Aboveground and Belowground Carbon Stocks in Mangrove Ecosystems Along Carigara Bay in Leyte, Philippines

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Abstract

Mangrove forest ecosystems are known to sequester large quantities of carbon in biomass. This paper presents a quantification of carbon stocks in aboveground (standing trees, palm, shrub, standing dead trees, downed wood, and litter), belowground (root), and total carbon stocks, and further compared between forest types (fringe and riverine) and zones (landward, middleward, and seaward/along water) of mangrove forests along the Carigara Bay in Leyte, Philippines. The aboveground carbon stocks for the standing trees were found to be higher in riverine (297.94 ± 58.39) compared to fringe mangrove forests (188.92 ± 18.51), with an overall average of 243.43 ± 31.09 Mg ha^{-1}. Shrub mangroves were found to be the second most contributor to aboveground carbon stocks which was significantly higher in middleward zone (14.88 ± 6.11 Mg ha^{-1}), though no variation was found between mangrove forest types. Whereas, all other aboveground components were the least contributors (< 1% combined), with a total average of 0.31 ± 0.10, 0.32 ± 0.10, 1.57 ± 0.27, and 0.19 ± 0.02 Mg ha^{-1} for palm (*Nypa fruticans*), standing dead tree, downed wood and litter, respectively. Meanwhile, no significant variations were detected for belowground (roots) carbon stock, with an average of 65.23 ± 6.84 Mg ha^{-1}. Total carbon stocks were higher in the riverine (380.83 ± 70.91), with an average of 317.19 ± 37.88 Mg ha^{-1}. Overall, the results of the study highlight the significant amount of carbon stored in the biomass of the studied mangrove forests, which indicates their potential role in climate change mitigation.

Introductions

Mangrove forests are unique coastal wetland ecosystems however being threatened by human destruction for various developmental needs (Sreelekshmi et al. 2018). These ecosystems are represented by unique forests characterized by highly specialized vegetation and typically under a limiting environment (Walsh 1974). Essentially, mangroves provide various ecosystem services such as habitat for a variety of species, spawning areas of aquatic fauna, maintenance of the marine food chain, provision of food and wood (Petrosian et al. 2016; Singh 2020) and even protection from calamities (e.g., typhoons, tsunamis, and storm surges) (Patindol and Casas Jr. 2019). Above all, biogeochemical cycling (e.g., carbon storage) is the most important environmental service provided by mangrove forests (Sitoe et al. 2014).

Mangrove ecosystems have been globally recognized for their vital function as carbon sinks (blue carbon) since these ecosystems often sequester large quantities of atmospheric carbon (Kauffman and Bhomia 2017). Particularly, mangrove ecosystems can sequester carbon in vegetation especially in mangroves trees (Cleyndert et al. 2020), which accounts for 3–4% of global carbon sequestration by the total tropical forest (Bhomia et al. 2016, Alongi et al. 2020). This is reflected in their global mean biomass of 247 tons per hectare which is equivalent to the global average biomass of tropical humid evergreen forests (Alongi 2009, Camacho et al. 2011, Donato et al. 2012). And since about half of the biomass in mangrove trees is carbon, large amounts of carbon are potentially stored in mangrove forests, suggesting that they may be the largest stores of carbon in coastal areas (Suratman 2008).

Due to the exceptionally high capacity of mangroves to sequester and store carbon, it has drawn interest that mangrove ecosystems be included in climate change mitigation strategies (Kauffman and Bhomia 2017; Cleyndert et al. 2020; Kauffman et al. 2020) focusing on reducing carbon emissions through the reduction of deforestation (Kauffman et al. 2011). As carbon-rich ecosystems, mangroves warrant preservation and restoration because they capture and preserve significant amounts of carbon, however, they become significant sources of greenhouse gases when disturbed through land-use change (Kauffman et al. 2020). Therefore, policy and decision makers should strike a balance between the ecological importance of mangroves as carbon storage, especially with economic activities.

The Philippines is a tropical country that also possessed lush mangrove forest ecosystems along its extensive coastlines. However, human activities have degraded and denuded much of the mangrove forests within the country over the past century (Long and Giri 2011), whereby the total mangrove area has decreased by almost half (Field et al. 1998), from an estimated 500,000 ha in 1918 (Brown and Fischer 1918). With respect to issues on climate change, the country's mangrove ecosystems may have been a significant contributor to greenhouse gas emissions into the atmosphere as reflected by the area of extent of mangrove loss. Despite, the country's extensive mangrove cover which is distributed throughout the archipelago, and the continuous destruction by human activities, few studies exist regarding the estimations of carbon storage among these mangrove ecosystems (Gevaña et al. 2008, Camacho et al. 2011).

Specifically, the study was conducted in the coastal areas of Carigara Bay in Leyte. The island possesses around 5,807.07 ha or 2.26% of the country's mangrove areas (Long and Giri 2011) of which significant mangrove cover can be found in the study area. As observed, the mangrove ecosystems along the bay face numerous threats, a few of which are aquaculture and developments that involves the clearing of mangrove forests. Nevertheless, virtually there are no existing studies documenting the carbon storage (aboveground and belowground) of mangroves in the area, which is important as baseline information for the effective management and conservation of these ecologically significant ecosystems. Therefore, the study was conducted to quantify and determine any difference in aboveground (live trees, palm, shrubs, standing dead trees, downed wood, and litter), belowground (root), and total carbon stocks between forest types (fringe and riverine) and zones (landward, middleward, and seaward/along water) in the mangrove forests along the Carigara Bay in Leyte, Philippines.

Materials and Methods

Study Area and Sites

The study was conducted on the mangrove forest areas along the Carigara Bay in Leyte Island (Fig. 1). Mangrove forest ecosystems 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). However significant areas of mangrove forests along the bay have been lost because of land use conversion mainly due to aquaculture and settlements.

The climate of the study area is characterized as equatorial rainforest-fully humid (Kottek et al 2006). It has no dry season and has more or less evenly distributed rainfall throughout the year. The warmest month is April with a mean annual temperature of 27 ºC and pronounced wetness occurring in the months of November, December, and January with annual total precipitation of 2293 mm (Quiñones and Asio 2015, Marteleira 2019).

The sites considered in the present study included fringe and riverine mangrove forests located along the bay. The fringe mangroves considered were those mangrove forest stands bordering the beach/coastline of the bay. 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 500 m away from each other. The stands of fringe mangroves sampled were about 60–200 m wide from the landward to the seaward zone. The nearest community was about 500 m away, though minor disturbances could be observed in the mangrove areas such as the cutting of branches and harvesting of nipa leaves (*Nypa fruticans*) leaves and collection of other resources (e.g., mud crabs and edible mollusks).

Similarly, two riverine mangrove stands located near the estuary from two different rivers draining toward Carigara Bay were sampled. The first mangrove stand was in Barangay Bagacay of the municipality of San Miguel. The river is approximately 3.2 km in length and starts flowing from the western side of the Babatngon Range. The sampled mangrove stand was located 200 m from the mouth of the river and was adjacent to a highway. The other riverine mangrove stand was located in Barangay Minuhang of the municipality of Barugo. The mangrove stand was approximately 800 m from the estuary, with settlements on the opposite side of the river. The river is approximately 4.4 km in length and originates from hilly areas located in the southern direction of the river system. Typically, both mangrove stands are characterized by the presence of large-sized mangrove trees (> 100 cm DBH). Minor disturbances were observed from these mangrove stands such as the cutting of small branches or small mangrove trees, as well as harvesting of nipa leaves for making nipa shingles.

Plot Establishment and Sampling

Reconnaissance surveys were conducted first to identify mangrove stands to be sampled. The field data collection was conducted from the months of July to October 2022. The geographic location of each sampling station was determined using a handheld GPS (Model etrex). All the field samplings were carried out between July 2022 to February 2023.

Aboveground Carbon Stocks

Standing Trees

The method proposed by Kauffman et al. (2011) was used to sample live mangrove trees. The method employed the establishment of a 125 m-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 15 m from the adjacent terrestrial forest, as well as transect line at the seaward zone was laid approximately 15 m from the ecotone. Along the transect line, a 7 m radius circular plot with an area of 154 m^2 was demarcated at 25 m 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 that is 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 ≥ 5 cm inside the plot were counted and measured for DBH and height. The height of the tree was visually determined using a 2-m long calibrated pole (Madeira et al. 2009, Decena et al. 2022). Each tree individual sampled was identified up to the species level using The Field Guide to Philippine Mangroves of Primavera (2009), and 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 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 (154 m^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 with the default carbon value of 0.47 recommended by the Intergovernmental Panel on Climate Change (IPCC) (2006).

Palms

The biomass of the non-woody nipa palms (e.g., *N. fruticans*) was sampled either by non-destructive or destructive methods. The average mass of the palm leaves was determined by harvesting 22 palm 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 (> 6 m in height), the total fresh weight of the whole leaf was determined in the field using a digital weighing scale. Then, only subsamples of two 300 g were taken each from leaflets and rachis for oven-drying. The fresh and oven-dry weights of the sub-samples were subsequently used for computing/adjusting 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 (< 5 cm DBH) were sampled from the nested 2 m radius circular plots located at the center of the main plot. For each of the individuals, the main stem diameter (30 cm above the ground) and height were measured 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,

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

where D_{30} is the diameter 30 cm 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 (12.57 m^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

Within each main plot, standing dead trees were also recorded. 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 still retained 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 biomass of the dead tree (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 involves first the determination of volume using an equation for a frustum (truncated cone). To accomplish this, the diameter at the base, DBH, and tree height were determined. Eventually, biomass was derived by multiplying the volume by the wood density. Then the biomass was converted using a conversion factor of 0.50 (Kauffman et al. 1995).

Downed wood

To sample downed wood (≤ 7.6 cm diameter), the planar intercept method (Brown 1974, Waddell 2002) was employed by establishing four 12 m transects extending from the center of the circular main plot, oriented at 45° along the transect. The downed wood with a diameter ≤ 7.6 cm was tallied according to size classes along the subsections of the sampling plane: 0.6–2.5 cm, 3 m plane; 2.5–7.6 cm, 10 m plane. Whereas downed wood with a diameter of > 7.6 cm was measured in actual diameter (cm) along a 12 m sampling plane and further noted in terms of decay status whether sound or rotten. The smallest class of downed wood (0–0.6 cm) was rather 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,

$$\mathrm{QMD} = \sqrt{\frac{\left(\Sigma \mathrm{d}_\mathrm{i}^2\right)}{\mathrm{n}}}$$

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,

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

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 (> 7.6 cm diameter) downed wood, the equation is,

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

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 is converted to carbon mass using an acceptable default value of 0.50 based on carbon concentrations of dead wood in tropical forests.

Litter

The litter layer was sampled using two microplots with a dimension of 0.50 m x 0.50 m laid 2 m 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 (< 0.6 cm in diameter) were collected and placed in properly 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 carbon content.

Belowground Carbon Stocks

Tree Roots

To estimate the root biomass (W_R) of mangrove trees, still, 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 computation 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 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).

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 total carbon stocks. The GLMs analyses used gamma distribution with a log link function as the analysis involved continuous data. Post-hoc tests were performed whenever there were significant variations at $\alpha = 0.05$, using pairwise comparisons. The statistical analysis was performed using SPSS 20 for Windows.

Results

Aboveground and Belowground Carbon Stocks

The GLMs analysis revealed that standing tree carbon stocks differed significantly between mangrove forest types, but not with zones (Table 1; Fig. 2a). The standing tree carbon stocks were higher in riverine (297.94 ± 58.39) compared to fringe mangrove forests (188.92 ± 18.51), with an overall average of 243.43 ± 31.09 Mg ha^{-1}. The nipa palm (*N. fruticans*) carbon stocks only differed significantly between zones (Table 1; Fig. 2b) where it was higher in the landward (0.71 ± 0.26) compared to the middleward (0.04 ± 0.02), but not with the seaward/along water (0.19 ± 0.08 Mg ha^{-1}). Similarly, shrub carbon stocks differed significantly between zones, as well with significant interaction (Table 1; Fig. 2c). Shrub carbon stocks were higher in the middleward (14.88 ± 6.11 Mg ha^{-1}) compared to both landward and seaward/along water for fringe mangrove forests. In the riverine mangrove forests, significant differences in shrub carbon stocks were observed between all the zones which linearly increased from landward (1.88 ± 0.59), middleward (6.61 ± 2.64), and then seaward/along water (11.94 ± 2.89 Mg ha^{-1}). Meanwhile, standing dead trees, as well as litter did not differ significantly either between mangrove forest types and zones (Table 1; Fig. 2d & f). In terms of downed wood carbon stocks, it differed significantly both between mangrove forests types and zones, and with significant interaction (Table 1; Fig. 2e). The downed wood carbon stocks for fringe were higher compared to riverine mangrove forest types both in the landward (1.47 ± 0.34) and middleward (4.38 ± 1.17 Mg ha^{-1}), but there was no difference in the seaward/along water. Downed carbon stocks were higher in the middleward compared to the landward and seaward/along water in fringe mangrove forests, whereas there was no difference in carbon stocks between zones in riverine mangrove forests. Lastly, 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 Mg ha^{-1}) (Table 1; Fig. 2g).

For belowground (roots) carbon stocks, no significant differences were observed either between mangrove forest types or zones (Table 1; Fig. 3). Nevertheless, the average root carbon stocks were 56.20 ± 4.62 and 74.26 ± 12.79 Mg ha^{-1} for fringe and riverine mangrove forests.

Table 1
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
Zones	1.13	2	0.569
Interaction	0.66	2	0.719
Palm C (Mg ha^{-1})			
Mangrove forest type	0.37	1	0.542
Zones	19.95	2	< 0.001
Interaction	-	-	-
Shrub C (Mg ha^{-1})			
Mangrove forest type	0.19	1	0.661
Zones	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
Zones	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
Zones	14.23	2	0.001
Interaction	8.21	2	0.017
Litter C (Mg ha^{-1})			
Mangrove forest type	1.11	1	0.292
Zones	4.45	2	0.108
Interaction	2.02	2	0.363
Total aboveground C (Mg ha^{-1})			

Variable	Wald Chi-Square	df	p
Mangrove forest type	4.94	1	0.026
Zones	1.54	2	0.464
Interaction	0.39	2	0.823
Belowground (Root) (Mg ha^{-1})			
Mangrove forest type	2.08	1	0.149
Zones	0.84	2	0.657
Interaction	0.76	2	0.685
Total C (Mg ha^{-1})			
Mangrove forest type	4.29	1	0.038
Zones	1.38	2	0.502
Interaction	0.46	2	0.793

Species-Wise Contribution to Standing Tree and Root Carbon Stocks

Figure 4a 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 *Sonneratia alba* with a value of 116.18 ± 20.68, followed by other two species with larger carbon stocks such as *Avicennia rumphiana* (37.13 ± 14.92) and *Avicennia marina* (25.14 ± 8.29 Mg 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 ± 60.82 Mg ha^{-1} (Fig. 4b). 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, then followed by other two species such as *Sonneratia alba* (60.70 ± 12.33) and *A. marina* (14.41 ± 4.09 Mg ha^{-1}) (Fig. 4c).

The pattern for belowground (root) carbon stocks contribution by mangrove species was similar in the standing tree carbon stocks. In the fringe mangrove forests, the largest root carbon stocks 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 ± 2.29 Mg ha^{-1}, respectively (Fig. 5a). Meanwhile, the *A. rumphiana* had the most significant root carbon stocks contribution (62.29 ± 13.53 Mg ha^{-1}) in the riverine mangrove forests (Fig. 5b). Finally, fringe and mangrove forests combined, still the *A. rumphiana* accounted 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 ± 1.23 Mg ha^{-1}) (Fig. 5c).

Total Carbon Stocks (Aboveground and Belowground)

For the total carbon stocks (aboveground and belowground), a significant difference was observed between mangrove forest types (Table 1; Fig. 6). Total carbon stocks were higher in the riverine (380.83 ± 70.91) compared to fringe mangrove forests (253.56 ± 23.68), with an average of 317.19 ± 37.88 Mg ha^{-1}). Though total carbon stocks did not vary significantly between zones, they typically ranged from 274.03 ± 46.71 (seaward/along water) to 369.07 ± 57.22 Mg ha^{-1} (middleward).

Discussion

Aboveground Carbon Stocks

Tropical mangroves can store significant carbon in their biomass (Donato et al. 2011, Adame et al. 2013), and the present study showed that mangrove forests (riverine and fringe) along the Carigara Bay in Leyte had an estimated total average standing tree carbon stocks of 243.43 ± 31.09 Mg ha^{-1}. The carbon stocks were higher when compared to the estimated carbon stocks with the same formula used for mangroves in the coastal areas of San Juan, Batangas, Philippines (103.50-125.79 Mg ha^{-1}, Gevaña et al. 2008), small estuarine mangroves in Tanga, Tanzania (54.88-167.84 Mg ha^{-1}, Alavaisha and Mangora 2016), mangrove forests in the northern region of Kerala, India (123.28 Mg ha^{-1}, Harishma et al. 2020), and mangroves within the Zambezi River Delta, Mozambique (140.82 Mg ha^{-1}, Stringer et al. 2015). Typically, the higher carbon-storing capacity of mangroves can be directly associated with the increment in biomass (O'Connor 2003), resulting from photosynthetic activities and eventually leading to horizontal and vertical growth (Syamani et al. 2012). In addition, the observed higher standing tree carbon stocks in the riverine compared to the fringe mangrove forests in the study area can be associated with the higher inputs of nutrients in sediments and freshwater from the river flow resulting in higher productivity in mangroves (Fatoyinbo et al. 2008). This is indicated by the presence of huge and adult mangrove trees (> 100 cm DBH) specifically the species *A. rumphiana* dominating the riverine mangrove forests. Adame et al (2013) arrived at the highest carbon estimates for mangroves in site associated with freshwater springs. But also, other factors may contribute to the on-site carbon stocks variability, such as variation in tree age, species composition, geomorphology, and tidal influences (Bouillon et al. 2008, Alongi 2014, Zhang et al. 2019).

The carbon stocks for nipa palm (*N. fruticans*) accounted for only a very small proportion (0.12% or 0.31 Mg ha^{-1}) of the total aboveground carbon stocks. Ita (2020) found much higher carbon stocks for *N. fruticans* in the mangrove ecosystems of Akwa Ibom State, Nigeria, though it is an introduced and invasive species in the region. Based on the study of Kauffman et al. (2020), nipa-dominated ecosystems had much lower aboveground carbon stocks than those that are dominated by mangrove tree species (e.g., *Sonneratia*, *Bruguiera*, *Rhizophora*). However, nipa in the Asia-Pacific region can become an important carbon stock component where it may be the dominant species in some locations (Fourqurean et al. 2014). Likewise in this study, some of the areas particularly in the landward zone of the riverine mangrove forests were dominated by nipa which contributed significantly to the aboveground carbon stocks, along with shrubs. The nipa was abundantly growing either in the landward or river's edge of the riverine mangrove forests where there is much freshwater flow.

As compared to nipa, shrubs had much higher and second highest contributors to carbon stocks, accounting for about 2.44% of the total aboveground carbon stocks. The total average shrub carbon stocks were 5.47 ± 2.30 and 6.81 ± 1.46 Mg ha^{-1} for fringe and riverine mangrove forests, respectively, which were higher than those observed in the coastal wetlands of the Mexican Caribbean (2.46 Mg ha^{-1}, Adame et al. 2013), and Sofala Bay mangrove forests, central Mozambique (1.93 Mg ha^{-1}, Sitoe et al. 2014), but comparable in the mangroves of Dominican Republic (5.71 Mg ha^{-1}, Kauffman et al. 2014), and mangroves within the Zambezi River Delta, Mozambique (3–11 Mg ha^{-1}, Stringer et al. 2015). Virgulino-Júnior et al. (2020) showed that the important determinants of lower or scrub mangrove biomass on the Brazilian Amazon coast are the increasing interstitial salinity and topography which result in an increase in the percentage contribution of aboveground biomass or carbon. In the study area, the middleward zone of the fringe mangrove forest had the highest carbon stocks for shrubs, which were mainly dominated by the shrub mangrove species *A. corniculatum*. The species was very common and grows in clumps in the fringe mangroves under the regular influence of tide and with higher soil salinity (2.11 ± 0.09%) as recorded. Meanwhile, shrub carbon stocks in the riverine mangrove forests increased from the landward towards the river's edge which can be attributed to more open canopy that allowed the establishment of regenerants that were mainly composed of *Avicennia* spp.

Significant variations in standing dead tree carbon stocks in the studied mangrove forests were not observed. But the total average dead tree carbon stocks (0.32 ± 0.10 Mg ha^{-1}) are generally lesser compared to the estimated dead tree carbon stocks of mangrove ecosystems in other parts of the world including in Sofala Bay, Central Mozambique (1.70 Mg ha^{-1}, Sitoe et al. 2014), and Zambezi River Delta, Mozambique (3.7–11 Mg ha^{-1}, Stringer et al. 2015). Similarly, the recorded carbon stocks for downed wood were lower than those in the mangroves of coastal wetlands in the Mexican Caribbean (4.9–11.8 11 Mg ha^{-1}, Adame et al. 2013), and Micronesian mangrove forests (13–30 Mg ha^{-1}, Kauffman and Cole 2010, Kauffman et al. 2011, Donato et al. 2012). The observed higher downed wood carbon stocks in the fringe mangrove forests may suggest a significant impact on carbon dynamics (Romero et al. 2005). Might as well, the presence of downed wood debris can alter the tidal flow pattern, and influencing the accumulation of sediments (Allen et al. 2000) which is the largest pool for carbon in mangrove forests (Cleyndert et al. 2020).

The litter layer in the mangrove forest is characterized by dead leaves, flowers, fruits, seeds, bark fragments, and small wood pieces. However, in most mangrove ecosystems, the amount of biomass and therefore carbon is usually negligible as a result of the high efficiency of detritus-consuming crabs, and the export through tides and seasonal river flooding (Kauffman and Donato 2012). This might be the probable reason why the litter layer is seldom included in the quantification of carbon stocks in mangrove ecosystems. In fact, litter accounted for the smallest carbon stock components (0.08%) in the present study with a total average of 0.19 ± 0.02 Mg ha^{-1}, with a similar observation also in the previous study of Stringer et al. (2015) in deltaic mangrove ecosystems.

Lastly, the trend in the variation of total aboveground carbon stocks mirrors that of the standing tree carbon stocks which were still highest in the riverine as compared to the fringe mangrove forests. The average total aboveground carbon stocks (251.96 ± 31.08 Mg ha^{-1}) in the current study surpassed those of the carbon estimates for the community-managed mangrove forest in Bohol, Philippines (106.4 Mg ha^{-1}, Camacho et al. 2011), and Kanhlyashay natural mangrove forest, Myanmar (113.44 Mg ha^{-1}, Aye et al. 2022). While the present value appeared to be comparable to the total aboveground carbon stocks for mangroves ecosystems in Tanga, Tanzania (64.13-301.53 Mg ha^{-1}, Alavaisha and Mangora 2016), and Zambezi River Delta, Mozambique (75.4-268.5 Mg ha^{-1}, Stringer et al. 2015). Therefore, the high aboveground carbon stocks in the studied mangrove ecosystems most especially riverine implies the importance of protection, as it serves as a significant carbon reservoir.

Belowground (Root) Carbon Stocks

The belowground biomass or carbon 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). 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 calculations of biomass (Stringer et al. 2015). Root carbon stocks varied from 56.20 ± 4.62 and 74.26 ± 12.79 Mg 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 (25.22 Mg ha^{-1}, Sitoe et al. 2014), but comparable to the coastal mangroves of the Mexican Caribbean (59.24 Mg ha^{-1}, Adame et al. 2013). In contrast, measured root carbon stocks for Micronesian mangroves (68–203 Mg ha^{-1}, Kauffman et al. 2011, Donato et al. 2012) were generally higher than in the studied mangroves.

Mangrove Species-Wise Contribution to Carbon Stocks

The accumulation of biomass (carbon) in mangroves can be due to adaptabilities to environmental factors such as climate, proximity to water channels, nutrients in sediments, and as well as depending on the species and tree age (Kairo et al. 2008, Fatoyinbo et al. 2008). There is a great variation in mangrove species (as well as carbon quantity) across tropical regions that accumulate the largest carbon in biomass. Several studies have shown that *A. marina* in the Philippines and India accumulated the largest carbon (aboveground and belowground) where values may range from 71.3-81.09 Mg 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* (80.28 Mg ha^{-1}) in Malaysia (Islam et al. 2022)d *officinalis* (3.92 Mg ha^{-1}) in Myanmar (Aye et al. 2022). Even in the present study, mangrove species that contributed the largest aboveground and belowground carbon stocks varied between mangrove forest types. For example, *S. alba* contributed the largest aboveground and belowground (root) carbon stocks (116.18 ± 20.68 and 34.69 ± 5.72 Mg ha^{-1}, respectively), a dominant species in the seaward zone of fringe mangrove forests. The tolerance of *S. alba* to salinity could be the reason for its ability to accumulate high biomass (carbon) in a high-salinity environment (Banerjee et al. 2013). Whereas *A. rumphiana* in the riverine mangrove forests contributed the largest aboveground (259.60 ± 60.82) and belowground carbon stocks (62.29 ± 13.53 Mg ha^{-1}), where this mangrove is associated with riverine ecosystems with high sediment and freshwater inputs in rivers. For the whole mangrove ecosystem, *A. rumphiana*, followed by *S. alba* contributed the largest mangrove carbon stocks, suggesting their exceptional capacity to sequester large quantities of carbon.

Total Carbon Pools

The overall average of combined aboveground components and belowground carbon stocks in the mangrove ecosystems along Carigara Bay was 317.19 ± 37.88 Mg ha^{-1}. The estimated total carbon stocks in this study were higher than those reported in previous studies for total vegetation carbon stocks for mangrove ecosystems in San Juan, Batangas, Philippines (115.45-141.71 Mg ha^{-1}, Gevaña et al. 2008), Kerala, India (58.56 Mg ha^{-1}, Harishma et al. 2020), East Coast of India (89.4 Mg ha^{-1}, Sahu et al. 2016), and Myanmar (150.25 Mg ha^{-1}, Aye et al. 2022), but lower when compared to mature planted mangroves in Bohol, Philippines (370.7 Mg ha^{-1}, Camacho et al. 2011). The larger carbon stocks in the study area can be strongly attributed to the larger DBH of mangrove trees, though other authors found tree density as the most important determinant of carbon stocks (Camacho et al. 2011, Sahu et al. 2016). Similar to the trend for tree carbon stocks, total carbon stocks varied between forest types where it was higher in the riverine, which is directly explained by the presence of mature mangrove trees. This further implies that riverine mangrove ecosystems require greater protection efforts as these ecosystems have a higher potential for climate change mitigation due to large carbon stocks (Adame et al. 2013).

Conclusions

Mangrove forests are unique wetland ecosystems that are very important for their various ecological services, particularly carbon storage (Kauffman et al. 2011). The present study on the quantification of the carbon stocks (aboveground and belowground) in the mangrove forests along Carigara Bay resulted in an estimation of 317.19 Mg ha^{-1}, which is generally higher than the reported total vegetation carbon stocks in mangrove forests from other parts of the world. Among the various components, standing trees accounted for the largest proportion of the total carbon stocks of which the largest mangrove carbon stocks were associated with *A. rumphiana* and *S. alba*. In addition, riverine was found to be carbon-rich as compared to fringe mangrove forests which can be attributed to greater mangrove ecosystem productivity. Lastly, the exceptionally high carbon stored in the biomass of the studied mangrove forests implies that there should be sustainable management and firm implementation of forest protection for their role in climate change mitigation.

Declarations

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

Data availability Interested party may request data and materials from the corresponding author

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References

1. Adame MF, Kauffman JB, Medina I, Gamboa JN, Torres O, Caamal JP, Reza M, Herrera-Silveira JA (2013) Carbon stocks of tropical coastal wetlands within the karstic landscape of the Mexican Caribbean. PLoS ONE 8(2):e56569. https://doi.org/10.1371/journal.pone.0056569
2. Alavaisha E, Mangora MM (2016) Carbon stocks in the small estuarine mangroves of Geza and Mtimbwani, Tanga, Tanzania. Int J Forestry Res 1–11. https://doi.org/10.1155/2016/2068283
3. Allen JA, Ewel KC, Keeland BD, Tara T, Smith TJ (2000) Downed wood in Micronesian mangrove forests. Wetlands 20:169–176
4. Alongi DM (2009) The Energetics of Mangrove Forests. Springer, Dordrecht
5. Alongi DM (2014) Carbon cycling and storage in mangrove forests. Annual Rev Mar Sci 6(1):195–219. https://doi.org/10.1146/annurev-marine-010213-135020

6. Alongi DM (2020) Global significance of mangrove blue carbon in climate change mitigation. Science 2(3):67
7. Aye WN, Tong X, Tun AW (2022) Species diversity, biomass and carbon stock assessment of Kanhlyashay natural mangrove forest. Forests 13(7):1–16. https://doi.org/10.3390/f13071013
8. Banerjee K, Sengupta K, Raha A, Mitra A (2013) Salinity based allometric equations for biomass estimation of Sundarban mangroves. Biomass and Energy 382–391. http://doi.org/10.1016/j.biombioe.2013.05.010
9. Bhomia RK, Kauffman JB, McFadden TN (2016) Ecosystem carbon stocks of mangrove forests along the Pacific and Caribbean coasts of Honduras. Wetlands Ecol Manage 24:187–201. https://doi.org/10.1007/s11273-016-9483-1
10. Bouillon S, Borges AV, Castaneda-Moya E, Diele K, Dittmar T, Duke NC, Kristensen E, Lee SY, Marchand C, Middelburg JJ, Rivera-Monroy V, Smith TJ, Twilley RR (2008) Mangrove production and carbon sinks: a revision of global budget estimates. Glob Biogeochem Cycles 22:GB2013
11. Brown JK (1971) A planar intersect method for sampling fuel volume and surface area. For Sci 17:96–102
12. Brown JK (1974) Handbook for inventorying downed woody material. General Technical Report GTR-INT-16. USDA Forest Service, Missoula
13. Brown WH, Fischer AF (1918) Philippine Mangrove Swamps. Bureau of Printing, Manila, Philippines, p 132
14. Brown JK, Roussopoulos PJ (1974) Eliminating biases in the planar intersect method for estimating volumes of small fuels. For Sci 20:350–356
15. Camacho LD, Gevaña DT, Carandang AP, Camacho SC, Combalicer EA, Rebugio LL, Youn Y-C (2011) Tree biomass and carbon stock of a community-managed mangrove forest in Bohol, Philippines. For Sci Technol 7(4):161–167. https:doi.org/10.1080/21580103.2011.621377
16. Cintrón G, Schaeffer-Novelli Y (1984) Methods for studying mangrove structures. In The mangrove ecosystem: research methods, ed. S. C. Saenger, and J. G. Snedaker, 91–113. UNESCO Monographs in Oceanographic Methodology 8
17. Cleyndert GDJ, CuniSanchez A, Seki HA, Shirima DD, Munishi PKT, Burgess N, Calders K, Marchant R (2020) The effects of seaward distance on above and below ground carbon stocks in estuarine mangrove ecosystems. Carbon Balance Manag 15:27. https://doi.org/10.1186/s13021-020-00161-4
18. Decena SCP, Villacorta-Parilla S, Arribado AO, Macasait DR Jr, Arguelles MS, Salamia SS, Relevo ES (2022) Impact of land use conversion on carbon stocks and selected peat physico-chemical properties in the Leyte Sab-a Basin Peatland, Philippines. Wetlands 42(2). https://doi.org/10.1007/s13157-021-01520-8
19. Donato DC, Kauffman JB, Mackenzie RA, Ainsworth A, Pfleeger AZ (2012) Whole-island carbon stocks in the tropical Pacific: implications for mangrove conservation and upland restoration. J Environ Manage 97:89–96. https:doi.org/10.1016/j.jenvman.2011.12.004

20. Donato DC, Kauffman JB, Murdiyarso D, Kurnianto S, Stidham M, Kanninen M (2011) Mangroves among the most carbon-rich forests in the tropics. Nat Geosci 4:293–297. https://doi.org/10.1038/ngeo1123
21. Fatoyinbo TE, Simard M, Washington-Allen RA, Shugart HH (2008) Landscape-scale extent, height, biomass, and carbon estimation of Mozambique's mangrove, forests with Landsat ETM + and Shuttle Radar Topography Mission elevation data. J Geophys Research: Biogeosciences 13:G02S06
22. Field CB, Osborn JG, Hoffmann LL, Polsenberg JF, Ackerly DD, Berry JA, Bjorkman O, Held Z, Matson PA, Mooney HA (1998) Mangrove biodiversity and ecosystem function. Global Ecol Biogeogr Lett 7:3–14. https://doi.org/10.2307/2997693
23. Fourqurean J, Johnson B, Kauffman JB, Kennedy H, Lovelock C, Saintilan N, Alongi DM, Cifuentes M, Copertino M, Crooks S, Duarte C, Fortes M, Howard J, Hutahaean A, Kairo J, Marbà N, Murdiyarso D, Pidgeon E, Ralph P, Serrano O (2014) Field sampling of vegetative carbon pools in coastal ecosystems. pp. In book: Coastal Blue Carbon: Methods for assessing carbon stocks and emissions factors in mangroves. tidal marshes. and seagrass meadows Chap. 4. Conservation International, Intergovernmental Oceanographic Commission of UNESCO. Jennifer Howard, International Union for Conservation of Nature Editors, pp 67–108. Sarah Hoyt, Kirsten Isesnsee, Maceij Telszewski, Emily Pidgeon
24. Gevaña DT, Pulhin FB, Pampolina NM (2008) Carbon stock assessment of a mangrove ecosystem in San Juan, Batangas. J Environ Sci Manage 11(1):15–25
25. Harishma KM, Sandeep S, Sreekumar VB (2020) Biomass and carbon stocks in mangrove ecosystems of Kerala, southwest coast of India. Ecol Processes 9(31):1–9. https://doi.org/10.1186/s13717-020-00227-8
26. Intergovernmental Panel on Climate Change (2006) Good practice guidelines for National Greenhouse gas inventories. Switzerland
27. Islam MA, Idris MH, Bhuiyan MDKA, Ali MS, Abdullah MT, Kamal AHM (2022) Floristic diversity, structure, and carbon stock of mangroves in a tropical lagoon ecosystem at Setiu, Malaysia. Biodiversitas 23(7):3685–3696. https://doi.org/10.13057/biodiv/d230746
28. Ita RE (2020) Differential biomass apportionments and carbon stocks in vegetation of natural and artificial ecosystems in Akwa Ibom State, Nigeria. World Sci News 146:1–21
29. International Center for Research in Agroforestry (ICRAF) (2023) Tree functional attributes and ecological database. http://db.worldagroforestry.org/wd
30. Kairo JG, Lang'at JKS, Dahdouh-Guebas F, Bosire J, Karachi M (2008) Structural development and productivity of replanted mangrove plantations in Kenya. For Ecol Manag 255:2670–2677. https://doi.org/10.1016/j.foreco.2008.01.031
31. Kauffman JB, Adame MF, Arifanti VB, Schile-Beers LM, Bernardino AF, Bhomia RK, Donato DC, Feller IC, Ferreira TO, Garcia MDCJ, Mackenzie RA, Megonigal JP, Murdiyarso D, Simpson L, Trejo HH (2020) Total ecosystem carbon stocks of mangroves across broad global environmental and physical gradients. Ecol Monogr 90(2):e01405

32. Kauffman JB, Bhomia RK (2017) Ecosystem carbon stocks of mangroves across broad environmental gradients in West-Central Africa: global and regional comparisons. PLoS ONE 12(11):e0187749
33. Kauffman JB, Cole TG (2010) Micronesian mangrove forest structure and tree responses to a severe typhoon. Wetlands 30:1077–1084. http://doi.org/10.1007/s13157-010-0114-y
34. Kauffman JB, Cummings DL, Ward DE (1998) Fire in the Brazilian Amazon: 2. Biomass, nutrient pools and losses in cattle pastures. Oecologia 113:415–427. http://doi.org/10.1007/s004420050394
35. Kauffman JB, Cummings DL, Ward DE, Babbitt R (1995) Fire in the Brazilian Amazon: 1. Biomass, nutrient pools, and losses in slashed primary forests. Oecologia 104:397–408. https://doi.org/10.1007/BF00341336
36. Kauffman JB, Donato DC (2012) Protocols for the measurement, monitoring and reporting of structure, biomass and carbon stocks in mangrove forests. Working Paper 86. CIFOR, Bogor, Indonesia
37. Kauffman JB, Heider C, Cole TG, Dwire KA, Donato DC (2011) Ecosystem carbon stocks of Micronesian mangrove forests. Wetlands 31:343–352. http://doi.org/10.1007/s13157-011-0148-9
38. Kauffman JB, Heider C, Norfolk J, Payton F (2014) Carbon stocks of intact mangroves and carbon emissions arising from their conversion in the Dominican Republic. Ecol Appl 24(3):518–527. http://doi.org/10.1890/13-0640.1
39. Komiyama A, Ong JE, Poungparn S (2008) Allometry, biomass, and productivity of mangrove forests: a review. Aquat Bot 89(2):128–137. https://doi.org/10.1016/j.aquabot.2007.12.006
40. Komiyama A, Poungparn S, Kato S (2005) Common allometric equations for estimating the tree weight of mangroves. J Trop Ecol 21:471–477. https://doi.org/10.1017/S0266467405002476
41. Kottek M, Grieser J, Beck C, Rudolf B, Rubel F (2006) World map of the Köppen-Geiger climate classification updated. Meteorol Z 15(3):259–263. http://doi.org/10.1127/0941-2948/2006/0130
42. Long JB, Giri C (2011) Mapping the Philippines' mangrove forests using Landsat imagery. Sensors 11:2972–2981. http://doi.org/10.3390/s110302972
43. Madeira BG, Espírito-Santo MM, Neto SD', Nunes YRF, Azofeifa GAS, Fernandes GW, Quesada M (2009) Changes in tree and liana communities along a successional gradient in a tropical dry forest in south-eastern Brazil. Plant Ecol 201:291–304. https://doi.org/10.1007/s11258-009-9580-9
44. Marteleira RGS (2019) Improving the resilience of water supply towards climate change impacts in Tacloban, Philippines. PhD dissertation, Universidade Nova de Lisboa, 1–179
45. O'Connor E (2003) ENERGY CROPS | Biomass Production. 266–273 pp. In Encyclopedia of Applied Plant Sciences; Elsevier: Amsterdam, The Netherlands
46. Patindol TA, Casas EV Jr (2019) Species diversity and composition of mangroves in Tacloban City. Philippines Annals of Tropical Research 41(2):67–75

47. Petrosian H, Kar AD, Ashrafi S, Feghhi J (2016) Investigating environmental factors for locating mangrove ex-situ conservation zones using GIS spatial techniques and the Logistic Regression Algorithm in mangrove forests in Iran. Pol J Environ Stud 25(5):2097–2106. http://doi.org/10.15244/pjoes/62640
48. Primavera JH (2009) Field Guide to Philippine Mangroves
49. Primavera JH, Sadaba RB, Lebata MHL, Altamirano JE (2004) Handbook of Mangroves in the Philippines - Panay. SEAFDEC Aquaculture Department, Iloilo, Philippines, p 106
50. Quiñones CMO, Asio VB (2015) Soils derived from ophiolitic rocks in northeastern Leyte: morphological, physical, and chemical properties. Annals of Tropical Research 37:36–56
51. Romero LM, Smith TJ, Fourqurean JW (2005) Changes in mass and nutrient content of wood during decomposition in a south Florida mangrove forest. J Ecol 93:618–631. http://doi.org/10.1111/j.1365-2745.2005.00970.x
52. Sahu SC, Kumar M, Ravindranath NH (2016) Carbon stocks in natural and planted mangrove forests of Mahanadi Mangrove Wetland, East Coast of India. Curr Sci 110(12):2253–2260. http://doi.org/10.18520/cs/v110/i12/2253-2260
53. Singh JK (2020) Structural characteristics of mangrove forest in different coastal habitats of Gulf of Khambhat arid region of Gujarat, west coast of India. Heliyon 6:e04685. https://doi.org/10.1016/j.heliyon.2020.e04685
54. Sitoe AA, Mandlate LJC, Guedes BS (2014) Biomass and carbon stocks of Sofala Bay mangrove forests. Forests 5:1967–1981. http://doi.org/10.3390/f5081967
55. Sreelekshmi S, Preethy CM, Varghese R, Joseph P, Asha CV, Nandan SB, Radhakrishnan CK (2018) Diversity, stand structure, and zonation pattern of mangroves in southwest coast of India. J Asia-Pacific Biodivers 11:573–582. https://doi.org/10.1016/j.japb.2018.08.001
56. Stringer CE, Trettin CC, Zarnoch SJ, Tang W (2015) Carbon stocks of mangroves within the Zambezi River Delta, Mozambique. For Ecol Manag 354:139–148. http://doi.org/10.1016/j.foreco.2015.06.027
57. Suratman MN (2008) Carbon Sequestration Potential of Mangroves in Southeast Asia. 297–314 pp. In Managing Forest Ecosystems: The Challenge of Climate Change. F. Bravo (eds.)
58. Syamani RA, Agustina, Susilawati, Yusanto N (2012) Carbon stocks above the soil surface at various land cover systems in Amandit Watersheds. Jurnal Hutan Tropis 13(2):152–153 (in Indonesian)
59. van Wagner CE (1968) The line intersect method in forest fuel sampling. For Sci 24:469–483
60. Virgulino-Júnior PCC, Carneiro DN, Nascimento WR Jr, Cougo MF, Fernandes MEB (2020) Biomass and carbon estimation for scrub mangrove forests and examination of their allometric associated uncertainties. PLoS ONE 15(3):e0230008. https://doi.org/10.1371/journal. pone.0230008
61. Waddell KL (2002) Sampling coarse woody debris for multiple attributes in extensive resource inventories. Ecol Ind 1:139–153. https://doi.org/10.1016/S1470-160X(01)00012-7

62. Walsh GE (1974) Mangroves: a review. 51–174 pp. In: Reinhold RJ, Queen WH (eds) Ecology of Halophytes. Academic Press, New York
63. Zhang X, Zhang X, Han H, Shi Z, Yang X (2019) Biomass accumulation and carbon sequestration in an age-sequence of Mongolian pine plantations in Horqin sandy land. China Forests 10(2):1–18

Figures

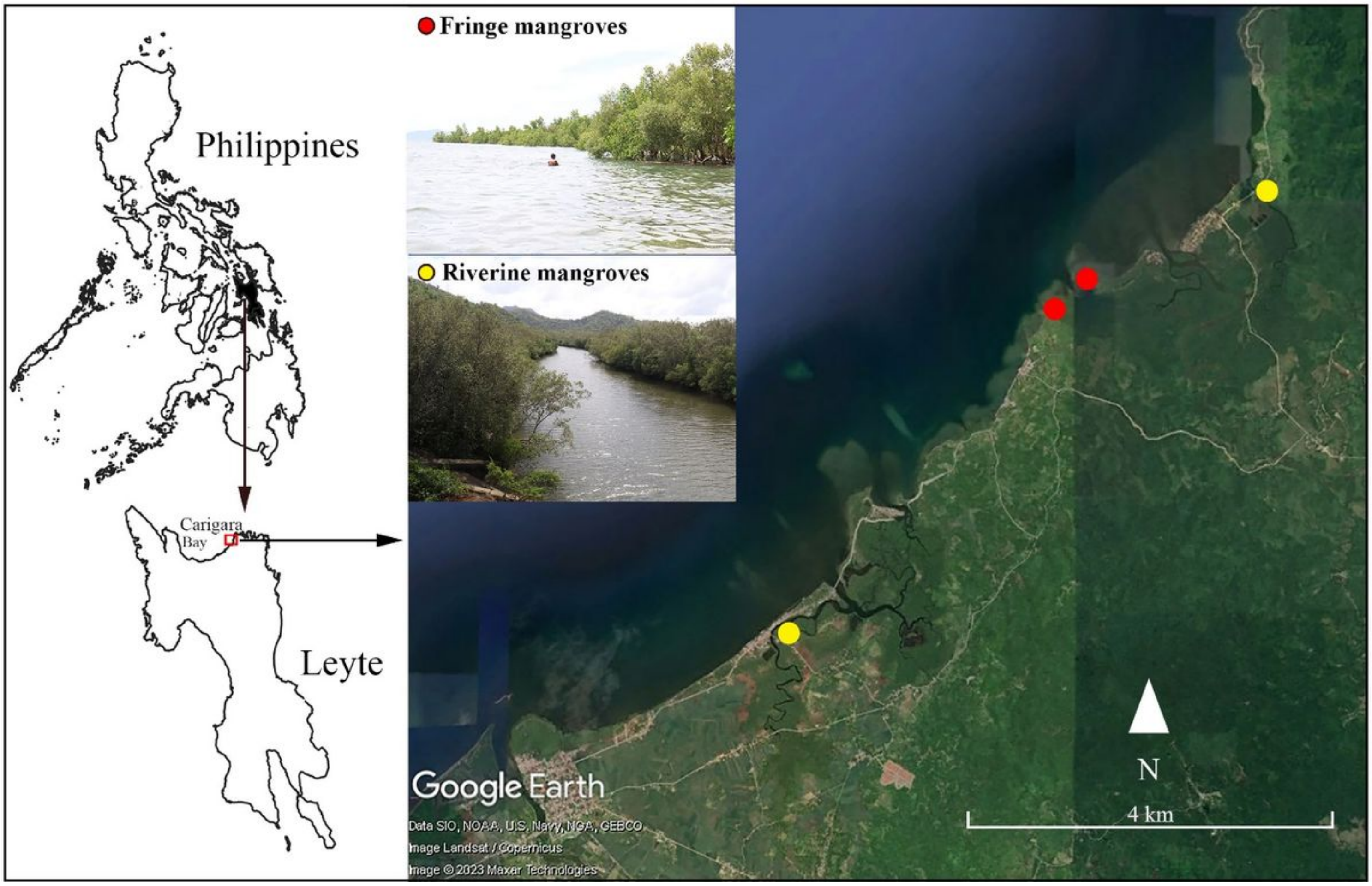

Figure 1

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

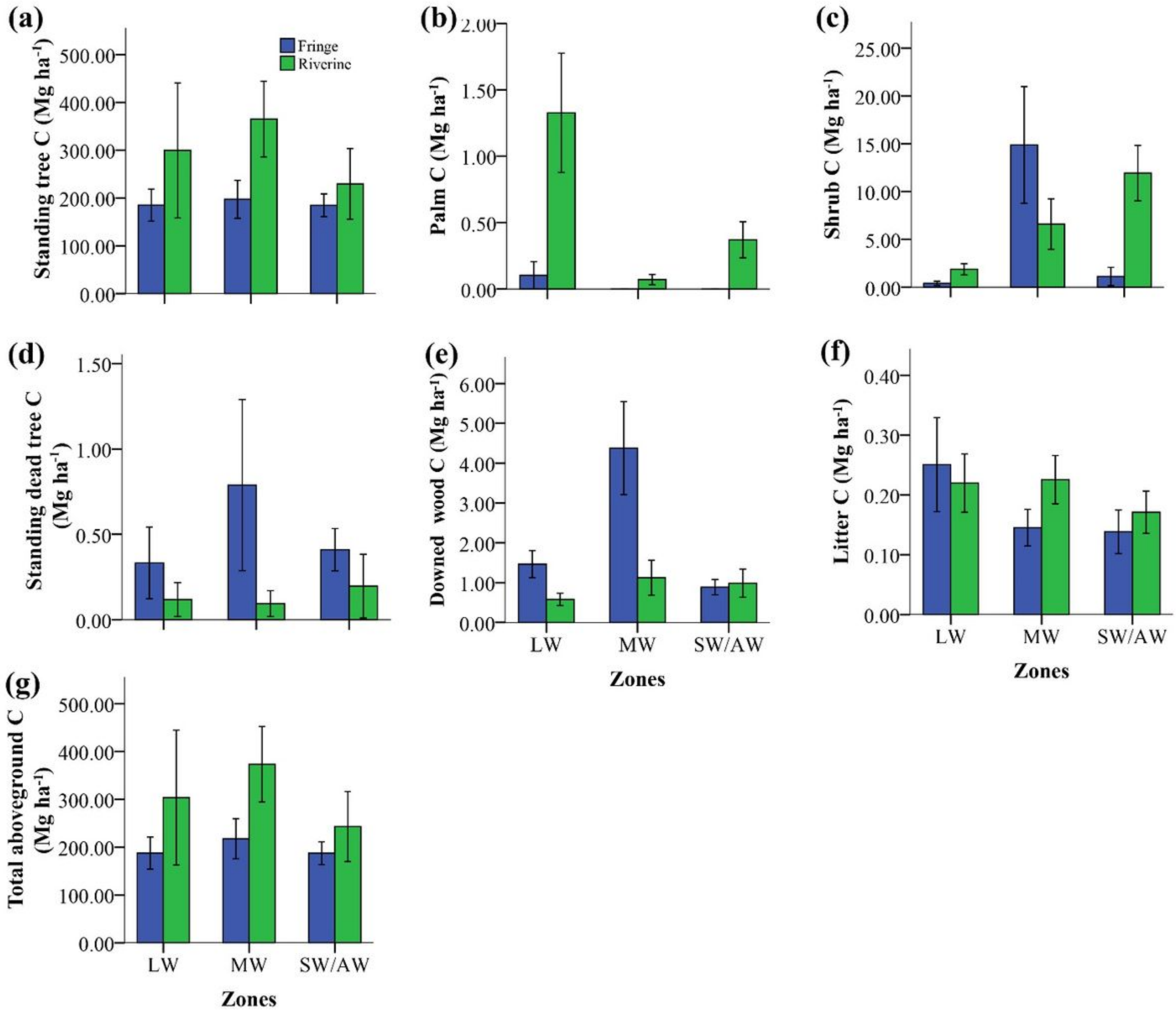

Figure 2

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

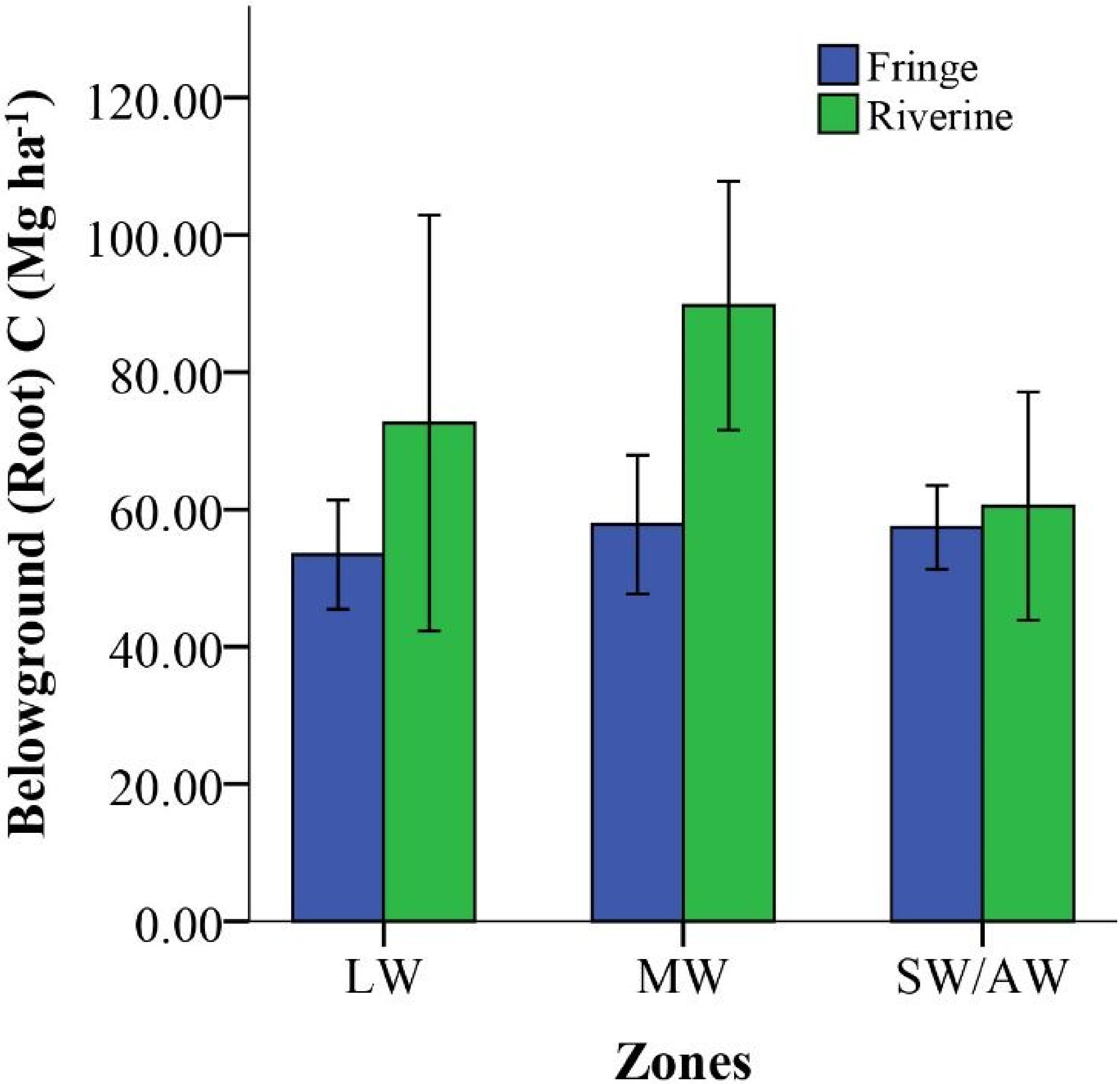

Figure 3

The differences in belowground (root) carbon stocks of mangrove ecosystems along the Carigara Bay in Leyte, Philippines. LW–landward, MW–middleward, SW/AW–seaward/along water

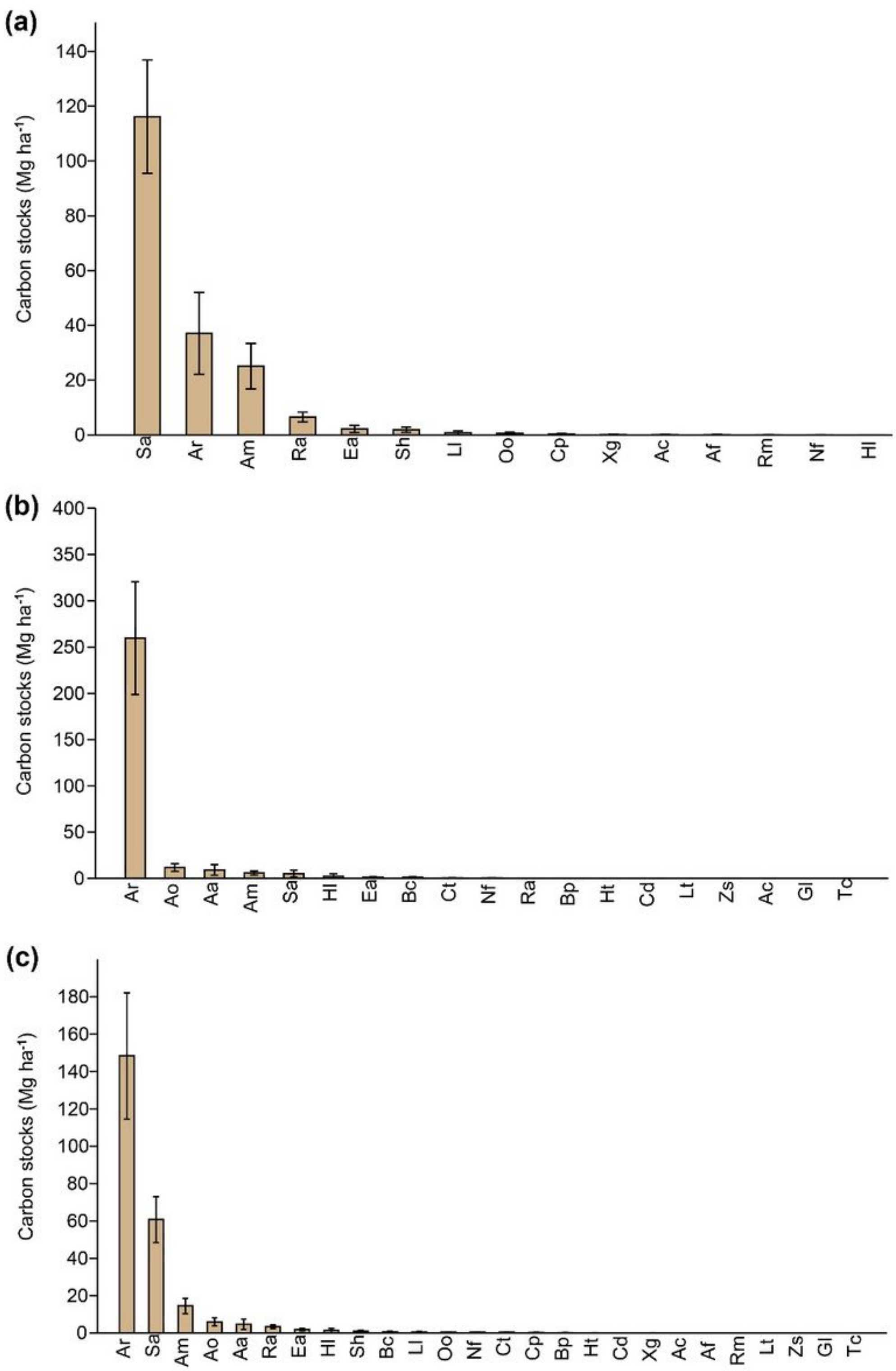

Figure 4

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*

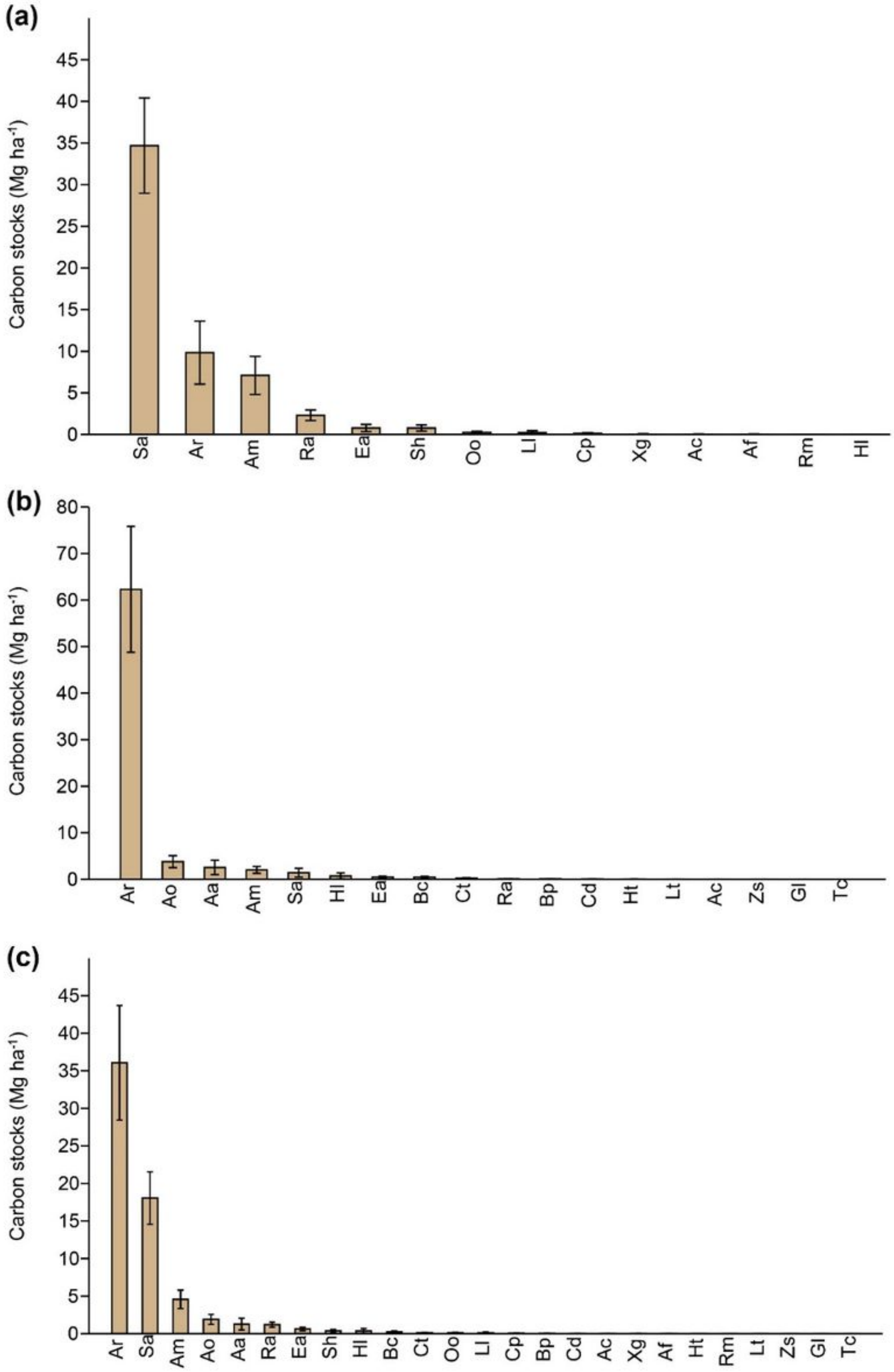

Figure 5

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*

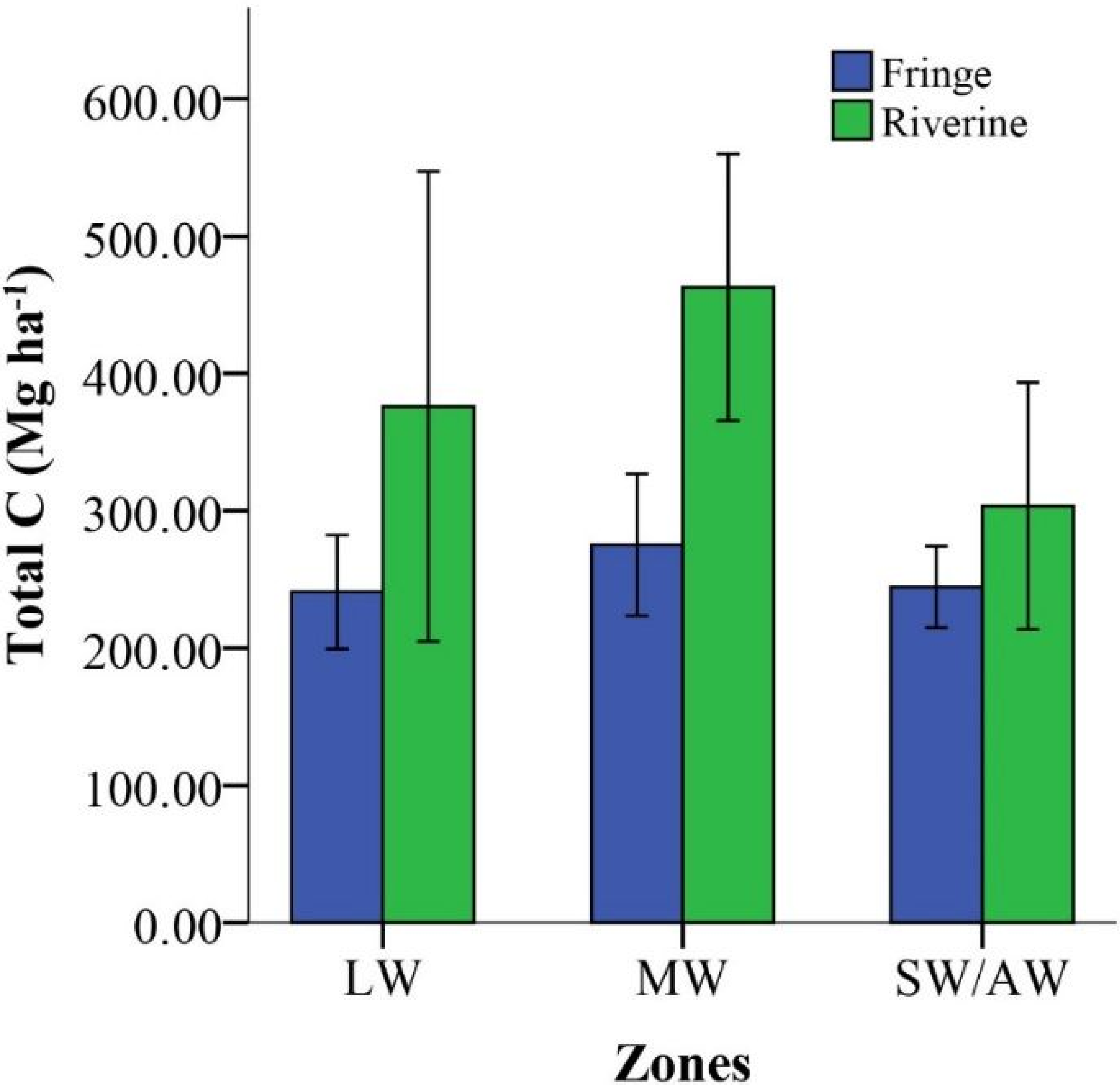

Figure 6

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