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Impact of Mangrove Land Use on the Carbon Stock in an Abandoned Shrimp Pond: A Case Study at Samut Songkhram Campus, Suan Sunandha Rajabhat University, Thailand

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ABSTRACT

Changes in land use within coastal areas have significantly impacted the carbon stock of mangrove forests. This study examined three different land-use types including the abandonment of shrimp ponds characterized as restored mangrove forests (RMF), logged *Avicennia marina* (LAM) stands, and abandoned shrimp ponds (ASP) on the carbon stock in plant and soil. Eight experimental plots, each measuring 20 m x 20 m, were established in the RMF and LAM to assess the forest structure. The diameter and height of mangrove trees were measured, and both the above and belowground biomass were estimated. Three soil samples were collected randomly from each site at four different depths (0–15 cm, 15–30 cm, 30–50 cm, and 50–100 cm) to analyze the soil characteristics. Bulk density and carbon concentration were then determined from these samples. The Tukey test estimated and statistically analyzed vegetation, soil, and carbon stocks. The results indicate that the forest structure and biodiversity in RMF were higher than in LAM. Additionally, vegetation biomass and carbon stock in RMF exceeded the values estimated for LAM. The soil carbon stock at 0–100 cm depths across RMF, LAM, and ASP was similar, ranging from 204.52 to 220.20 $t.C.ha^{-1}$. Nonetheless, the largest ecosystem carbon stock was estimated for RMF (306.52 $t.C.ha^{-1}$), demonstrating the influence of land-use patterns on ecosystem carbon storage. According to the results, it might take longer for the ecosystem carbon in the abandoned shrimp pond in ASP to recover than it would in RMF and LAM. However, mangrove restoration in abandoned shrimp ponds is crucial to improve the forest structure, encourage ecological advantages, and accelerate carbon stock recovery.

1. Introduction

Mangrove forests play an important role in both socio-economic and ecological systems. Mangrove forests are the sources of medicinal plants and play an important role in preventing coastal disasters (Murniasih et al. 2022; Duryat et al. 2024). The forests can significantly absorb carbon emissions and increase carbon stock (Akram et al. 2023; Alongi 2014; Kauffman et al. 2014). The carbon stocks in mangroves can be from vegetation and soil, with an estimated 10.8 Pg of carbon stored globally (Kauffman et al. 2018). The loss of mangrove forests can potentially deteriorate the coastal ecosystem by reducing the carbon stored in soil and vegetation (Kauffman and Bhomia 2017; Kauffman et al. 2014). Additionally, mangrove deforestation can negatively impact the soil's physical and chemical properties (Santos-Andrade et al. 2021). One of the main causes of the decline in vegetation, carbon reserves, and soil quality in mangrove forests is the conversion of the forest into shrimp ponds (Merecí-Guamán et al. 2021; Pérez et al. 2020).

Mangrove restoration is crucial for improving the forest structure and species diversity and enhancing carbon stock (Kauffman and Bhomia 2017; Wongprom et al. 2023a). It supports residents' livelihoods and ecotourism and serves diverse natural homeostasis processes of coastal ecosystems, including nutrient cycling. (Akram et al. 2023; Alongi 2014; Kauffman and Bhomia 2017). Restoring mangroves is an effective way to provide a wide range of ecosystem services, particularly in mitigating climate change and enhancing carbon stock. Trees absorb carbon and accumulate in the soil. However, the carbon stock of mangrove ecosystems varies significantly depending on management practices, age, and geography (Cadiz et al. 2020; Wongprom et al. 2023a). Through the process of natural succession of mangrove restoration, the vegetation structure, diversity, production, and carbon stock can be improved (Nam et al. 2016). However, natural succession can take a long time to increase the biomass and carbon stock. Planting mangrove species on degraded lands can rapidly increase biomass and carbon stock. Wongprom et al. (2023a) found that vegetation biomass and carbon stock of 14-year-old *Rhizophora apiculata* and *R. mucronata* in abandoned shrimp pond was 230.99 $t.ha^{-1}$ and 102.54 $t.C.ha^{-1}$, respectively. In addition, the soil carbon stock of abandoned shrimp ponds can increase with age from restoration and hydrological processes (Sakai et al. 2023). Carbon storage of soil was significantly related to nutrient cycling. The litter production of mangrove forests was relatively high at 10.10 $t.ha^{-1}$ (Kamruzzaman et al. 2019). Moreover, the litter decomposition rate of mangrove forests was high, leading to large soil carbon and nutrients. Soil carbon stock of mangrove forests was a major ecosystem carbon stock (Elwin et al. 2019; Harishma et al. 2020). However, soil carbon stock varied according to site conditions and management. More understanding of abandoned shrimp pond restoration benefits mangrove management and climate change mitigation.

However, although there are studies on carbon stocks in different land use patterns in mangrove forests, including studies in shrimp farms with plants already growing in the area, there is still a lack of studies on carbon sequestration in shrimp farms that are uncovered, comparing it to nearby areas with completely different land use patterns. In the Samut Songkhram area, where land use changes according to the purpose of the land owner, there are differences in land use patterns. Comparative studies will show the trend of soil carbon accumulation recovery in areas with different land uses close to each other.

In Thailand, the mangrove forests have been disturbed for over 30 years due to the conversion of mangroves into aquaculture farms (Sampantamit et al. 2020). Samut Songkhram is a coastal province of Thailand whose mangrove areas have been substantially converted to shrimp ponds, salt fields, fisheries farms, and bare land since 1961 (Phonphan and Thanakunwutthirot 2020; Sampantamit et al. 2020). The mangrove forest area in Samut Songkhram decreased from 10,934 ha in 1961 to 48.96 ha in 1986 (Pumijumnong 2014). However, the forest area increased to 2,201.44 ha in 2007 (Pumijumnong 2014). The land use of mangrove forests in this area was characterized by various types, such as plantation, restoration, and conservation. Restoration of abandoned shrimp ponds is vital and urgent to enhance the livelihood of local people and the local ecosystem. However, abandoned shrimp ponds have been used for various purposes, including restoration and logging. This resulted in an ecosystem of mangrove forests and increased carbon stocks. In addition, Samut Songkhram Province is one of the famous tourist towns with various cultural characteristics, ways of life of people, high-quality seafood and unique markets such as Mae Klong railway market or “Hoop Rom market” (Khamwachirapithak and Khongouan 2024). The natural resources of this area are very important to the tourist industry. Seafood, including shrimp and mackerel, is an important product in this area, and they are sold in the market as raw food products. The coastal area of Samut Songkhram is an important area where Thai mackerel fish are captured, and they are the unique fish that is stated to be the geographical indication (GI) product that can be found in the sea around the inner part of the Gulf of Thailand (Viboonkit et al. 2023). Therefore, conserving mangrove areas and restoring carbon stock in this area’s ecosystem is important to conserve the marine ecosystem for sea animals. Hence, the objectives of this study were to investigate the carbon stocks of mangrove forests under various land use types in the abandoned shrimp ponds. These results could be useful in managing mangrove forests and improve our knowledge related to such forests.

2. Materials and Methods

2.1. Study Area

The study area is located at the Suan Sunandha Rajabhat University Campus, in Samut Songkhram Province, central Thailand (latitude 13°24'58" N, longitude 100°02'30" E) **(Fig.1)**. Around 30 years ago, the mangrove forest in this area was converted into shrimp ponds, which have since been abandoned. The climate of the region is characterized by tropical monsoons, consisting of a dry season (February–April), a rainy season (May–October), and a cool season (November–January). The average temperature ranges between 28–30°C, with a mean annual rainfall of around 1,085 mm (Samut Songkhram Meteorological Station, Thailand Meteorological Department). During the cool season, the neap tide occurs in this area, and the maximum high tide reaches the inner part of the mangrove forest, which is located in the landward.

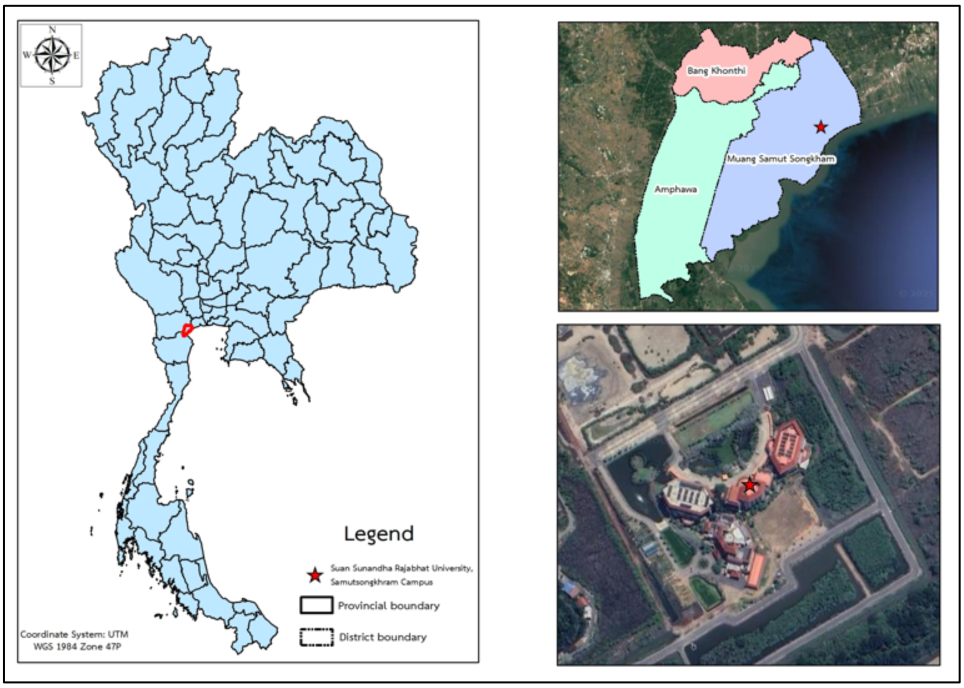

Fig. 1. Location of the Suan Sunandha Rajabhat University Campus in Samut Songkhram Province.

2.2. Sampling Plot

The experimental plots were established in three land-use types: a 15-year-old restored mangrove forest (RMF) consisting of *Rhizophora mucronata* and *R. apiculata*, The embankment of the shrimp pond in RMF was adjusted by reducing its size, and some parts of the embankment were removed, and an approximately 20-year-old abandoned shrimp pond (ASP). The embankment of the shrimp pond was adjusted by reducing its size, and some parts of the embankment were removed.

Avicennia marina was observed to grow in a narrow strip along the boundary of the abandoned shrimp pond. *Avicennia marina* naturally regenerated after the area was clear-cut. Logging of *A. marina* in the abandoned shrimp pond was managed through a second rotation. The embankment of the shrimp pond was removed. In addition, water flooding of RMF and ASP has occurred following sea tides. The third land use type was a logging area of *A. marina* (LAM) on an abandoned shrimp pond, where natural regeneration occurred after clear-cutting. Local farmers harvest the trees for charcoal every 5–6 years; this was the second harvesting rotation. The embankments of shrimp ponds in both the LAM and ASP had been removed, allowing seawater to enter the plots through small canals. The inundation of seawater follows the tidal cycle of the area.

2.3. Forest Structure

Eight experimental plots measuring 20 m x 20 m were established at each site to investigate the forest structure. Each plot was further divided into four 10 m x 10 m subplots. The height (H) of mangrove trees with a diameter at the breast (DBH) ≥ 4.0 cm in RMF and LAM was measured and identified. For *R. mucronata* and *R. apiculata*, the diameter at 30 cm above the highest prop root (D30) was measured. The Importance Value Index (IVI) of mangrove forests in RMF and LAM was calculated based on relative density (RD), relative frequency (RF), and relative dominance (RDo).

2.4. Parameters and Measurements

2.4.1. Vegetation biomass and soil carbon stocks

The aboveground biomass (AGB) and belowground biomass (BGB) of each plant species were determined following the equation of Komiyama et al. (2005) as follows:

$$AGB = 0.251\,\rho\,DBH^{2.46} \quad (1)$$

$$BGB = 0.199\,\rho\,0.899\,DBH^{2.22} \quad (2)$$

where the ρ stands for the wood density. The wood density for *A. marina* used in this study was calculated based on the work of Purwiyanto and Agustriani (2017), while the values for *R. apiculata* and *R. mucronata* were based on the values reported by Komiyama et al. (2005). The plant carbon content was calculated by multiplying the biomass by 0.47, as specified in IPCC (2006).

2.4.2. Soil sample collection and Assessment of carbon stock

Because the study area is the forest, the plant's roots will penetrate the deep soil and can influence the carbon stock. Soil samples from each area were collected using a PVC tube, which was 100 cm in length and 5 cm in diameter. Samples were taken from three points at four soil depths: 0–15 cm, 15–30 cm, 30–50 cm, and 50–100 cm.

The samples were dried in an oven at 80°C until a constant weight was achieved to analyze the soil bulk density (BD). The soil samples were combusted at 975°C for carbon concentration analysis using a CNHS analyzer.

Carbon stock in the soil samples collected from mangrove forest was calculated using soil bulk density (BD; g cm^{-3}), carbon concentration (C; %), and soil depth (D; cm).

$$Soil\ carbon\ stock = BD \times C \times D \quad (3)$$

The plant carbon was calculated by multiplying the individual tree biomass with the carbon concentration of each species using the following equation;

$$Carbon\ storage\ in\ ecosystem\ (t.C.ha^{-1}) = C_{tree\ AGB} + C_{tree\ BGB} + C_{soil} \quad (4)$$

2.5. Data Analysis

Differences in soil bulk density, soil carbon stock, and ecosystem carbon stock were determined using Analysis of Variance (ANOVA). A 95% confidence level ($p < 0.05$) was used to assess any statistically significant differences. The means were compared with the Tukey HSD test at a 5% probability level.

3. Results and Discussion

3.1. Mangrove Structure

Three species were found in the RMF, which included *A. marina*, *R. apiculata*, and *R. mucronata*. *A. marina* had the highest IVI in RMF, followed by *R. mucronata* and *R. apiculata* (112.52, 104.38, and 83.10, respectively). In contrast, *A. marina* was the only species found in LAM (**Table 1**). This result indicates that *A. marina* is well-suited for natural regeneration in restored mangrove and coastal areas (Azman et al. 2021; Kamali and Hashim 2011). In the RMF plot, *A. marina* had a higher IVI than *R. apiculata* and *R. mucronata* despite the latter two species being initially planted for restoration.

Table 1. The ecological characteristics of mangrove forest under RMF, LAM, and ASP in the Samut Songkhram Province, Thailand

Site	Species	DBH	H	Density	RD	RF	RDo	IVI
RMF	*A. marina*	7.60	7.76	743.75	40.20	41.67	30.65	112.52
	R. apiculata	9.32	13.27	475.00	25.68	27.78	29.65	83.10
	R. mucronata	9.64	12.68	631.25	34.12	30.56	39.70	104.38
LAM	*A. marina*	5.30	6.22	7,812.25	100	100	100	300

Notes: DBH is diameter at breast height, H is tree height, RD is relative density, RF is relative frequency, RDo is relative dominance, and IVI is The Importance Value Index.

DBH and H of *R. apiculata*, and *R. mucronata* in RMF was good. The DBH of RMF was higher than that of the 15-year-old *R. apiculata* plantation in Sumut Songkham Province, central Thailand (6.26 cm and 12.36 m, respectively) (Wechakit 1990). The good growth of *R. apiculata in* the *R. apiculata* plantation in Samut Songkhram Province (10,300 stem ha^{-1}) (Wechakit 1990). A low density of trees resulted in a light competition for resources. This result positively influenced the DBH of trees (Wongprom et al. 2023b). In addition, good growth of *R. mucronata* and *R. apiculata* was related to the soil properties and site conditions, such as higher proportions of silt and clay contents and mud flats in abandoned shrimp ponds (Wongprom et al. 2023a) as well as water salinity and tidal conditions (Aksornkoae 1993).

The density of *A. marina* in RMF and LAM was 1,150 and 7,182.25 trees per hectare, respectively. However, a high density of *A. marina* in the abandoned shrimp ponds was managed for wood utilization purposes. Mangrove plantations in the Samut Songkhram Province have been traditionally planted for over 50 years as the source of fuel, particularly charcoal production (Adulcharoen et al. 2020). *A. marina* is commonly used in the charcoal industry in this region due to its robust growth and ability to re-establish (Kamali and Hashim 2011). *A. marina* is a pioneer mangrove species that thrives in open and restored areas (Tamin et al. 2011).

3.2. Vegetation Biomass

The aboveground biomass (AGB) of RMF and LAM was 156.33 and 69.44 $t.ha^{-1}$, respectively (**Fig. 2**). High growth of mangroves in RMF was positively influenced by the aboveground biomass, especially *R. apiculata* and *R. mucronata*. The aboveground biomass strongly correlated with DBH and density (Roy et al. 2021). In addition, these species can be selected for planting in abandoned shrimp ponds with high biomass (Sakai et al. 2023; Wongprom et al. 2023a). In contrast, the stand's rotation determined a low aboveground biomass of LAM. Although the tree density in LAM was higher than in RMF, the smaller trees of *A. marina* found in LAM were mostly young. However, the aboveground biomass of RMF (156.63 $t.ha^{-1}$) was similar to that of 14-year-old *Rhizophora* spp. stand (155.27 $t.ha^{-1}$) in an abandoned shrimp pond (Wongprom et al. 2023a). The aboveground biomass of LAM (69.44 $t.ha^{-1}$) was similar to the 6-year-old *A. marina* stand (69.74 $t.ha^{-1}$) (Azman et al. 2021). With older stand ages (10 years), the aboveground biomass at the study site was similar to that of stands of the same species that were only 6 years old. This indicates that the growth of *A. marina* in the study area is slower than the study site reported by Azman (2021).

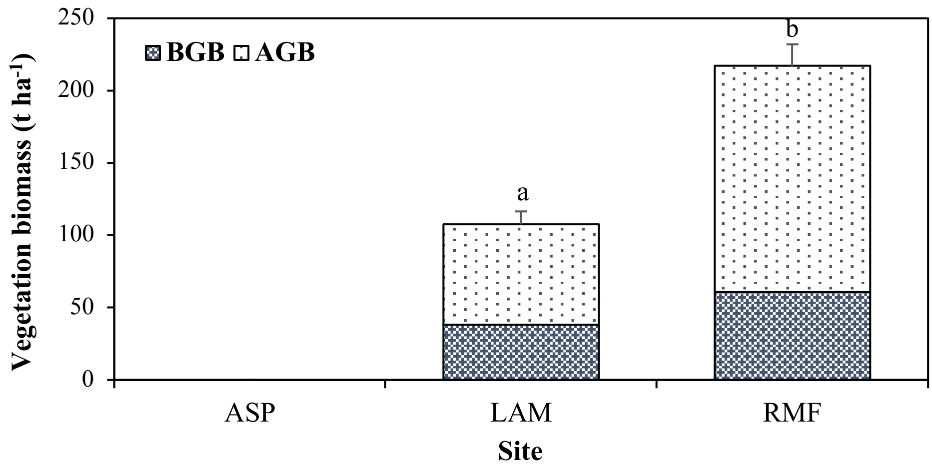

Fig. 2. Aboveground biomass (AGB) and belowground biomass (BGB) in ASP, LAM, and RMF. The different letters (a and b) above bars indicate significant differences at $p < 0.05$, as determined by the Tukey test.

The belowground biomass (BGB) of RMF and LAM was 60.69 and 38.04 tons per hectare, respectively. The difference in mangrove species had a significant influence on the belowground biomass. Root biomass depends on mangrove species, ages, and site conditions (Azman et al.

2021; Chatting et al. 2020). The roots made a significant contribution to mangrove biomass. In this study, the belowground biomass in RMF was lower than that in 14-year-old *Rhizophora* spp. stand (74.76 $t.ha^{-1}$) in abandoned shrimp pond (Wongprom et al. 2023a) and a secondary mangrove forest dominated by *Ceriops tagal* was 87.50 $t.ha^{-1}$ (Komiyama et al. 2000). However, the belowground biomass of RMF was higher than that of protected mangrove forest (41.89 $t.ha^{-1}$) in Chanthaburi Province, eastern Thailand (Wongprom et al. 2023a). While the belowground biomass in LAM was similar to the naturally regenerated 6-year-old *A. marina* stand (38.25 $t.ha^{-1}$) in Malaysia (Azman et al. 2021). The forest structure and stand age can significantly influence the vegetation biomass. Additionally, rotational tree harvesting every 5–6 years in LAM resulted in a lower biomass. In general, the tree biomass increases with the ages of the restored mangrove forest (Azman et al. 2021).

3.3. Carbon Stock in Mangrove Forest

The soil BD at depths of 0–15 cm, 15–30 cm, and 30–50 cm was not significantly different among RMF, LAM, and ASP ($p > 0.05$). However, ASP was higher than RMF at a depth of 50–100 cm ($p < 0.05$), as shown in **Fig. 3**, panel A. The recovery of mangrove trees in RMF and LAM resulted in a lower soil BD at the lowest depth (50–100 cm). Tree recovery can be important in reducing soil compactness and increasing soil nutrients (Wongprom et al. 2020). Additionally, higher root production and decomposition in mangroves can increase soil carbon stock (Zhang et al. 2021).

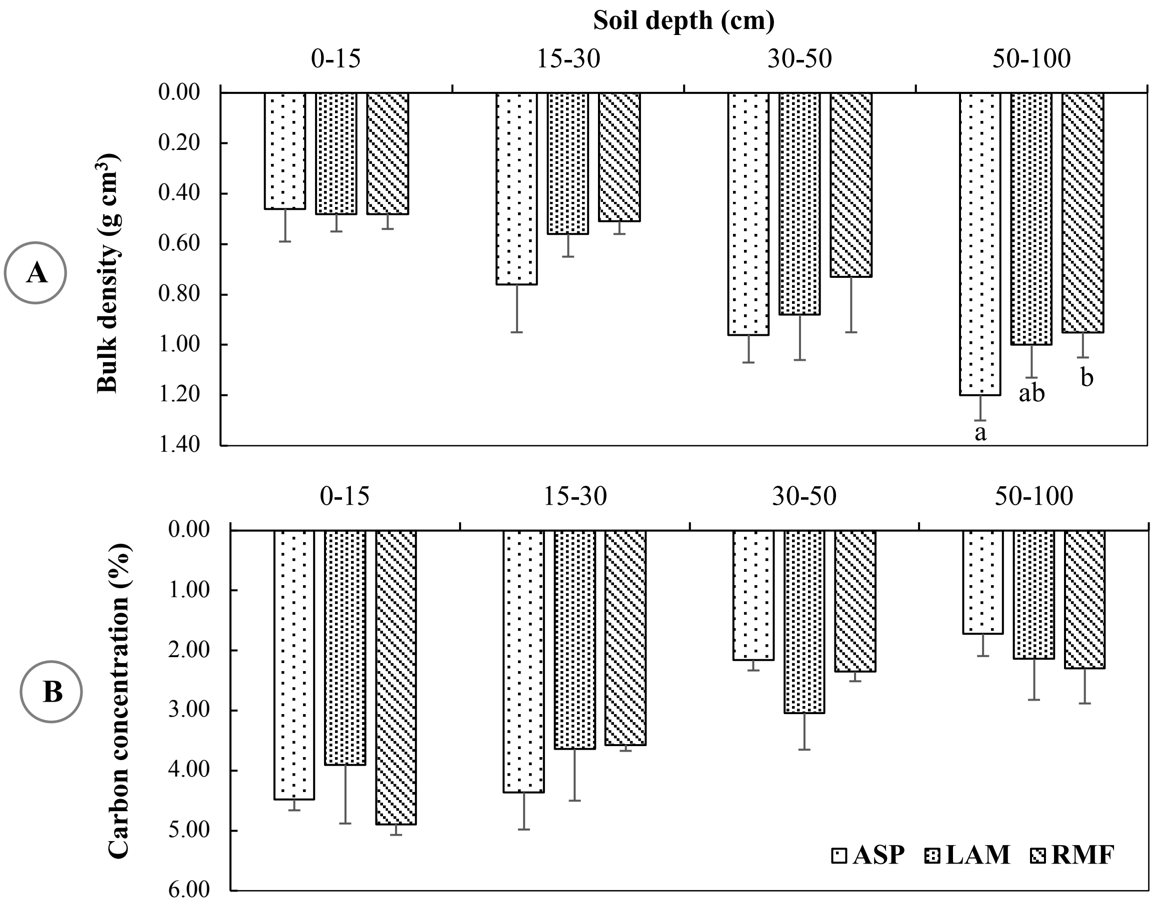

Fig 3. Soil bulk density (A) and carbon concentration (B) in ASP, LAM, and RMF with the different letters a and b below the bars, indicating significant differences at $p < 0.05$, as determined by the Tukey test.

Among the three locations, RMF, LAM and ASP, soil carbon concentrations at depths of 0–15, 15–30, 30–50, and 50–100 cm were not significantly different (p > 0.05). The soil carbon concentration decreased with increasing depth, as shown in **Fig. 3**, panel B. The high carbon concentration estimated in all the areas primarily accumulated in the topsoil, consistent with findings from other sites (Kauffman and Bhomia 2017; Mercí-Guamán et al. 2021).

Soil carbon stock among land use types was not significantly different (p > 0.05), except at depths between 30–50 cm in LAM, which had the highest value. However, the total soil carbon stock at depths between 0–100 cm across RMF, LAM, and ASP was similar, ranging from 200 to 220 $t.C.ha^{-1}$, as shown in **Table 2**. This result suggests that land use and site management variations can influence soil carbon stock. In RMF, mangrove restoration and litterfall may have contributed to carbon accumulation, particularly due to the embankment built around the abandoned shrimp pond. In contrast, logging was conducted in LAM, where tree stems were harvested for charcoal and other uses, but residual branches, leaves, and roots remained in the plot and decomposed, increasing the soil carbon in LAM.

Table 2. The estimated soil carbon stock in ASP, LAM, and RMF

Soil depth (cm)	Soil carbon stock ($t.C.ha^{-1}$)			F-value
	ASP	LAM	RMF	
0–15	60.91	27.57	35.10	0.81[ns]
15–30	35.34	31.02	26.58	0.64[ns]
30–50	41.15[a]	57.87[b]	34.87[a]	5.17*
50–100	103.13	103.74	107.97	1.29[ns]
Total	210.53	220.20	204.52	

Notes: ns = non-significant; significantly different at $p<0.05$, and the letters a and b in the same row indicate significant differences at $p<0.05$, as determined by the Tukey test.

According to Murdiyarso et al. (2021), the logging of mangroves has a relatively low impact on ecosystem carbon stock because most carbon is stored underground. Additionally, mangrove tree roots in LAM and RMF likely played an important role in increasing the soil carbon at subsoil levels, especially at depths between 30–50 cm, through root decomposition and carbon sequestration by soil organisms (Tinh et al. 2020; Zhang et al. 2021). The removal of embankments in LAM and ASP allowed seawater to flow more easily, with tidal dynamics controlling the movement of carbon and nutrients (Li et al. 2024), which may have contributed to the increase in soil carbon in ASP.

In this study, the *A. marina* stand in LAM was harvested, but most of the roots remained in the soil, contributing to carbon accumulation at subsoil levels. While the soil carbon stock in LAM, ASP, and RMF was similar, the recovery of soil carbon in ASP would likely take longer compared to LAM and RMF. Elwin et al. (2019) stated that carbon stock in abandoned shrimp ponds can recover through hydrological processes, and soil carbon stock in mangrove forests tends to increase with age. Inundation from the tidal cycle brings organic matter into the abandoned areas, enhancing soil carbon stock. The findings from this study correspond with those of Elwin et al. (2019), who showed that even in the absence of mangrove vegetation, soil carbon stock in abandoned shrimp ponds can increase due to the influence of sea hydrological dynamics (Li et al. 2024).

The ecosystem carbon stock estimated in this study ranged from 210.53 to 306.52 $t.C.ha^{-1}$, as shown in **Table 3**. The highest values were found in RMF, while the lowest were estimated in ASP. Differences in land use and management activities significantly impacted ecosystem carbon stock in the mangroves. Converting forest land into aquaculture farms can affect the fertility of the forest and carbon stock in the ecosystem (Bryan-Brown et al. 2020). Ecosystem carbon stock varies depending on forest structure, age, site conditions, and management practices (Kauffman and Bhomia 2017; Kauffman et al. 2014; Nam et al. 2016; Wongprom et al. 2023a).

Table 3. The vegetation, soil, and ecosystem carbon stocks in ASP, LAM, and RMF

Area	Carbon stock ($t.C.ha^{-1}$)		
	Vegetation	Soil	Ecosystem
ASP	0.00	210.53	210.53^{b}
LAM	50.52	220.20	270.72^{ab}
RMF	102.00	204.52	306.52^{a}

Notes: ns = non-significant; significantly different at $p > 0.05$, and the letters a and b in the same column indicated significant differences at $p < 0.05$, as determined by the Tukey test.

The patchy distribution of mangrove forests in this study area largely reflected landowners' objectives. The harvesting of mangrove trees was observed in LAM, but the soil carbon stock in LAM did not differ significantly from that of RMF and ASP. However, the vegetation carbon stock in LAM was lower than in RMF. Restoration of mangroves in RMF improved the vegetation carbon stock and enhanced the forest structure, diversity, functionality, and ecological benefits. This process occurred over a shorter timeframe compared to natural succession. Nevertheless, physical and hydrological restoration and the natural seedling of the mangrove plants should be implemented to ensure the success of mangrove recovery (Ray et al. 2024).

The ecosystem carbon stock across all plots was relatively low compared to several other studies (Elwin et al. 2019; Kauffman et al. 2018; Wongprom et al., 2023a). For example, the carbon stock in an 80-year-old mangrove forest in Yingluo Bay, China, was 380.72 $t.C.ha^{-1}$ (Yu et al. 2021) and the world mangrove mean was 386 $t.C.ha^{-1}$ (IPCC 2014), which is higher than the values estimated in this study. This suggests that the carbon stock in mangrove forests can recover over time through natural succession.

4. Conclusions

This study investigated the carbon stock of mangrove forests under different land-use practices, including restoration, logging, and abandonment, to assess how these practices influence ecosystem carbon dynamics. Proper restoration of mangroves in RMF can increase vegetation biomass, diversity, and ecological benefits of mangrove forests. In contrast, mangrove logging of *A. marina* contributes to landowners' income. The residual tree matter in LAM plays a significant role in carbon storage within the mangroves. Vegetation carbon in RMF was higher than in LAM, but soil carbon stock in RMF, LAM, and ASP was similar, suggesting that mangrove forests can recover their carbon stock over time. However, the recovery of soil carbon in ASP would take longer than in RMF and LAM. The pattern of land use in mangrove forests has a significant influence on the ecosystem's carbon stock. Therefore, restoring mangroves in abandoned shrimp ponds is essential for improving forest structure and accelerating carbon stock recovery.

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