



Millennial-scale carbon accumulation and dynamics in mangroves: A case study from the Upper Gulf of Thailand

Ausanee Suttiwong^{a,b}, Paramita Punwong^{a,b,*}, Rob Marchant^{a,b}, Apichaya Englong^{b,c}, Luke Andrews^d, Nathsuda Pumijumnong^a, Wanwisa Pansak^a, Pasin Maprasop^e

^a Faculty of Environment and Resource Studies, Mahidol University, Phutthamonthon Sai 4 Road, Nakhon Pathom, 73170, Thailand

^b York Institute of Tropical Ecosystems, Department of Environment and Geography, University of York, York, YO10 5NG, UK

^c Department of Plant Science, Faculty of Science, Mahidol University, Bangkok, 10400, Thailand

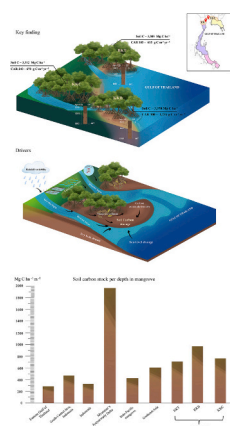
^d School of Biological and Geographical Sciences, Liverpool John Moores University, Liverpool, UK

^e Mangrove Research and Development Institute, Department of Marine and Coastal Resources, Ministry of Natural Resources and Environment, 120 Ratthaprasanaphakdi Building, Chaengwattana Road, Thung Song Hong, Lak Si, Bangkok, 10210, Thailand

HIGHLIGHTS

- Mangrove soil carbon stocks ranged ~3300–3970 Mg C ha⁻¹ in the upper Gulf of Thailand
- Soil carbon accumulated over millennial-scale mangrove sediment records.
- Carbon accumulation rates varied widely, from 185 to 1256 g C m⁻² yr⁻¹.
- Long-term soil carbon storage was controlled by multiple factors.
- Sea-level rise and wet phases enhanced sediment accretion and carbon burial.

GRAPHICAL ABSTRACT



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ABSTRACT

Mangroves are among the most carbon-rich tropical ecosystems; however, the long-term dynamics of their carbon storage in Thailand remain poorly understood. This study integrates palaeoecological records, sedimentological variables, and soil carbon to evaluate the drivers that influence millennial-scale carbon accumulation in two estuarine mangrove ecosystems from two case study sites (Bang Khun Thian and Klong Kone) in the upper Gulf of Thailand. Across the study sites, total soil carbon (Soil C) storage, determined from accumulating the organic carbon density throughout each sediment profile, ranged from approximately 3300 to 3970 Mg C ha⁻¹. The carbon accumulation rates (CAR) varied substantially, ranging from 185 to 1256 g C m⁻² yr⁻¹ over the last millennium. The results showed that long-term soil carbon storage was not controlled by a single factor but by interactions among dry bulk density, CAR, sediment texture, mangrove occurrence, and past environmental

* Corresponding author at: Faculty of Environment and Resource Studies, Mahidol University, Phutthamonthon Sai 4 Road, Nakhon Pathom, 73170, Thailand.
E-mail address: paramita.pun@mahidol.ac.th (P. Punwong).

Sea-level change
Climate change

conditions. Soil C was more closely linked to mangrove presence and fine-grained sediment retention, whereas CAR was more sensitive to hydrological connectivity. Palaeoecological records indicate that estuarine geomorphology was strongly influenced by sea-level change, sediment inputs from both allochthonous and autochthonous sources, and mangrove vegetation cover. During periods of rising sea levels and wet climatic conditions, mangrove expansion promoted high sediment accretion and carbon burial, whereas periods of marine regression led to mangrove retreat. Reduced tidal influence and land-use changes have lowered carbon input and storage. These patterns reflect the combined influences of sediment supply, hydrological connectivity, and vegetation change. Gathering data from deeper soil layers and conducting site-specific factor analyses are crucial for a more precise and comprehensive evaluation of coastal carbon storage. Therefore, long-term data are critical for designing climate adaptation policies that safeguard mangrove persistence and maximise the role of blue carbon in climate change mitigation.

1. Introduction

Mangrove forests are among the most carbon-rich coastal ecosystems and play an important role in climate change mitigation through carbon storage. Carbon in mangrove ecosystems is stored in the aboveground biomass, belowground biomass, non-living biomass, and soil (McLeod et al., 2011). Carbon stocks can be assessed using both field-based and spatial modelling approaches (Drygal et al., 2025). In mangrove ecosystems, sediment carbon, often referred to as soil carbon (soil C), accounts for 50–95% of the total ecosystem carbon stocks, reflecting the high carbon storage capacity of these systems (Kauffman et al., 2020; Sugiatmo et al., 2023). This heightened carbon storage is also attributed to prolonged retention periods in coastal sediments, facilitated by anaerobic conditions that impede the decomposition of organic matter (Donato et al., 2011). Over time, often up to millennia, organic matter can accumulate to depths of several meters (Howard et al., 2014), effectively locking away carbon.

In the eastern Gulf of Thailand, the storage of soil C in mangrove soils to a depth of 3.5 m is more than four times greater than that in mangrove forests elsewhere in Thailand, with soil C of approximately 1000 Mg C ha⁻¹ (Kida et al., 2021). Previous studies have shown that mangrove carbon stocks vary spatially depending on sediment depth, geomorphology, vegetation composition, hydrology, sea-level change, and climate variability (Alongi, 2018; Sasmito et al., 2020). Soil depth is particularly important because deeper sediment layers can contain substantial carbon stocks, and the inclusion of soil carbon below 1 m can potentially increase estimates of blue carbon storage (Sasmito et al., 2020). However, in Thailand, many carbon assessments have focused mainly on biomass carbon or soil carbon at depths not exceeding 1 m (Wanthongchai and Pongruktham, 2019). This leads to a significant underestimation of the long-term carbon storage potential of mangrove ecosystems along the Thai coast and in other regions of the world.

Long-term mangrove carbon dynamics are influenced by sedimentary and post-depositional processes. The integration of geomorphological and palaeoecological approaches can advance blue carbon research by linking carbon storage with past hydrodynamic changes and environmental variability (Costa et al., 2022), particularly in deltaic coastlines that are strongly affected by sediment supply, shoreline erosion, and coastal engineering structures, which can alter erosion–accretion patterns and coastal sediment dynamics (Aziz, 2024). Therefore, key factors such as vegetation composition, sea-level change, climate fluctuation, sediment texture, and sediment deposition can influence the long-term carbon sequestration in mangrove soils (Alongi, 2018; Wang et al., 2024). Mangrove development is closely related to tidal elevation and sediment deposition, particularly in areas where sediment accumulation can keep pace with relative sea-level rise (Jacotot et al., 2018; Punwong et al., 2018). Mangrove dynamics have been studied across the upper Gulf of Thailand using palaeoecological approaches involving pollen, charcoal, loss on ignition, and particle size, which have contributed significantly to our understanding of the long-term responses of mangroves to sea-level fluctuations, climate variation, and anthropogenic impacts (Punwong et al., 2018, 2023). However, these studies have not explored the intricate interactions between

natural processes and human activities in coastal environments that drive carbon accumulation in mangroves.

Therefore, this study explored the factors controlling carbon sequestration in mangrove sediments by investigating the factors that drive carbon accumulation over the last millennium: a case study from the upper Gulf of Thailand retrieved from three cores, one from Bang Khun Thian and two from Klong Kone. This was achieved by combining soil carbon stock assessment, age-depth modelling sediment accumulation rate (SAR) and carbon accumulation rate (CAR) estimates, soil properties, pollen assemblages, and analysis of environmental variables associated with soil C storage. We tested whether long-term soil carbon accumulation is controlled by a single factor or by interactions among sediment accumulation, sediment properties, vegetation history, and past environmental settings. This integrated approach allows us to distinguish between carbon storage and sediment-based carbon accumulation, thereby providing a more mechanistic understanding of the factors that drive mangrove blue carbon dynamics over centennial-to-millennial timescales.

2. Materials and methods

2.1. Study sites

2.1.1. General settings

Mangrove areas are located in the upper Gulf of Thailand, namely Klong Kone in Samut Songkhram Province, where the Mae Klong River discharges into the Gulf of Thailand (Fig. 1). This area features a dense mangrove belt oriented in a northwest-southeast direction, with widths ranging from 100 to 1200 m (Punwong et al., 2018). Previous carbon stock assessments in Klong Kone reported aboveground biomass carbon of 81.73–189.97 t C ha⁻¹, belowground biomass carbon of 32.54–77.71 t C ha⁻¹, and soil carbon stocks of 43.71–60.95 t C ha⁻¹ in the upper 30 cm (Swangjang and Panishkan, 2021). The Bang Khun Thian mangrove forest area in Bangkok is located on the central coast of the Gulf, intersected by the Chao Phraya and Tha Chin rivers, which flow into the Gulf of Thailand. Bang Khun Thian is the only mangrove area in Bangkok by a small belt of dense mangroves arranged in an east–west alignment, extending 150 m in width. It spans approximately 5 km in length (Department of Marine and Coastal Resources, 2018a). This site faces severe challenges, such as environmental degradation, coastal erosion, climate change, and land-use changes (Yasmeen et al., 2024). Mangrove forests in the area have been significantly reduced because of industrial expansion, community development, and coastal erosion. However, a project launched in 2017 was established to promote the management, storage, and conservation of these vital ecosystems (Department of Marine and Coastal Resources, 2018a).

2.1.2. Geology and geomorphology

The mangrove areas in the upper Gulf of Thailand are situated within the Lower Central Plain coasts, characterised by muddy sediments deposited in tidal waters during the Holocene, referred to as the Bangkok clay layer, which spans a thickness of 1–20 m (Department of Marine and Coastal Resources, 2018a). This layer is approximately 5–10

m thick and overlies a Pleistocene compact clay layer. The upper Gulf of Thailand functions as a major depositional basin receiving sediments from the Mae Klong, Tha Chin, Chao Phraya, and Bang Pakong rivers. Within mangrove ecosystems, sediment accretion is further enhanced by tidal deposition and the capacity of mangrove vegetation to trap and stabilise fine-grained sediments, thereby promoting long-term sediment accumulation (Hongwiset et al., 2022). These geomorphological and geological characteristics indicate that the three study sites are located within a broadly comparable deltaic–tidal flat sedimentary setting (Eadsain, 2023). Although the three sediment cores were not intended to provide a statistically representative assessment of the entire upper Gulf of Thailand, they provide case study records of comparable mangrove depositional settings within the upper Gulf of Thailand and are suitable for investigating long-term carbon accumulation under similar geomorphological conditions.

2.1.3. Climate and mangrove vegetation

The upper Gulf of Thailand experiences a tropical monsoon climate characterised by consistently high humidity throughout the year, with temperatures ranging from 25 to 33 °C. The climate is driven by the southwest (May–September) and northeast (October–February) monsoons (Inthacha, 2011). The average annual rainfall is approximately 1500 mm yr⁻¹.

In Bang Khun Thian, the Department of Marine and Coastal

Resources (2018a) reported 5303 ha of mangrove forest within Bangkok, comprising four species: *Avicennia marina*, *A. alba*, *A. officinalis*, and *Rhizophora apiculata*. In Samut Songkhram Province, the Department of Marine and Coastal Resources (2018b) reported that mangroves cover approximately 12,745 ha. Vegetation surveys recorded seven families, seven genera, and 13 species in the area. The dominant family was Rhizophoraceae, with *R. apiculata* as the dominant species.

2.2. Fieldwork, sampling and laboratory work

The sediment core dataset was collected in 2015 (Fig. 1) by Punwong et al. (2018, 2023) using a Russian corer with a 50 cm corer length and 5 cm diameter. One core was obtained from Bang Khun Thian (BKT, 4.5 m long). Two cores were collected at Klong Kone along a transect perpendicular to the shoreline: KKB (seaward; 4.1 m long) and KKC (landward margin; 4.4 m long).

One cm³ sediment samples were taken at 10 cm intervals, as conducted by Punwong et al. (2018, 2023), for laboratory analyses, including dry bulk density (DBD), loss on ignition (LOI) at 550 °C, and pollen analysis. DBD (g cm⁻³) was determined from 1 cm³ volumetric subsamples collected using a calibrated syringe from the least disturbed sediment matrix within each interval. Visible roots were manually removed from the subsamples prior to drying and weighing, and coarse fragments were avoided during subsampling. Each subsample was oven-

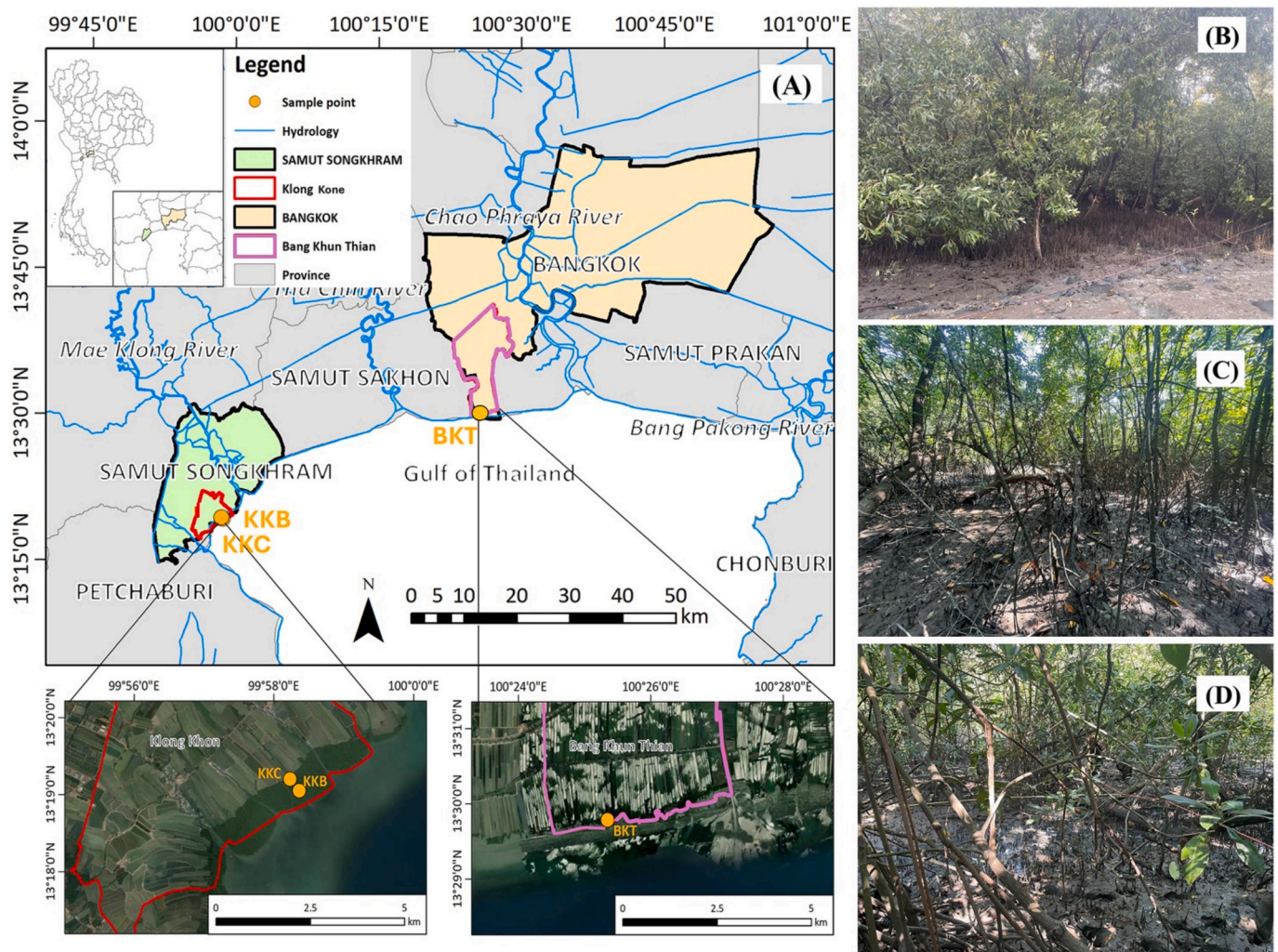


Fig. 1. Study locations in the upper Gulf of Thailand. (A) Regional map showing mangrove sediment core sites and biomass, as identified by Punwong et al. (2018, 2023). (B-D) Plot maps: (B) Bang Khun Thian (BKT; *A. officinalis* dominant), (C) Klong Kone Site B (KKB; *R. mucronata* dominant), and (D) Klong Kone Site C (KKC; *R. apiculata* dominant).

dried at 105 °C for at least 24 h until a constant weight was reached, and DBD was calculated as the oven-dried sediment mass divided by the original sample volume (Howard et al., 2014; Ray et al., 2023). The LOI was determined following the procedure described by Heiri et al. (2001). Oven-dried sediment samples were combusted at 550 °C for 4 h in a muffle furnace and subsequently cooled in a desiccator before being reweighed. The organic matter content was estimated from the difference between the oven-dry weight before combustion and the dry weight after combustion. The % LOI was calculated as follows:

$$\%LOI = \left[\frac{(\text{dry mass precombustion} - \text{dry mass postcombustion})}{\text{dry mass precombustion}} \right] \times 100 \quad (1)$$

Soil texture was determined through particle size analysis (PSA) using a Malvern Mastersizer 2000 and GRADISTAT software. Chronologies of the KKB and KKC cores were re-established using Bayesian age–depth modelling by rBacon and included uncertainty ranges and 95% confidence, while that of BKT was based on Punwong et al. (2023) to calculate the sediment accumulation rates (SAR) for each core (Blaauw et al., 2021).

2.3. Carbon stock calculations

Organic matter content (%OM) was estimated from the LOI data and then converted to the percentage organic carbon (%Corg). %Corg was estimated from %LOI using the regression relationship developed for mangrove sediments by Kauffman et al. (2011),

$$\%Corg = 0.415 \times \%LOI550 + 2.89 \quad (2)$$

Carbon density (CD; g C cm⁻³) was calculated using %Corg and DBD data derived from Punwong et al. (2018, 2023), following Howard et al. (2014):

$$CD \text{ (g/cm}^3\text{)} = \text{dry bulk density (g/cm}^3\text{)} \times (\%Corg/100) \quad (3)$$

Soil C stock (Mg C ha⁻¹) was subsequently calculated following Howard et al. (2014) by integrating CD across all sediment intervals within each sediment core. In this study, Soil C refers to the soil carbon stock integrated over the entire sediment profile. The carbon content of each sediment interval was calculated as:

$$\begin{aligned} \text{Carbon content of sediment interval (g/cm}^2\text{)} \\ = CD \text{ (g/cm}^3\text{)} \times \text{thickness interval (cm)} \end{aligned} \quad (4)$$

Total soil carbon stock for each sediment core was calculated by integrating carbon density across all sediment intervals and converting the resulting values to Mg C ha⁻¹ following Howard et al. (2014):

$$\text{Soil C (Mg C ha}^{-1}\text{)} = \Sigma(CD_i \times \Delta z_i) \times 100 \quad (5)$$

where CD_i is the carbon density of sediment interval *i* (g C cm⁻³), Δ*z*_i is the thickness of sediment interval *i* (cm), and the factor 100 converts g C cm⁻² to Mg C ha⁻¹.

Carbon accumulation rate (CAR; g C m⁻² yr⁻¹) was determined following Jennerjahn (2021) as:

$$CAR = DBD \times (\%Corg/100) \times SAR \quad (6)$$

2.4. Statistical analysis

The factors affecting long-term soil carbon storage were investigated using data from a study on the historical development of mangrove ecosystems through palaeoecological approaches that included vegetation groups (mangroves, back-mangroves, terrestrial herbaceous, and non-mangrove arboreal) and PSA (percentages of sand, silt, and clay), as reported by Punwong et al. (2023, 2018). Principal Component Analysis (PCA) was performed on the variables measured at 10 cm intervals. The analysis focused on variables related to soil carbon storage, including

soil C, DBD, CAR, PSA, and pollen percentages including mangrove taxa consisting of *Rhizophora*, *Avicennia*, and *Bruguiera*, back-mangrove taxa consisting of *Sonneratia caseolaris* and *Suaeda*, and terrestrial herbaceous taxa consisting of Poaceae, cereal, Cyperaceae, and Asteraceae. Non-mangrove arboreal taxa include Fagaceae and *Casuarina*. PCA was conducted by extracting three principal components (PC1, PC2, and PC3) from all study sites. Separate PCA analyses were conducted for each site to assess site-specific controls on carbon accumulation. For these site-level analyses, key pollen taxa were included because the dominant taxa of each vegetation type may differ among sites and may have different relationships with DBD, CAR, PSA, and soil carbon storage. The analysis was conducted using R statistical language (version 4.1) (R Core Team, 2019).

3. Results

3.1. Soil carbon stocks and carbon accumulation rates

The total soil C stock across the three sediment cores ranged from 3305 to 3972 Mg C ha⁻¹ (Table 1), with the highest value recorded at KKB. The DBD also varied among the sites and sediment depths, ranging from 0.58 to 2.76 g cm⁻³ (Table 1). Three sediment cores represented different chronological ranges of mangrove sediment accumulation (Table 1). The BKT core covered the longest record, extending from approximately 879 CE to 2015 (~1071 cal yr BP onwards) (Punwong et al., 2023) (Fig. 2A), followed by KKB from 1203 CE to 2015 (from ~747 cal yr BP onwards) (Fig. 2B) and KKC from 1182 CE to 2015 (~768 cal yr BP onwards) (Fig. 2C). SAR ranged from ~3–6 mm yr⁻¹ and CAR ranged from 185 to 1256 g C m⁻² yr⁻¹, and both values increased toward the later part of the period across all study sites (Fig. 2). The SAR and CAR estimates of both cores from Klong Kone (KKB and KKC) were higher than those of the core from Bang Khun Thian (BKT). Notably, the soil C and CAR were highest in the KKB core, with the shortest depth among the three cores.

3.2. Environmental factors influencing long-term soil C

PCA was applied to combine the dataset of all three study sites to identify the main environmental factors associated with long-term soil C dynamics.

At the initial stage of the PCA of all sites, examination of the scree plot indicated that the first three principal components (PC1, PC2, and PC3) explained 28.0%, 23.7%, and 16.1% of the total variance, respectively, accounting for 67.8% of the cumulative variance (Fig. 3). PC1 was primarily characterised by positive contributions from CAR, soil C, DBD, and mangrove cover. This axis was positively associated with soil carbon-related variables and mangrove taxa. In contrast, terrestrial herbaceous taxa and sand content were negatively associated along the PC1 axis (Fig. 3A), positioned on the opposite side of the

Table 1

Summary of soil carbon stocks, soil properties, sedimentation, and carbon accumulation rates with chronological ranges across the study sites.

Results of each core	Bang Khun Thian	Klong Kone (B)	Klong Kone (C)
Depth (cm.)	447	407	440
Total soil carbon stock (Mg C ha ⁻¹)	3305.26	3971.62	3312.71
Dry bulk density (g cm ⁻³)	0.90–1.65	1.08–2.12	0.58–2.76
Chronological range (Common Era: CE) (Punwong et al., 2018, 2023)	881–2015	1203–2015	1182–2015
Sediment accumulation rate (mm yr ⁻¹)	3–6	4–11	4–6
Carbon accumulation rate (g C m ⁻² yr ⁻¹)	185–614	300–1256	240–670

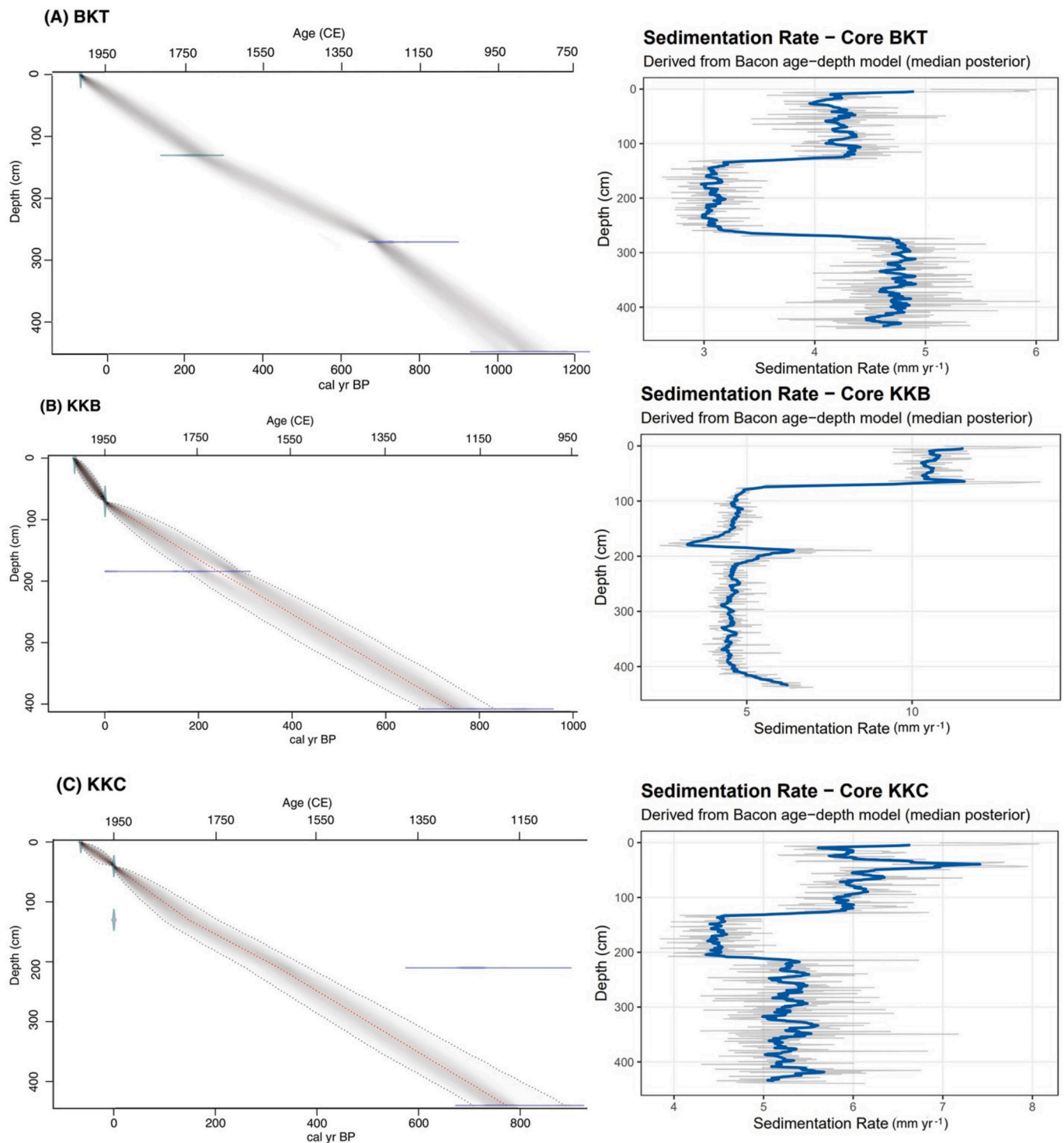


Fig. 2. rBacon age–depth models and sedimentation rates of the three mangrove sediment cores. (A) Bang Khun Thian (BKT) (modified from [Punwong et al. \(2023\)](#)), (B) Klong Kone Site B, and (C) Klong Kone Site C (KKC).

ordination space from soil C and CAR values. These patterns suggest a separation between carbon-rich mangrove-associated environments and sand-dominated terrestrial herbaceous areas in the study region. PC2 (23.7%) was mainly associated with soil texture variables, particularly silt, sand, and clay, together with back-mangrove and terrestrial herbaceous taxa (Fig. 3C). This axis appeared to represent a sediment texture gradient, contrasting sand-dominated environments with finer soils (silt and clay). In the ordination plot, finer soils were more closely associated with back-mangrove taxa, whereas sand content was aligned

with terrestrial herbaceous taxa (Fig. 3A). PC3 (16.1%) further explained the differences in vegetation composition and its link to the selected PSA (Fig. 3A). Non-mangrove and terrestrial herbaceous vegetation showed positive contributions, followed by soil C, back mangroves, and mangroves (Fig. 3D). Clay and silt showed moderate contributions, whereas sand and CAR contributed slightly to this axis. These results indicate that PC3 reflects variations associated with vegetation distribution and associated PSA changes. Therefore, the PCA results (PC1–PC3) suggest that long-term soil carbon storage in

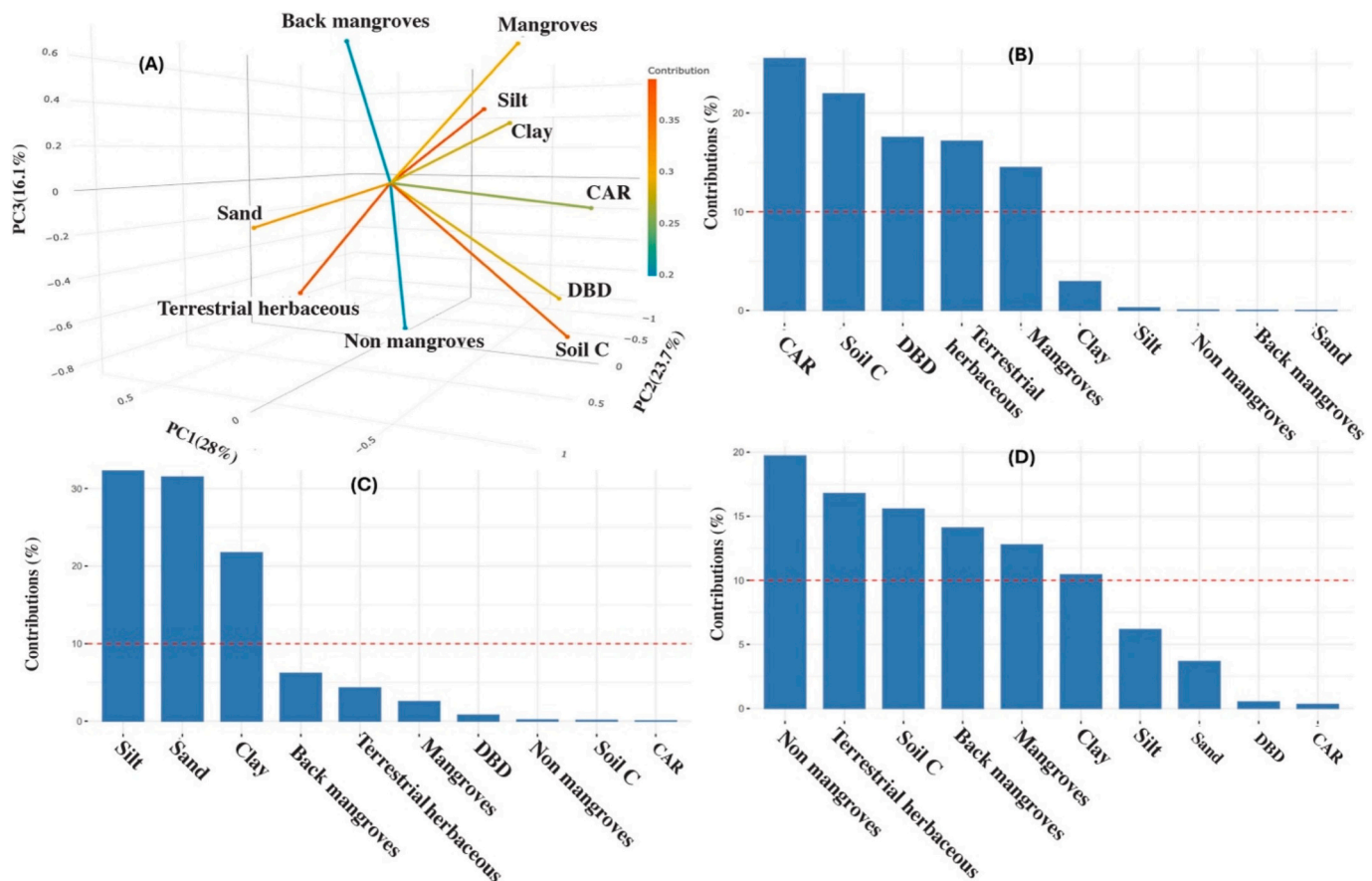


Fig. 3. Principal component analysis (PCA) of environmental variables associated with soil carbon storage in the study area. (A) Three-dimensional PCA biplot showing the relationships among variables along the PC1, PC2, and PC3 axes. Arrows indicate the direction and relative magnitude of the variable loadings, while the colours represent the variable contributions to the PCA ordination. (B–D) Contributions of environmental variables to PC1, PC2, and PC3. The red dashed line indicates the expected average contribution; variables above this line are considered to be important contributors to each principal component.

mangrove ecosystems is jointly controlled by multiple factors, including carbon accumulation processes, particle size, and vegetation composition. CAR and soil C were closely linked to mangrove vegetation cover. In contrast, sandy particles were generally separated from the carbon-related variables. Finer soil fractions, such as silt and clay, were more closely related to mangrove environments.

For site-specific PCAs, the variable drivers of soil carbon accumulation differed among sites. At BKT, the first two components explained 26.4% and 21.3% of the total variance, respectively (Fig. 4A). The PCA further refined these patterns by showing that soil C and CAR were most closely associated with *Rhizophora* and, to a lesser extent, *Avicennia*, suggesting that intervals of stronger mangrove dominance, especially those characterised by *Rhizophora*-rich assemblages, were more strongly linked to enhanced carbon accumulation. In contrast, DBD was positioned closer to silt, clay, Poaceae, and Cyperaceae than to soil C and CAR, indicating that DBD at BKT was more strongly related to sediment texture than to carbon enrichment. Sand was plotted opposite silt and clay and away from the mangrove–carbon cluster, reinforcing the interpretation that coarser sediment input was associated with reduced carbon storage efficiency. The separation of terrestrial indicators, such as Fagaceae, *Suaeda*, and cereals, from the mangrove carbon group further suggests intermittent terrestrial influence during phases of reduced mangrove dominance. Notably, cereals also appeared to be negatively associated with CAR, suggesting that periods with stronger terrestrial or cultivated land influence were less favourable for carbon accumulation.

At KKB (Fig. 4B), PC1 and PC2 explained 25.0% and 18.5% of the total variance. Soil C and DBD were closely aligned on the positive side

of PC1, indicating a strong positive association between the carbon stock and DBD. In contrast, CAR was more closely grouped with *Avicennia* and *Sonneratia caseolaris*, suggesting that CAR at KKB was more strongly linked to mangrove assemblages and back mangroves than to soil C alone. Sand, *Bruguiera*, *Rhizophora*, and *Suaeda* were plotted on the positive side of PC2, whereas silt, clay, Poaceae, and cereals were oriented in the opposite direction, indicating a separation between coarser, mangrove-associated depositional settings and finer or more terrestrially influenced phases. Notably, the ordination showed a partial separation between soil C and CAR, implying that long-term carbon storage at KKB may have been regulated by different processes: soil C was more closely associated with sediment packing and longer-term stocks, whereas CAR responded more strongly to shifts in vegetation composition and depositional dynamics.

For KKC, the PCA further clarified these relationships (Fig. 4C). PC1 and PC2 explained 40.0% and 16.6% of the total variances, respectively. Soil C and DBD were closely aligned with *Rhizophora* and *Bruguiera* on the positive side of PC1, indicating that long-term soil carbon storage at KKC was strongly associated with well-developed mangrove assemblages and relatively dense sediments. In contrast, Poaceae, cereals, and Asteraceae were positioned on the negative side of PC1, suggesting that intervals with stronger terrestrial or open habitat influences were less favourable for long-term carbon storage. Notably, CAR was plotted closer to sand than to soil C and DBD, indicating that carbon accumulation rate may have responded more strongly to depositional dynamics than to carbon stock alone. The separation of silt and clay from sand further highlights the importance of sediment texture in structuring the environmental variation at this site. Overall, the KKC record suggests

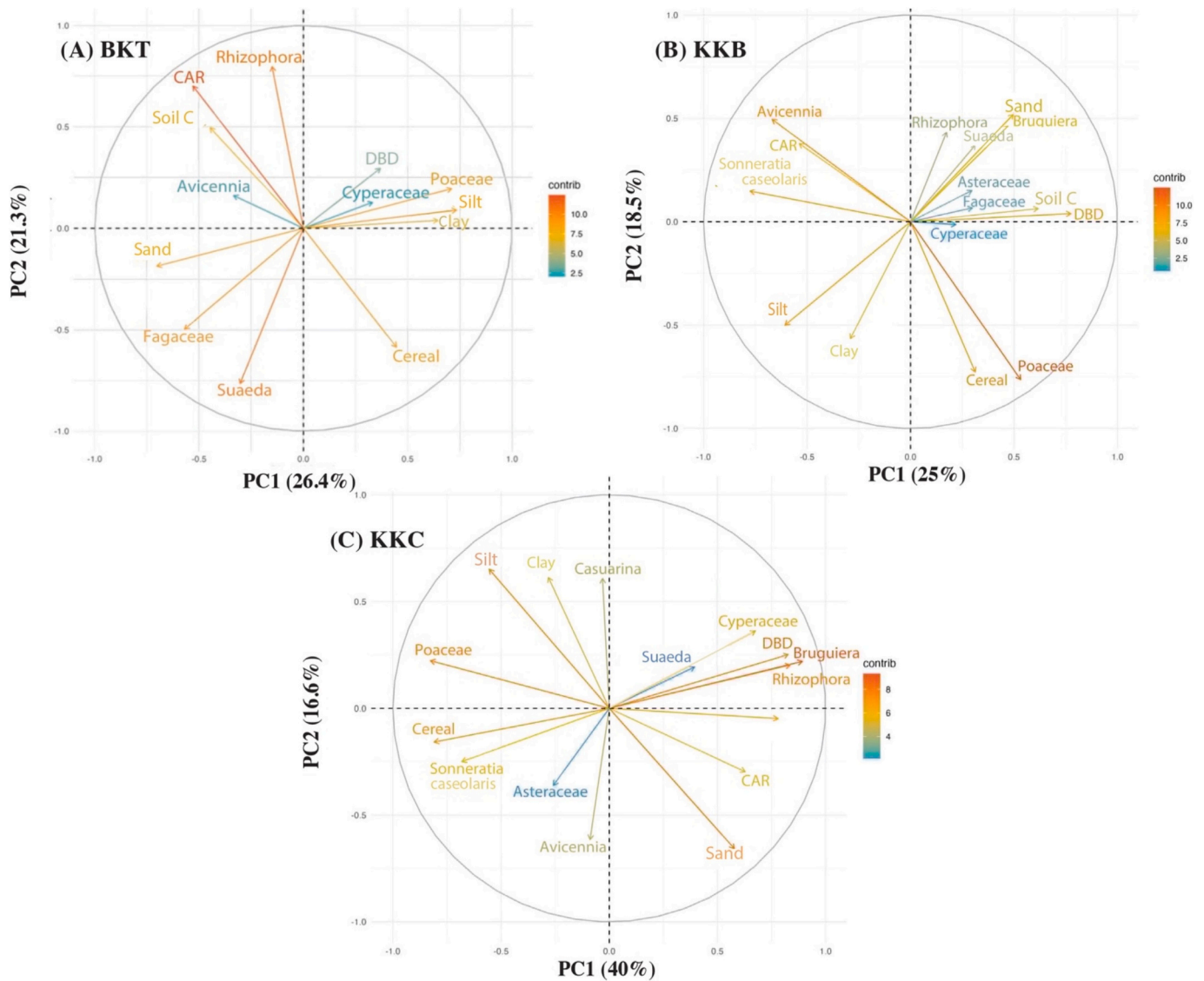


Fig. 4. PCA correlation circles of pollen taxa and environmental variables for (A) BKT, (B) KKB, and (C) KKC. Arrows indicate variable loadings, and the colours represent their contributions to the PCA ordination.

that long-term soil carbon storage is jointly influenced by mangrove composition, sediment properties, and shifts between mangrove and terrestrial influences.

Taken together, these results suggest that mangrove soil carbon dynamics are shaped by regional-scale patterns and local environmental controls. Across the three sites, mangrove vegetation appeared to support carbon accumulation and storage; however, the specific taxa associated with higher soil carbon differed among the sites. Silt and higher bulk density were generally linked to carbon storage, whereas coarser sediment inputs and stronger terrestrial or open habitat influences were associated with reduced carbon storage or different accumulation pathways. Therefore, the PCA results highlight that long-term mangrove carbon storage reflects complex interactions between vegetation history, sedimentary processes, and site-specific environmental conditions.

3.3. Historical environmental factors and long-term carbon storage

The PCA results indicated that CAR, DBD, and vegetation cover are key factors affecting soil C. Therefore, long-term carbon dynamics, including both soil C and CAR with their environmental factors, are

shown in Fig. 5 and described as follows.

3.3.1. Bang Khun Thian (BKT)

The soil sample depth was 447 cm, representing approximately 1100 years of sediment accumulation (CE ~880–2015). The results showed that soil carbon values fluctuated over time (Fig. 5A).

Between 880 CE and 1230 (at depths of 447–280 cm), high soil C levels were observed, particularly at ~430 cm (916 CE), where the soil C peaked (~135 Mg C ha⁻¹). Similarly, the CAR was highest during this period (~615 g C m⁻² yr⁻¹), and the SAR also reached its peak at 5 mm yr⁻¹ (Fig. 2A). The DBD was moderate (~1.2–1.4 g cm⁻³). This phase coincided with mangrove-dominated pollen assemblages and a relatively high silt content (Punwong et al., 2023).

Subsequently, between 1200 CE and 1755 (at depths of 280–120 cm), soil C initially decreased and then gradually increased (~54–75 Mg C ha⁻¹), following a trend similar to the CAR (~175–290 g C m⁻² yr⁻¹). The DBD initially declined but then rose sharply between 1320 CE and 1680, reaching its peak during this period (~1–1.6 g cm⁻³). The SAR showed a steep decline around 1350 CE (approximately 3 mm yr⁻¹). This trend corresponded with a rapid decline in mangroves and an increase in terrestrial herbaceous plants. Increased sand deposition was

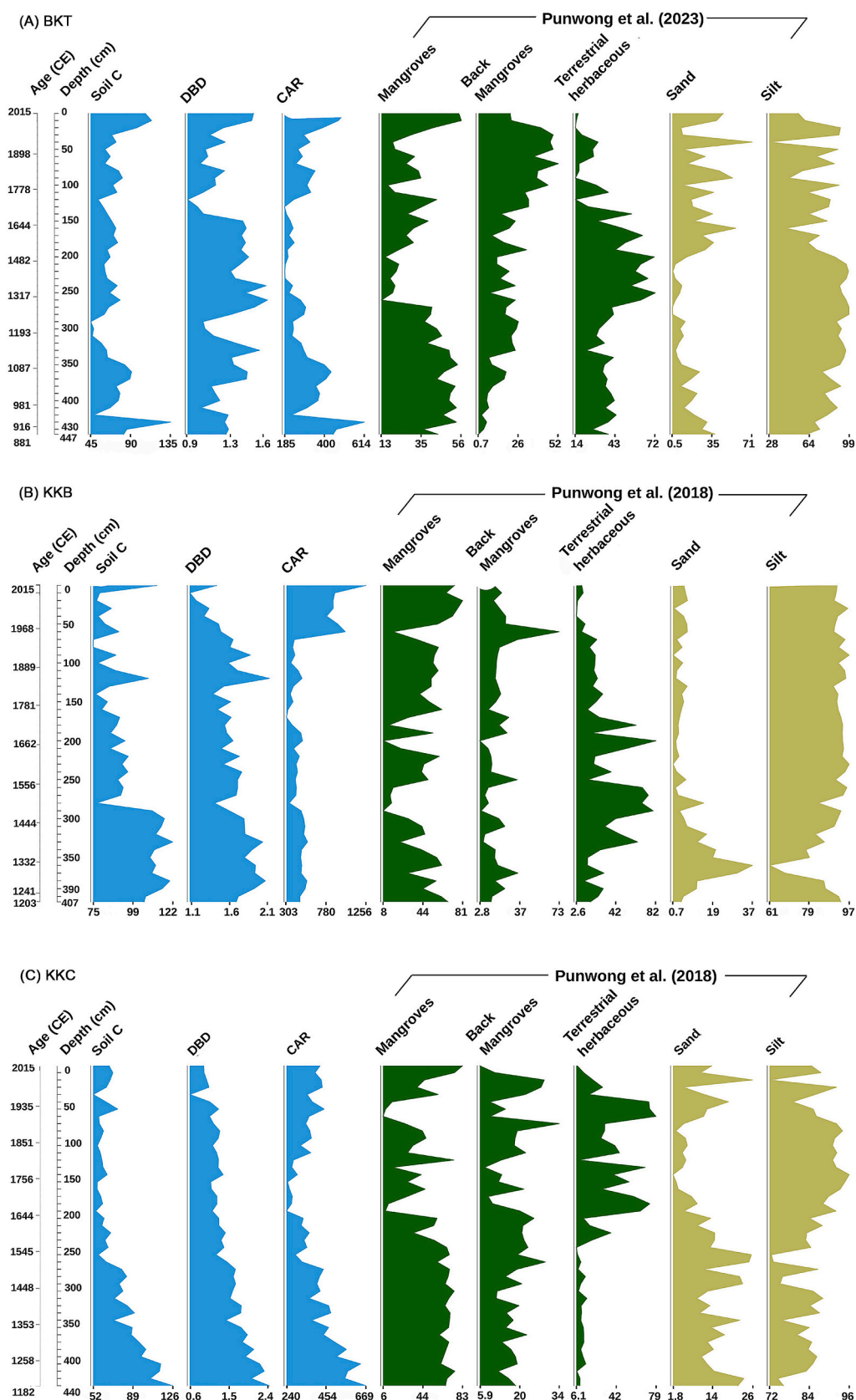


Fig. 5. Diagram showing the dynamics of soil C (Mg C ha⁻¹), dry bulk density (DBD: g cm⁻³), and carbon accumulation rates (CAR: g C m⁻² yr⁻¹), with percentages of pollen compositions (mangroves, back-mangroves, and terrestrial herbaceous) and particle size (sand and silt) at the study sites modified and redrawn of the original datasets retrieved from Punwong et al. (2018, 2023), with additional re-analysis in the present study. (A) BKT, (B) KKB, and (C) KKC plots.

also observed around 1500 CE (Punwong et al., 2023).

From 1755 CE to 2015 (at depths of 110–0 cm), the trends in SAR ($\sim 4 \text{ mm yr}^{-1}$), soil C ($\sim 60\text{--}114 \text{ Mg C ha}^{-1}$), and CAR ($\sim 245\text{--}510 \text{ g C m}^{-2} \text{ yr}^{-1}$) gradually increased. In contrast, DBD showed a decreasing trend ($\sim 0.9\text{--}1.5 \text{ g cm}^{-3}$). This upper core correlation was associated with an increase in soil carbon, SAR, and CAR, likely related to increased back-mangrove influence (Punwong et al., 2023).

3.3.2. Klong Kone (KK)

3.3.2.1. KKB. In this area, the soil sample depth was 407 cm, representing approximately 800 years of sediment accumulation (1203–2015 CE) (Fig. 5B). Soil C, DBD, and CAR showed similar trends, whereas SAR remained relatively constant with a sudden increase toward the end (Fig. 2B). The changes in these factors can be divided into distinct periods.

From 1203 CE to 1490 (at depths of 407–280 cm), soil C remained relatively high ($\sim 77\text{--}122 \text{ Mg C ha}^{-1}$), and the DBD was comparatively high ($\sim 1.4\text{--}2.0 \text{ g cm}^{-3}$). In contrast, CAR remained moderate to high during this phase ($\sim 337\text{--}556 \text{ g C m}^{-2} \text{ yr}^{-1}$). SAR remained relatively stable ($\sim 4 \text{ mm yr}^{-1}$) (Fig. 2B). Mangrove coverage was present during this period, although the expansion of terrestrial herbaceous plants began around 1360 CE. There was an increasing trend in sand content, followed by a gradual decline, with silt becoming more dominant and persisting throughout the core (Punwong et al., 2018).

Between 1490 CE and 1950 (at depths of 280–70 cm), soil C ($\sim 77\text{--}107 \text{ Mg C ha}^{-1}$), SAR ($\sim 4.5 \text{ mm yr}^{-1}$), and CAR ($\sim 356\text{--}497 \text{ g C m}^{-2} \text{ yr}^{-1}$) showed a continuous declining trend. The DBD remained moderate to high ($\sim 1.4\text{--}2.0 \text{ g cm}^{-3}$). This interval corresponds to fluctuating mangrove abundance, repeated expansion of terrestrial herbaceous taxa, and persistent silt-dominated sediments.

During 1950–2015 CE (at depths of 70–0 cm), CAR ($\sim 785\text{--}1256 \text{ g C m}^{-2} \text{ yr}^{-1}$) and SAR ($\sim 11 \text{ mm yr}^{-1}$) increased sharply and reached their highest values in the surface section, whereas soil C also increased to more than 110 Mg C ha^{-1} in the uppermost layers. DBD ($\sim 1.1\text{--}2.1 \text{ g cm}^{-3}$) showed a slight increasing trend with increasing temperature. This phase coincided with strong mangrove dominance, expansion of back-mangrove vegetation in the upper-middle section, low sand content, and a consistently high silt percentage (Punwong et al., 2018).

3.3.2.2. KKC. The collected sample depth was 440 cm, with a sediment age of approximately 800 years (1182–2015 CE) (Fig. 5C). The variables exhibited patterns similar to those observed for KKB. Soil C, DBD, and CAR exhibited similar trends, whereas SAR increased rapidly during the later period (Fig. 2C).

Between 1182 CE and 1450 (depths of 440–300 cm), soil C was relatively high ($\sim 70\text{--}126 \text{ Mg C ha}^{-1}$), and DBD ($\sim 1.2\text{--}2.8 \text{ g cm}^{-3}$) exhibited high values at this site. SAR and CAR were moderate to high during this interval and reached one of their highest values in the lower core ($\sim 5 \text{ mm yr}^{-1}$ and $\sim 360\text{--}670 \text{ g C m}^{-2} \text{ yr}^{-1}$). This phase coincided with high mangrove pollen percentages, low terrestrial herbaceous abundance, low sand content and persistently high silt values.

During 1450–1900 CE (depths of 290–100 cm), soil C ($\sim 52\text{--}75 \text{ Mg C ha}^{-1}$) and DBD ($\sim 1.09\text{--}1.2 \text{ g cm}^{-3}$) remained relatively stable, with a slight increase toward the core top. Similarly, the SAR (approximately 5 mm yr^{-1}) and CAR ($\sim 270\text{--}370 \text{ g C m}^{-2} \text{ yr}^{-1}$) showed increased values and remained consistently high throughout the study period. Mangrove and back-mangrove vegetation remained dominant, whereas terrestrial herbaceous taxa showed relatively high values during the later part of this period (1644–1780 CE). Although silt remained the dominant sediment fraction throughout most of the core, short-term increases in sand were observed in the middle section.

From 1860 CE to 2015 (90–0 cm), soil C increased again in the uppermost section ($\sim 52\text{--}75 \text{ Mg C ha}^{-1}$) SAR ($\sim 6 \text{ mm yr}^{-1}$), and CAR also rose toward the core top ($\sim 345\text{--}430 \text{ g C m}^{-2} \text{ yr}^{-1}$). In contrast, the DBD

exhibited a decreasing trend near the surface. The DBD continued to decrease and reached its lowest value around 1995 CE, which is likely related to the increased sand content in sediment. During this period, mangrove and back-mangrove forests began to replace terrestrial vegetation, and the proportion of silt fluctuated in the final period (Punwong et al., 2018).

4. Discussions

The discussion is divided into three sections. First, we assessed the carbon storage capacity of the mangrove ecosystems at the study sites. This is followed by environmental factors that drive long-term carbon dynamics. Finally, the integrated palaeoecological and new carbon datasets were used to evaluate how mangrove carbon dynamics responded to past environmental fluctuations.

4.1. Carbon storage capacity of the studied mangrove ecosystems

Quantifying the dominance of soil carbon highlights the vital function of mangrove ecosystems as long-term blue carbon reservoirs. The results of the total soil C stock ranged from 3305 to 3972 Mg C ha^{-1} ; these high average soil C values were due to the depth of the sediment cores that extended to approximately 4.1–4.5 m. These values are higher than the soil C stock reported for a 3.5 m mangrove sediment core from the eastern Gulf of Thailand ($\sim 1000 \text{ Mg C ha}^{-1}$; Kida et al., 2021), although direct comparison is limited because Kida et al. (2021) quantified SOC in the $<2 \text{ mm}$ sediment fraction using an elemental analyser. More broadly, the average soil C stock in this study exceeded previously reported values across Thailand and several Southeast Asia (Table 2), including those from the northern and western Philippines, where soil carbon storage was reported as 586 Mg C ha^{-1} (Salmo et al., 2024). Similarly, intact undisturbed mangroves in West Papua, Indonesia, have been reported to store total ecosystem carbon stocks of $1087 \pm 584 \text{ Mg C ha}^{-1}$, with approximately 89% stored in the soil pool. This corresponds to an estimated soil carbon stock of approximately 967 Mg C ha^{-1} for soils up to 3 m deep (Sasmitho et al., 2020). In contrast, mangroves in Myanmar's Ayeyarwady Delta showed substantially higher soil C storage, reaching $1955 \text{ Mg C ha}^{-1}$ (Pandey et al., 2024). However, when comparisons were standardised to equivalent soil depths, the soil C stock in this study was comparable to values reported for Indo-Pacific mangroves (Donato et al., 2011) (Table 2). Nevertheless, comparisons

Table 2

Mangrove total soil carbon stocks and soil carbon stock per depth in this study compared with other regions at different soil depths and different methods.

Region/Country	Depth (m)	Total soil C (Mg C ha^{-1})	Total soil C per depth ($\text{Mg C ha}^{-1} \text{ m}^{-1}$)	Method
This study	4.0–4.4	3305–3972	$\sim 751\text{--}993$	LOI
Eastern Gulf of Thailand, Trat (Kida et al., 2021)	3.5	962	275	Elemental analyser
West and North Philippine (Salmo et al., 2024)	1.0	586	586	Elemental analyser
West Papua, Indonesia (Sasmitho et al., 2020)	3.0	967	322	Elemental analyser
Ayeyarwady Delta, Myanmar (Pandey et al., 2024)	1.0	1954	1954	LOI
Indo-Pacific mangroves (Donato et al., 2011)	3.0	1023	341	Elemental analyser

among published soil carbon stocks should be interpreted with caution because different studies have employed different analytical methods for estimating soil carbon. Such methodological differences may contribute to variations in reported soil carbon stocks. As soil carbon stock and CAR calculations depend partly on %Corg estimates, the uncertainty associated with LOI-derived %Corg should also be considered. Although LOI-derived %Corg may involve greater uncertainty than direct elemental carbon analysis, recent studies have demonstrated that ecosystem-specific calibration equations can substantially reduce uncertainty in LOI-based organic carbon estimates (Breithaupt et al., 2023). Therefore, this study estimated %Corg from %LOI using the mangrove-specific LOI-%Corg regression developed by Kauffman et al. (2011) to ensure consistent estimation of %Corg throughout all sediment cores. Although the use of an LOI-based approach may partly influence the comparison, it is unlikely to fully explain the higher Soil C values observed in this study. Recent evidence from Southeast Asian mangroves has shown that the conventional based LOI conversion equation may overestimate soil carbon stock by approximately 20% in north and west Philippine mangrove settings (Salmo et al., 2024). Even with a conservative 20% reduction as an example, the adjusted Soil C values in this study would still be higher than the values previously reported and listed for comparison in Table 2. This suggests that the higher Soil C values are not solely attributable to the LOI-based estimation method, but also reflect site-specific sedimentary characteristics and geomorphological controls. Our findings indicate that the relatively high soil carbon content at the study sites may be partly attributed to their geomorphological setting within estuarine mangrove and tidal-flat systems similar to the Ayeyarwady Delta. These coastal environments are shaped by intertidal flooding and sediment deposition, which promote the accumulation and storage of organic-rich sediments derived from both autochthonous and allochthonous sources, including riverine inputs (Zhang et al., 2024). This depositional setting is consistent with the relatively high SAR and CAR recorded in this study, which ranged from 3 to 11 mm yr⁻¹ and 180 to 1256 g C m⁻² yr⁻¹, respectively. These CAR values suggest that carbon storage at Bang Khun Thian and Klong Kone is associated with high soil carbon stocks and sustained sediment accretion and burial processes. Mangroves situated in estuarine environments, such as those in this study, typically exhibit a higher CAR than the global average (~233 g C m⁻² yr⁻¹) (Jennerjahn, 2021). Similarly, Brazilian mangroves located near estuaries also show high CAR values, ranging from 65 to 1073 g C m⁻² yr⁻¹ owing to frequent tidal inundation, precipitation runoff, and sediment input from both marine and terrestrial sources (Hatje et al., 2020). This is because estuarine mangroves receive abundant fine sediments and organic matter from both marine sources, such as suspended particles and phytoplankton, and terrestrial sources, including riverine and catchment-derived materials (Sugiatmo et al., 2023). Our study sites are situated on low-gradient muddy tidal flats of the upper Gulf of Thailand, where fine-grained sediments are supplied by riverine discharge and redistributed by tidal processes. The dominance of fine-grained sediments in the studied cores likely enhanced organic matter retention and storage, thereby supporting both high soil carbon stocks and long-term carbon accumulation (Saintilan et al., 2020; Feng et al., 2024). Therefore, the CAR values observed in this study were within the relatively high range reported for estuarine and sediment-rich mangrove systems and exceeded the global average for mangrove ecosystems. This detailed insight underscores that direct comparison and extrapolation should be performed with caution, as CAR is strongly influenced by sedimentation rate, dating resolution, geomorphological setting, and the temporal scale of calculation.

4.2. Environmental factors driving carbon dynamics

The PCA analysis in this study highlighted the pivotal role of soil properties (DBD and PSA) and mangrove presence in explaining the variability in soil carbon storage. This is consistent with previous studies that documented the ability of mangroves to store carbon in their soil

owing to their high productivity and organic matter inputs (Alongi, 2018). Additionally, the complex root systems of mangroves and their ability to trap sediments further enhance soil carbon accumulation (Donato et al., 2011). Root exudates released under anoxic conditions can add dissolved organic carbon and create a negative priming effect that suppresses decomposition (Panchal et al., 2022). Consequently, the surface soils beneath the mangrove vegetation tended to have lower DBD than the deeper layers. This indicates higher porosity in the surface horizons, likely reflecting substantial inputs from leaf litter, root decomposition, and other debris from less-dense mangrove vegetation (Ma et al., 2024). Although fine-textured soils, such as silt and clay, generally retain more carbon than sand because sand particles have a lower capacity to hold organic matter (MacKenzie et al., 2021), soil C in this region appears to be more strongly controlled by tidal flat factors than by the soil texture.

Moreover, the site-specific PCA results across different sites indicate that the mechanisms of carbon accumulation in mangrove ecosystems vary at the local scale and are governed by multiple interacting factors. Across the study sites, mangrove taxa such as *Rhizophora*, *Avicennia*, and *Bruguiera* were generally associated with soil C, CAR, and DBD, suggesting that mangrove vegetation is a key driver of long-term carbon dynamics in mangrove ecosystems. Rather than indicating entirely different mechanisms among sites, these species-level differences reflect variations in modern mangrove zonation and local habitat conditions.

Previous studies have shown that modern vegetation and below-ground biomass primarily influence %Corg within the upper soil profile, for example, up to approximately 75–80 cm (Wen et al., 2022). While pollen contribute to the soil organic carbon pool, they serve as an essential proxy for reconstructing past vegetation. The relationships observed between mangrove taxa and carbon variables must therefore be interpreted within a temporal context. Modern vegetation primarily influences pollen deposition in contemporary surface sediments, whereas pollen assemblages preserved within dated, deeper sediment layers represent the vegetation present at the time each layer was deposited (Phumphumirat et al., 2016).

Accordingly, the pollen record presented in this study was interpreted within a robust chronological framework and integrated with SAR, CAR, sedimentological evidence, and soil carbon stocks to reconstruct long-term vegetation dynamics and carbon accumulation, rather than serving as a direct reflection of present-day vegetation. Consequently, the associations between pollen taxa and soil carbon variables identified by the PCA reflect long-term ecological dynamics over time, rather than the direct influence of extant surface vegetation. For example, *Rhizophora* and *Bruguiera* are commonly associated with more developed mangrove stands and can enhance carbon storage through dense root systems and organic matter inputs, whereas *Avicennia* is often found in more seaward settings where tidal inundation and sediment deposition are active (Jacotot et al., 2018; Zulhalifah et al., 2021). Therefore, even when different species are identified as important contributors to each core, they can be interpreted as part of the broader mangrove functional group that supports carbon accumulation through vegetation productivity, root development, and sediment retention. Terrestrial and back-mangrove indicators, including *Suaeda*, Poaceae, cereal, Asteraceae, and Fagaceae, were generally separated from the mangrove-carbon group. Periods with a stronger terrestrial or open-habitat influence, reduced tidal influence, and mangrove retreat coincide with reduced carbon storage compared to periods dominated by mangrove vegetation. This ecosystem transition may have increased terrestrial conditions which could reduce carbon storage (Hatje et al., 2020). However, terrestrial sediments may also contribute additional allochthonous carbon to the system through river discharge (Zhang et al., 2024). These contrasting effects highlight the importance of vegetation structure and species composition in regulating organic matter inputs and maintaining blue-carbon storage.

Other PCA variables further indicated that carbon dynamics were controlled by both vegetation and sedimentary processes. Soil C was

commonly associated with mangrove taxa and DBD, suggesting that long-term carbon storage is related to both organic matter input and sediment consolidation.

The positive association between Soil C and DBD does not indicate that high DBD directly increases organic carbon concentration. Rather, Soil C in this study represents the soil carbon stock, which was calculated from both DBD and %Corg integrated throughout the sediment profile. In estuarine mangrove environments, fine-grained mineral sediments and organic matter are buried together during long-term sediment accretion. Therefore, progressive sediment burial and sediment consolidation allow relatively high soil carbon stocks to occur in sediments with comparatively high DBD. However, CAR was more strongly influenced by sediment accretion and depositional dynamics, particularly where it was associated with SAR or sand content. This distinction indicates that soil C and CAR are related but non-interchangeable indicators: soil C reflects longer-term carbon storage, whereas CAR is more sensitive to sediment accumulation rate, and depositional changes. Overall, the PCA results suggest that the main drivers of carbon dynamics across the study sites were not individual species alone, but the ecological functions represented by mangrove groups, together with sediment texture, DBD, and SAR.

4.3. Carbon dynamics in response to past environmental fluctuations

Combined PCA and historical records showed that long-term mangrove soil carbon dynamics are controlled by multiple interacting factors. These include vegetation history, sediment texture, DBD, SAR, sea level change, climate variability, and land-use change within each site's geomorphic setting. PCA identified relationships among soil C, CAR, DBD, sediment texture and pollen assemblages. Meanwhile, the age–depth records provided a temporal context for interpreting when these relationships changed over the past millennium (Fig. 6).

4.3.1. From ~840–1240 CE (~1110–710 cal BP)

During this period, the trends of soil C, CAR, and mangrove percentage were consistent across all study sites, reflecting relatively high carbon storage (Fig. 6). Previous palaeoecological studies in Bang Khun Thian and Klong Kone indicate that mangrove-dominated intertidal conditions occurred approximately at 840–1240 CE and 1130 CE–1230 respectively, reflecting periods of relatively strong sea-level influence and tidal inundation (Punwong et al., 2018, 2023), which facilitated expansion of mangroves, and soil carbon accumulation. Mangrove vegetation acts as a primary source of organic matter input (Zhang et al., 2024), whereas intertidal flooding and sediment deposition enhance the burial and storage of this carbon which likely contributes to elevated

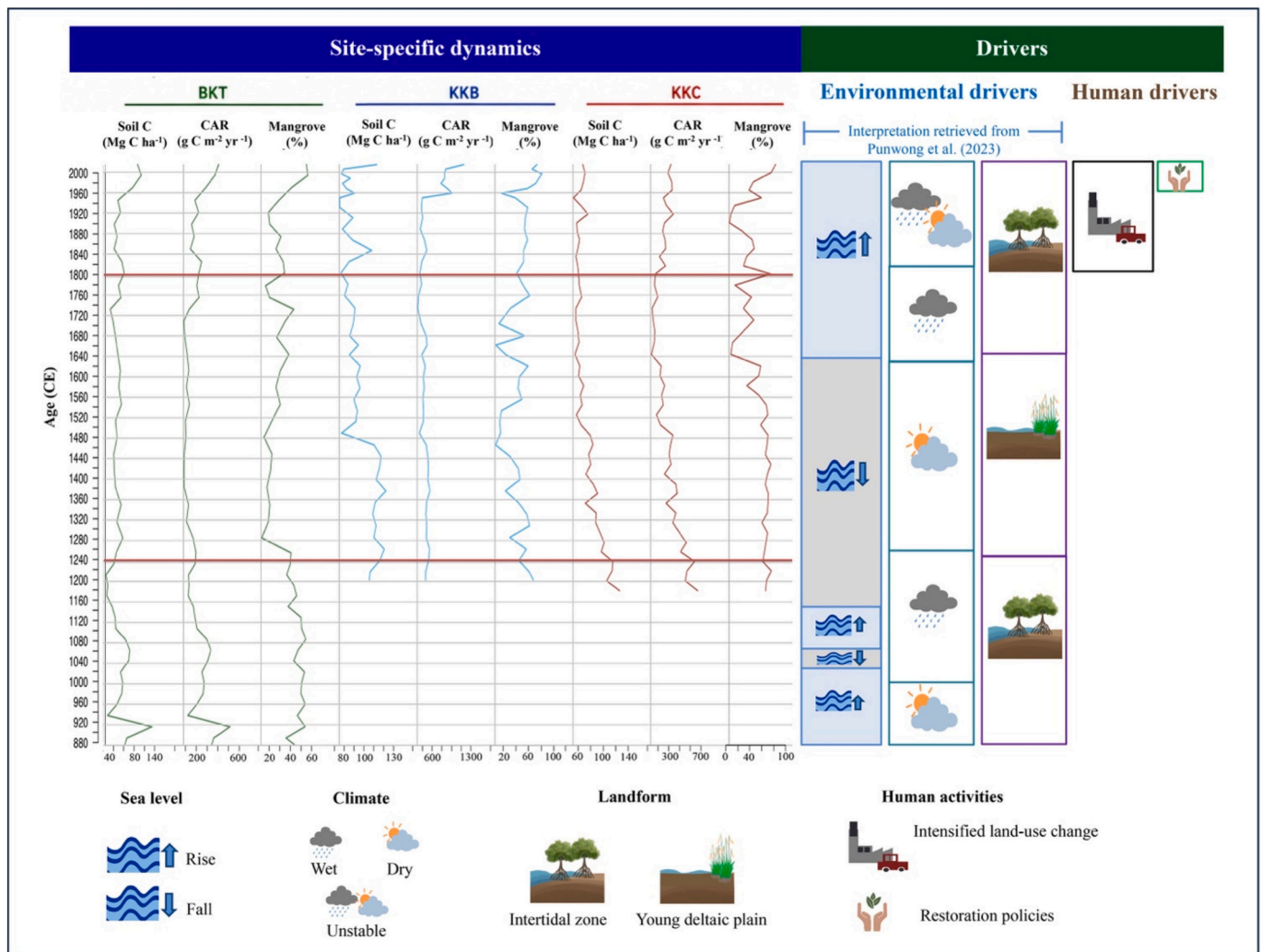


Fig. 6. Diagram showing mangrove dynamics associated with soil C and CAR across the three study sites. The columns display the environmental driver identified by Punwong et al. (2023), including sea-level trends, climate conditions, and landform changes in the upper Gulf of Thailand. The orange line represents the key transition period.

SAR. A higher SAR would increase the burial rate of organic matter, thereby supporting a higher CAR.

Furthermore, after approximately 1050 CE, the presence of back mangrove species, such as *Sonneratia caseolaris* and *Melaleuca*, indicates the influence of freshwater from rivers during this period (Punwong et al., 2018), which contributed to increased sediment and soil carbon accumulation. This timing coincided with the strengthening of the Southeast Asian summer monsoon during 1050–1100 CE (Baker and Phongpaichit, 2014). Therefore, carbon dynamics during this interval were likely driven by the combined effects of mangrove expansion, enhanced riverine sediment supply, and wetter monsoon conditions. Mangrove vegetation would have increased autochthonous organic matter inputs through litter and root production, while freshwater and riverine inputs supplied allochthonous organic matter and mineral sediments to the tidal-flat system (Jennerjahn, 2021). These combined inputs promoted CAR from both autochthonous and allochthonous sources, consistent with studies showing that developing or expanding mangrove stands can enhance belowground and detrital inputs and increase sediment accumulation rate (Sasmitho et al., 2020).

4.3.2. From ~1240–1810 CE (~710–140 cal BP)

Between 1240 CE and 1450, soil C and CAR declined across all study sites, reflecting decreased carbon storage efficiency in the mangrove ecosystem during this period (Fig. 6). This decline coincided with the retreat of mangrove forests and the expansion of terrestrial and herbaceous vegetation (Punwong et al., 2018, 2023), indicating a marine regression. This interpretation is supported by palaeo-sea-level models showing a general sea-level fall over the past millennium (Tanabe et al., 2003). Under these conditions, the study areas likely developed into young deltaic plains as freshwater sediment deposition increased and marine influence retreated (Punwong et al., 2018, 2023). This geomorphic transition promoted the replacement of mangroves by terrestrial herbaceous vegetation (Fig. 6). Mangrove retreat reduces autochthonous organic matter inputs from litter and roots, which are important sources of sedimentary organic carbon in intact mangrove stands (Suello et al., 2022). Simultaneously, weaker tidal inundation and reduced sediment supply would have limited fine-sediment burial and the trapping of organic-rich suspended material, thereby lowering sediment accretion and carbon burial efficiency (Saintilan et al., 2020). Drier climatic conditions may have also reduced organic matter production and sediment delivery to the coastal zone, further limiting soil carbon accumulation compared to the preceding period. Consequently, soil C and CAR declined across the study sites. After the development of young deltaic conditions, the increase in Poaceae and the occurrence of cereal pollen may indicate early cultivation or agricultural activity near the study areas (Punwong et al., 2018, 2023). This land use coincided with a declining CAR, suggesting that human influence may have further altered the sedimentary organic matter sources and reduced mangrove-derived carbon inputs (Feng et al., 2024). Therefore, the decline in CAR during 1240–1450 CE was likely driven primarily by marine regression, reduced tidal influence, mangrove retreat, and drier conditions, with early land-use change as an additional contributing factor. Nevertheless, soil C and CAR did not disappear entirely, suggesting that residual runoff and freshwater sediment supply continued to provide allochthonous organic matter and mineral sediments to the area. Low runoff during the dry period may have continued to transport sediments and nutrients from upland areas to the coast, partially sustaining soil carbon inputs during this interval (MacKenzie et al., 2021).

From 1450 CE to 1810, mangrove forests gradually expanded across all study sites, corresponding to rising sea levels and increased rainfall, which enhanced tidal influence and sediment input (Punwong et al., 2018, 2023). This period represents improved hydrological connectivity, which promotes higher SAR and greater carbon burial efficiencies. The renewed mangrove expansion would have increased autochthonous organic inputs, whereas stronger tidal inundation and sediment supply enhanced organic matter burial. These processes increased the potential

for both CAR and long-term storage. Consequently, soil C and CAR gradually increased, particularly in Bang Khun Thian, which exhibited the most pronounced increase in carbon storage. In contrast, the landward site at Klong Kone responded more slowly to sea-level rise, reflecting delayed tidal inundation and sediment delivery, which led to slower changes in the ecosystem. The gradual return of mangroves, increased rainfall, and stronger tidal influences likely improved the carbon storage conditions. Mangrove recovery would have increased organic matter input from litter and roots. Simultaneously, enhanced tidal connectivity and sediment delivery promote the vertical accretion and burial of both autochthonous and allochthonous organic carbon, improving long-term storage (Collins et al., 2017). This period explains the gradual increase in soil C and CAR, especially at BKT, where stronger tidal connectivity plausibly allowed a faster carbon response than at more landward sites, which is consistent with higher burial and accretion where tidal and sediment inputs are greater.

4.3.3. From ~1810 CE to present (~140 cal BP to present)

Soil C during this period generally showed a decreasing trend in the early phase, followed by an increase in the later phase, except at the Klong Kone seaward site (KKB), where soil C increased during the early part of the interval. The CAR generally increased toward the upper part of the cores, particularly after approximately 1950 CE, although the magnitude of the increase varied among sites. This pattern broadly coincided with a later increase in soil C, suggesting enhanced carbon accumulation during the recent period, likely due to recent sea-level rise in the Gulf of Thailand, averaging approximately 4.5 mm yr⁻¹ over the past 50 years (Trisirisatayawong et al., 2011) (Fig. 6). This increase aligns with the expansion of mangrove forests, particularly *Avicennia*, seaward species, in both Klong Kone and Bang Khun Thian, which may have enhanced organic matter input, sediment trapping, and carbon burial. These conditions would enhance soil C and CAR by increasing both autochthonous organic inputs from mangrove vegetation and allochthonous sediment and organic matter delivered from adjacent watersheds. However, the relatively high CAR observed from ~1810 CE onwards did not always correspond to equally high soil C values (Fig. 6). This contrast may reflect the influence of rapid sediment accretion and changes in sediment composition, which can increase carbon burial rates while simultaneously diluting organic carbon concentrations. Although mineral inputs were not directly quantified in this study, the combination of high CAR, rapid accretion, and relatively low %Corg is consistent with observations from other mangrove and deltaic settings, where enhanced allochthonous mineral sediment delivery has been linked to the sediment-dilution effect (Suello et al., 2022). This controversy regarding soil C and CAR is probably because, from the early eighteenth century onwards, coastal landscapes in the upper Gulf of Thailand began to be settled and agricultural land expanded. Mangrove wood has been increasingly exploited for building material fuel and charcoal production, reflecting a transition from natural mangrove ecosystems to subsistence agroecosystems (Punwong et al., 2023). From ~1880 CE, logging concessions have further intensified commercial mangrove extraction (Komiyama et al., 1992). This disturbance was further amplified under the Third National Economic and Social Development Plan in 1972, when government policies promoted the utilisation of idle coastal lands and issued extensive concessions for mangrove logging and aquaculture development. Together, these activities have contributed to widespread mangrove deforestation, reduced mangrove biomass and root-derived organic matter inputs, weakened sediment-trapping capacity, and disturbed organic-rich surface soils. By the 1970s, rapid industrial and urban expansion had further altered sediment and nutrient fluxes in downstream mangrove ecosystems, thereby modifying the coastal sedimentation patterns (Baker and Phongpaichit, 2014; Punwong et al., 2023). This increased disturbance likely reduces mangrove biomass and belowground organic matter inputs, while weakening sediment-trapping capacity and disturbing organic-rich surface soils. This land-use disturbance explains the

decline in mangrove cover observed in the Bang Khun Thian and Klong Kone landward zones (KKC). Reduced mangrove cover would lower in situ organic matter production and weaken belowground carbon inputs. Consistent with evidence that mangrove land-use and land-cover changes, including logging, agriculture, settlements, and aquaculture, allow for large losses of biomass (~80%) and substantial reductions in soil carbon stocks (Saintilan et al., 2020). In contrast, mangroves at the seaward Klong Kone site (KKB) persisted more strongly because frequent tidal inundation continued to support sediment delivery and the establishment of mangroves. This apparent contrast may be explained by enhanced sediment erosion and runoff from adjacent agricultural and developed lands, which transport mineral sediments and organic materials into mangrove zones. However, the carbon stored during this period was lower than that in natural mangrove ecosystems, as it primarily originated from agricultural soil, which is more labile and prone to decomposition (Datta et al., 2015).

However, when considering soil C, CAR, and mangrove extent, an increasing trend was evident, indicating ecosystem recovery beginning in the mid-twentieth century and becoming more pronounced around 1995 CE. This increase coincides with the implementation of national mangrove restoration policies, such as reforestation and replanting programs, community-based rehabilitation, and shoreline protection measures, which collectively promote mangrove expansion and the progressive recovery of degraded coastal ecosystems (Wanthongchai and Pongruktham, 2019). These restoration efforts have enhanced sediment trapping and increased sedimentation in tidal zones. In mangrove systems, tidal inundation transports suspended sediments into the forest, while reduced flow velocity during slack water and vegetation-induced drag promote sediment settling and retention (Jacotot et al., 2018). This interpretation is consistent with recent evidence from southern Thailand, where mangrove recovery in former aquaculture areas was driven by aquaculture decline, community engagement, and supportive policy frameworks (Rattanasat et al., 2025).

Moreover, mangroves in the upper Gulf of Thailand are vulnerable to fluctuations in sea level and future changes in land use or policies that disrupt the sediment balance. For instance, the enforcement of a land tax on idle or undeveloped areas may incentivise the conversion of mangrove forests into other land uses, whereas the construction of coastal structures that obstruct sediment transport could further intensify vulnerability in the long term. Mangroves are vulnerable to coastal erosion, with sediment accumulation often lagging behind sea-level rise and limited migration space; therefore, both mangrove ecosystems and their carbon stocks are at risk (Saintilan et al., 2020).

Each period reflects a dynamic interplay between sea level, climate variability, and land use change, all of which collectively influence mangrove expansion or retreat, and in turn, affect soil C and the CAR. These relationships are not linear but involve multiple feedbacks. For instance, climate-driven changes in monsoon intensity alter sea levels and sediment supply, influencing mangrove colonisation and organic matter accumulation. Land-use changes within mangrove zones, such as logging or conversion to aquaculture, directly reduce soil C storage. In contrast, land-use changes in surrounding catchments, including agriculture and urban development, can temporarily increase carbon inputs through upland erosion of runoff and sediment delivery, although the degradation of mangrove vegetation limits long-term carbon burial. National mangrove restoration policies have enhanced sediment trapping and promoted long-term carbon storage in restored zones. Recognising this interplay highlights the need to integrate palaeoecological records, geomorphological data, and land-use histories to fully understand the mechanisms controlling long-term carbon sequestration in mangrove ecosystems and guide sustainable management.

5. Conclusions

Long-term carbon storage in mangrove soils results from interactions

among mangrove vegetation history, species composition, soil texture, DBD, CAR, sea-level change, climate variability, land-use changes, and the geomorphic setting of each site. Environmental factors and past environmental records indicate that soil C and CAR describe different aspects of mangrove carbon dynamics. Soil C represents the amount of carbon retained in the sediment over time, whereas CAR represents the rate at which carbon is buried through the SAR. Therefore, a high CAR does not necessarily indicate a high soil C stock, particularly when rapid sedimentation dilutes the organic carbon concentration or when the buried material includes externally derived mineral sediments. Soil C is therefore more closely related to vegetation occurrence, while CAR is more sensitive depositional dynamics that related to sea-level changes, climate variability and land-use change. The results further showed that BKT was more sensitive to terrestrial/open-habitat influence and sand input, KKB reflected a clearer distinction between carbon stock storage and carbon accumulation rate, as relatively high CAR values did not always coincide with equally high soil C stocks. While, KKC showed a stronger coupling between mangrove dominance, fine-grained sedimentation, and carbon storage.

This study emphasises the importance of incorporating palaeoecological insights into mangrove management, focusing on maximising carbon storage potential. By studying historical fluctuations and their effects on carbon dynamics, we can better understand the long-term potential of mangrove ecosystems. Without the effective enforcement of land-use planning and sediment management policies, mangroves will continue to be degraded, and the vital carbon store will be eroded with national and global implications. These results provide new insights into the long-term mangrove carbon dynamics in the upper Gulf of Thailand. Future studies should incorporate broader spatial sampling, higher-resolution dating, sediment-source tracing, and hydrological monitoring. Integrating restoration history and coastal management policy would also help clarify how human disturbance and ecosystem rehabilitation influence long-term CAR and soil C.

CRedit authorship contribution statement

Ausanee Suttiwong: Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis. **Paramita Punwong:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Rob Marchant:** Writing – review & editing, Supervision. **Apichaya Englong:** Writing – review & editing. **Luke Andrews:** Writing – review & editing. **Nathsuda Pumijumnon:** Writing – review & editing, Supervision. **Wanwisa Pansak:** Writing – review & editing. **Pasin Maprasop:** Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

[Dataset for the upper Gulf of Thailand carbon storage \(Original data\)](#)
(Mendeley Data)

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