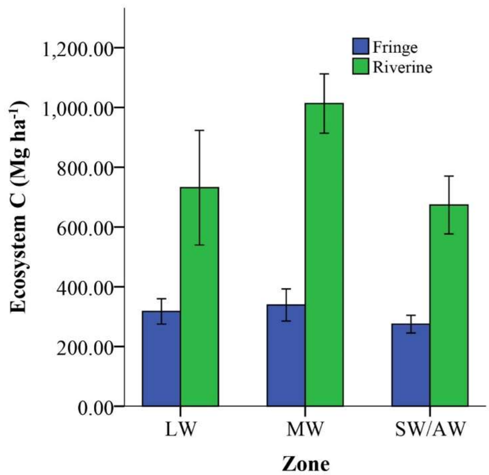

Figure 7. The difference in the ecosystem carbon stocks (aboveground and belowground) of mangrove ecosystems along the Carigara Bay in Leyte, Philippines. LW–landward, MW–middleward, SW/AW–seaward/along water

Environmental Factors and Ecosystem Carbon Stocks

The ecosystem carbon stocks in a mangrove ecosystem have been shown to be affected by suites of environmental factors such as temperature, precipitation, salinity, nutrients and topography (Adame et al 2013, MacKenzie et al 2021). In this study, two significant predictors of ecosystem carbon stocks of mangrove forests along Carigara Bay were interstitial soil salinity (Figure 8A) and gravimetric water (Figure 8B). There exist inverse relationships between them, where increases in interstitial soil salinity and soil water content are accompanied by a decrease in ecosystem carbon stocks. For example, Adame et al (2013) found that sites with the lowest ecosystem carbon stocks in tropical coastal wetlands of the Mexican Caribbean were associated with high salinity. Specifically, high salinity conditions reduce mangrove productivity and significantly impede forest growth with reduced stand structural properties (Ahmed et al 2022). Similarly, soil water content reduces ecosystem carbon stocks, where the lowest ecosystem carbon stocks have been observed in fringe mangrove forests. The soils at these sites were highly saturated and constantly influenced by higher tidal ranges. Here soils are likely to experience lower decomposition rates, with less nutrients being available for tree growth (Komiyama et al 2008), and anoxic soil conditions that would facilitate carbon accumulation (Schmidt et al 2011).

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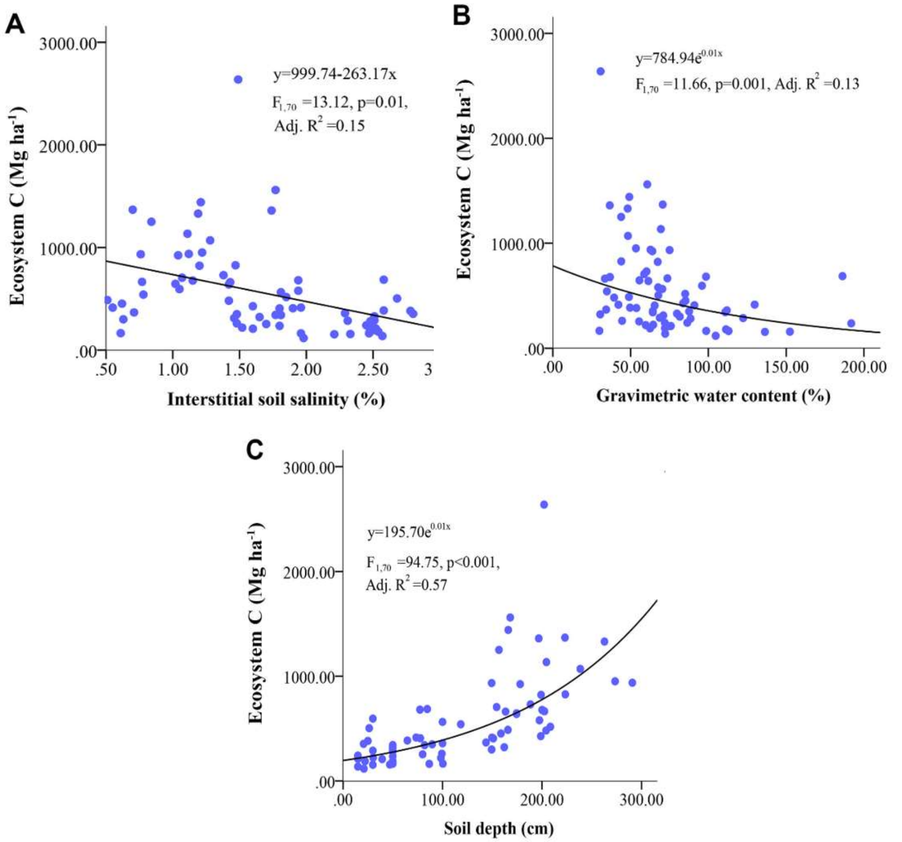

Figure 8. The relationships between (A) interstitial soil salinity and ecosystem carbon stocks, (B) gravimetric water content and ecosystem carbon stocks, (C) soil depth and ecosystem carbon stocks. The significant regression lines and their equations, R^2, F, and p-values are presented

Most importantly, soil depth (Figure 8C) was the strongest predictor, explaining much of the variation in ecosystem carbon stocks. The direct positive relationship suggests that the increasing soil depth equates to a larger ecosystem carbon stock. This finding supports the conclusion in the previous studies of Kauffman et al (2020) and Sasmito et al (2020b), where large ecosystem carbon stocks are explained by deeper soil or sediment deposits. In the study area, large ecosystem carbon stocks were observed in the riverine sites with deep soil layers of about 3m, coupled with large-size mangrove trees (*A. rumphiana*). At these sites, a large proportion of total ecosystem carbon stocks is accounted for in soils, indicating a more significant carbon burial under waterlogged and anoxic conditions (MacKenzie et al 2021).

Lastly, as a limitation of the study, other environmental factors, including, but not limited to, tidal height, elevation and sediment deposition rate, could have been considered to better capture the variability of carbon stocks in the studied mangrove ecosystems.

CONCLUSIONS

Mangrove forests are unique wetland ecosystems that store large quantities of carbon, and thereby, they play an important role in climate change mitigation. The present study on the quantification of the carbon stocks (aboveground and belowground) resulted in an ecosystem carbon stock estimate of 558.02Mg ha^{-1}, indicating that the mangrove forests along Carigara Bay are a significant carbon sink. The forest types influence carbon stock distribution, whereby the greatest ecosystem carbon stocks were found in riverine mangrove forests. The studied mangrove ecosystems had more or less the same proportion of the amount of carbon stored in biomass and soil, particularly in the carbon-rich riverine mangrove ecosystems. Additionally, the capacity of the mangrove forests to store large amounts of carbon was strongly influenced by increasing soil depth. Therefore, the exceptionally high carbon-storing potential of the studied mangrove forests can be regarded as the basis for the establishment of a local conservation area to sustain its function as a carbon sink and for other ecological services.

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AUTHOR CONTRIBUTIONS

All the authors contributed significantly to the development of the manuscript. SCPD and AOA designed the study. All the authors (SCPD, AOA, CAA, DRM) performed the field data collection and analyses. SCPD and CAA prepared the initial draft of the manuscript, and all authors commented on previous versions. All authors read and approved the final manuscript.

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AVAILABILITY OF DATA AND MATERIALS

The raw data associated with this study is available from the corresponding author upon reasonable request.

ETHICAL CONSIDERATION

Ethics approval is not applicable.

COMPETING INTEREST

There are no competing interests to disclose.

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