

A global assessment of mangrove soil organic carbon sources and implications for blue carbon credit

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Mangroves can retain both autochthonous and allochthonous marine and/or terrestrial organic carbon (OC) in sediments. Accurate quantification of these OC sources is essential for the proper allocation of blue C credits. Here, we conduct a global-scale analysis of sediments autochthonous and allochthonous OC contributions in estuarine and marine mangroves using stable isotopes. Globally, mangrove-derived autochthonous OC was the main contributor to estuarine and marine mangrove top-meter soil organic carbon (SOC) (49% and 62%, respectively). Less marine allochthonous OC (21%) was deposited than terrestrial allochthonous OC (30%) in estuarine mangrove sediments. Estuarine mangroves accumulated more SOC in sediments than marine mangroves (282 ± 8.1 Mg C ha⁻¹ and 250 ± 5.0 Mg C ha⁻¹, respectively), primarily due to the additional terrestrial OC inputs. Globally, marine mangroves held 67% of the total mangrove SOC, reaching 3025 ± 345 Tg C, while 1502 ± 154 Tg C was stored in estuarine mangrove sediments. The findings emphasize the substantial influence of coastal environmental settings on OC contributions, underlining the necessity of accurate OC source quantification for the effective allocation of blue carbon credits.

Mangrove forests are one of the most productive blue carbon ecosystems (BCEs), offering a range of ecosystem services including fisheries production, coastal protection, sediment fixation, and notably, carbon sequestration^{1–3}. Mangrove sediments hold approximately 70% of the whole ecosystem's carbon (C) storage, varying in magnitude geographically, which is primarily determined by coastal environmental settings (CES, such as estuarine and marine mangroves)^{4,5}.

Blue C ecosystems not only sequester atmospheric carbon dioxide (CO₂) through biogenic processes but also serve as repositories for C transported from external sources^{4,6}. Mangrove sediments, in

particular, accumulate both allochthonous organic carbon (OC) from marine or terrestrial origins, facilitated by tidal exchanges, and autochthonous OC derived from mangrove vegetation. Accurate quantification of these OC fractions is essential for the proper allocation of C credits under certification standards such as the Verified Carbon Standard (VCS) methodology (VM0033)⁷. Specifically, the VCS protocol requires the deduction of allochthonous C contributions from the total C sequestration calculations in tidal wetland restoration initiatives⁸. This distinction not only aligns with the additionality principle—guaranteeing that C credits support authentic greenhouse

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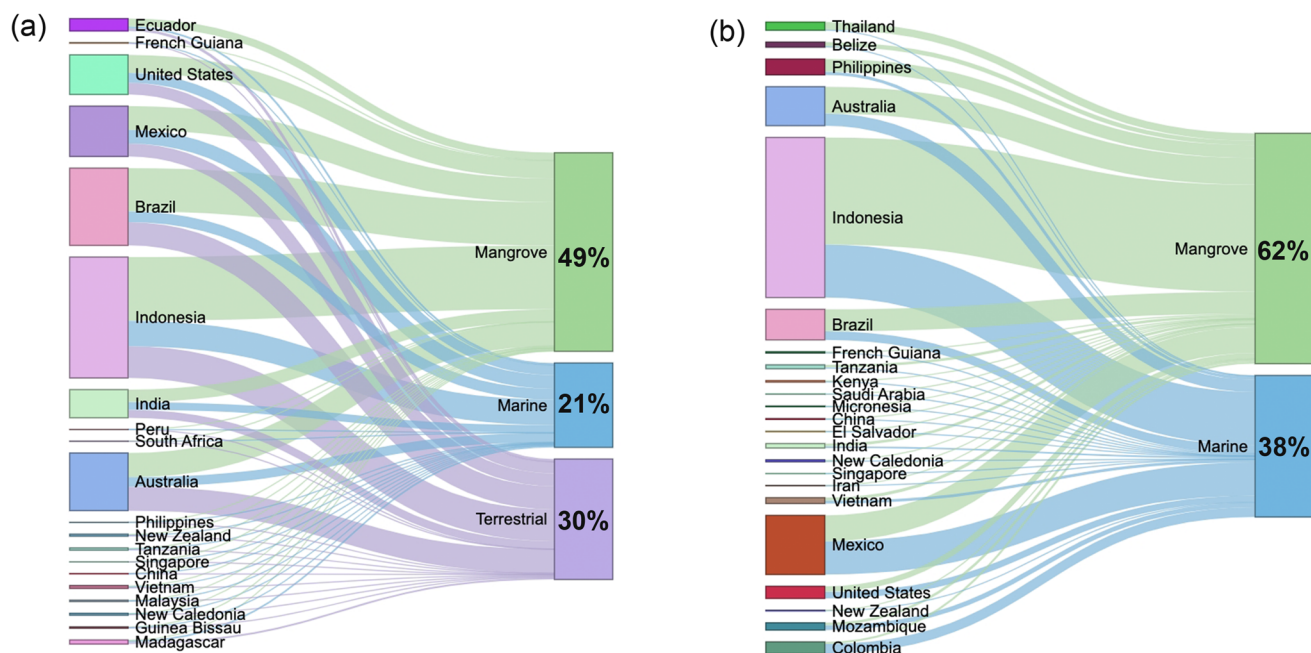


Fig. 1 | Relative contributions of organic carbon (OC) sources to estuarine and marine mangrove sediment OC. The relative contribution of OC, marine OC, and terrestrial OC to the OC in estuarine mangrove sediments (a) and marine OC and

mangrove OC contribution to OC in marine mangrove sediments (b). Source data are provided as a Source Data file.

gas reduction efforts—but also ensures the strategic deployment of resources to projects with tangible climate mitigate benefits^{7,9,10}. Thus, the study of sediment OC sources in mangroves is not merely an academic pursuit but a practical necessity for validating the environmental and economic value of tidal wetland restoration projects.

Here, we conduct global-scale analysis of the provenance of soil organic carbon (SOC) sources in mangroves. This study incorporates a comprehensive dataset of stable isotope signatures, nitrogen to carbon ration (N/C) values and SOC of mangrove sediments, along with relevant environmental and socioeconomic information, including the proximity of mangroves to rivers. We identified the sources of OC, compared SOC stocks between estuarine and marine mangroves and employed machine learning algorithms to explore the primary factors influencing SOC sources in mangroves. By shedding light on the SOC sources under different CESs, this study offers new insights into the variations in mangrove SOC, thereby contributing to a more comprehensive understanding of C cycling in BCEs.

Results and discussion

Organic carbon sources of mangrove sediments

This study first compiled 441 observations of $\delta^{13}\text{C}$ values of mangrove sediments worldwide, covering most of the mangrove distributed areas (Fig. S1). $\delta^{13}\text{C}$ values varied from -30.7‰ (*Rhizophora apiculata* and *Avicennia marina* forest sediments in Malaysia) to -6.20‰ (*Sonneratia alba* forest sediments in Tanzania), with the mean value of -25.1‰ (Fig. S1). Surprisingly, the mangrove sediment $\delta^{13}\text{C}$ value was less influenced by dominant species and CES. Locations (longitude and latitude), tidal range, mean annual temperature (MAT), salinity, total nitrogen content and soil particle size fraction were the main drivers of mangrove sediment $\delta^{13}\text{C}$ variation (Table S1). Our analysis of global observations revealed that mangrove plant-derived autochthonous OC is the main contributor to the top-meter SOC in both estuarine and marine mangrove sediments, accounting for 49% and 62% respectively (Fig. 1). In estuarine mangroves, terrestrial OC contributed a notable 30%, contrasting with less marine OC deposition (21%) (Fig. 1a). Continental values of autochthonous OC varied from 15% in South Africa to 57% in South America (Table 1). To identify the sources of OC, we

considered mangrove litterfall and belowground root production as endmembers, using their mean values for source identification. However, it is worth noting that the contribution of autochthonous OC to the sediment may be underestimated in this study, as mangrove roots and woody materials may have slightly more enriched $\delta^{13}\text{C}$ values than leaves⁴, and our dataset primarily consisted of mangrove leaves.

The contributions of different OC sources were significantly influenced by CES, with varying contributions observed across different countries (Fig. 1, Fig. S2, Table. S2 and Table. S3). In marine mangrove sediments, marine allochthonous OC accounted for 38% of the total OC, with autochthonous OC contributing the remaining 62% (Fig. 1b). Individual values of autochthonous OC contribution ranged from 13% in Iran to 92% in Thailand (Fig. 1a and Table. S3). Autochthonous OC contribution was the highest in South Africa (73%) and the lowest in South Asia (35.7%, Table 1). Marine OC contributions tended to increase with particulate organic carbon (POC), while factors like canopy height and mean annual precipitation (MAP) were linked to lower proportional marine OC contributions (Fig. S2a and Figs. S3d, h, j). In estuarine regions, mangrove sediments were found to contain a smaller amount of marine OC compared to terrestrial OC (Fig. 1a), consistent with previous findings¹¹. The marine OC retained in mangrove sediments is highly regulated by carbon accumulation rate (CAR) and POC contents (Fig. S2a). Marine particles usually had low OC content, therefore higher sedimentation of marine particles would cause less particulate organic matter (OM) to be imported into estuarine mangroves¹². Instead, abundant POC can continuously provide C sources for mangrove sediments, resulting in more marine OC retained¹³.

Mangrove autochthonous OC contributions were mainly regulated by location, soil properties, and climatic conditions (Fig. S2b). Autochthonous OC contribution decreased along with longitude (Fig. S4a). Higher MAT and MAP favored plant OC input into soils. Areas with intense anthropogenic activities or greater development might exhibit a greater autochthonous OC contribution (Figs. S4e and I). It is worth noting that areas with high population density exhibit higher autochthonous contributions to sediment OC. Anthropogenic nutrient fluxes can act as fertilizers for

Table 1 | Marine, mangrove and terrestrial organic carbon (OC) contribution to OC in estuarine and marine mangrove sediments in different continent where data were collected, N is the number of observations in each continent

| | N | Estuarine mangroves | | | N | Marine mangroves | |
|----------------|----|---------------------|--------------------|--------------------|----|--------------------|--------------------|
| | | Marine OC (%) | Mangrove OC (%) | Terrestrial OC (%) | | Marine OC (%) | Mangrove OC (%) |
| Oceania | 8 | 17.3 (15.8 ~ 34.8) | 41.4 (29.6 ~ 45.7) | 41.3 (28.9 ~ 49.2) | 40 | 40.4 (27.1 ~ 68.3) | 59.6 (31.7 ~ 72.9) |
| East Asia | 54 | 25.9 (14.6 ~ 45.5) | 40.5 (15.5 ~ 68.9) | 33.6 (16.5 ~ 61.7) | 16 | 36.6 (12.6 ~ 56.2) | 63.4 (43.8 ~ 87.4) |
| West Asia | 0 | | | | 10 | 46.9 (26.7 ~ 87.0) | 53.1 (13.0 ~ 73.3) |
| South Asia | 52 | 24.3 (11.9 ~ 41.8) | 48.7 (18.6 ~ 74.3) | 26.9 (13.8 ~ 42.6) | 13 | 64.3 (27.2 ~ 91.1) | 35.7 (8.90 ~ 72.8) |
| Southeast Asia | 28 | 21.0 (11.9 ~ 43.3) | 53.2 (23.3 ~ 74.1) | 25.8 (14.0 ~ 45.4) | 78 | 34.0 (7.80 ~ 61.6) | 66.0 (38.4 ~ 92.2) |
| East Africa | 2 | 20.6 (17.8 ~ 23.3) | 44.3 (36.4 ~ 52.2) | 35.2 (30.0 ~ 40.3) | 22 | 35.1 (18.6 ~ 64.4) | 64.9 (35.6 ~ 81.4) |
| West Africa | 2 | 26.3 (24.3 ~ 28.3) | 30.8 (18.4 ~ 43.1) | 43.0 (32.6 ~ 53.4) | 0 | | |
| South Africa | 4 | 41.8 (36.6 ~ 47.4) | 14.7 (13.4 ~ 15.4) | 43.6 (37.5 ~ 48.7) | 2 | 26.9 (53.8 ~ 64.3) | 73.1 (53.8 ~ 46.2) |
| North America | 3 | 29.0 (27.9 ~ 30.1) | 44.8 (42.5 ~ 46.4) | 26.2 (24.7 ~ 27.4) | 23 | 31.4 (8.90 ~ 65.6) | 68.6 (34.4 ~ 91.1) |
| South America | 34 | 13.9 (10.6 ~ 47.0) | 57.0 (30.2 ~ 69.3) | 29.0 (11.9 ~ 55) | 27 | 32.5 (11.4 ~ 82.1) | 67.5 (17.9 ~ 88.6) |

Source data are provided as a Source Data file.

mangroves, enhancing their growth and consequently increasing the input of autochthonous OC^{14,15}.

Generally, terrestrial allochthonous OC only contributes to OC in estuarine mangrove sediments, which are more susceptible to anthropogenic activities (Fig. S2c and Figs. S5c, I). Terrestrial OM is abundant in lignin-phenols, while marine OM is characterized by low C/N ratios and simple composition, which might result in the preferential decomposition of light fractions in marine OM^{11,16}. We found that greater GDP and human development index (HDI) were negatively correlated with terrestrial OC contribution (Fig. S5c, I). Anthropogenic activities such as extensive water use for agricultural purposes will reduce the river's natural flow downstream, which could decrease the C exchange between mangroves and rivers¹⁷. Eutrophic estuaries under intense anthropogenic activities have been found to exhibit high OC decomposition, leading to increased C emissions¹⁸. Moreover, dam construction might have influence on the terrestrial OC retained in mangroves due to blocking the river and the terrestrial OC transported by the river¹⁹.

SOC stocks of estuarine and marine mangroves

The areal extent of estuarine mangroves is far less than marine mangroves, being 43,669 km² and 103,573 km², respectively (Fig. 2d, Table. S4 and S5). Globally, SOC stock per unit area was significantly higher in estuarine mangroves (282 ± 8.1 Mg C ha⁻¹) than marine mangroves (250 ± 5.0 Mg C ha⁻¹, $P < 0.05$, Figs. 2a, b, c). Combining the mangrove distribution and the Kriging interpolation, the SOC stocks of the estuarine and marine mangroves were 1502 ± 154 Tg C and 3025 ± 345 Tg C, respectively (Figs. S6, Table S4 and S5).

Autochthonous and marine allochthonous contribution to sediment OC in estuarine mangroves was lower than in marine mangroves (Fig. 1), which can be attributed to the additional input of terrestrial allochthonous OC²⁰. Estuarine mangroves held greater SOC stock per unit area than marine mangroves (Fig. 2c), indicating the contribution of terrestrial allochthonous OC to mangrove sediments. The observed pattern was in accordance with that reported by Donato, et al.¹. Conversely, Weiss, et al.²⁰ reported a higher sediment SOC stock in marine mangroves (570 Mg C ha⁻¹) than in the estuarine mangroves (310 Mg C ha⁻¹), and a global synthesis showed that marine mangroves presented a greater C density than estuarine mangroves⁵. The disparity could be caused by variance in sampling size. Previous global synthesis resulted from field sampling of 81 observations from 27 sites⁵, while this study used a much larger dataset of 2356 observations worldwide. As such, the extensive sampling variance may account for the differences observed in the results.

Despite accounting for only 33% of the global mangrove SOC stock (Fig. 3), estuarine mangroves may face more threats than marine

mangroves due to the influx of terrestrial pollutions (including the nitrogen and phosphorus nutrients) carried by rivers, facilitating anthropogenic and environmental changes within estuarine mangrove ecosystems²¹.

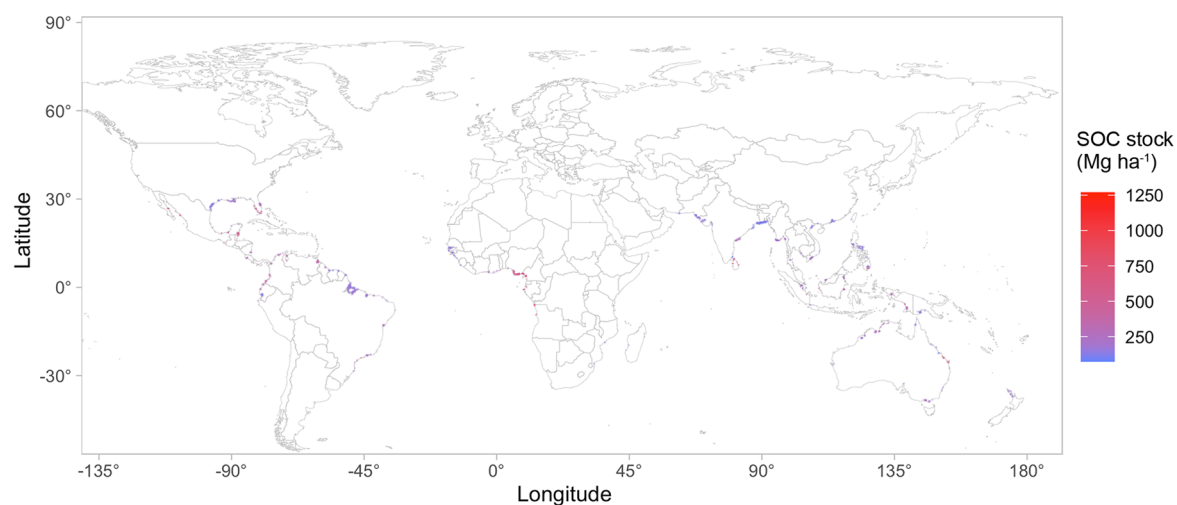
Implications

There is increasing interest in using blue carbon ecosystems (BCEs) for their potential climate mitigation and adaptation benefits through management interventions. This study provided a global dataset of the mangrove sediment OC sources, which can guide future mangrove restoration projects to receive VCS-approved C credits⁸. Generally, utilized by microbes and transformed into more recalcitrant C (like mineral-associated OC), allochthonous OC can be more stable than autochthonous OC when deposited in mangrove sediments²². This global-scale analysis of the provenance of soil OC sources in mangroves reveals the intricate balance between autochthonous and allochthonous OC contributions to the C sequestration capacity of mangrove sediments. The findings underscore the predominant role of mangrove-derived autochthonous OC in both estuarine and marine settings, while also highlighting the significant, though variable, contribution of allochthonous OC from terrestrial and marine sources⁸, facilitated by the later C flux. This distinction is crucial for the development and implementation of C crediting mechanisms, such as those prescribed by the VCS⁸, which require accurate accounting of allochthonous and autochthonous OC sources to ensure that credits support genuine greenhouse gas reduction efforts⁹. The refinement of our understanding and ability to identify OC sources in these BCEs are important research areas that can lead to improvements of the calculation of C credit.

Moreover, our exploration of how factors such as CAR, POC and socioeconomic variables like GDP and HDI impact the contributions of different OC sources offers vital insights into the anthropogenic and natural processes affecting mangrove carbon sequestration. The correlation between higher GDP and HDI with autochthonous OC contributions, for instance, suggests that economic development and human activities can significantly influence mangrove C dynamics, potentially through the enhancement of mangrove growth via anthropogenic nutrient inputs.

Future research should aim to further refine our understanding of OC sources in mangrove sediments, incorporating additional isotopic analyses and considering the impacts of global challenges such as climate change, deforestation, and land use change. Only through such comprehensive and nuanced approaches can we fully understand the climate mitigation potential of mangroves and ensure the preservation of their invaluable ecosystem services for future generations.

(a) SOC stock in estuarine mangroves



(b) SOC stock in marine mangroves

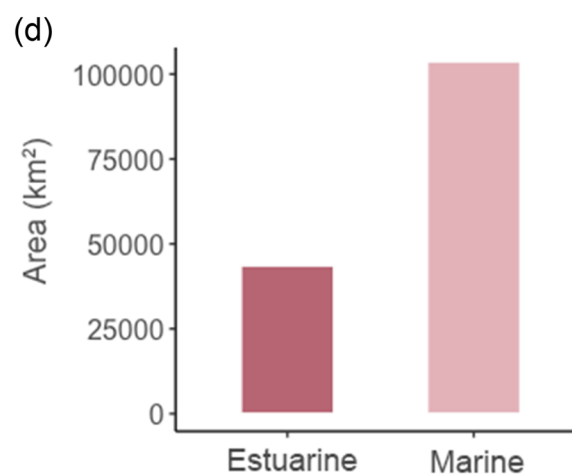
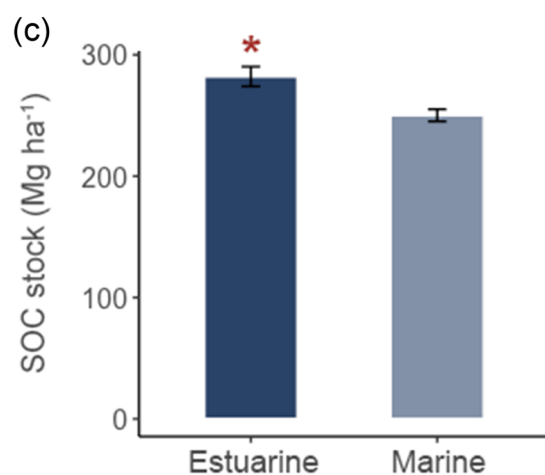
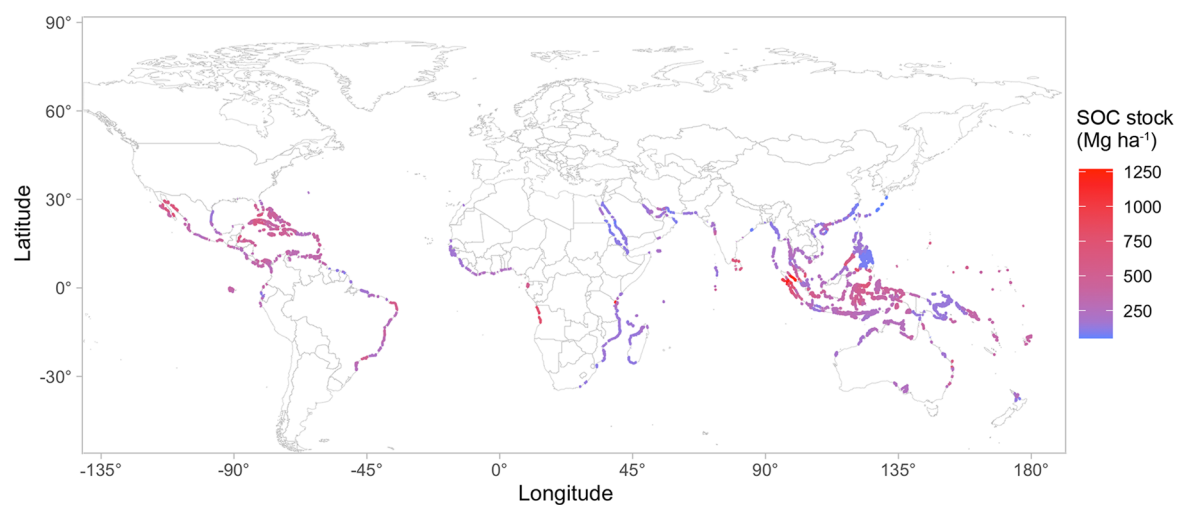
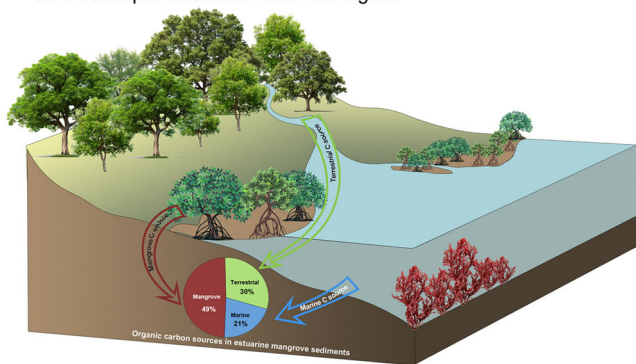


Fig. 2 | Soil organic carbon (SOC) stocks and distribution of estuarine and marine mangroves. SOC stock per unit area in estuarine mangroves (a) and marine mangroves (b) demonstrated as line segments. The bar plot showing the

comparison of SOC stock per unit area in global scale (c), where the values are mean \pm standard value (SE) and the asterisk (*) shows the significance of $P < 0.05$. The areal extents of estuarine and marine mangroves are shown (d).

(a) Organic carbon sources in estuarine mangrove sediments

Total SOC stock: 1502 ± 154 Tg C Area: 43669 km^2
 SOC stock per unit area: $282 \pm 8.1 \text{ Mg ha}^{-1}$



(b) Organic carbon sources in marine mangrove sediments

Total SOC stock: 3025 ± 345 Tg C Area: 103573 km^2
 SOC stock per unit area: $250 \pm 5.0 \text{ Mg ha}^{-1}$

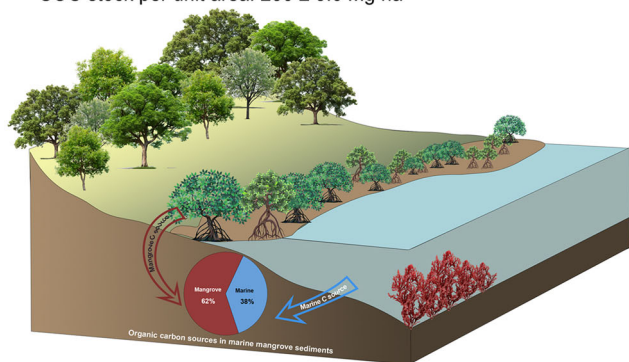


Fig. 3 | A conceptual diagram summarizing organic carbon (OC) sources in estuarine and marine mangrove sediments. The areal extent, soil organic carbon (SOC) stock and OC sources in estuarine mangroves (a) and marine mangroves (b). Values are mean \pm SE.

Methods

Organic carbon source identification

We compiled published data on isotope ($\delta^{13}\text{C}$, $\delta^{15}\text{N}$) and N/C values of global mangrove sediments from the Web of Science using combinations of keywords “mangrove C* source”, “mangrove isotope”, “mangrove source”, utilizing 100 studies and 441 observations. The database should meet the following requirements: (1) parameters that used to calculate the OC sources should be reported (either $\delta^{13}\text{C}$ and N/C or $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$); (2) the work must have been published in peer-reviewed publications; (3) the study must have been a field study in natural conditions without artificial manipulation. The relative contribution of marine (phytoplankton and macroalgae), mangrove, and terrestrial organic matter to the carbon pools in the top meter of the mangrove sediments was estimated using two-tracer stable isotope analysis in R (MixSIAR), one of the more modern Bayesian mixing models²³. From the literature, we collected isotope and N/C values for mangrove tissues, riverine POM, phytoplankton, and microalgae to generate mangrove, terrestrial and marine endmembers. Phytoplankton and macroalgae were combined as a single OC source since their published $\delta^{13}\text{C}$ or $\delta^{15}\text{N}$ and N/C were largely overlapped. The average values of those end members were calculated and then used for OC source identification for the geographically nearest estimate. When the $\delta^{13}\text{C}$ and N/C values are reported in a study, we preferred to use those values to determine the OC sources. When only $\delta^{15}\text{N}$ and N/C were reported in a study, those values were used. Therefore, 362 observations of OC source were identified by $\delta^{13}\text{C}$ and N/C values, with the rest identified

by $\delta^{15}\text{N}$ and N/C values. We assumed a standard deviation (SD) equals 0.5 or 0.005 to reflect similar variability of the isotope or N/C values as for the replicated sources of OC²⁴. We looked through all of the collected publications and we find that among 441 isotope data, 164 of them reported their locations to tidal/ river channel margins, and most of the sampling sites were fringe mangroves ($n = 129$), while only 25 and 16 were located in interior and transition zones, respectively. This corresponds to our concerns that most of the samples were fringe mangroves because of the easy access and might have influence on the results. We further conducted analysis to test whether sampling location (interior or fringe) would have influence on the marine OC, mangrove OC and terrestrial OC contribution to mangrove sediments using GAM, respectively (Table. S7–S9). Models were built by the influencing factors ranks top 30% in each OC random forest model to prevent overfitting. For the continental or global average OC source contributions, we used the estuarine or mangrove SOC stock to calculated the weighted average. For the detailed information of the datasets, please check the supporting Excel spreadsheet file.

Primary regulators of organic carbon sources

The 441 isotope observations were further separated into estuarine and marine mangroves according to the following conditions: (1) if the sampling site was clearly defined as estuarine or marine mangroves, we used its original classification; (2) when the sampling site did not meet condition 1, but the sampling map were provided in the literature, we classified estuarine or marine mangroves by the appearance of river or estuaries; (3) if the condition 1 and 2 were not meet, we used the global estuarine and marine mangrove maps generated in the following steps (Estuarine and marine mangrove mapping) to identify their environmental settings^{25–27}. Additional data were collected to find the primary regulators of OC sources in mangrove sediments. Reported soil properties, including pH, salinity, and particle size (sand, silt and clay content), were collected. Not all studies reported soil and vegetation properties, data from the nearest site are used to complete the datasets. Mangrove canopy heights were extracted from public Google Earth Engine (GEE) datasets as vegetation properties in this study²⁸. Open-access global datasets were used to extract the geomorphic and climatic properties. Tidal range and mean sea level were extracted from Muis, et al.²⁹ in Copernicus platform (<https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-water-level-change-indicators-cmip6?tab=overview>). The particulate organic matter (POC) data were extracted in GEE entitled with Ocean Color SMI: Standard Mapped Image MODIS Aqua data. (https://developers.google.com/earth-engine/datasets/catalog/NASA_OCEANDATA_MODIS-Aqua_L3SMI). We use the Coastal DEM database³⁰ to retrieve the coastal elevation. We additionally calculated the relationship of the site elevation within the tidal frame (Z^*_{MHHW}) using the following equation^{31,32}:

$$Z^*_{MHHW} = \frac{\text{Elevation} - \text{MSL}}{\text{MHHW} - \text{MSL}}$$

where the Elevation is the data extracted from the above-mentioned DEM datasets, MSL is mean sea level, MHHW is mean higher high water extracted from Muis, et al.²⁹. Recent 60-year relative sea level rise (RSLR) was provided by Wang, et al.³³. The nearest tide gauge data were chosen as the corresponding RSLR of our sampling site. Climatic properties, including mean annual temperature (MAT) and mean annual precipitation (MAP), were collected from WorldClim (<https://www.worldclim.org>). Additionally, anthropogenic activities might influence the OC sources of mangrove sediments. Therefore, socioeconomic properties include gross domestic production (GDP), human development index (HDI), population density, and urbanization. The global urbanization dataset was from Li, et al.³⁴, and we used the mean value between 2000 to 2013 because most of the collected observations were in this range. GDP and HDI data were from Kummu, et al.³⁵. Population density data

were from the WorldPop website (<https://www.worldpop.org>). All these socioeconomic databases were available in GEE.

Random forest is an integrated machine-learning approach that generates multiple decision trees and captures nonlinear interactions³⁶. Random forest was applied to the soil, vegetation, geomorphic, climatic, and socioeconomic properties as mentioned above to find the primary regulators of OC sources in mangrove sediments. Models were separately conducted for the relative contribution of mangrove, marine, and terrestrial OC to mangrove sediments. The percentage increases in the mean squared error (%IncMSE) were used to assess the relative importance of each influencing factor using the “randomForest” package³⁷. Moreover, we used “rfPermute” package to assess the significance of each influencing factors³⁸.

We used the general additive models (GAM) to determine the general negative or positive patterns. Factors that ranked at the top 60% in the random forest model were analyzed in the GAM to see their influence on the marine, mangrove, and terrestrial OC source contribution to mangrove sediments. When none of those factors is significant in the GAM, we still plot the correlation charts between each influencing factor and OC source contribution to see the trend.

Estuarine and marine mangroves mapping

The mapping of estuarine and marine mangroves contains two steps, the mapping of global mangroves and the mapping of estuarine regions. The Global Mangrove Watch datasets are the most commonly used mangrove datasets with public access. Therefore, we extracted the global mangrove distribution in 2020 from Global Mangrove Watch³⁹. For the estuarine region mapping, we applied a mask of the global estuary distribution developed by Sea Around Us project to mangrove distribution^{25–27}. However, we noticed that the estuary distribution only covers the water, while mangroves around the estuary was overlooked. We therefore combine the estuary distribution with the sampling point in our collection which was clearly defined as estuarine mangroves to manually draw the boundaries between estuarine and marine mangroves (Fig. S7).

SOC stocks in estuarine and marine regions

We constructed a comprehensive global mangrove SOC stock database, collecting as many experiments that fulfilled our criteria as possible. The basic topsoil (0–1 m) mangrove SOC stock per unit area was from Ouyang and Lee⁴⁰. We searched the *Web of Science*, *China Knowledge Resource Integrated Database* using combinations of keywords “mangrove Carbon”, “mangrove C* stock”, “mangrove SOC” that were published after 2020, and our unpublished field survey data across China.

The database should meet the following requirements: (1) SOC stocks or parameters necessary for estimating SOC stocks (bulk density (BD), SOM or SOC concentration) were reported; (2) the work must have been published in peer-reviewed publications; (2) the study must have been a field study in natural conditions without artificial manipulation. We further fulfill our dataset with data from Coastal Carbon ATLAS⁴¹ (mostly published after 2020 or unpublished data). The final database has 2356 SOC observations, where 1682 observations were extracted from Ouyang and Lee⁴⁰, 476 observations were additionally added and 198 observations are from Coastal Carbon ATLAS.

To compare the SOC stocks per unit area in global estuarine and marine mangroves, we used one-way ANOVA to determine the significance. We then analyzed those differences in each country where data were collected to see whether this pattern applies to the national scale. To estimate the total SOC stock in estuarine and marine mangroves, we conducted the Kriging interpolation in GEE using the collected SOC stock datasets and mangrove mappings.

Data availability

The estuarine and marine mangrove distribution in 2020 generated in this study has been deposited in Data Center of South China National

Botanical Garden, CAS (<https://cstr.cn/32129.11.scbg.n57jtsGX>) and the Figshare (https://figshare.com/articles/dataset/Global_marine_and_estuarine_mangrove_distribution_in_2020/27129174). The source data used for organic carbon source identification has been deposited in Data Center of South China National Botanical Garden, CAS (<https://cstr.cn/32129.11.scbg.n57jtsGX>) and the Figshare (https://figshare.com/articles/dataset/Source_data_of_A_global_assessment_of_mangrove_soil_organic_carbon_sources_and_implications_for_blue_carbon_credit/2712919?file=49475862). Source data are provided with this paper.

Code availability

All custom code that has been used in this study is available from authors by request.

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Author contributions

J.Z. and F.W. conceived and designed the study. J.Z. collected the data and conducted the analysis, and J.Z. and F.W. prepared and wrote the draft. S.G., P.Y., J.Z. (Jing Zhou), X.H., H.C., H.H., N.S., and C.S. helped revise the draft.

Competing interests

The authors declare no competing interests.

Additional information

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