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A hidden blue carbon sink in Nipa Palm sediment: A pioneer study of the Nipa Palm ecosystem in Trang Province, southern Thailand

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Abstract This pioneering study on Nipa palm mangroves is demonstrated their importance as carbon sinks. In this work, sediment cores from a Nipa palm mangrove forest in the Trang River estuary, Thailand, a mangrove ecosystem that is found to be little attention which are utilised to investigate the dynamics of total organic carbon (TOC), total nitrogen (TN), soil organic carbon (SOC), and perform grain size analysis. Three sediment cores (KT01, KT02, and KT03; depths 76–82 cm) were analysed at 2 cm sediment intervals to determine their TOC, TN, C/N ratios, SOC stocks, and grain size. The findings indicated that the SOC stock of the three cores ranged between about 322– 355 Mg C_{org} ha^{-1}. The surface enrichment at KT01 (depths 0–10 cm) had much greater TOC (5.73–9.04%) whereas TN was similar throughout the whole depth for 3 cores (0.21–0.58%). A key observation at surface (0-10 cm deep) TN was 33-37% of the total TN, highlighting active nitrogen cycling near the root zone. The C/N ratio tended to fluctuate (14–24) with depth, indicating mixing between vascular pant debris and vascular land plants except at the layer 0–2 cm deep of KT 02 which was sourced from algae. The vertical distribution of TOC and TN tended to decrease with depth at KT0. It is noticed that carbon burial was suggested by mid-depth SOC maxima (depths 48–58 cm), whereas the deeper layers (depths 60–82 cm) retained approximately 30 % of total SOC. The grain size analysis of three sediment cores indicated that all samples were within the silt size fraction, mainly very fine silt, with no presence of sand or clay-sized particles. The information obtained from this pioneer study is offered baseline data for future comparison to other mangrove varieties.

Keywords: Climate change, Organic matter, Mangrove, Andaman Sea, Tidal cycle

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Introduction

Blue carbon plays an important role in mitigating climate change and global warming. Marine and coastal ecosystems such as seagrass beds, mangrove forests and floodplains absorb carbon dioxide from the air, and store it in soil, above-ground living biomass (leaves, branches and trunks), below-ground living biomass (roots) and abiotic biomass (e.g. dead wood and debris) (Mcleod *et al.,* 2011). Since carbon stored in coastal soils can be stored in the soil over very long time periods, it results in a significant amount of carbon sequestration in soils (Duarte *et al*., 2005), compared to carbon stored in aboveground living biomass. These ecosystems can store organic carbon for thousands of years because they successfully trap and preserve organic materials in deep soil layers (Lovelock and Duarte, 2019). Mangrove forests are blue carbon ecosystem and are vital wetlands and green ecosystems located between the sea and the coastline and play a crucial role in mitigating the impact of greenhouse gases from human activities by sequestering carbon and acting as carbon sinks and storage from the atmosphere (Akram *et al*., 2023). This is because mangrove plants can absorb carbon dioxide from the atmosphere and store it in the form of biomass within their wood. Carbon content can be estimated by the diameter or circumference of the tree (Isnani and Masjud, 2024).

It is therefore important to study soil carbon sequestration in blue carbon ecosystems because the objective of long-term stored blue carbon as a carbon sink is the most important factor in considering the carbon reduction potential (IPCC, 2007; United Nations, 1998). Changes in soil carbon stocks can occur due to several factors, including geobiochemical processes (soil grain characteristics, soil nutrients such as nitrogen and phosphorus, soil pH, slope), and physical processes (e.g. currents, tides, and erosion), human disturbance processes and climate change (e.g. sea level rise, flooding duration, and storms). Carbon stock is the amount of organic carbon (C_{org}) stored in an ecosystem. Carbon stock (topsoil, defined as from the soil surface to a depth of 1 metre) is usually reported in megagrams of organic carbon per hectare (Mg C_{org} ha^{-1}). Blue carbon ecosystems typically have organic-rich soils that range from 10 cm to more than 3 m deep (Fourqurean *et al.,* 2014). Therefore, it is important to sample at depths up to 1 metre.

Additionally, it is necessary to study nitrogen in the soil at varying depths to understand nutrient cycling in coastal ecosystems. Mangrove forests require nitrogen to absorb dissolved substances for plants and soil. The rate of nitrogen cycling and transformation is rapid—particularly in the soil—and varies depending on environmental factors such as soil type, salinity, temperature, and the growth of tree species in the forest (Alongi, 2021). The mangrove forests in

Thailand are the most important blue carbon ecosystems in Southeast Asia. In 2020, the total mangrove area along the Gulf of Thailand and the Andaman Sea was 277,923 ha (Chaiklang *et al*., 2024). Kida *et al*. (2021) highlights the importance of mangrove areas, reporting that roots play a major role in soil carbon storage, with carbon density reaching 1113.2 Mg C ha^{-1} in mangrove sediments in Trat Province, Thailand.

Nypa fruticans, or nipa palm, is a dominant species of the tropical mangrove in the Indo-West Pacific region and its distribution spans the world. The distributed such as found in Sri Lanka, the Ganges Delta, Myanmar, and to the Malay Peninsula, Thailand, Indonesia, Papua New Guinea and the Solomon Island (Tsuji *et al.,* 2011). Nipa palm grows in brackish environments, such as estuaries, mangrove forests, or swampy waters. It also colonises the upper tidal zone of the river along the coastline. The root system and biochemical processes of the mangrove tree allow the soil in that area to accumulate more nitrogen (N), which is 'trapped' in various forms such as: Organic Nitrogen (Organic N), ammonium (NH_4^+), and (NO_3^-). Nipa is sometimes called "the mangrove palm" because it thrives well in the mangrove environment, favouring brackish water environments such as estuaries or shallow lagoons (Baja-Lapis *et al*., 2004), throughout Southeast Asia, including Trang Province, Thailand. Nipa palms have a low canopy, resulting in an underestimate of their carbon storage potential. The root systems of Nipa palm include deep, fibrous roots that efficiently trap silt and store soil organic carbon, but specific data is limited. This is presented a research gap, because despite its enormous coverage, its role in carbon sequestration has received little attention compared to other mangroves such as Rhizophora and Avicennia. Few studies have been conducted on the Nipa palm, which has a high potential for soil carbon accumulation.

Materials and methods

Study area

The study area is in Nipa plam (*Nypa fruticans*) area located in Trang River, Kantang District, Trang province between geographical coordinates Latitude 7°26'10.80" ′ ~ 7°26'11.41"N longitude 99°31'6.84" ′ ~ 99°31'14.99"E (Figure 1). It is a part of a plantation nipa palm (Figure 2) zone, extending along the Trang riverbank. This river is a main river**,** major source of fishing and important aquaculture area (Tee-hor *et al.,* 2024) and draining toward the Andaman Sea on the west coast of Southern Thailand. The nipa palm plantation covers an area of along the riverbanks. The sampling was conducted during the dry season (April, 2025).

Nipa palm is characterised by large colonies formed by rhizomes that extend about half a metre horizontally beneath the ground, with new plants growing at the ends of these rhizomes (Figure 2). The Nipa palm acts as the primary barrier against the destructive effects of tsunamis, hurricanes, and cyclones. Their horizontal creeping stem stabilises riverbanks, preventing soil erosion, and new fronds emerge quickly after damage and so quickly protect the land after storms. Nipa palm can also contribute significantly to global carbon budgets (Robertson *et al*., 2020). Nipa palm is widely used for traditional products such as roofs, brooms, baskets, and traditional medicine.

Sample collection and pre-treatment

Three sediment cores, KT01, KT02, and KT03 were collected at roughly 150-200-metre intervals within the plantation nipa palm zone (Figure 1). Each core was collected using a PVC tube (3 inch in diameter and 130 cm long) which was manually hammered it to a depth of 100 cm below the surface. After collection, the cores were tightly sealed for transport to prevent sediment mixing and then preserved at 4°C in the laboratory. In preparation for analysis, the frozen cores were melted and sediment was sliced into 2 cm intervals. Each sectioned sample was placed into aluminum containers and oven-dried at 60°C for several days until fully dry.

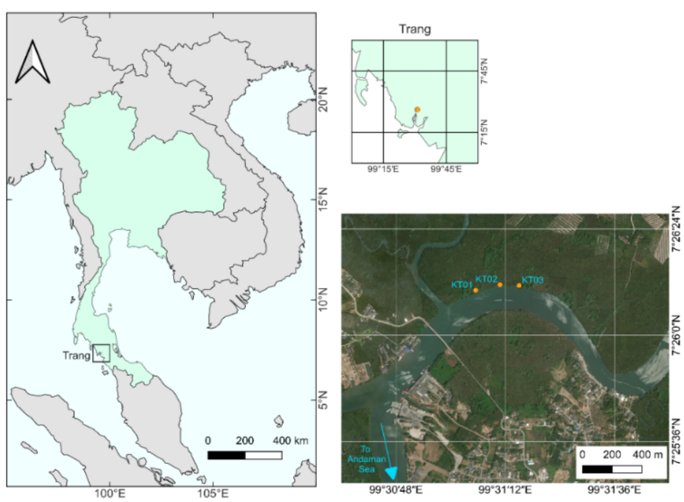

Figure 1. The location of the study area with the sediment sampling areas indicated by the solid circles (KT01, KT02, and KT03)

Figure 2. Nipa palm in the study area along river back (left) and Nipa palm tree (right)

Determination of total organic carbon and total nitrogen

The total organic carbon (TOC) and total nitrogen (TN) content of the sediment samples were measured using an elemental analyser (model: CN 628 Series, LECO Corporation, United States of America). A sediment sample weighing 0.1 g was placed in a tin foil cup and analysed with the elemental analyser. The results were reported as %TOC and %TN. For the analysis standard, a 0.2 g sample of EDTA LCRM (LECO Corporation, United States of America) was utilised.

Particle size analysis of mangrove sediments

The particle size analysis of mangrove sediments was performed by taking 10 g of dried sediment samples which were soaked in 20 mL of distilled water for 30-60 minutes to ensure that the sediments became homogeneous. The samples were then analysed using a laser particle size analyser (model: ANALYSETTE 22 NanoTec, FRITSCH, Germany) using the wet dispersion unit method. The analyser can measure particles ranging from 0.08 to 2000 μm and report as the cumulative percentage distribution of particles across different size classes (% size class).

Data analysis

Descriptive data were analysed using Microsoft Excel. The OC storage in each layer of the sediment was calculated as explained in Guo et al. (2024), which in brief is as follows:

$$D_{dry}(g{\cdot}cm^{-3}) = \frac{M_{dry}(g)}{V_{wet}(cm^3)} \quad (1)$$

$$TOC_{layer}(g) = D_{dry}(g{\cdot}cm^{-3}){\cdot}H(cm){\cdot}A(cm^2){\cdot}TOC(\%){\cdot}0.01 \quad (2)$$

$$SOC\ (MgC_{org}{\cdot}ha^{-1}) = \frac{100{\cdot}TOC_{layer}(g)}{A\ (cm^2)} \quad (3)$$

where D_{dry} is the density, M_{dry} is the dry subsample, V_{wet} is the wet sample, H is the height of the sample, and A is the surface area of the sample. The sum of the SOC was calculated using linear interpolation techniques.

The method for data analysis is involved examining the distribution of mean grain size and sorting using the Kolmogorov-Smirnov method. When the data are normally distributed, a variance analysis of mean grain size and sorting is conducted, categorized by station or depth level using one-way ANOVA. Additionally, a comparison of soil types and identification is based on the stations using the chi-square method.

Results

Sediment characteristic

Bulk densities of the mangrove soils, which are found to be mineral soils of similar textures (KT01: 0.47–0.68 g cm^{-3}; KT02: 0.47–1.01 g cm^{-3}; KT03: 0.45-1.01 g cm^{-3}). The main sediment texture was silt for 3 sediment cores. The grain size and sorting analysis of the 3 sediment cores, KT01, KT02, and KT03, indicated that all samples were within the silt size fraction, mainly very fine silt, with no presence of sand or clay-sized particles. The sediments were consistently found to be poor to very poor sorted. KT01 at a depth of 0-76 cm which had a mean grain size ranging between 6.00 and 9.32 microns. The upper layer between 0-38 cm mainly consisted of fine silt, whereas the deeper levels transition into very fine silt. All samples of KT02 had a mean grain size within 6.48-9.29 microns and are classified as very fine silt, with only the 48-50 cm depth classified as fine silt. The KT03 sample had a mean grain size between 4.64 and 8.75 microns, with 5 samples classified as very fine silt and 2 samples as fine silt. The finest sediment (0.005 mm) appeared in the 36–38 cm sample of KT03, suggesting a pulse of extremely low-energy conditions or highly organic deposition. Sorting values ranged from 1.68 to 1.98 phi, which is classified these sediments as very poor to sort at the surface, and poorly sorted at lower depths. The results of the study on Mean Grain Size and sorting are classified by station or depth show no statistically significant difference ($p>0.05$). The soil type is found to be mostly very fine silt, followed by fine silt (66.7% and 33.3%, respectively), there was no statistically significant difference ($p>0.05$) among station. The soil in the sampling area is found to be mostly poorly sorted, followed by very poorly sorted (71.4% and 28.6%, respectively, there was no statistically significant difference ($p>0.05$).

Vertical distribution of TOC and TN in sediment cores

In surface layers (0–10 cm), all cores (KT01, KT02, and KT03) displayed the highest TOC and TN with KT01 showed the highest values (9.04% TOC, 0.37% TN at depths 0–2 cm) (Figure 3a, b). Although concentrations showed occasional peaks (e.g., KT01 at 20–22 cm: 6.86% TOC; KT02 at 48–50 cm: 7.95% TOC), they mainly decreased with depth. KT02 showed a larger mean TOC (5.16-7.95%) compared to KT03 (0.22–6.56%). TN followed a similar trend for the whole depth of all three cores (Figure 3b) and tended to decrease with depth. At the surface layer (0-2 cm), TN values were the highest (0.58%). C/N values show similar trend for three cores except at the surface (0–2 cm) of KT02 which was the lowest (10.22) (Figure 3c). Bulk density tended to increase with depth and shows a maximum value around the middle-depth (50-60 cm) at KT02 and KT03 (Figure 3d). Higher bulk density (>1 g cm^{-3} in deeper layers of KT02/KT03) correlates with lower TOC and higher SOC (e.g., KT02 at 80-82 cm: 10.40 Mg C_{org} ha^{-1}), indicating that compaction improves long-term C storage.

SOC accumulation

KT01 had the highest SOC stocks (8.53-11.51 Mg C_{org} ha^{-1}) in the upper 60 cm, which correlated with lower bulk density (0.47-0.66 g/cm^3). Sharp reductions below 58 cm (5.50 Mg C_{org} ha^{-1} at 74-76 cm) indicated to decrease preservation. SOC peaks at mid-depths (KT02: 11.18 Mg C_{org} ha^{-1} at 48-50 cm, KT03: 10.37 Mg C_{org} ha^{-1} at 64-66 cm) indicated the burial of organic-rich strata. The Nipa palm system is effectively traps labile carbon, since surface layers (0-30 cm) hold about30-50% of total SOC.

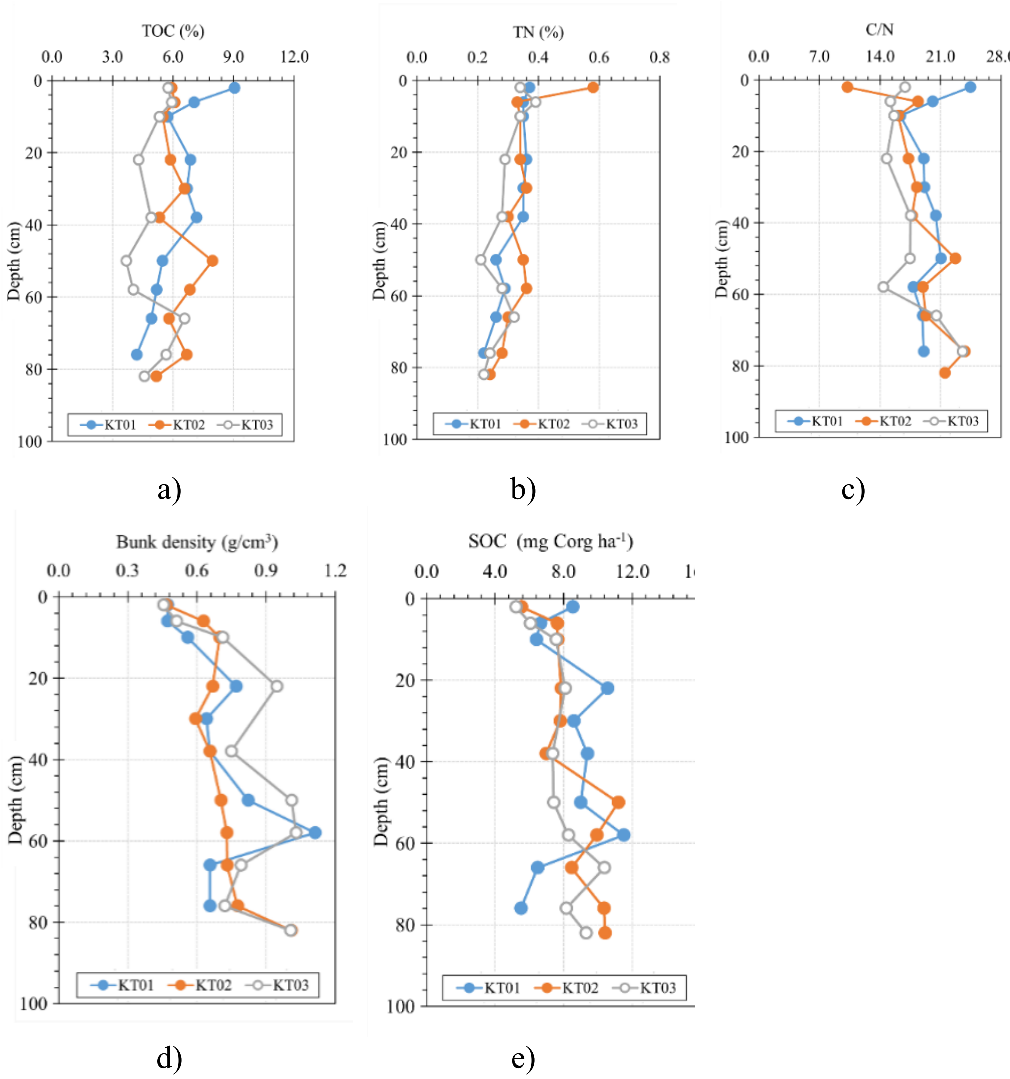

Figure 3. Depth profile of **(a)** TOC, **(b)** TN, **(c)** T/N, **(d)** Bulk density, and **(e)** SOC

Discussion

Soil serves as a crucial repository of organic C (Alongi, 2020; Kauffman *et al*., 2020). In the current study, the OC stock in the 1 metre top sediments is estimated to be in the range of 322.43 – 355.45 Mg C_{org} ha^{-1}. This estimated value for SOC stocks is closely reported a value in Songkhla and Pattani provinces in Thailand (Hu *et al.,* 2024) but higher than Pearl Bay, China (Guo *et* *al*., 2024) and similar to global estimates of SOC stocks: 369 Mg C_{org} ha^{-1} (Jardine and Siikamäki, 2014). In mangrove forests, sedimentary organic carbon (OC) is a combination of allochthonous inputs from river and marine environments, as well as autochthonous inputs such as above-ground biomass (such as leaves and branches) and below-ground biomass (such as fine roots) (Sasmito *et al*., 2020). Form the present study, higher bulk density (>1 g cm^{-3} in deeper layers of KT02/KT03) and higher SOC (e.g., KT02 at 80–82 cm: 10.40 Mg C_{org} ha^{-1}, KT03 at 80-82 cm: 9.31 Mg C_{org} ha^{-1}) suggest that compaction enhances long-term C storage. The presence of mid-depth SOC peaks (48–50 cm in KT02/KT03) aligns with several studies that report subsurface carbon enrichment in mangrove and wetland systems, suggesting alternative mechanisms for mid-depth SOC accumulation. In addition to mangrove forests, tropical countries are focused on Nypa palm trees in forest restoration efforts, as these plants act as carbon sinks. However, Nypa palm tree forests found to be a lower carbon sequestration efficiency in aboveground biomass (0.02 $MgCha^{-1}$) compared to mangrove forests (85.48 $MgCha^{-1}$) (Nur *et al*., 2022) because Nipa palm trees have less efficient carbon storage capabilities in their stems compared to mangrove species like Rhizophora or Avicennia. Nevertheless, mangrove trees can store carbon in the soil quite effectively due to their extensive root systems that accumulate organic matter underground (Donato *et al*., 2011).

The sediments characteristic in the study area are found to be consistently poorly to very poorly sorted, reflecting deposition in a calm environment such as an estuarine setting with variable but generally low energy. KT01 showed slightly coarser material and higher sorting variability than KT02 and KT03, which suggested more dynamic depositional conditions or episodic reworking. In contrast, KT02 exhibits the finest and most consistently sorted sediments, indicative of continuous calm water deposition, whereas KT03 reflected similar characteristics with slightly better sorting, possibly due to localised geomorphological or hydrodynamic factors.

This study revealed distinct vertical trends in total nitrogen (TN) content across different soil depths. In the surface layer (0–20 cm), TN was highest in KT01 (0.37% at 0–2 cm) and KT02 (0.58% at 0–2 cm), likely due to microbial activity and fresh organic matter accumulation from Nipa palm litter. In contrast, KT03 exhibited more stable TN levels (0.34–0.39%), possibly due to uniform tidal influences. Below 20 cm, all cores showed a gradual decline in TN with depth while KT02 and KT03 maintained moderate TN levels (0.21–0.36%), with minor mid-depth fluctuations. A key observation was that surface sediment (0-10 cm) TN was 33-37% of the total TN, highlighting active nitrogen cycling near the root zone, likely driven by plant uptake and microbial mineralization. When compared to Rhizophora-dominated mangroves, our TN levels were found to be higher than those reported by Marchand *et al.* (2003), likely because Rhizophora litter decomposes faster, reducing long-term nitrogen retention. These differences underscore how vegetation type, microbial activity, and hydrology shape nitrogen distribution in mangrove ecosystems. Fluctuations in TOC/TN ratios in mangrove sediments indicated mixing of different organic matter sources. In the surface layer (depths 0-20 cm), KT01 had a high C/N ratio (20-24), indicating that vascular land plants sources (>20), notably Nipa palm litter, was found to be the primary source of input. In contrast, KT02 and KT03 had lower C/N ratios (10-18), indicating a mixed contribution from marine/algae and vascular plant debris. Below depths 20 cm, KT01 and KT02 maintained relatively high C/N ratios (17-24), indicating delayed breakdown of woody debris, but KT03 had shown a larger range (14-23), most likely due to variable tidal impacts because the location of site is in the area of river mouth.

Therefore, Nipa palms could be "hidden" carbon sinks with unrealised climate mitigation potential. This study emphasises their ecological significance and offered baseline data for future comparisons to other mangrove varieties. Finally, this research is contributed to support data on the carbon storage efficiency in plants and soil in mangrove forests and riverbank ecosystems to promote the concept and principle of forest planting to absorb carbon dioxide or greenhouse gases. This is aligned with the greenhouse gas reduction measures of many countries under the Paris Agreement, which collectively aims to limit the increase of the global average temperature to below 2°C and strives to limit the temperature increase to no more than 1.5°C. Future studies should increase interest in the study of blue carbon accumulated in sediment cores in the Nipa palm area and the factors affecting this accumulation as well as the sources of organic matter.

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Conflicts of interest

The authors declare no conflict of interest.

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