







RESEARCH ARTICLE

Deep Coring Shows That Mangrove Sediments in Matang (Malaysia) Store up to Five Times More Carbon Than Previously Estimated

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ABSTRACT

The carbon sequestration potential of mangroves, especially at sediment level, is known to be higher than other forest types. Sediment depth effects, however, have rarely been considered and carbon stock beyond 6 m depth has never been reported. The aim of this study is to account for deep sediment carbon storage to build a novel and more complete data set comprising all important ecosystem components, such as sediments, vegetation biomass, leaf litter and dead wood. For the first time, cores to a depth of 10 m were collected from the Matang Mangrove Forest Reserve (MMFR) in Malaysia. The 30-year silvicultural rotation, with two thinnings and a final clear-felling, enabled comparison of total carbon across different aged *managed* mangrove stands and the unmanaged. 3 protected forest, highlighting the impact of silviculture on carbon stocks. Our analysis suggests that the total carbon stock for the entire MMFR, when estimated to 10 m depth, is on the order of five times greater than earlier assessments, amounting to 107.34 Tg C. The carbon pool in the sediments was still around 100 Mg C ha⁻¹ at depths beyond 3–4 m, where most of the carbon was stored. Compared to the *managed* forest, the *protected* forest showed the highest sediment carbon pool (> 3000 Mg C ha⁻¹), proving that its unique set of biotic interactions, represented by flourishing burrowing crab communities and large amounts of decaying material on the sediment surface, allow the sediment to store at least 10% more carbon. On the other hand, the results from the *managed* stands showed the impact of clear-felling and thinning activities, with a loss of 456.7 and 284.8 Mg C ha⁻¹, respectively. Our deep coring approach complements the use of standard sampling techniques for mangrove sediment carbon estimation and highlights the importance of better assessments for future blue carbon projects worldwide.

1 | Introduction

Mangrove forests exhibit some of the highest carbon sequestration rates per unit area among coastal and terrestrial ecosystems, making them critical components of global climate mitigation strategies (Song et al. 2023; Lester 2023; Arkema et al. 2023). The global mangrove extent of 147,358 km² (Bunting et al. 2022) is estimated to contain 5.60–9.24 Pg of carbon (re-calculated from Alongi 2022), with an average burial rate of 184 g m⁻² y⁻¹ (Alongi 2022). Mangroves, however, are recurrently lost to different land reclamation processes (Goldberg et al. 2020), even in protected areas (Heck et al. 2024), and these losses are posing a major threat to the mangrove carbon sequestration potential (Chatting et al. 2022). For instance, conversion to aquaculture ponds was estimated to release 72 ± 44 Mg C ha⁻¹ (Sasmito et al. 2019), and emissions from mangrove deforestation could reach 2391 Tg CO₂eq by the end of the century (Adame, Connolly, et al. 2021). Such scenarios enhanced the prominence of blue carbon projects aimed to mitigate climate change by protecting and restoring mangroves, both locally and regionally (Macreadie et al. 2021).

For terrestrial forests, the aboveground biomass contributes to major carbon stock whereas in mangroves the anoxic sediment, with incomplete decomposition of organic matter (Donato et al. 2011), holds at least 74% of the carbon. Carbon, both from autochthonous and allochthonous sources (Bouillon et al. 2003), is retained in mangrove sediments through accretion and progressively transferred to deeper layers via the burrowing activities of brachyuran fauna, which enhance vertical transport and sediment mixing (Andreotta et al. 2014; Agosto et al. 2021; Zhang et al. 2024). Simultaneously, the continuous accumulation of sediments promotes compaction and stabilization, facilitating long-term carbon sequestration in deeper, more anoxic layers where preservation conditions are enhanced (Arnaud et al. 2025). Despite these processes, the influence of sediment depth on carbon stock accumulation remains relatively underexplored in mangrove systems (Cooray et al. 2024).

While the international standard for sediment carbon accounting is set to 1 m depth (IPCC 2014), many mangrove studies have focused on samples collected from an average depth of 0.51 ± 0.37 m (Fest et al. 2022), sometimes due to the lack of site-specific geological characteristics (e.g., sediment depth), but often limited by manpower and/or equipment available. So far, only a few authors sampled below 1 m (Nam et al. 2016; Kida et al. 2021; Trettin et al. 2021; Murdiyarto et al. 2021), with the notable exception of Adame, Santini, et al. (2021), who were the first to collect and analyse the sediment carbon from 6 m depth in Mexico. It is likely that mangrove carbon stocks are underestimated in many areas (especially in geomorphological settings that allow deep sediment formation) and still need a clearer picture with respect to the sediment depth (Cooray et al. 2024). Moreover, there is a lack of standardization in sediment depth measurements, often with use of rods limited to 3 m (Kauffman et al. 2020), that does not always capture the real measure of sediment depth.

The extraction of mangrove wood is illegal in many parts of the world (Rasquinha and Mishra 2021), while a few countries like Thailand, Vietnam, Malaysia, and Indonesia are still

practicing silvicultural management for commercial reasons (Saenger 2002; Chong 2006; Sillanpää et al. 2017; Satyanarayana et al. 2021). The Matang Mangrove Forest Reserve (MMFR) in Peninsular Malaysia is well known for its century-old management to produce poles and charcoal since 1902 (Satyanarayana et al. 2021; Chen et al. 2024). The extensive MMFR encompasses *protected* and *managed* forest areas, where the latter is subjected to a systematic 30-year silvicultural rotation of *Rhizophora* spp. with two intermediate thinnings (for poles) and a final clear-felling (for charcoal). Although several studies have been carried out on the vegetation biomass of the MMFR (Putz and Chan 1986; Gong and Ong 1990; Goessens et al. 2014; Hamdan et al. 2014; Otero et al. 2018; Lucas et al. 2020), only Adame et al. (2018) measured the sediment carbon at a depth of 1 m and projected it up to 2.5 m depth.

In the present study, we took advantage of both *protected* and *managed* forest areas in the MMFR to highlight the effects of silvicultural extractive practices on mangrove biomass and sediment carbon stocks. We extended sediment coring to an unprecedented depth of 10 m below the surface, opening a new frontier in understanding the role of “deep” carbon.

Our primary aim was to generate a comprehensive local dataset on ecosystem carbon stocks, including vegetation biomass, dead wood, leaf litter, and deep sediment carbon within the MMFR across a chronosequence of different aged forest stands. While our core focus remains on the MMFR, this study also informs the broader implications of deep sediment carbon. We highlight both the vulnerability and the untapped potential of mangroves as critical carbon reservoirs, underscoring their importance in climate mitigation and ecosystem resilience.

2 | Methodology

2.1 | Study Area

The MMFR, located in the State of Perak in Peninsular Malaysia (Figure 1), covers more than 40,000 ha and is managed by the Forestry Department through 10-year working plans. The reserve encompasses protected forest areas referred to by the local management as protective zones (formed by new, pristine and non-economic functional forests, and solely used for nature conservation, education, ecotourism, and research), and silviculturally managed forest areas that includes the so called productive zone (the forest for commercial exploitation based on a 30-year rotation cycle), the restrictive productive zone (formed by environmentally sensitive and marginally productive forests) as well as an unproductive zone (mostly transitional, coastal and dryland forest used for agriculture bunds and human settlements) (Ariffin and bin Nik Mustafa 2013). About 75% of the MMFR (i.e., 30,120 ha) belongs to the *managed* area and contains 108 compartments to support pole production from two intermediate thinnings (at 15- and 20-year-old stands) and charcoal production from a final clear-felling (at 30-year-old stands). The clear-felled area with <90% natural regeneration of *Rhizophora apiculata* Bl. and *Rhizophora mucronata* Lamk. (the target species for pole and charcoal production) are manually replanted after 2 years (Goessens et al. 2014). The floral diversity of mangroves is also

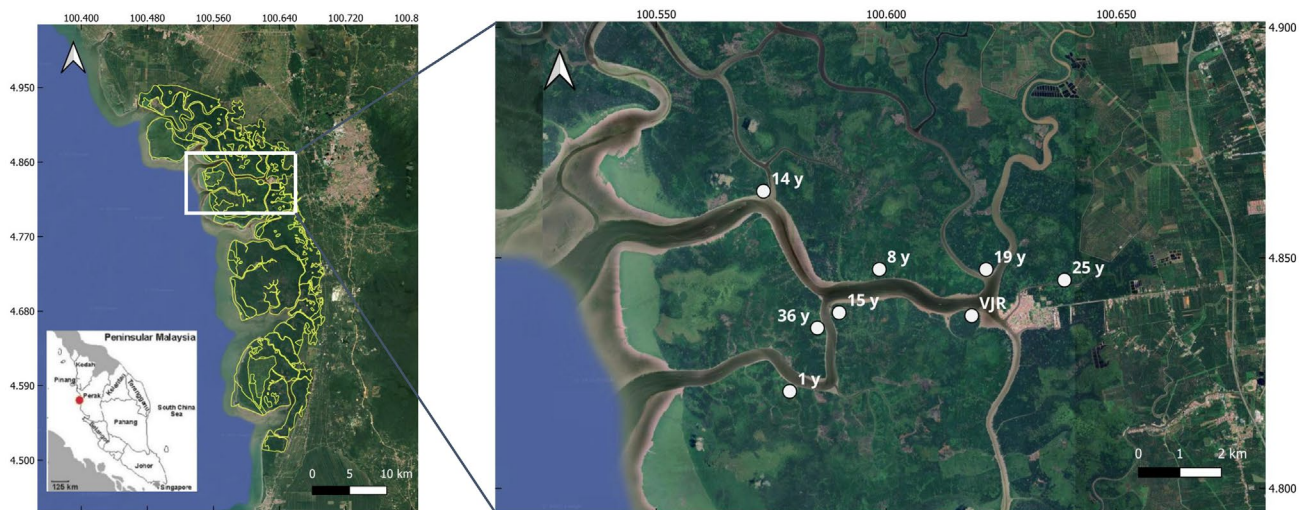


FIGURE 1 | Map of the sampling locations in the Kuala Sepetang district of the Matang Mangrove Forest Reserve. VJR, Virgin Jungle Reserve; Y, Years. Basemap: Google Satellite imagery (Google 2025).

represented by several other species such as *Avicennia marina* (Forsk.) Vierh. ex-NC Duke, *Bruguiera gymnorhiza* (L.) Lamk., *Bruguiera parviflora* Wight and Arnold ex Griffith, *Ceriops tagal* (Perr.) C.B. Robinson and *Sonneratia caseolaris* (L.) Engler in the protected forest zones.

Our study was conducted in the Kuala Sepetang range of the MMFR. Seven sampling sites with different aged forest stands (of 1, 8, 14, 15, 19, 25, and 36 years old) in the *managed* forest and one nearly 100-year-old stand in the Virgin Jungle Reserve (VJR) of the *protected* zone were selected (Figure 1, Table S1). This would provide insight into carbon dynamics from a denuded to a mature forest while understanding the effects of thinning and clear-felling processes at fixed intervals. The VJR was sampled as a reference to compare the carbon stock between managed and unmanaged forests. The 36-year-old site was a managed forest but not yet assigned to any contractor for clear-felling. All sampling sites were located within a 10 km radius, positioned at similar elevations (ranging from 1.58 to 2.25 m above the MSL), and subject to comparable tidal inundation regimes and sediment granulometric characteristics (Ariffin and bin Nik Mustafa 2013).

2.2 | Vegetation Inventory

At each site, vegetation data were collected using 10 m × 10 m plots spaced at 25 m intervals along a transect extending from the riverbank (leaving a 15 m buffer zone) to the inside forest. In the 8 and 14-year-old forests, smaller 5 m × 5 m plots were used due to the high density of trees. For the 15- and 25-year-old forests, only nine plots were established, reflecting spatial limitations associated with the end of the concession area for those age classes. As a result, transect lengths varied depending on the number of plots established at each site, ranging from 280 m for sites with nine plots (15- and 25-year-old forests) to 315 m for sites with 10 plots.

In each plot, the live trees with a diameter (D_{130}) > 2.5 cm were considered as adult vegetation (cf. Goessens et al. 2014) to count,

identify (using taxonomic keys of Tomlinson 2016), and measure their height (using a Suunto PM-5 clinometer). For stem diameter observations (using a diameter tape), the methodology suggested by Dahdouh-Guebas and Koedam (2006) was followed. Dead trees in the plots were also considered for measurements sensu Kauffman and Donato (2012). In addition, three 10 m transects (along the two border sides and in the middle of each plot following the main transect line) were established to count the dead wood and separated into: small (< 2.5 cm), medium (2.5–7.6 cm), large (> 7.6 cm) categories (Kauffman and Donato 2012). The diameter of the large wood pieces and tree stumps (in clear-felled as well as thinning sites) was measured in the field at the midpoint for the wood debris and at 30 cm from the base for tree stumps.

2.3 | Plant Sample Collection and Analysis

Plant samples included mature leaves, aboveground stilt roots, stem wood, and leaf litter, all collected from the dominant mangrove species *R. apiculata*. Given that leaf carbon content is influenced by leaf age rather than forest age, we randomly selected three forest stands (aged 1, 36, and approximately 100 years) for the collection of 10 replicates of mature leaves of similar size. In contrast, stilt root samples were collected in 10 replicates from each forest age class. Wood samples were obtained from the trees harvested for poles and charcoal at 15, 20, and 30 years of age. Leaf litter was sampled using 40 cm × 40 cm microplots, with 10 replicates per site. All samples were placed in an icebox before reaching the laboratory and stored at -20°C . The samples were subsequently washed, oven-dried at 60°C for 48 h and ground to a fine powder (using an electric grinder). Dry sample weight (using a microbalance) was recorded for wood specific gravity and biomass calculations (details in data analysis).

2.4 | Sediment Sampling and Analysis

A 10 m deep core at each site was obtained from the middle of the vegetation inventory transect (ca. 160 m inside the forest)

(using the Eijkelkamp coring set for chemical analysis, The Netherlands). This one core approach was followed because of the amount of time and manpower needed for the sampling. To account for the variability in the top sediments, two additional 1 m cores were also collected from the first and last plots of the vegetation inventory. The core sediment extraction was confined to stainless steel tubes (20 cm long \times 4 cm diameter) attached each time to the extension rods while going deep into the sediment. All sediment samples, after extrusion from the steel tubes, were wrapped in polythene and aluminium foil, labelled and then stored at -20°C in the laboratory. Subsampling of the sediment was carried out every 20 cm for the first 2 m and every meter afterwards. The subsamples were oven-dried at 60°C for 48 h and the bulk density was derived as in Kauffman and Donato (2012). Finally, the samples were passed through a $63\mu\text{m}$ mesh sieve and analyzed for total carbon content (%) with the UNICUBE Elemental analyser (Elementar, Germany).

2.5 | Data Analysis

Aboveground and belowground biomass calculations were performed using the species-specific equations given by Komiyama et al. (2008). Dead wood biomass was calculated by multiplying the volume by its mean specific gravity (Kauffman and Donato 2012). Leaf litter biomass was estimated from the dry weight of the collected samples. All carbon values were obtained by multiplying the biomass values with a carbon conversion factor derived from the carbon content (%) that we measured from the samples collected via elemental analysis. For the sediment, carbon values were obtained by multiplying the carbon content (%) by the depth interval (20 cm) and the bulk density. For the first meter carbon, the mean of the three cores for each site was used.

All statistical analysis was done in Microsoft Excel and R studio (version 4.3.2). Differences in biomass and surface sediment carbon among sites were analyzed by ANOVA (followed by post hoc Tukey test) and *t*-tests, and in case of samples without normal distribution, a Kruskal–Wallis test was performed (followed by Dunn's post hoc test). To evaluate spatial variability at the surface level, we combined the results from three 1-m cores, pooling all 20-cm subsamples from each core for the depth interval 0–1 m.

Spatial distribution maps of sediment, vegetation, and dead wood carbon were generated by extrapolating values across a 0–30 year time range in QGIS 3.10 (A Coruña), using age-class maps from Lucas et al. (2020) and following the methods of Wolswijk et al. (2022) which used the sediment carbon data from Adame et al. (2018), with comparable age classes to those applied in the present study. The baseline age map developed by Lucas et al. (2020) incorporated remote sensing data spanning 1958–2016, with forest age determined from patterns of clear-felling and subsequent regrowth consistent with the silvicultural rotation cycle.

We also want to provide a hypothetical estimate of the global carbon stock by considering sediments to a depth of 10 m. The methodology employed for this estimation, along with the

corresponding results, is detailed in the Figure S2, Tables S3 and S4.

2.6 | Methodological Limitations

Generation of carbon data for mangrove sediments is a challenging task, limited by the tidal conditions, sediment granulometry, funding and availability of equipment/manpower, some of which also affected the present study. The intra-site variability was not assessed; however, the comparison with previous data (Adame et al. 2018) for shallow cores and the finding that the sediment carbon did not show much variation $< 5\text{ m}$ among different sites show us that a single core approach represents a good approximation for deep sediment. Nevertheless, we emphasize that replication was insufficient to support robust statistical testing of differences in the deep cores. Recovering 10-m sediment cores is labor-intensive and logistically challenging, but future studies should increase the number of replicate deep cores to strengthen inference and provide more reliable estimates of variability.

3 | Results

3.1 | Carbon in Different Mangrove Ecosystem Components

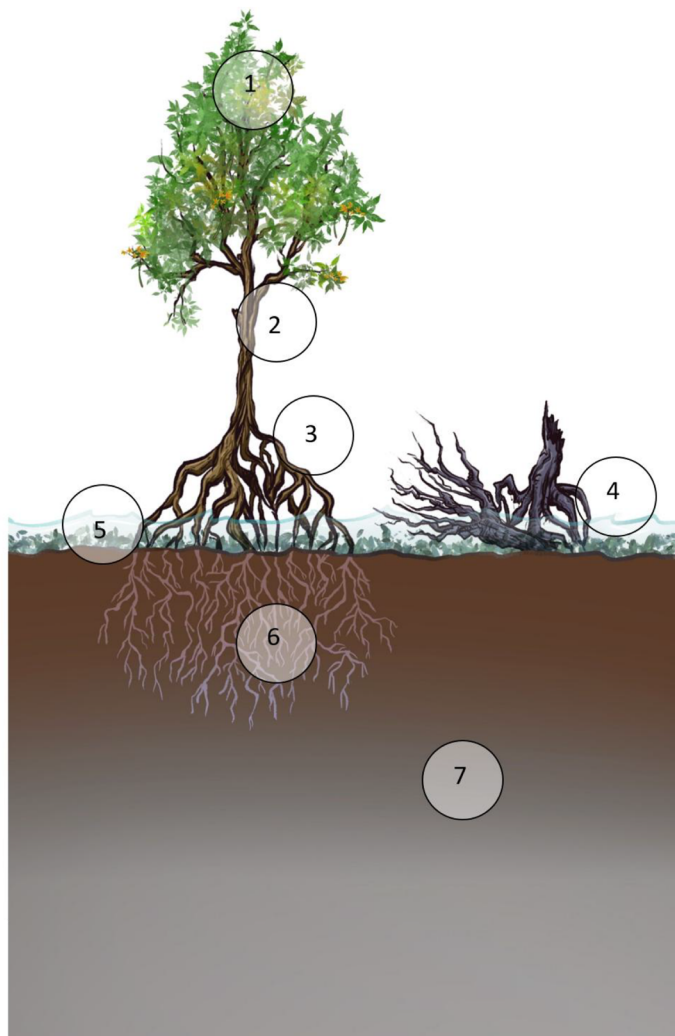
The sediment carbon pool represented more than 95% of the total ecosystem carbon stock, with values $> 700\text{ Mg C ha}^{-1}$ in the first 3–4 m that decreased until values $< 200\text{ Mg C ha}^{-1}$ in deeper layers. The carbon pool in the sediment never reached zero as a range between 87.3 and $121.5\text{ Mg C ha}^{-1}$ was still found at 10 m depth across the study sites (Figure 2, Figure S1). Although variability was evident in the upper 0 to 3–5 m of sediments (Figure S1), carbon storage below 5 m depth appeared broadly similar among sites.

Other mangrove ecosystem components (Figure 2) had relatively lower carbon pool compared to the sediment. The vegetation biomass from the aboveground components of the tree trunk, stilt roots, branches, and leaves reached up to $210.3\text{ Mg C ha}^{-1}$, whereas the belowground component of the roots contributed only 8.6 Mg C ha^{-1} . Dead wood and leaf litter had a maximum carbon pool of 27.4 and 15.7 Mg C ha^{-1} , respectively.

3.2 | Carbon Stock at Different Forest Ages Under Silvicultural Management

The carbon pool in the vegetation biomass showed an increasing trend with forest age i.e., from $2.3 \pm 0.7\text{ Mg C ha}^{-1}$ in the 1 year-old site to $209.9 \pm 30.9\text{ Mg C ha}^{-1}$ at the VJR (Figure 3A). The significant differences in the trees biomass/carbon with increasing forest age was tested with Kruskal–Wallis test ($H = 61.46$, $df = 7$, $p < 0.05$). This trend was interrupted by a marked decrease in biomass at 15 years, coinciding with the first artificial thinning, whereas the second thinning did not produce a noticeable effect between ages 19 and 25.

The sediment carbon pool showed a less clear pattern (Figure 3B). From the surface cores, for which three replicates per site were



1	Leaf biomass	0.2 – 7.2 Mg C ha ⁻¹
2	Wood AGB	2.0 - 178.4 Mg C ha ⁻¹
3	Stilt biomass	0.2 - 24.9 Mg C ha ⁻¹
4	Dead wood	1.4 – 27.4 Mg C ha ⁻¹
5	Leaf litter	0.6 – 15.7 Mg C ha ⁻¹
6 & 7	BGB	0.1 – 8.6 Mg C ha ⁻¹
	1 m	347 - 619 Mg C ha ⁻¹
	2 m	250 - 723 Mg C ha ⁻¹
	3 m	220 - 667 Mg C ha ⁻¹
	4 m	75 - 438 Mg C ha ⁻¹
	5 m	116 - 318 Mg C ha ⁻¹
	6 m	80 - 182 Mg C ha ⁻¹
	7 m	65 - 202 Mg C ha ⁻¹
	8 m	74 - 138 Mg C ha ⁻¹
	9 m	56 - 129 Mg C ha ⁻¹
10 m	73 - 169 Mg C ha ⁻¹	
TOTAL		1360– 3847 Mg C ha⁻¹

FIGURE 2 | Carbon content of the different components of the mangroves at Matang Mangrove Forest Reserve. The carbon (min–max) values for each component were recorded from 8 sampling sites characterized by different forest age (ranging 1 to nearly 100 years). The belowground biomass was mostly confined to the first meter of sediment, but some roots extended to deeper layers. The total range for all ecosystem components is given. Conversion factors for the carbon estimates were obtained through direct measurements of carbon for all components, except the roots for which literature-based values from Kauffman and Donato (2012) were followed. The carbon values measured up to 10 m deep are 5 times higher than carbon estimates based on measurements of just one or a few meters.

available (Table S1), the first meter in the 15 year-old site showed significantly lower carbon compared to the pre-thinning 14 year-old site (ANOVA, $F = 3.89$, $df = 7$, $p = 0.005$). Although statistical analysis was not possible for deeper sediment layers, the sediment carbon stock below 3 m seemed to be less impacted by the silvicultural rotation compared to the surface.

Based on the age-class distribution for 2022, the year in which the sampling was conducted, the total carbon stock of the MMFR was calculated (Figure 4). Forest age was standardized according to the 30-year rotation cycle defined in the management plan, using age maps developed by Lucas et al. (2020) for 2016 adjusted to the year of sampling. While occasional deviations from the cycle occur (e.g., the 36 year-old site), these are relatively rare and do not substantially affect the overall age-class representation. The total carbon stock in the MMFR was estimated at 106.67 Tg, comprising sediment (103.4 Tg C), vegetation (3.27 Tg C), dead wood (0.51 Tg C), and leaf litter (0.02 Tg C).

4 | Discussion

4.1 | Depth Variations of Sediment Carbon

Our results strongly highlight the importance of soil depth in the measurement of the sediment carbon pool, with values at 10 m still comparable to the biomass carbon pool (73–169 Mg C ha⁻¹). Remarkably, the carbon stocks assessed from our 10 m deep cores at all sites were more than five times the amounts measured at 1 m, using the same cores. The measurements for 2.5 m were rather complementary to the estimated findings of Adame et al. (2018) (Table 1). Furthermore, at depths < 5 m the eight cores showed similar carbon content, suggesting that historical carbon pools are less spatially variable. These findings suggest that our single deep core approach per forest age class represents a good approximation of the deep sediment carbon. Such an approach, although limited in terms of spatial replications and statistical relevance, can give preliminary estimates of deep carbon stock in logistically limiting habitats, such as

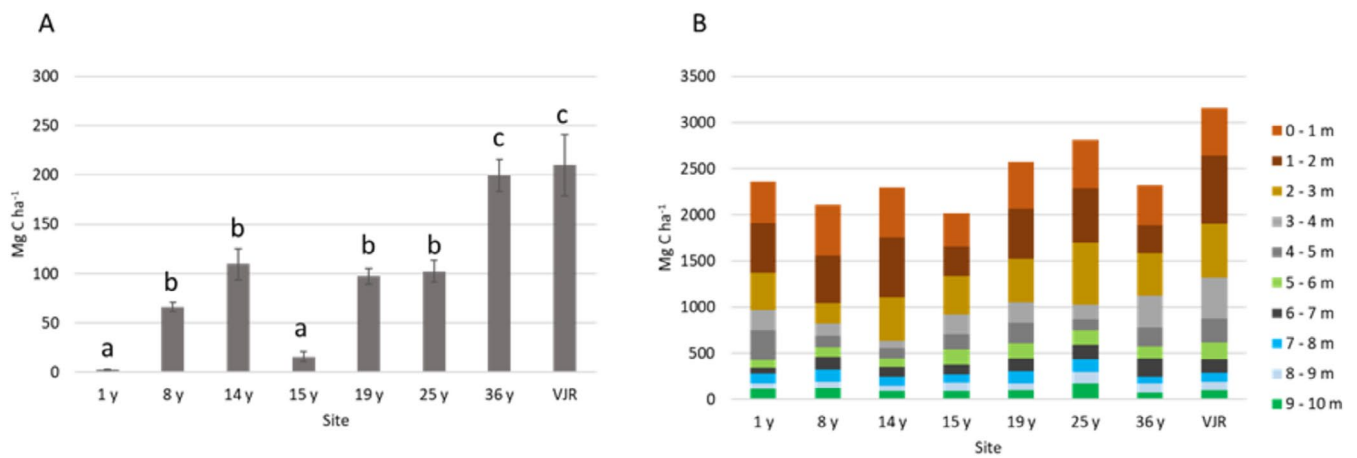


FIGURE 3 | Trends of total carbon in vegetation (A), and in 10m sediment cores (B) at different aged forest stands of the Matang Mangrove Forest Reserve. y: Years, the vegetation data was combined for AGB: Aboveground biomass (components n° 1,2 and 3 in Figure 1) and BGB: Belowground root biomass (Component n° 6 in Figure 1). The different colors in the sediment chart represent depth intervals of 1 m and follow the same order as in the legend. The 14- and 15-year-old forests were sampled just before and after the first thinning, while the 19-year-old forest was sampled before the second thinning. The 36-year-old forest is yet to be clear-felled. The protected forest site called Virgin Jungle Reserve (VJR) had an estimated age of nearly 100 years at the sampling time (Putz and Chan 1986). The lower-case letters in panel A indicate statistical differences in the biomass carbon among sites (Kruskal–Wallis $p < 0.05$). For sediment cores (panel B), statistical interpretation was constrained to the surface level by limited replication and sampling difficulty, and is therefore not reported in the figure.

mangrove forests, and is in line with protocols commonly applied in stratigraphic studies (e.g., Ellison 2008).

Importantly, the more biodiverse protected forest showed the highest sediment and biomass carbon pool, showing that older, mature mangroves are essential for the maintenance of a large carbon stock. Interestingly, at this location the second meter of sediment was enriched with more carbon than the first meter (Figure S1). The recorded enrichment is most probably associated with the leaf-storing behaviour of large sesarmid crabs, dominant in this area. In fact, the burrows of *Neosarmatium* and *Episesarma* are deeper than 1 m and these crabs store abundant vegetation material (leaves and propagules) in them, preventing the outwelling of nutrients from mangroves (Kristensen 2008; Berti et al. 2008; Andretta et al. 2014; Arnaud et al. 2022; Agosto et al. 2022). These data clearly show that the organic matter accumulation does not stop at 1 m (as informed by the IPCC criteria for sediment sampling for carbon studies) and can go even down to 4–5 m since we found dead and live root material in most of the cores, especially when brachyuran fauna was abundant. As mentioned also by other studies (Adame et al. 2017), such knowledge on the underground root penetration of mangroves is also limited and requires further research.

4.2 | Carbon Stocks Variability With Forest Age and Management Practices

In the MMFR, the age of mangrove trees plays an important role not only in determining the carbon stock of the vegetation biomass, as largely expected, but also in increasing total carbon in the sediment. Indeed, the total sediment carbon pool showed a peak in the *protected* forest up to 3154 Mg C ha⁻¹. The variability in the sediment carbon at different sites could be explained by site specific environmental factors, such as changes in geo-hydrological conditions (Murdiyarso et al. 2021) and change in

the diversity and abundance of leaf-storing and burrowing crabs (Andretta et al. 2014). In this context, both natural and anthropogenic disturbances are important and affect the sediment carbon (Eddy et al. 2021). For example, the lower carbon in the 36-year-old mangrove stand, as opposed to the majority of sites, could be linked to the presence of an already clear-felled (open) area next to it. The disturbed forest areas with more sunlight penetration also promote carbon loss in the sediment (Granek and Ruttenberg 2008; Lovelock et al. 2017). Significant variation of sediment carbon between 14- and 15-year-old stands in the first meter (Table S2) as well as in the vegetation carbon stock (Figure 3A) was apparently due to the forest (1st) thinning that significantly reduces the density of vegetation (Fontalvo-Herazo et al. 2011; Goessens et al. 2014). Also, the total loss of 456.75 Mg C ha⁻¹ in the sediment due to clear-felling, observed between the 25- and the 1-year-old stands, is noteworthy. These losses concern mainly the surface sediment up to 3 m depth, while the sediment below was not affected by short-term changes in the forest cover caused by thinning and clear-felling. As previously reported by Alongi et al. (1998), clear-felling operations in the MMFR negatively affect particulate organic matter and promote aerobic and suboxic processes at surface level, in contrast to the more stable conditions observed in undisturbed forested areas. In this paper, we do not aim to investigate the origin of the deep sediment carbon stock, but to emphasize the importance of the mangrove cover for its stable maintenance. At this point, the 30-year silvicultural rotation cycle in the MMFR is still allowing a recovery of the carbon lost by clear-felling and thinning operations in the selective areas (Yusop and Muhamad Nor 2021). Importantly, both *managed* and *protected* forest stands are together contributing to the carbon neutrality at the MMFR (Wolswijk et al. 2022).

Concerning the vegetation biomass at different aged forest stands (Figure 3A), from 1 to 36 years in the *managed* forest and nearly 100 years in the *protected* forest, we observed a significant

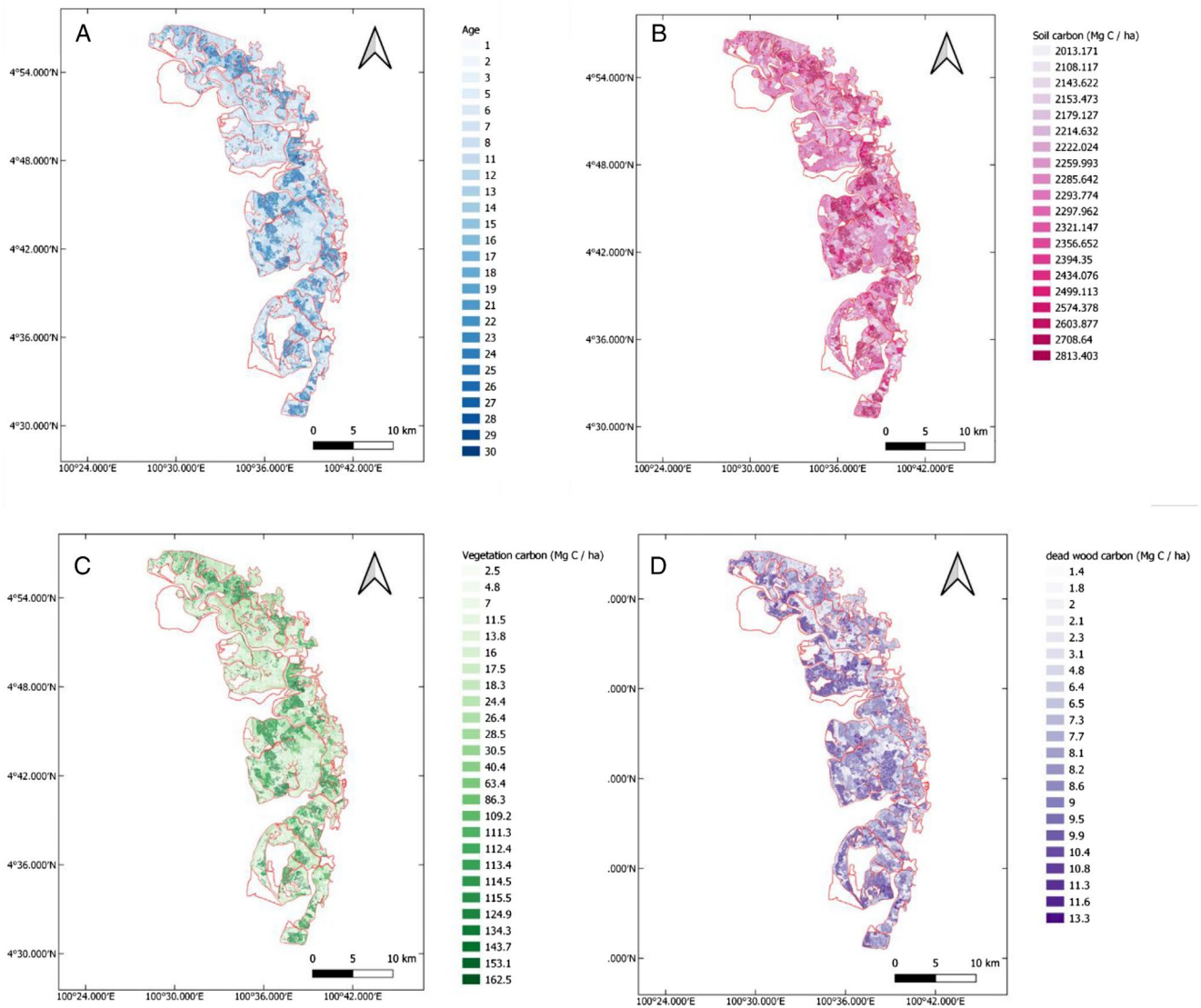


FIGURE 4 | Maps of the Managed areas of the Matang Mangrove Forest Reserve indicating—(A) Age of the mangroves in different compartments of the managed zone as of 31/12/2021 derived from Lucas et al. (2020) which included environmental covariates such as vegetation structure and elevation; (B) Sediment total carbon at 10 m depth; (C) Total carbon in the vegetation biomass (aboveground, belowground and stilt biomass combined); and (D) Total carbon in the dead wood biomass (downed wood and standing dead trees combined). For the sediment carbon (B) the interpolated surface is based on eight sediment cores and represents a coarse extrapolation across the MMFR. For the biomass (C) and dead wood (D) the interpolation was based on the data collected in 10 replicate plots for 8 sampling locations of different ages. Spatial patterns should be interpreted with caution due to the limited sampling density.

increase in the tree biomass/carbon with the increasing forest age, which is consistent with the previous estimates of Goessens et al. (2014), with a range of 83–145 Mg C ha⁻¹ between 15- and 100-year-old stands.

According to Bourgeois et al. (2024), planted mangroves can accumulate 75% of the carbon stock of a natural forest after 20 years. In the case of the MMFR, the biomass carbon stock of the 19-year-old forest was found equivalent to 54% of the carbon stock in the protected forest. The lower values are attributable to the first thinning practice that is specific to the pole production industry. Bourgeois et al. (Ibid.) also mentioned an 18% increase in sediment carbon in the first meter after 8 years of plantation which aligns with the present study, while there was more variability at lower depths.

4.3 | Total Carbon Stock for the MMFR

The historical subdivision of the MMFR into 108 compartments, that are harvested at different time intervals for the silvicultural rotation cycle, has created a mosaic of different-aged forest patches (Figure 4A). The projected sediment carbon (Figure 4B) and the vegetation carbon (Figure 4C) show scattered patterns of carbon stock distribution that can be useful to observe the changes associated with the ongoing MMFR management. The dead-wood carbon (Figure D) was high after the events of thinning and clear-felling. This carbon stock component is also influenced by natural tree mortality and fallen branches resulting from lightning strikes (Amir 2012) which was mostly evident in the protected forest. Compared to previous estimates from Wolswijk et al. (2022),

based on 1 m sediment data from Adame et al. (2018), the total sediment carbon pool showed a five-time increase from 19.4 to 103.4 Tg C, while the results for the vegetation were in the same range (Table 2).

TABLE 1 | Comparison of 10 m deep sediment carbon measurements in the present study with previous estimates at the Matang Mangrove Forest Reserve (Adame et al. 2018). All values reported are averages (\pm standard errors from 6 replicates, in the case of the literature data) and are reported in Mg C ha⁻¹. The sampling sites with different ages belong to the managed productive forest, and the Virgin Jungle Reserve (VJR) belongs to the unmanaged protected forest.

Site	Depth	Adame et al. (2018)	Present study
Clear-felled – 1 year	Total 0–1 m	385.2 \pm 72.6	447
	Total 0–2.50 m	1018 \pm 33.0	1187.9
	Total 0–10 m		2356.6
5–8 years	Total 0–1 m	460.8 \pm 14.8	549
	Total 0–2.50 m	1234 \pm 18	1179.2
	Total 0–10 m		2108.1
15 years	Total 0–1 m	483.2 \pm 22.1	360.8
	Total 0–2.50 m	1169 \pm 68.8	886.8
	Total 0–10 m		2013.2
30 years – 25 years	Total 0–1 m	497.5 \pm 21.5	525.5
	Total 0–2.50 m	1240 \pm 45.2	1451.8
	Total 0–10 m		2813.4
40 years – 36 years	Total 0–1 m	454.3 \pm 21.3	435.4
	Total 0–2.50 m	1187 \pm 100	966.0
	Total 0–10 m		2316.9
VJR	Total 0–1 m	545.0 \pm 113.4	511.1
	Total 0–2.50 m	1309 \pm 270	1545.7
	Total 0–10 m		3154.0

4.4 | Implications for a Worldwide Mangrove Deep Carbon Stock Assessment

Our data from MMFR complements the use of standard 1 m deep cores for mangrove sediment carbon estimation. While we recognize that deep coring is not always feasible due to the logistical difficulties of working in mangrove forests, our results underscore the importance of considering deeper sediments in carbon stock calculations to avoid systematic underestimation. Mangrove sediment carbon stock can vary significantly from region to region due to differences in sedimentary setting and geomorphology along with variations in temperature and precipitation rate (Rovai et al. 2018; Kauffman et al. 2020; Worthington et al. 2020; MacKenzie et al. 2021). These characteristics will also affect the maximum depth at which the carbon will be accumulated, and the relative amount at each layer. We could expect deep carbon stocks in areas that have similar characteristics to the MMFR. For instance, large deltas and estuaries are likely to have deeper sediments compared to lagoon and open coast mangroves, thanks to the input of sediments and organic matter from allochthonous origin (Cooray et al. 2024).

Mangroves in terrigenous sedimentary settings showed to exhibit higher carbon burial rates, compared to carbonate settings, ranging from 132.8 to 190.1 g OC m⁻²yr.⁻¹ and from 84.5 to 123.6 g OC m⁻²yr.⁻¹, respectively (Breithaupt and Steinmuller 2022). This disparity is largely attributed to the greater influx of suspended sediments and nutrients from riverine sources, as well as high primary productivity in large riverine settings (Robertson et al. 1992). Deltaic and estuarine mangroves, in particular, benefit from enhanced primary productivity due to elevated nutrient availability, which in turn promotes increased organic carbon burial (Twilley et al. 2018). Over millennial timescales, these depositional environments facilitate the formation of deep sediment layers, where organic carbon becomes increasingly stabilized through reduced bioturbation and chemical transformation (Arnaud et al. 2025).

Evidence from sediment cores used in sea-level reconstruction studies further supports the presence of deep sedimentary deposits in deltaic mangrove systems. For example, sediment depths of at least 5 m have been recorded in the Mekong Delta, Vietnam (Woodroffe et al. 2016), and the Doce River estuary in southern Brazil (França et al. 2013). These depths may well exceed 10 m in some locations, comparable to or even deeper than those observed in the MMFR, suggesting the potential for substantial long-term carbon storage in these ecosystems.

TABLE 2 | Comparison of sediment and vegetation carbon stocks in different zones of the Matang Mangrove Forest Reserve in the present study with previous estimates from Wolswijk et al. (2022).

Zone	Area (ha)	Sediment C (Tg) present study	Sediment C (Tg) Wolswijk et al. (2022)	Vegetation C (Tg) Present study	Vegetation C (Tg) Wolswijk et al. (2022)
Managed	30,464	70.5	13.6	2.03	2.01
Protected	11,661	32.80	5.80	1.24	1.62
Total	42,136	103.40	19.40	3.27	3.63

On this theoretical basis, and to highlight the possible importance of deep carbon sinks in blue carbon studies, we provide an exploratory prediction of mangrove sediment carbon stocks to 10 m depth at a global scale (Figure S2; Table S3) based on country-level data from the Global Mangrove Watch Version 3 (2022), with sediment carbon stock values derived from 1 m depth estimates at 30 m spatial resolution (Sanderman et al. 2018), and deltaic and estuarine classification from Worthington et al. (2020) (see supporting information for details). Our preliminary estimates, based on our local-scale measurements, suggest a global stock approximately 3.5 times higher than the amount previously reported from 1 m cores. We emphasize that these values are conceptual extrapolations, assuming that deltaic and estuarine mangroves elsewhere may exhibit sediment depths comparable to the MMFR. Carbonate and sandy coastal mangroves, which lack deep unconsolidated sediments, were excluded. We acknowledge that both horizontal and vertical variability in sediment carbon concentration remain significant sources of uncertainty (Yando et al. 2025; Piñeiro-Juncal et al. 2025). Our own dataset illustrates variability within the first meters, with some cores showing higher carbon pools in the second meter before declining and stabilizing below 4–5 m. Such patterns reinforce the ecological plausibility of deep carbon storage but highlight the need for expanded replication across diverse geomorphic settings.

In the current era of climate change, our results emphasize the primary importance of conserving mangrove forest and their communities for maintaining the carbon sequestration service and their value as blue carbon sinks. The deep sediment carbon is particularly important under the scenario of land conversions, like aquaculture pond construction, that imply changes in sediment elevation of at least 1.5 m depth (FAO 2012; Sasmito et al. 2019), or infrastructure construction that requires the excavation of deep sediment for foundation purposes, with subsequent risk of releasing a massive amount of carbon back into the atmosphere.

Author Contributions

Giovanna Wolswijk: conceptualization, methodology, software, validation, formal analysis, investigation, data curation, writing – original draft, writing – review and editing, visualization, funding acquisition. **Behara Satyanarayana:** conceptualization, methodology, validation, investigation, resources, data curation, project administration, visualization, supervision, funding acquisition, writing – review and editing. **Nur Hannah Abd Rahim:** investigation, writing – review and editing. **Che Mohd Kamarul Anuar Che Abdullah:** investigation, writing – review and editing. **Ahmad Nazila Ali:** investigation, writing – review and editing. **Louise Wolswijk:** investigation, visualization, writing – review and editing. **Mohamad Khalies Hami Hamzah:** investigation, writing – review and editing. **Stefano Cannicci:** writing – review and editing. **Farid Dahdouh-Guebas:** conceptualization, methodology, validation, investigation, resources, data curation, project administration, visualization, supervision, funding acquisition, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are openly available in Figshare at <https://doi.org/10.6084/m9.figshare.29906495>.

References

- Adame, M. F., S. Cherian, R. Reef, and B. Stewart-Koster. 2017. “Mangrove Root Biomass and the Uncertainty of Belowground Carbon Estimations.” *Forest Ecology and Management* 403: 52–60. <https://doi.org/10.1016/j.foreco.2017.08.016>.
- Adame, M. F., R. M. Connolly, M. P. Turschwell, et al. 2021. “Future Carbon Emissions From Global Mangrove Forest Loss.” *Global Change Biology* 27: 2856–2866. <https://doi.org/10.1111/gcb.15571>.
- Adame, M. F., N. S. Santini, O. Torres-Talamante, and K. Rogers. 2021. “Mangrove Sinkholes (Cenotes) of the Yucatan Peninsula, a Global Hotspot of Carbon Sequestration.” *Biology Letters* 17, no. 5: 20210037. <https://doi.org/10.1098/rsbl.2021.0037>.
- Adame, M. F., R. M. Zakaria, B. Fry, et al. 2018. “Loss and Recovery of Carbon and Nitrogen After Mangrove Clearing.” *Ocean and Coastal Management* 161: 117–126. <https://doi.org/10.1016/j.ocecoaman.2018.04.019>.
- Agusto, L. E., S. Fratini, P. J. Jimenez, A. Quadros, and S. Cannicci. 2021. “Structural Characteristics of Crab Burrows in Hong Kong Mangrove Forests and Their Role in Ecosystem Engineering.” *Estuarine, Coastal and Shelf Science* 248: 106973. <https://doi.org/10.1016/j.ecss.2020.106973>.
- Agusto, L. E., G. Qin, B. Thibodeau, et al. 2022. “Fiddling With the Blue Carbon: Fiddler Crab Burrows Enhance CO₂ and CH₄ Efflux in Saltmarsh.” *Ecological Indicators* 144: 109538. <https://doi.org/10.1016/j.ecolind.2022.109538>.
- Alongi, D. M. 2022. “Impacts of Climate Change on Blue Carbon Stocks and Fluxes in Mangrove Forests.” *Forests* 13, no. 2: 149. <https://doi.org/10.3390/f13020149>.
- Alongi, D. M., A. Sasekumar, F. Tirendi, and P. Dixon. 1998. “The Influence of Stand Age on Benthic Decomposition and Recycling of Organic Matter in Managed Mangrove Forests of Malaysia.” *Journal of Experimental Marine Biology and Ecology* 225, no. 2: 197–218.
- Amir, A. A. 2012. “Canopy Gaps and the Natural Regeneration of Matang Mangroves.” *Forest Ecology and Management* 269: 60–67. <https://doi.org/10.1016/j.foreco.2011.12.040>.
- Andreetta, A., M. Fusi, I. Cameldi, F. Cimò, S. Carnicelli, and S. Cannicci. 2014. “Mangrove Carbon Sink. Do Burrowing Crabs Contribute to Sediment Carbon Storage? Evidence From a Kenyan

- Mangrove System." *Journal of Sea Research* 85: 524–533. <https://doi.org/10.1016/j.seares.2013.08.010>.
- Ariffin, R., and N. M. S. bin Nik Mustafa. 2013. *A Working Plan for the Matang Mangrove Forest Reserve, Perak*. Perak State Forestry Department.
- Arkema, K. K., J. M. S. Delevaux, J. M. Silver, et al. 2023. "Evidence-Based Target Setting Informs Blue Carbon Strategies for Nationally Determined Contributions." *Nature Ecology & Evolution* 7: 1045–1059. <https://doi.org/10.1038/s41559-023-02081-1>.
- Arnaud, M., A. J. Baird, P. J. Morris, et al. 2022. "The Effect of Crab Burrows on Soil-Water Dynamics in Mangroves." *Hydrological Processes* 36, no. 3: e14522. <https://doi.org/10.1002/hyp.14522>.
- Arnaud, M., C. E. Lovelock, M. Maceiras, et al. 2025. "The Nature of Soil Blue Carbon Varies Across Mangrove Geomorphic Settings." *Communications Earth & Environment* 6, no. 1: 743. <https://doi.org/10.1038/s43247-025-02531-7>.
- Berti, R., S. Cannicci, S. Fabbri, and G. Innocenti. 2008. "Notes on the Structure and the Use of Neosarbatium Meinerti and Cardisoma Carnifex Burrows in a Kenyan Mangrove Swamp (Decapoda Brachyura)." *Ethology Ecology & Evolution* 20: 101–113. <https://doi.org/10.1080/08927014.2008.9522531>.
- Bouillon, S., F. Dahdouh-Guebas, A. V. V. S. Rao, N. Koedam, and F. Dehairs. 2003. "Sources of Organic Carbon in Mangrove Sediments: Variability and Possible Ecological Implications." *Hydrobiologia* 495, no. 1: 33–39. <https://doi.org/10.1023/A:1025411506526>.
- Bourgeois, C. F., R. A. MacKenzie, S. Sharma, et al. 2024. "Four Decades of Data Indicate That Planted Mangroves Stored up to 75% of the Carbon Stocks Found in Intact Mature Stands." *Science Advances* 10, no. 27: eadk5430. <https://doi.org/10.1126/sciadv.adk5430>.
- Breithaupt, J. L., and H. E. Steinmüller. 2022. "Refining the Global Estimate of Mangrove Carbon Burial Rates Using Sedimentary and Geomorphic Settings." *Geophysical Research Letters* 49, no. 18: e2022GL100177. <https://doi.org/10.1029/2022GL100177>.
- Bunting, P., A. Rosenqvist, L. Hilarides, et al. 2022. "Global Mangrove Extent Change 1996–2020: Global Mangrove Watch Version 3.0." *Remote Sensing* 14, no. 15: 3657. <https://doi.org/10.3390/rs14153657>.
- Chatting, M., I. Al-Maslami, M. Walton, et al. 2022. "Future Mangrove Carbon Storage Under Climate Change and Deforestation." *Frontiers in Marine Science* 9: 781876. <https://doi.org/10.3389/fmars.2022.781876>.
- Chen, D., B. Satyanarayana, G. Wolswijk, et al. 2024. "Historical Ecological Monitoring and Appraisal for Extractive Uses and Other Mangrove Values in Malaysia Unveils Consequences of Regime Shifts in 120 Years of Forest Management." *Journal for Nature Conservation* 79: 126582. <https://doi.org/10.1016/j.jnc.2024.126582>.
- Chong, V. C. 2006. "Sustainable Utilization and Management of Mangrove Ecosystems of Malaysia." *Aquatic Ecosystem Health & Management* 9, no. 2: 249–260. <https://doi.org/10.1080/14634980600717084>.
- Cooray, I. G., G. Chalmers, and D. Chittleborough. 2024. "The Impact of Sampling Depths on Quantification of Soil Organic Carbon Stock in Mangrove Environments." *Catena* 246: 108398.
- Dahdouh-Guebas, F., and N. Koedam. 2006. "Empirical Estimate of the Reliability of the Use of the Point-Centred Quarter Method (PCQM): Solutions to Ambiguous Field Situations and Description of the PCQM+ Protocol." *Forest Ecology and Management* 228, no. 1–3: 1–18. <https://doi.org/10.1016/j.foreco.2005.10.076>.
- Donato, D. C., J. B. Kauffman, D. Murdiyarso, S. Kurnianto, M. Stidham, and M. Kanninen. 2011. "Mangroves Among the Most Carbon-Rich Forests in the Tropics." *Nature Geoscience* 4, no. 5: 293–297. <https://doi.org/10.1038/ngeo1123>.
- Eddy, S., N. Milantara, S. D. Sasmito, T. Kajita, and M. Basyuni. 2021. "Anthropogenic Drivers of Mangrove Loss and Associated Carbon Emissions in South Sumatra, Indonesia." *Forests* 12, no. 2: 187. <https://doi.org/10.3390/f12020187>.
- Ellison, J. C. 2008. "Long-Term Retrospection on Mangrove Development Using Sediment Cores and Pollen Analysis: A Review." *Aquatic Botany* 89, no. 2: 93–104. <https://doi.org/10.1016/j.aquabot.2008.02.007>.
- FAO. 2012. *The State of World Fisheries and Aquaculture 2012*. Food and Agriculture Organization of the United Nations.
- Fest, B. J., S. E. Swearer, and S. K. Arndt. 2022. "A Review of Sediment Carbon Sampling Methods in Mangroves and Their Broader Impacts on Stock Estimates for Blue Carbon Ecosystems." *Science of the Total Environment* 816: 151618. <https://doi.org/10.1016/j.scitotenv.2021.151618>.
- Fontalvo-Herazo, M. L., C. Piou, J. Vogt, U. Saint-Paul, and U. Berger. 2011. "Simulating Harvesting Scenarios Towards the Sustainable Use of Mangrove Forest Plantations." *Wetlands Ecology and Management* 19: 397–407. <https://doi.org/10.1007/s11273-011-9224-4>.
- França, M. C., M. C. Cohen, L. C. Pessenda, et al. 2013. "Mangrove Vegetation Changes on Holocene Terraces of the Doce River, Southeastern Brazil." *Catena* 110: 59–69. <https://doi.org/10.1016/j.catena.2013.06.011>.
- Goessens, A., B. Satyanarayana, T. Van der Stocken, et al. 2014. "Is Matang Mangrove Forest in Malaysia Sustainably Rejuvenating After More Than a Century of Conservation and Harvesting Management?" *PLoS One* 9, no. 8: e105069. <https://doi.org/10.1371/journal.pone.0105069>.
- Goldberg, L., D. Lagomasino, N. Thomas, and T. Fatoyinbo. 2020. "Global declines in human-driven mangrove loss." *Global Change Biology* 26: 5844–5855. <https://doi.org/10.1111/gcb.15275>.
- Gong, W. K., and J. E. Ong. 1990. "Plant Biomass and Nutrient Flux in a Managed Mangrove Forest in Malaysia." *Estuarine, Coastal and Shelf Science* 31, no. 5: 519–530. [https://doi.org/10.1016/0272-7714\(90\)90010-O](https://doi.org/10.1016/0272-7714(90)90010-O).
- Granek, E., and B. I. Ruttenberg. 2008. "Changes in Biotic and Abiotic Processes Following Mangrove Clearing." *Estuarine, Coastal and Shelf Science* 80, no. 4: 555–562. <https://doi.org/10.1016/j.ecss.2008.09.012>.
- Hamdan, O., H. K. Aziz, and I. M. Hasmadi. 2014. "L-Band ALOS PALSAR for Biomass Estimation of Matang Mangroves, Malaysia." *Remote Sensing of Environment* 155: 69–78. <https://doi.org/10.1016/j.rse.2014.04.029>.
- Heck, N., L. Goldberg, D. A. Andradi-Brown, et al. 2024. "Global Drivers of Mangrove Loss in Protected Areas." *Conservation Biology* 38, no. 6: e14293. <https://doi.org/10.1111/cobi.14293>.
- IPCC. 2014. (2013) *Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. IPCC. <http://www.ipcc-nggip.iges.or.jp>.
- Kauffman, J. B., M. F. Adame, V. B. Arifanti, et al. 2020. "Total Ecosystem Carbon Stocks of Mangroves Across Broad Global Environmental and Physical Gradients." *Ecological Monographs* 90, no. 2: e01405. <https://doi.org/10.1002/ecm.1405>.
- Kauffman, J. B., and D. C. Donato. 2012. *Protocols for the Measurement, Monitoring and Reporting of Structure, Biomass and Carbon Stocks in Mangrove Forests*. Vol. 86. Cifor.
- Kida, M., I. Watanabe, K. Kinjo, et al. 2021. "Organic Carbon Stock and Composition in 3.5-m Core Mangrove Soils (Trat, Thailand)." *Science of the Total Environment* 801: 149682. <https://doi.org/10.1016/j.scitotenv.2021.149682>.
- Komiyama, A., J. E. Ong, and S. Pongparn. 2008. "Allometry, Biomass, and Productivity of Mangrove Forests: A Review." *Aquatic Botany* 89, no. 2: 128–137. <https://doi.org/10.1016/j.aquabot.2007.12.006>.

- Kristensen, E. 2008. "Mangrove Crabs as Ecosystem Engineers; With Emphasis on Sediment Processes." *Journal of Sea Research* 59: 30–43. <https://doi.org/10.1016/j.seares.2007.05.004>.
- Lester, S. E. 2023. "Blue Carbon for Climate and Co-Benefits." *Nature Ecology & Evolution* 7: 967–968. <https://doi.org/10.1038/s41559-023-02034-8>.
- Lovelock, C. E., T. Atwood, J. Baldock, et al. 2017. "Assessing the Risk of Carbon Dioxide Emissions From Blue Carbon Ecosystems." *Frontiers in Ecology and the Environment* 15, no. 5: 257–265. <https://doi.org/10.1002/fee.1491>.
- Lucas, R., R. Van De Kerchove, V. Otero, et al. 2020. "Structural Characterisation of Mangrove Forests Achieved Through Combining Multiple Sources of Remote Sensing Data." *Remote Sensing of Environment* 237: 111543. <https://doi.org/10.1016/j.rse.2019.111543>.
- MacKenzie, R., S. Sharma, and A. R. Rovai. 2021. "Environmental Drivers of Blue Carbon Burial and Soil Carbon Stocks in Mangrove Forests." In *Dynamic Sedimentary Environments of Mangrove Coasts*, 275–294. Elsevier. <https://doi.org/10.1016/B978-0-12-816437-2.00006-9>.
- Macreadie, P. I., M. D. Costa, T. B. Atwood, et al. 2021. "Blue carbon as a natural climate solution." *Nature Reviews Earth & Environment* 2, no. 12: 826–839. <https://doi.org/10.1038/s43017-021-00224-1>.
- Murdiyarso, D., S. D. Sasmito, M. Sillanpää, R. MacKenzie, and D. Gaveau. 2021. "Mangrove Selective Logging Sustains Biomass Carbon Recovery, Soil Carbon, and Sediment." *Scientific Reports* 11: 12325. <https://doi.org/10.1038/s41598-021-91502-x>.
- Nam, V. N., S. D. Sasmito, D. Murdiyarso, J. Purbopuspito, and R. A. MacKenzie. 2016. "Carbon Stocks in Artificially and Naturally Regenerated Mangrove Ecosystems in the Mekong Delta." *Wetlands Ecology and Management* 24: 231–244. <https://doi.org/10.1007/s11273-015-9479-2>.
- Otero, V., R. Van De Kerchove, B. Satyanarayana, et al. 2018. "Managing Mangrove Forests From the Sky: Forest Inventory Using Field Data and Unmanned Aerial Vehicle (UAV) Imagery in the Matang Mangrove Forest Reserve, Peninsular Malaysia." *Forest Ecology and Management* 411: 35–45. <https://doi.org/10.1016/j.foreco.2017.12.049>.
- Piñeiro-Juncal, N., M. Á. Mateo, C. Leiva-Dueñas, et al. 2025. "Soil Organic Carbon Depth Profiles and Centennial and Millennial Decay Rates in Tidal Marsh, Mangrove and Seagrass Blue Carbon Ecosystems." *Communications Earth & Environment* 6, no. 1: 504. <https://doi.org/10.1038/s43247-025-02390-2>.
- Putz, F. E., and H. T. Chan. 1986. "Tree Growth, Dynamics, and Productivity in a Mature Mangrove Forest in Malaysia." *Forest Ecology and Management* 17, no. 2-3: 211–230.
- Rasquinha, D. N., and D. R. Mishra. 2021. "Impact of Wood Harvesting on Mangrove Forest Structure, Composition and Biomass Dynamics in India." *Estuarine, Coastal and Shelf Science* 248: 106974. <https://doi.org/10.1016/j.ecss.2020.106974>.
- Robertson, A. I., D. M. Alongi, and K. G. Boto. 1992. "Food Chains and Carbon Fluxes." In *Tropical Mangrove Ecosystems*, edited by A. I. Robertson and D. M. Alongi, 293–326. American Geophysical Union.
- Rovai, A. S., R. R. Twilley, E. Castañeda-Moya, et al. 2018. "Global Controls on Carbon Storage in Mangrove Soils." *Nature Climate Change* 8, no. 6: 534–538. <https://doi.org/10.1038/s41558-018-0162-5>.
- Saenger, P. 2002. "Mangrove Silviculture and Restoration." In *Mangrove Ecology, Silviculture and Conservation*. Springer. https://doi.org/10.1007/978-94-015-9962-7_8.
- Sanderman, J., T. Hengl, G. Fiske, et al. 2018. "A Global Map of Mangrove Forest Soil Carbon at 30 m Spatial Resolution." *Environmental Research Letters* 13, no. 5: 055002. <https://doi.org/10.1088/1748-9326/aabelc>.
- Sasmito, S. D., P. Taillardat, J. N. Clendenning, et al. 2019. "Effect of Land-Use and Land-Cover Change on Mangrove Blue Carbon: A Systematic Review." *Global Change Biology* 25: 4291–4302. <https://doi.org/10.1111/gcb.14774>.
- Satyanarayana, B., M. R. Quispe-Zuniga, J. Hugé, I. Sulong, H. Mohd-Lokman, and F. Dahdouh-Guebas. 2021. "Mangroves Fueling Livelihoods: A Socio-Economic Stakeholder Analysis of the Charcoal and Pole Production Systems in the World's Longest Managed Mangrove Forest." *Frontiers in Ecology and Evolution* 9: 621721. <https://doi.org/10.3389/fevo.2021.621721>.
- Sillanpää, M., J. Vantellingen, and D. A. Friess. 2017. "Vegetation Regeneration in a Sustainably Harvested Mangrove Forest in West Papua, Indonesia." *Forest Ecology and Management* 390: 137–146. <https://doi.org/10.1016/j.foreco.2017.01.022>.
- Song, S., Y. Ding, W. Li, et al. 2023. "Mangrove Reforestation Provides Greater Blue Carbon Benefit Than Afforestation for Mitigating Global Climate Change." *Nature Communications* 14, no. 1: 756. <https://doi.org/10.1038/s41467-023-36477-1>.
- Tomlinson, P. 2016. *The Botany of Mangroves*. 2nd ed. Cambridge University Press. <https://doi.org/10.1017/CBO9781139946575>.
- Trettin, C. C., Z. Dai, W. Tang, et al. 2021. "Mangrove Carbon Stocks in Pongara National Park, Gabon." *Estuarine, Coastal and Shelf Science* 259: 107432. <https://doi.org/10.1016/j.ecss.2021.107432>.
- Twilley, R. R., A. S. Rovai, and P. Riul. 2018. "Coastal Morphology Explains Global Blue Carbon Distributions." *Frontiers in Ecology and the Environment* 16, no. 9: 503–508. <https://doi.org/10.1002/fee.1937>.
- Wolswijk, G., A. Barrios Trullols, J. Hugé, et al. 2022. "Can Mangrove Silviculture be Carbon Neutral?" *Remote Sensing* 14, no. 12: 2920. <https://doi.org/10.3390/rs14122920>.
- Woodroffe, C. D., K. Rogers, K. L. McKee, C. E. Lovelock, I. A. Mendelssohn, and N. Saintilan. 2016. "Mangrove Sedimentation and Response to Relative Sea-Level Rise." *Annual Review of Marine Science* 8: 243–266. <https://doi.org/10.1146/annurev-marine-122414-034025>.
- Worthington, T. A., P. S. Zu Ermgassen, D. A. Friess, et al. 2020. "A Global Biophysical Typology of Mangroves and Its Relevance for Ecosystem Structure and Deforestation." *Scientific Reports* 10, no. 1: 14652. <https://doi.org/10.1038/s41598-020-71194-5>.
- Yando, E. S., J. B. Alemu, K. E. Lim, et al. 2025. "Edge Effects Impact Blue Carbon Dynamics Across Coastal Ecotones in a Tropical Seascape." *Limnology and Oceanography* 70, no. 1: 54–67. <https://doi.org/10.1002/lno.12734>.
- Yusop, M. Z., and N. L. Muhamad Nor. 2021. *Rancangan Kerja Hutan Paya Laut Matang 2020–2029*. Perak forestry department.
- Zhang, F., X. Liu, J. Chen, C. Lu, G. Chen, and Y. Ye. 2024. "Differences in Organic Carbon Accumulation in Mangrove Soils due to Foraging by Herbivorous Crabs." *Marine Environmental Research* 194: 106332. <https://doi.org/10.1016/j.marenvres.2023.106332>.

Supporting Information

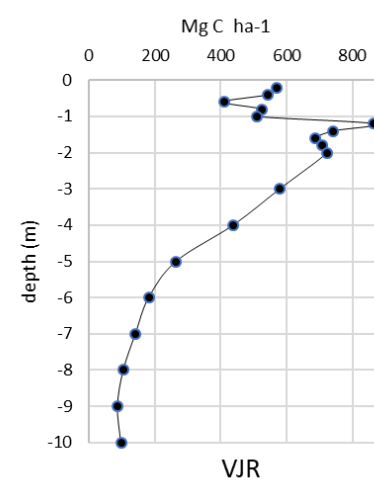
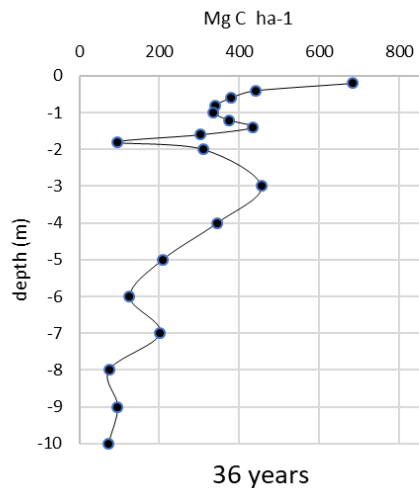
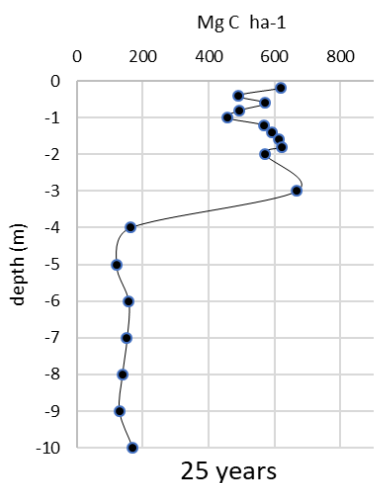
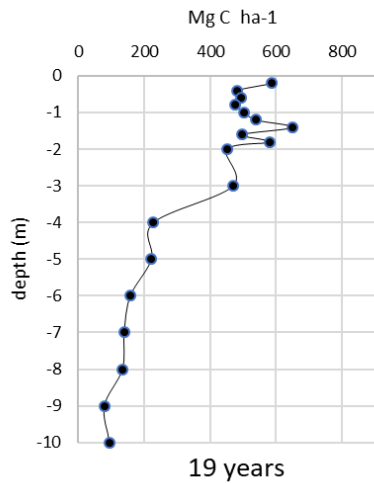
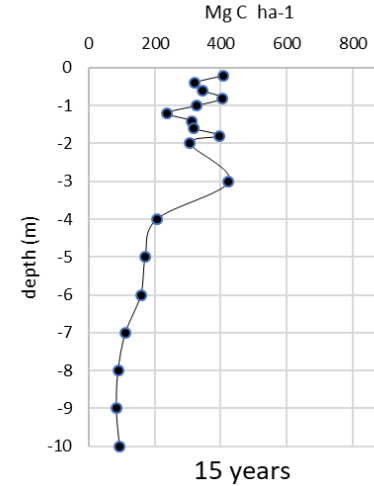
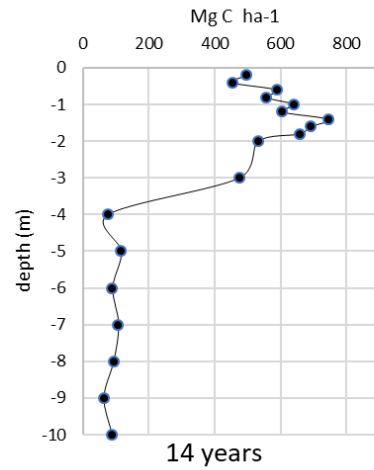
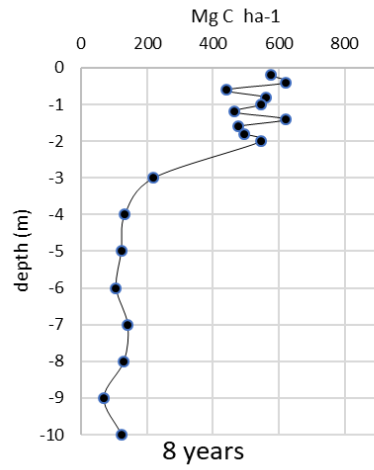
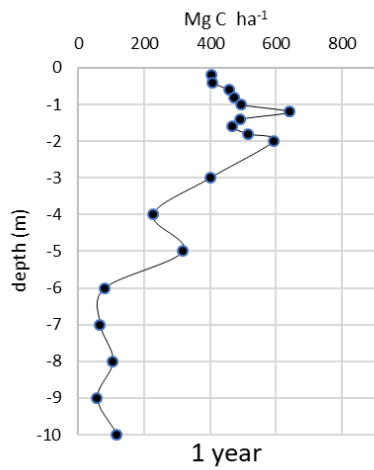
Additional supporting information can be found online in the Supporting Information section. **Data S1:** Supplementary Figures and Tables.

Supporting information

Table S1. Location per compartment of the different study sites with respective GPS location and sampling date.

Age	compartment	GPS location		Date sampling
36 years	39	N 04°50'07.7"	E 100°35'10.1"	6-8 January 2022
25 years	29	N 04°50'40.5"	E 100°35'18.1"	17 and 19 May 2022
19 years	18	N 04°50'51.1"	E 100°37'23.7"	19-21 July 2022
15 years	38	N 04°50'10.6"	E 100°35'18.4"	15-17 January 2022
14 years	26	N 04°51'52.3"	E 100°34'27.3"	17-19 July 2022
8 years	19	N 04°50'44.0"	E 100°35'54.6"	15-17 July 2022
1 year	37	N 04°49'20.6"	E 100°34'46.6"	12-14 January 2022
VJR	18A	N 04°50'17.8"	E 100°37'07.3"	9-11 January 2022

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Figure S1. Sediment total carbon distribution profiles (Mg C ha^{-1}) for the different aged managed and unmanaged (virgin jungle reserve - VJR) locations at the Matang Mangrove Forest Reserve. The data for the first meter is a combination of the results from three cores. The first two meters were subsampled for every 20 cm, while deeper layers were sampled for every meter. The protected forest (VJR) shows much higher carbon content than the managed areas.

Table S2. Results from the statistical analysis of the first meter of sediment carbon. Five subsamples of 20 cm from the three surface replicate cores were considered for the statistical analysis. Statistical significance ($p < 0.05$) was tested with t-tests for pair comparisons and ANOVA for multiple comparisons.

1 st meter	Group 1	Group 2	p value	Significant difference ($p < 0.05$)
Clearfelling	1 year	25 years	0.07	no
Thinning I	14 years	15 years	0.008	yes
Thinning II	19 years	25 years	0.2	no
Managed vs protected	1,8,14,15,19,25 and 36 years	VJR	0.8, 0.9, 0.9, 0.05, 1, 0.9, 0.7	Only 15 years different

Exploratory prediction at global scale

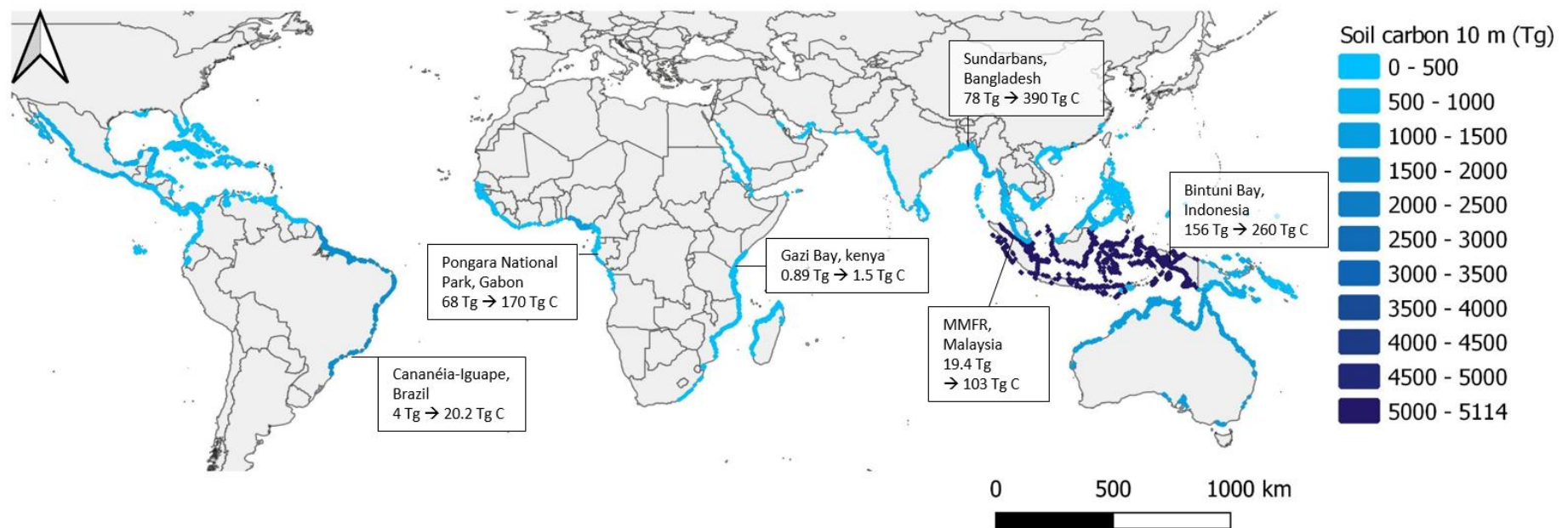
To evaluate the potential impact of considering 10 m deep sediments at a global scale, we computed an estimate of mangrove carbon stock to this depth using QGIS 3.10 (A Coruña) (Figure S2, Table S3). The analysis was based on country-level data from the Global Mangrove Watch Version 3 (2022), with sediment carbon stock values derived from 1 m depth estimates at 30 m spatial resolution (Sanderman et al., 2018), and extrapolated using the mangrove typology classification from Worthington et al. (2021). According to the latter, mangroves can be classified into four categories: estuarine, deltaic, open coast and lagoonal. Each of these can be either on a terrigenous or carbonate setting. Mangrove areas that could possibly have deeper sediments and similar conditions to the MMFR are likely of deltaic and estuarine nature (and mostly terrigenous), therefore we utilized the percentage of these two typologies to calculate the prediction of carbon stock for 10 m depth per country by using a ×5 factor on the 1 m sediment carbon stock data. The use of this multiplier represents a first-order approximation, intended to capture the potential magnitude of deep sediment carbon stocks at global scale.

Concerning this exploratory prediction at global scale, the lack of data on maximum sediment depth limits the possibility to assess whether all the sites with deltaic and estuarine conditions have sediments penetrable up to 10 m depth and the values being reported for other areas are valid. We acknowledge that extrapolating deep sediment carbon estimates from a limited number of cores within a single forest system (MMFR) introduces uncertainty when applied at the global scale. Mangrove sediment characteristics (including depth, carbon density, and accumulation rates) are known to vary across geomorphic settings, tidal regimes, vegetation types, and disturbance histories (Rovai *et al.*, 2018). Our extrapolation is therefore intended as a first-order approximation, restricted to deltaic and estuarine mangrove systems where sedimentary conditions are broadly comparable to those of the MMFR. While this approach provides a useful benchmark for evaluating the potential magnitude of deep sediment carbon stocks, we emphasize that it does not capture the full heterogeneity of global mangrove environments.

Comparisons with case studies (Table S4) illustrate how possible estimates based on 10 m depth diverge sharply from those based on 1–3 m cores, particularly in extensive mangrove systems such as the Sundarbans (Bangladesh) and Bintuni Bay (Indonesia), where deep sediment

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carbon could exceed 200 Tg C. These examples underscore the importance of targeted deep coring campaigns to refine global assessments. Future efforts should incorporate a broader range of geomorphic contexts and regional datasets to refine these estimates and increase within-site replication, despite its labour-intensiveness. However, due to the latter such global-scale studies might take decades to be carried out and published. We hope that refining global assessments of deep carbon in each of the >120 countries and territories with mangroves will become a priority that will be considered relevant at the science-policy interface.



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Figure S2. Exploratory prediction of global mangrove sediment carbon stocks to 10 m depth, based on Global Mangrove Watch (GMW) v3.0 (Sanderman et al., 2018; Bunting et al., 2022b) and mangrove typology classification by Worthington et al. (2020). Estimates were recalculated per country using the percentage of deltaic and estuarine mangroves (Table S3), excluding countries with <5 km² mangrove cover. Insets illustrate the change in sediment carbon stock estimates from 1–3 m (depending on previous sampling depth) to 10 m for selected case studies with prior sediment core measurements (Table S4), together with our site-specific results for the Matang Mangrove Forest Reserve (MMFR), Malaysia. These projections are presented as exploratory and conceptual, intended to highlight the potential importance of deep sediment carbon pools rather than provide definitive global estimates.

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Table S3. Exploratory estimates of sediment carbon for 10 m depth used to create the map in Figure 4. Country level data were obtained from the Global Mangrove Watch v3.0 (Sanderman *et al.*, 2018) and percentages of deltaic and estuarine cover were derived from Worthington *et al.* (2021).

Country/Territory	mangrove extent (Km ²)	sediment carbon 1m (Mt CO ₂ eq)	Sediment carbon 1 m (Tg C)	Estuarine type %	Deltaic type %	Sediment carbon 10 m (Tg C)
Indonesia	29,534	5,008	1364.7	30.9	37.8	5114.9
Brazil	11,415	1,335	363.7	16.6	68.4	1600.2
Australia	10,171	1,131	308.3	57.8	2.1	1046.8
Mexico	10,055	1,259	343.1	12.7	9.3	645.0
Nigeria	8,442	1,034	281.7	38.9	56.6	1357.6
Myanmar	5,435	533	145.1	30.9	37.8	543.9
Malaysia	5,246	901	245.5	30.9	37.8	920.3
Papua New Guinea	4,525	739	201.4	11.0	41.2	622.0
Bangladesh	4,484	202	55.0	6.1	83.7	252.8
India	4,038	275	75.1	6.1	83.7	344.7
Cuba	3,597	597	162.7	12.7	9.3	305.8
Mozambique	3,027	267	72.8	45.1	34.2	303.7
Philippines	2,848	442	120.5	30.9	37.8	451.5
Venezuela	2,847	351	95.6	16.6	68.4	420.7
Colombia	2,808	417	113.6	16.6	68.4	499.9
Madagascar	2,776	243	66.1	45.1	34.2	275.7
Guinea-Bissau	2,688	270	73.6	38.9	56.6	354.8
Thailand	2,528	248	67.7	30.9	37.8	253.8
United States	2,329	391	106.5	12.7	9.3	200.2
Guinea	2,211	202	55.1	38.9	56.6	265.4
Cameroon	1,970	257	69.9	38.9	56.6	337.0
Viet Nam	1,871	158	43.1	30.9	37.8	161.5
Gabon	1,747	286	77.9	38.9	56.6	375.4
Bahamas	1,541	224	61.1	12.7	9.3	114.9

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Country/Territory	mangrove extent (Km ²)	sediment carbon 1m (Mt CO ₂ eq)	Sediment carbon 1 m (Tg C)	Estuarine type %	Deltaic type %	Sediment carbon 10 m (Tg C)
Panama	1,536	219	59.7	12.7	9.3	112.2
Ecuador	1,535	197	53.6	16.6	68.4	235.8
Sierra Leone	1,529	128	34.8	38.9	56.6	167.7
Senegal	1,270	138	37.7	38.9	56.6	181.7
Tanzania	1,108	121	33.0	45.1	34.2	137.8
Pakistan	828	67	18.2	6.1	83.7	83.5
Suriname	800	92	25.0	16.6	68.4	110.2
Nicaragua	747	103	28.0	12.7	9.3	52.7
French Guiana	630	46	12.6	16.6	68.4	55.3
Cambodia	627	66	17.9	30.9	37.8	67.1
Gambia	610	53	14.4	38.9	56.6	69.3
Honduras	606	89	24.2	12.7	9.3	45.5
Kenya	544	74	20.1	45.1	34.2	83.7
Belize	529	71	19.2	12.7	9.3	36.2
Solomon Islands	527	91	24.7	11.0	41.2	76.2
Fiji	488	79	21.6	11.0	41.2	66.6
El Salvador	373	41	11.1	12.7	9.3	20.9
Costa Rica	371	45	12.3	12.7	9.3	23.1
New Caledonia	334	35	9.4	11.0	41.2	29.1
New Zealand	296	41	11.1	57.8	2.1	37.7
Guyana	289	46	12.6	16.6	68.4	55.3
Angola	284	51	14.0	38.9	56.6	67.4
Equatorial Guinea	256	36	9.8	38.9	56.6	47.0
Guatemala	250	26	7.2	12.7	9.3	13.5
Democratic Republic of the Congo	237	41	11.2	38.9	56.6	53.8

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Country/Territory	mangrove extent (Km ²)	sediment carbon 1m (Mt CO ₂ eq)	Sediment carbon 1 m (Tg C)	Estuarine type %	Deltaic type %	Sediment carbon 10 m (Tg C)
China	216	14	3.8	82.3	0.6	16.2
Sri Lanka	199	29	7.9	6.1	83.7	36.2
Dominican Republic	192	29	8.0	12.7	9.3	15.0
Liberia	183	19	5.2	38.9	56.6	25.2
Ghana	180	21	5.8	38.9	56.6	27.7
Turks and Caicos Islands	165	27	7.3	12.7	9.3	13.8
Haiti	154	26	7.0	12.7	9.3	13.2
Brunei	115	19	5.2	30.9	37.8	19.5
Iran	112	11	2.9	6.1	83.7	13.4
Jamaica	99	15	4.0	12.7	9.3	7.5
Micronesia	88	2	0.5	11.0	41.2	1.5
Puerto Rico	83	13	3.7	12.7	9.3	6.9
Trinidad and Tobago	82	8	2.1	12.7	9.3	4.0
Eritrea	78	9	2.5	45.1	34.2	10.6
Saudi Arabia	77	8	2.2	0.0	3.8	2.5
United Arab Emirates	74	11	2.9	0.0	3.8	3.4
Palau	57	12	3.3	11.0	41.2	10.3
Peru	55	4	1.2	16.6	68.4	5.1
Côte d'Ivoire	54	6	1.7	38.9	56.6	8.3
Cayman Islands	45	8	2.3	12.7	9.3	4.3
Somalia	35	2	0.7	45.1	34.2	2.7
Guadeloupe	34	7	1.8	12.7	9.3	3.5
Benin	29	0	0.0	38.9	56.6	0.2
South Africa	26	3	0.7	45.1	34.2	2.9

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Country/Territory	mangrove extent (Km ²)	sediment carbon 1m (Mt CO ₂ eq)	Sediment carbon 1 m (Tg C)	Estuarine type %	Deltaic type %	Sediment carbon 10 m (Tg C)
Martinique	19	3	0.8	12.7	9.3	1.4
Vanuatu	16	3	0.7	11.0	41.2	2.1
Yemen	16	2	0.5	0.0	3.8	0.6
Timor-Leste	11	1	0.3	30.9	37.8	1.1
Tonga	10	0	0.0	11.0	41.2	0.0
Japan	10	1	0.4	82.3	0.6	1.6
Sudan	9	0	0.1	45.1	34.2	0.5
Antigua and Barbuda	9	1	0.4	12.7	9.3	0.7
Djibouti	8	1	0.2	45.1	34.2	0.6
Singapore	7	1	0.3	30.9	37.8	1.0
Mayotte	7	1	0.2	45.1	34.2	0.9

Table S4. Conceptual estimation of sediment carbon stock over 10 m depth for well-known mangrove areas around the world with previous carbon stock measurement at depth 1-3 m.

reference	Site	Area (ha)	Depth measured (m)	C stock (Mg C ha ⁻¹)	C stock 10 m (Mg C ha ⁻¹)	C stock 1 m (Tg)	C stock 10 m (Tg)
Gress <i>et al.</i> , 2017	Gazi Bay, Kenya	600	3	1485	2475	0.29	1.5

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reference	Site	Area (ha)	Depth measured (m)	C stock (Mg C ha ⁻¹)	C stock 10 m (Mg C ha ⁻¹)	C stock 1 m (Tg)	C stock 10 m (Tg)
Murdiyarso <i>et al.</i> , 2021	Bintuni Bay, Indonesia	124,850	3	1250	2083	52	260
Trettin <i>et al.</i> , 2021	Pongara National Park, Gabon	96,302	2	707	1767	34	170
Rovai <i>et al.</i> , 2021	Cananéia- Iguape, Brazil	15,000	1	270	1350	4	20.2
Uddin <i>et al.</i> , 2023	Sundarbans, Bangladesh	601,700	1	129.8	649	78	390

References Supplementary information

Gress, S. K., Huxham, M., Kairo, J. G., Mugi, L. M., and Briers, R. A. (2017). Evaluating, predicting and mapping belowground carbon stores in Kenyan mangroves. *Global change biology*, 23(1), 224-234. <https://doi.org/10.1111/gcb.13438>

Murdiyarso, D., Sasmito, S. D., Sillanpää, M., MacKenzie, R., and Gaveau, D. (2021). Mangrove selective logging sustains biomass carbon recovery, soil carbon, and sediment. *Scientific Reports*, 11(1), 1-10. <https://doi.org/10.1038/s41598-021-91502-x>

Rovai, A.S., Twilley, R.R., Castañeda-Moya, E., Riul, P., Cifuentes-Jara, M., Manrow-Villalobos, M., Horta, P.A., Simonassi, J.C., Fonseca, A.L. and Pagliosa, P.R. (2018). Global controls on carbon storage in mangrove soils. *Nature Climate Change*, 8(6), 534-538. <https://doi.org/10.1038/s41558-018-0162-5>

Wolswijk, G., B. Satyanarayana, N.H. Abd Rahim, C.M.K.A. Che Abdullah, N. Ali Ahmad, L. Wolswijk, M.K. Hami Hamzah, S. Cannicci & F. Dahdouh-Guebas, 2026. Deep coring shows that mangrove sediments in Matang (Malaysia) store up to five times more carbon than previously estimated. *Global Change Biology* 32: e70773. <https://doi.org/10.1111/gcb.70773>

Rovai, A.S., Coelho-Jr, C., de Almeida, R., Cunha-Lignon, M., Menghini, R.P., Twilley, R.R., Cintrón-Molero, G. and Schaeffer-Novelli, Y. (2021). Ecosystem-level carbon stocks and sequestration rates in mangroves in the Cananéia-Iguape lagoon estuarine system, southeastern Brazil. *Forest Ecology and Management*, 479, 118553.

<https://doi.org/10.1016/j.foreco.2020.118553>

Sanderman, J., Hengl, T., Fiske, G., Solvik, K., Adame, M. F., Benson, L., ... and Duncan, C. (2018). A global map of mangrove forest soil carbon at 30 m spatial resolution. *Environmental Research Letters*, 13(5), 055002. <https://doi.org/10.1088/1748-9326/aabe1c>

Trettin, C.C., Dai, Z., Tang, W., Lagomasino, D., Thomas, N., Lee, S.K., Simard, M., Ebanega, M.O., Stoval, A. and Fatoyinbo, T.E. (2021). Mangrove carbon stocks in Pongara National Park, Gabon. *Estuarine, Coastal and Shelf Science*, 259, 107432. <https://doi.org/10.1016/j.ecss.2021.107432>

Uddin, M. M., Abdul Aziz, A., and Lovelock, C. E. (2023). Importance of mangrove plantations for climate change mitigation in Bangladesh. *Global Change Biology*, 29(12), 3331-3346. <https://doi.org/10.1111/gcb.16674>

Worthington, T.A., Zu Ermgassen, P.S., Friess, D.A., Krauss, K.W., Lovelock, C.E., Thorley, J., Tingey, R., Woodroffe, C.D., Bunting, P., Cormier, N. and Lagomasino, D. (2020). A global biophysical typology of mangroves and its relevance for ecosystem structure and deforestation. *Scientific reports*, 10(1), p.14652.

<https://doi.org/10.1038/s41598-020-71194-5>

Wolswijk, G., B. Satyanarayana, N.H. Abd Rahim, C.M.K.A. Che Abdullah, N. Ali Ahmad, L. Wolswijk, M.K. Hami Hamzah, S. Cannicci & F. Dahdouh-Guebas, 2026. Deep coring shows that mangrove sediments in Matang (Malaysia) store up to five times more carbon than previously estimated. *Global Change Biology* 32: e70773.

<https://doi.org/10.1111/gcb.70773>