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Vegetation structure and carbon stock of restored mangrove on abandoned shrimp pond in the International Mangrove Botanical Garden Rama IX, Thailand

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Abstract. *Wongprom J, Maneeanakekul S, Tara A, Chandaeng W, Duangnamon D, Rueangket A, Wechakit D, Wanthongchai P, Maknual C. 2023. Vegetation structure and carbon stock of restored mangrove on abandoned shrimp pond in the International Mangrove Botanical Garden Rama IX, Thailand. Biodiversitas 24: 5820-5829.* The conversion of mangrove forest into shrimp aquaculture has severely impacted biodiversity and increased carbon emissions. Restoration program is thus urgently needed for such mangrove forests. In this study, we investigated the vegetation structure and composition, and biomass and carbon stock of restored mangrove on abandoned shrimp pond. Observation plots at restoration sites with age of 3-year-old (MF3) and 14-year-old (MF14) were established in the International Mangrove Botanical Garden Rama IX, Chanthaburi Province, Thailand and at abandoned shrimp pond (ASP) and protected mangrove forest (PMF) as reference sites. The diameters and heights of mangrove species were measured and identified in order to determine the vegetation structure, composition, biomass, and carbon stock. Soil samples from four soil depths, i.e. 0-15, 15-30, 30-50, and 50-100 cm, were collected to quantify the soil carbon stock. The results showed the good growth of *Rhizophora* stand planted at the restored sites with high vegetation biomass and carbon stock. This species also promoted species diversity, suggesting that *Rhizophora* spp. are suitable species for the restoration of abandoned shrimp pond. The vegetation biomass and carbon stock of MF14 (230.99 t ha^{-1} and 102.54 t C ha^{-1}, respectively) was higher than that of PMF (133.84 t ha^{-1} and 64.94 t C ha^{-1}, respectively). Higher vegetation and soil carbon stocks of the restored mangrove forest was positively influenced by the *Rhizophora* stand. However, the ecosystem carbon pool of PMF was higher (366.38 t C ha^{-1}). This result indicates that the conservation of mangrove forest is significant to maintain the forest diversity, ecosystem function, and reducing carbon emissions, while mangrove forest restoration is essential to improve the vegetation structure and increase the soil and vegetation carbon stocks.

Keywords: Abandoned shrimp pond, biomass, carbon stock, vegetation structure, International Mangrove Botanical Garden Rama IX

INTRODUCTION

Mangrove forest is an ecosystem located in the transitional zones (ecotone) between terrestrial and marine realms such as estuaries and coastlines. Mangrove forests play various roles in term of ecological and socio-economic aspects. In term of ecological importance, mangrove forests can serve as a natural barrier of tsunamis as well as strong waves and winds which can cause abrasion. Mangrove ecosystem is also an important habitat for various marine biota and breeding grounds of fishes. From the perspective of socio-economic, mangrove forests are a source of livelihood of local people (e.g., the collection of charcoal and fuelwood), and nowadays have been promoted for ecotourism and recreation (Lee et al. 2014; Satyanarayana et al. 2021; Akram et al. 2023).

Mangrove ecosystem is very unique since it is characterized by several environmental factors such as the presence of tidal waves, high salinity, rainfall, sedimentation, temperature and nutrients. These factors can affect the structure, composition and species distribution of mangrove forest along the environmental gradients (Hossain and Nuruddin 2016; Kauffman and Bhomia 2017). Mangrove species can grow well and colonize the intertidal flats and shorelines, resulting in an inward expansion from the sea. However, the expansion of many species are limited by soil properties, salinity, and tidal frequency (Hossain and Nuruddin 2016).

More recently, many studies have revealed the importance of mangrove forests as a carbon sink for climate change mitigation. Climate change is a global phenomenon of rising temperatures caused by the emissions of greenhouse gases, particularly carbon dioxide, leading to various environmental problems, such as sea level rise, higher ocean temperatures, increase in intensity and frequency of precipitation, and extreme climate events such as cyclones and severe droughts (Ellison 2015; Alongi 2022). One of the sources of carbon emissions is from deforestation and land use changes including those occurring in mangrove forests (Kauffman et al. 2014;

Sasmito et al. 2019). Therefore, the protection and restoration of mangrove forest is important in climate change mitigation by sequestering and storing carbon.

Forests, including mangrove forest, can absorb carbon dioxide from the atmosphere and help to reduce the greenhouse gas emissions (Kauffman et al. 2020). In forests, carbon is primarily stored in vegetation biomass and soil (Murdiyarso et al. 2015; Kauffman et al. 2020; Kandasamy et al. 2021). Carbon stock in an ecosystem can vary depending on the geographic region. For example, mangrove forests in the tropical Southeast Asia are among the ecosystems with the highest carbon stock with an estimate of 1,016.5 t C ha^{-1}, which is higher than that in upland tropical forest (Alongi 2014). Carbon sequestration in mangrove forest is positively correlated with the biomass, and this is affected by tree composition and zonation (Kauffman et al. 2020; Harishma et al. 2020). For instance, *Rhizophora* ssp. community have higher carbon sequestration compared to *Lumnitzera* spp. and *Ceriops* spp. (Jachowski et al. 2013).

In mangrove restoration, some species are commonly planted including *Rhizophora apiculata* Blume and *Rhizophora mucronata* Lam. since these species have high adaptability, growth rate and biomass especially mangrove restoration conducted in abandoned shrimp ponds (Sakai et al. 2023). Beside the selection of species, other factors including soil and hydrological management might determine the success of mangrove restoration and affect the survival, growth and biomass accumulation (Djamaluddin et al. 2019). The success of mangrove restoration can be indicated by the improvement in soil properties, biodiversity and carbon stock in the restored areas (Salmo et al. 2013).

During the 1970s, shrimp farming was a popular economic activity in Thailand as it had a huge market demand and financial potential. As a result, during the following decade, shrimp farming spread widely throughout Thailand. As it was located along the coastline, shrimp farming was a major cause for reduction in the area under mangrove forests in Thailand. Conversion of mangrove forest to shrimp ponds resulted in losses of the soil and vegetation carbon stocks. The mean potential emissions arising from mangrove conversion to shrimp ponds was 1,390 Mg CO_2e ha^{-1} (Kauffman et al. 2018). The restoration of mangrove forests has hence been proposed to improve the forest structure, forest function, carbon storage, and ecological services (Kauffman and Bhomia 2017; Sakai et al. 2023). Very few studies have focused on carbon sequestration of rehabilitated mangrove forests on abandoned shrimp ponds. Additionally, the carbon stock of a mangrove forest can vary strongly depending on forest structure, site conditions, and management strategies (Djamaluddin et al. 2019; Kida et al. 2021). Therefore, this study aimed to investigate vegetation structure, biomass and carbon stock of restored mangrove on an abandoned shrimp pond. The results of this study will be useful in understanding the soil and biomass carbon stocks of such rehabilitated mangrove forests compared to natural mangrove forests and improve the knowledge on ecosystem carbon stock in the eastern part of Thailand.

MATERIALS AND METHODS

Study area and period

The study site was situated in the International Mangrove Botanical Garden Rama IX, Chanthaburi Province, in the Eastern Thailand and geographically located at latitude 12°31'45.64" N and longitude 102°5'41.52" E (Figure 1). Prior to the designation of botanic garden, the study site was an abandoned shrimp pond. The regional climate of this garden is characterized as monsoon tropical with a dry season (from November-April) and rainy season (from May-October). The average temperature is around 27°C and mean annual rainfall is around 2,750 mm (Chanthaburi Meteorological Station, Thailand Meteorological Department). Soil nutrients and organic matter of the abandoned shrimp pond were low (Sakai et al. 2023). For this study, experimental plots were set and field data was collected during May to July 2021.

Experimental procedure

The restoration of the abandoned shrimp pond was initiated in 2007 by planting *R. mucronata* and *R. apiculata* at a spacing of 1.5 × 1.5 m. Four experimental plots representing various vegetation conditions were established with a size of each plot was 40 × 40 m. The four experimental plots were located in a 3-year-old (MF3) and 14-year-old (MF14) mangrove stands, the abandoned shrimp pond (ASP) (without any mangrove trees) and the protected mangrove forest (PMF). *Lumnitzera* spp. and *Ceriops* spp. were commonly found in the PMF. Each sample plot was divided into 16 subplots of size 10 m x 10 m. The total height of all mangrove trees with a diameter at breast height (DBH) ≥4.5 cm in MF14 and PMF were measured, but for *R. mucronata* and *R. apiculata*, the diameter at 30 cm above the highest prop root (D_{30}) was measured. Additionally, stem diameter of *R. mucronata* and *R. apiculata* in MF3 was measured at 10 cm above the highest prop root.

The Important Value Index (IVI) of each site was estimated by accumulating the values of relative frequency, relative density, and relative dominance. Species diversity Index, H' (Shannon and Weaver 1949) and Pielou evenness (Pielou 1966) were also calculated.

Soil sample collection and carbon concentration

A PVC tube of length 100 cm and 5.0 cm in diameter was used for collecting the soil samples. Soil from four soil pits were randomly collected using the PVC tube during a low tide from the MF3, MF14, ASP, and PMF at four soil depths, i.e. 0-15, 15-30, 30-50 and 50-100 cm. From each section, a 10 cm subsample was taken to determine the soil bulk density. All the soil samples were oven dried at 80°C until a constant weight. After the removal of plant root and fauna, the remaining fresh soil samples were homogenized and subsampled again for carbon analysis. The soil samples were dried at room temperature for approximately two weeks and the dry soil samples were then sieved through a 2.00 cm sieve and were analyzed for carbon concentration (%). For carbon concentration, the samples were combusted at 975°C to determine the carbon concentration using a CNHS analyzer.

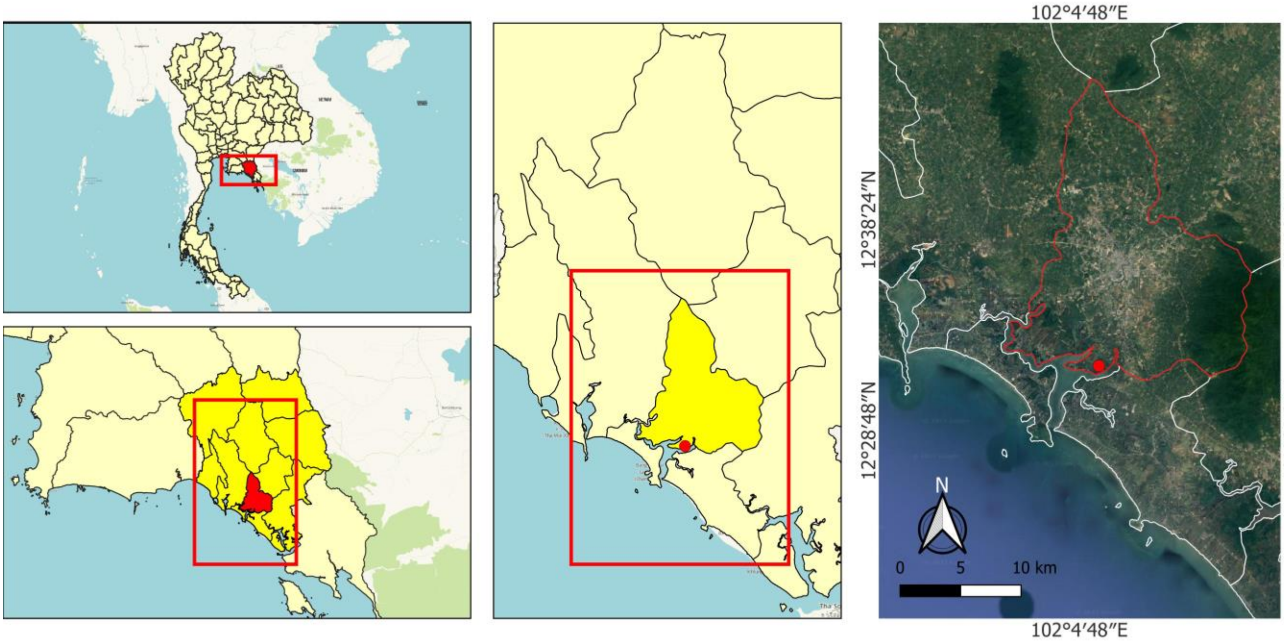

Figure 1. Location of study in the International Mangrove Botanical Garden Rama IX, Muang Chanthaburi District, Chanthaburi Province, Thailand

Determination of carbon stock in the soil and vegetation biomass

Carbon stock in mangrove soil was calculated as the product of soil bulk density (BD; g cm^{-3}), carbon concentration (C; %), and soil depth (d; cm). To estimate the plant carbon concentration, various plant components (leaf, branches, stem, and prop root) of the mangrove species at the study sites were collected under three classes (large, medium, and small trees based on their stem diameter in the experimental plots). In addition, the roots of *R. mucronata* and *R. apiculata* were also collected. The leaf, branch, stem, and prop root of each species were mixed and analyzed. The component of carbon concentration of each mangrove species (leaf, branch, stem and prop root) was measured after dry combustion using a CNHS analyzer and is given in Supplementary Tables 1 and 2.

Vegetation biomass

Allometric equations for the 14-year-old *R. mucronata* and *R. apiculata* trees in the restored shrimp pond were developed for estimating the biomass. In addition, the biomass equation for the 3-year-old *R. mucronata* stand was also developed. The biomass equation for the mangrove trees is usually developed using the mangrove trees with DBH ≥4.5 cm (Komiyama et al. 2005).

In this study, six sampled trees from different diameter above root collar (D) classes from the MF3 (1.7 to 4.5 cm D**)** and MF14 (4.9 to 13.6 cm D) were cut. Fresh weights of the stem, branch, leaf, and prop root were weighed in the field and representative samples from each tree were taken for the determination of dry weight. The stem, branch, leaves, and prop root samples were oven-dried at 70°C for 48 h to obtain a constant weight.

The vegetation biomass, i.e., stem (W_S), branches (W_B), and leaf (W_L), and prop root (W_R) of *R. mucronata* and *R. apiculata* were estimated using the allometric equation derived from destructive sampling as follows:

The 3-year-old *R. mucronata*

$W_S = 0.0271*(D^2*H)^{0.9621}$ ($R^2 = 0.9816$)

$W_B = 0.0269*(D^2*H)^{1.1274}$ ($R^2 = 0.8740$)

$W_L = 0.0716*(D^2*H)^{0.8131}$ ($R^2 = 0.8729$)

$W_R = 0.2414*(D^2*H)^{0.8031}$ ($R^2 = 0.9908$)

The 14-year-old *R. mucronata*

$W_S = 0.0314*(D^2*H)^{0.9771}$ ($R^2 = 0.9978$)

$W_B = 0.0027*(D^2*H)^{1.1083}$ ($R^2 = 0.9525$)

$W_L = 0.0002*(D^2*H)^{1.4373}$ ($R^2 = 0.9608$)

$W_R = 0.2414*(D^2*H)^{1.1074}$ ($R^2 = 0.9212$)

The 14-year-old *R. apiculata*

$W_S = 0.0216*(D^2*H)^{1.026}$ ($R^2 = 0.9984$)

$W_B = 0.0209*(D^2*H)^{9419}$ ($R^2 = 0.9765$)

$W_L = 0.0707*(D^2*H)^{0.6664}$ ($R^2 = 0.9760$)

$W_R = 0.0839*(D^2*H)^{0.8859}$ ($R^2 = 0.9903$)

$AGB = W_S+W_B+W_L$

$BGB = W_R$

Where:

W_S : the stem aboveground biomass (kg)

W_B : the branch aboveground biomass (kg)

W_L : the leaf aboveground biomass (kg)

W_R : the root biomass of, D is the diameter above root collar (cm), and H is the total height (m)

However, the aboveground biomass (AGB) and belowground biomass (BGB) of the other mangrove trees was estimated following Komiyama et al. (2005) as

$AGB = 0.251\, \rho\, DBH^{2.46}$,

$BGB = 0.199\, \rho^{0.899}\, DBH^{2.22}$, Where ρ is the wood density of the respective species. The wood density of other mangrove species was estimated using Komiyama et al. (2005) for *Bruguiera cylindrica* (L.) Blume, *Bruguiera gymnorrhiza* (L.) Lam., *Ceriops tagal* (Perr.) C.B.Rob., *Sonneratia caseolaris* (L.) Engl., *Sonneratia alba* Sm. and *Xylocarpus granatum* J.Koenig, while Jachowski et al. (2013) was used for *Ceriops decandra* (Griff.) Ding Hou, *Heritiera littoralis* Dryand. ex Aiton, *Lumnitzera* spp., *Sonneratia ovata* Backer, and Kamruzzman et al. (2017) for *Excoecaria agallocha* L.

The carbon content was calculated by multiplying the individual tree biomass with the carbon concentration of each species.

Ecosystem carbon stock (t C ha^{-1}) was estimated as = $C_{treeAGB} + C_{treeBGB} + C_{soil}$

In addition, soil carbon accumulation rate (R_{SC}) as the result of restoration in abandoned shrimp pond in the MF3 and MF14 was calculated as follows:

R_{SC} (t C ha^{-1} $year^{-1}$) = (Soil carbon stock (after *x* years) - Soil carbon stock in ASP) / *x*

Where *x* is the age of abandoned shrimp pond restoration

Data analysis

Analysis of Variance (ANOVA) was used to determine the differences of soil bulk density, soil carbon concentration, vegetation biomass, vegetation and soil carbon stocks, ecosystem carbon stock, and soil carbon accumulation rate. A p-value of 95% significant level was used to determine the statistical significance using SPSS statistical software (Version 17.0).

RESULTS AND DISCUSSION

Vegetation structure and species composition

Three mangrove species, i.e., *R. mucronata, R. apiculata* and *S. caseolaris* were recorded in the MF3, with *R. mucronata* being the dominant species at this site as it was the major species planted during the initial stages of restoration. In the MF14, *R. mucronata* was the dominant species followed by *R. apiculata* and *Avicennia alba* Blume, respectively (Table 1). Many mangrove species were observed to naturally regenerate in the MF14. These species were pioneer species, such as *S. caseolaris* and *A. alba* and have been reported to naturally regenerate in the restored mangrove area (Harefa et al. 2023). These species have small seed size, making it easier to disperse by floating water. This observation might help in promoting the natural succession of abandoned shrimp pond. However, these pioneer species had a relatively low density. Embankment of shrimp pond acted as a physical barrier impeding the distribution of mangrove species in the abandoned shrimp pond. However, water tide levels of the MF3 and MF14 were similar to the PMF.

Table 1. Species composition of mangrove vegetation at restoration sites in the International Mangrove Botanical Garden Rama IX, Chanthaburi Province

Mangrove sites	Mangrove species	RF (%)	RD (%)	RDo (%)	IVI
MF3	*Rhizophora mucronata*	64.00	95.88	3.44	163.32
	Sonneratia caseolaris	8.00	0.74	94.78	103.52
	Rhizophora apiculata	28.00	3.38	1.78	33.16
	Total				
		100	100	100	300
MF14	*Rhizophora mucronata*	47.20	62.97	17.45	127.62
	Rhizophora apiculata	32.80	34.92	12.58	80.30
	Avicennia alba	13.60	1.24	38.38	53.23
	Sonneratia alba	0.80	0.03	14.34	15.17
	Lumnitzera littorea	0.80	0.03	11.99	12.83
	Lumnitzera racemosa	3.20	0.38	2.51	6.09
	Hibiscus tiliaceus	0.80	0.38	2.31	3.49
	Bruguiera gymnorrhiza	0.80	0.03	0.44	1.27
	Total				
		100	100	100	300
PMF	*Lumnitzera racemosa*	27.84	42.69	40.55	111.08
	Lumnitzera littorea	21.65	22.00	25.45	69.10
	Ceriops tagal	24.23	24.15	20.46	68.84
	Rhizophora apiculata	8.76	6.00	8.62	23.38
	Ceriops decandra	9.79	2.77	0.86	13.42
	Excoecaria agallocha	3.09	1.46	1.19	5.74
	Avicennia alba	1.03	0.15	2.22	3.40
	Bruguiera gymnorrhiza	2.06	0.54	0.56	3.16
	Bruguiera sexangula	1.03	0.15	0.07	1.25
	Heritiera littoralis	0.52	0.08	0.02	0.61
	Total	100	100	100	300

Notes: RF: relative frequency; RD: relative density, RDo: relative dominance; IVI: the Importance Value Index (IVI); MF3: 3-year-old mangrove restoration; MF14: 14-year-old mangrove restoration; PMF: protected mangrove forest

The MF3 had the lowest species diversity with H' index of 0.19 since it was young stand (Table 2). As the restoration proceed, the diversity increased as indicated with the higher diversity index at the older restoration site (i.e., MF14 with H' of 1.42). The result of this study is in line with the study by Azman et al. (2021) which found that the diversity of mangrove increases with the age of rehabilitation. Interestingly, the diversity index in the MF14 is close to that in the protected mangrove forest (PMF) which had index of 1.50. Both the diversity index in the MF14 and PMF was higher than that of mangrove forest in Amphoe Khlung, Chanthaburi province (0.88) (Aksornkoae 1976). The diversity and evenness of mangrove species in PMF was similar to the mangrove forest in Trang province, located in the southern part of Thailand (1.10-1.99 and 0.51-0.80, respectively) (Sudtongkong and Webb 2008). Differences in mangrove diversity were observed according to the mangrove zonation (Aksornkoae 1976).

The DBH and height of mangrove species in the MF3, MF14, and PMF are presented in Table 2. The growth performance of *R. mucronata* in the MF3 and MF14 was good. The DBH and height of *R. mucronata* in the MF3 were similar to a 3-year-old *R. apiculata* plantation (0.94 cm and 1.76 m, respectively) in Samut Songkhram Province (Wechakit 1990). Moreover, the DBH of MF14 was higher than that of the *R. apiculata* plantation (Kridiborworn et al. 2012) and a 14-year-old *R. apiculata* plantation (5.98 cm and 11.40 m, respectively) in Samut Songkhram Province (Wechakit 1990). The good growth of *R. mucronata* observed in the MF14 could have resulted from a low density of mangrove trees compared to the *R. apiculata* plantation in Samut Songkhram Province (10,300 stem ha^{-1}) (Wechakit 1990). A high density of mangrove trees can negatively impact the growth due to a strong competition for resources and crown cover (Salmo et al. 2013). In addition, good growth of *R. mucronata* and *R. apiculata* was related to the soil properties and hydrological characteristics. *R. mucronata* and *R. apiculata* prefer higher proportions of silt and clay contents and mud flats (Aksornkoae 1976).

The mangrove tree density at the MF3 and MF14 was 3,904.69 and 4,525.00 stem ha^{-1}, respectively, which was higher than that of PMF. However, long term studies indicate that the density of mangrove trees can decrease as the age increases as the result of competition to obtain to environmental resources (Wechakit 1990). In this study, the density of mangrove forest in PMF was similar to the mangrove forest in Amphoe Khlung, Chanthaburi province, which had a density of 2,160-2,280 stem ha^{-1} (Aksornkoae 1976). The dominant mangrove community has a strong relation with the stem density. The density of primary mangrove forest, dominated by *Rhizophora* spp., was relatively low (1,313 stem ha^{-1}) (Jachowski et al. 2013).

Vegetation biomass

The aboveground biomass (AGB) of mangrove forest in the MF3, MF14, and PMF was 10.94, 155.27, and 91.49 t ha^{-1}, respectively. *R. mucronata* was the dominant tree species in both MF3 and MF14. This species has been frequently recommended as a potential species for restoration projects of abandoned shrimp pond with a high survival rate and AGB accumulation (Sakai et al. 2023). Age evidently affected the increase in AGB from age 3 years to 14 years of mangrove restoration in the abandoned shrimp pond. In the present study, the AGB of MF3 was similar to that of a *R. apiculata* plantation in Samut Songkhram Province with a value of 10.74 t ha^{-1} (Wechakit 1990). A relatively high AGB in the MF3 could be due to good growth and suitable environments for *R. mucronata* on the mud flats. However, the AGB of MF14 (155.27 t ha^{-1}) was lower than that of the previously reported 14-year-old *R. apiculata* plantation in Samut Songkhram Province (251.09 t ha^{-1}) (Wechakit 1990). The comparatively lower AGB in the MF14 is likely caused by the lower density of mangrove trees compared to that reported by Wechakit (1990), with a density of 11,500 stem ha^{-1}. However, the AGB of MF14 was higher than that of PMF. Generally, plantations are known for improving productivity. As *R. mucronata* grows well on the mud flats compared to other mangrove species, it can increase the short term productivity of the plantation and has been previously recommended for planting on an abandoned shrimp pond and degraded mangrove area (Salmo et al. 2013; Cadiz et al. 2020).

The recovery of vegetation structure and AGB is an indicator of the successes of a mangrove restoration. The AGB of MF14 was greater than that of 17-year-old *R. mucronata* in Kalibo, Philippines (101.80 t ha^{-1}) (Salmo et al. 2013). However, the AGB of PMF was relatively low (91.49 t ha^{-1}) compared to the other natural mangrove forests in Thailand and other tropical sites (Table 3). Darmawan et al. (2019) reported that AGB of primary mangrove forest in Chumphon Province, Thailand, dominated by *R. apiculata*, was 231.40 t ha^{-1}, which was significantly higher than that of PMF in our study. In addition, the AGB of PMF was lower than that of primary mangrove forests in the tropics such as in Indonesia (252.56 t ha^{-1}) (Darmawan et al. 2019), Sulaman Lake Forest Reserve, Malaysia (134.59 t ha^{-1}) (Suhaili et al. 2020) and the Sundarbans mangrove forest, Bangladesh (153.70 t ha^{-1}) (Kamruzzaman et al. 2018).

Table 2. The vegetation structure and diversity of mangroves at restoration sites in International Mangrove Botanical Garden Rama IX, Chanthaburi Province

Mangrove sites	Number of species	Tree density (stem ha^{-1})	Basal area (m^2 ha^{-1})	DBH (cm)	Height (m)	Species diversity	Evenness
MF3	3	3,904.69	3.13	2.84	2.63	0.19	0.17
MF14	8	4,525.00	25.38	8.21	10.78	1.42	0.62
PMF	10	2,028.13	15.02	8.60	6.31	1.50	0.65

Notes: MF3: 3-year-old mangrove restoration; MF14: 14-year-old mangrove restoration; PMF: protected mangrove forest

The belowground biomass (BGB) of MF3 and MF14 increased drastically from 12.58 t ha^{-1} to 74.76 t ha^{-1} after rehabilitation. The BGB of MF14 was higher than that in PMF (74.76 and 41.89 t ha^{-1}, respectively). This result indicates the role of *Rhizophora* spp. plantation in the restoration of abandoned shrimp pond. The roots contribute significantly to the mangrove biomass (Harefa et al. 2023). Mangrove forests have greater belowground biomass than upland tropical forests as reported by Alongi (2014). The percentage of root biomass of *Rhizophora* spp. in MF3 was 53.94% and was a major contributor to the total biomass pool for a young stand of *Rhizophora* spp., while the percentage contribution from the stem, branch, and leaves was relatively low (Figure 2). In contrast, for the older plantation, such as MF14, the proportion of root biomass was lower, while the contribution from the stem to the total biomass was higher (Analuddin et al. 2020).

A comparison of the MF14 and PMF with the other mangrove sites found that the BGB of MF14 and PMF (74.76 and 37.61 t ha^{-1}, respectively) was lower than a primary mangrove forest in Halmahera, Indonesia (110.8-180.7 t ha^{-1}) (Komiyama et al. 1988). However, in the present study, the BGB of MF14 was similar to that reported by Komiyama et al. (2000) in the Satun Province, southern Thailand who found that the belowground biomass of a secondary mangrove forest dominated by *C. tagal* was around 87.50 t ha^{-1}. Poungparn (2003) found that the belowground biomass of a mangrove forest in Trat Province, eastern Thailand (50.30 t ha^{-1}) was similar to that in the PMF. We indicate that the mangrove forest community at both sites was similar. The observed differences in vegetation biomass is significantly influenced by the dominant species composition, density, site management, proximity to water channel, soil properties, and water hydrology

Vegetation carbon stock

Vegetation carbon stock was significantly different among sites ($p<0.05$) (Table 4). Vegetation carbon stock of MF3, MF14, and PMF varied depending on the stand age and forest structure. However, the vegetation carbon stock of ASP could not be estimated as the natural succession of the mangrove was unsuccessful. *Avicennia* seedlings and shrub groups were found on the embankment of the shrimp pond, suggesting that human intervention by planting mangrove species should be done to ensure the establishment of the mangrove, especially on such abandoned shrimp ponds. Shrimp farming completely destroyed the aboveground and belowground carbon stocks of mangrove trees, leading to carbon loss in the mangrove ecosystem. In this study, we observed that *R. mucronata* in the MF3 had a high potential for vegetation carbon stock. Aboveground carbon biomass of *R. mucronata* in the MF3 was higher than *R. apiculata* plantation in Yeesarn, Samut Songkhram, Thailand of similar age (Kridiborworn et al. 2012). The high aboveground carbon biomass in the MF3 was resulted from a good growth of *R. mucronata*. Similarly, we report that the MF14 had a higher aboveground biomass carbon stock than PMF. The aboveground carbon of restored mangrove in the abandoned shrimp pond is strongly related with the age of the stand (Sasmito et al. 2019), mangrove species and hydrological factors (Cadiz et al. 2020). The aboveground carbon stock in the PMF was relatively low (42.33 t C ha^{-1}) compared to the mean aboveground carbon estimated for a mangrove forest located in southeast Asia (145.5 t C ha^{-1}) (Kauffman et al. 2020).

Table 3. Vegetation biomass of restoration sites in International Mangrove Botanical Garden Rama IX, Chanthaburi Province

Mangrove sites	Aboveground biomass (t ha^{-1})	Belowground biomass (t ha^{-1})	Total biomass (t ha^{-1})
MF3	10.94^{a}	12.58^{a}	23.52^{a}
MF14	155.27^{c}	74.76^{c}	230.99^{c}
PMF	91.49^{b}	41.89^{b}	133.84^{b}
F value	118.35**	104.95**	114.34**

Notes: **: significantly different at $p<0.01$, with the letters a, b and c in the same column indicating significant differences at $p<0.01$, as determined by Tukey HSD. MF3: 3-year-old mangrove restoration; MF14: 14-year-old mangrove restoration; PMF: protected mangrove forest

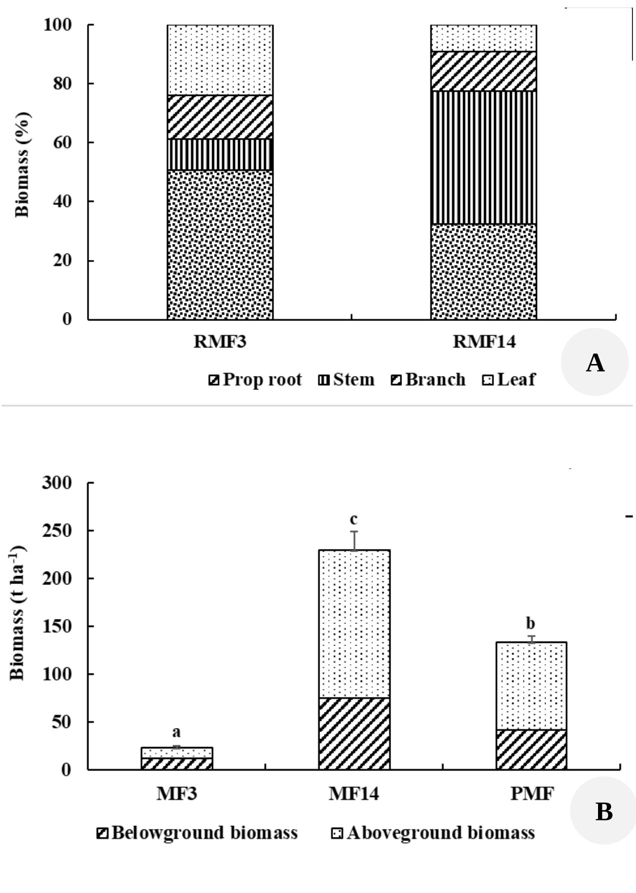

Figure 2. A. Distribution of the vegetation biomass of *Rhizophora* spp. growing in MF3 and MF14. B. Aboveground and belowground biomass of mangrove forest in MF3, MF14 and PMF. The letters a, b, and c above the bars indicate significant differences at $p<0.05$, as determined by Tukey HSD

Table 4. Soil carbon stock of various sites in International Mangrove Botanical Garden Rama IX, Chanthaburi Province

Soil depth (cm)	Mangrove sites				F value
	ASP	MF3	MF14	PMF	
0-15	87.22[a]	99.75[a]	181.76[b]	171.86[b]	14.35*
15-30	77.44[a]	86.98[a]	161.72[b]	195.36[c]	67.15**
30-50	99.79[a]	104.51[a]	150.79[b]	211.34[c]	39.49**
50-100	208.55[a]	221.52[a]	249.30[a]	627.17[b]	417.44**
Mean	118.25[a]	128.19[a]	185.89[b]	301.43[c]	324.23**

Notes: *: significantly different at p<0.05; **: significantly different at p<0.01; ns: not significant at p>0.05. The letters a, b, and c in the same row indicate significant differences at p<0.05 and p<0.01, as determined by Tukey HSD. ASP: abandoned shrimp pond; MF3: 3-year-old mangrove restoration; MF14: 14-year-old mangrove restoration; PMF: protected mangrove forest

The belowground carbon vegetation of MF14 was greater than that of PFM, which could be due to a different dominant species and forest structure. Meng et al. (2021) showed that the belowground carbon stocks was strongly correlated with the mangrove species. However, other main factors affecting the belowground carbon stock included the difference in habitats of mangrove ecosystems, soil properties, and geographical environments (Meng et al. 2021). The presence of mangrove species such as *Rhizophora* spp. and the forest structure, i.e., density and prop root can have a significant influence on the belowground carbon stock. *R. mucronata* planted on the abandoned shrimp pond exhibited remarkable potential for biomass carbon storage. Generally, the total biomass carbon stock increases with the age of the mangrove stand (Kandasamy et al. 2021). Carbon stock of the young stand in the MF3 was lower compared to the other sites, and was related to the age of the stand and the development of mangrove forest structure. On the other hand, the total biomass carbon stock in the MF14 was relatively high (102.54 t C ha^{-1}) compared to that in the PMF (64.94 t C ha^{-1}). Biomass carbon of MF14 was relatively high because the growth of *R. mucronata* was good both in term of DBH and height, and had a high density. High carbon stock of a vegetation is positively correlated with the tree density and stem diameter of the mangrove trees (Merecí-Guamán et al. 2021). *R. mucronata* was a major contributor to the biomass carbon stock in the MF3 and MF14 since it was the dominant tree. On the other hand, *L. racemosa, L. littorea,* and *C. tagal* were important species for biomass carbon stock in PMF. Differences in vegetation carbon stock of the mangrove forest was influenced by the vegetation structure and dominant species at each site. Kida et al. (2021) indicated that the carbon biomass of a mangrove forest can vary depending on the dominance of mangrove species. Carbon biomass of *Rhizophora* spp. community was higher than that of the dominant *Avicennia* spp. and *Xylocarpa* communities.

The vegetation carbon stock of the natural mangrove forest was different among sites in the region and at global scales (Sasmito et al. 2020; Kauffman et al. 2020), which varied depending on the forest structure, soil property, latitude, and salinity (Cadiz et al. 2020; Kauffman et al. 2020; Kida et al. 2021; Meng et al. 2021). Comparison of biomass carbon stock in PMF in this study with several sites in the tropics indicate that the biomass carbon stock of PMF was lower than that of the mangrove forest in Kerala, southwest India (58.56 t C ha^{-1}) (Harishma et al. 2020), in Can Gio Mangrove Biosphere Reserve, Vietnam (70.10 t C ha^{-1}) (Nam et al. 2016), and in Indonesian mangrove forest (211.4 t C ha^{-1}) (Murdiyarso et al. 2015).

Soil carbon stock

Soil bulk density and carbon concentration among sites are shown in Figure 3. The soil bulk density at depths of 0-15, 15-30, 30-50 cm was not different (p>0.05) among sites, but was different at a depth of 50-100 cm. In the present study, the bulk density of soil among sites was similar, ranging between 0.69-0.93 g cm^{-3}. However, the soil bulk density of PMF among various soil depths was similar, ranging between 0.57-0.77 g cm^{-3}. These values were lower than that of ASP, MF3, and MF14. A high bulk density measured at ASP and MF3 may have resulted from shrimp farming activities.

The soil carbon concentration of PMF was the highest with values between 16.63-18.72%. In contrast, the mean soil carbon concentration of ASP was the lowest, at around 6.00%. This result indicates the extreme impact of shrimp aquaculture on the loss of soil carbon. However, the mean soil carbon concentration of MF3 and MF14 was 6.65% and 11.46%, respectively. The soil carbon concentration increases with the age of mangrove restoration. The soil carbon concentration of this area in ASP, MP3, and MP14 was relatively high compared to abandoned shrimp pond (1.04%) and mangrove restoration at abandoned shrimp pond (approximately 2-3%) in southern Thailand (Sakai et al. 2023). This result showed that the soil carbon concentration of mangrove forest varied depending on geographic region. However, high soil carbon concentration was found in mangrove forest in Bunaken site (8.55-21.72%), Indonesia (Murdiyarso et al. 2015).

The soil carbon stock of the restored shrimp pond and PMF was significantly different (p<0.05) (Table 5, while that of the MF3 and MF14 was higher than the ASP. Large and dense crown cover observed in MF14 can result in high litter production. Kamruzzaman et al. (2019) indicated that mangrove forest had a high litterfall production (10.10 t ha^{-1} year^{-1}) with the leaves contributing the most to the litter pool. While, the litterfall of young *R. mucronata* was relatively high (5.22 t ha^{-1} year^{-1}) (Wang'ondu et al. 2014). Litter of mangrove forest had fast decomposition (Dewiyanti et al. 2019) and carbon sequestration in mangrove soil and vegetation biomass was combined with carbon fluxes via litterfall)Rovai et al. 2021(. In addition, high litter decomposition rate can cycle back the accumulation of soil carbon to the soil layer (Salmo et al. 2013) and it plays an important role in the ecosystem services, such as nutrient cycling and carbon storage (Rocha et al. 2022).

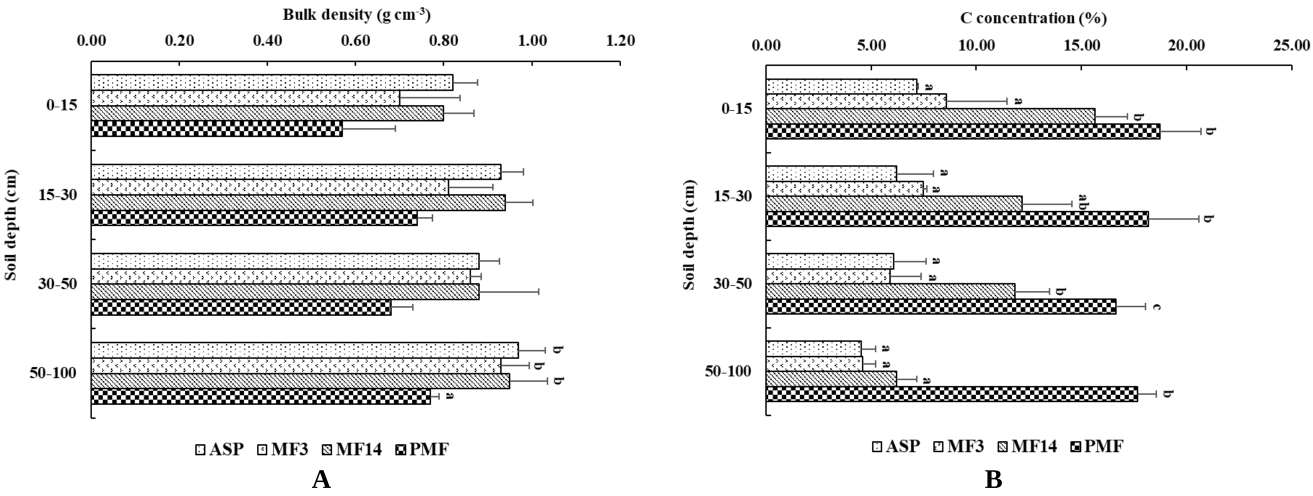

Figure 3. Soil bulk density (A) and carbon concentration (B) in 3-year-old mangrove (MF3), 14-year-old mangrove (MF14), abandoned shrimp pond (ASP) and protected mangrove forest (PMF) at International Mangrove Botanical Garden Rama IX, Chantaburi Province. The letters a, b, and c in the same soil depth indicate significant differences at p <0.05, as determined by Tukey HSD

Table 5. Vegetation carbon stock, soil carbon stock, and ecosystem carbon stock at various sites in International Mangrove Botanical Garden Rama IX, Chanthaburi Province

Mangrove sites	Vegetation carbon stock (t C ha^{-1})	Soil carbon stock (t C ha^{-1})	Ecosystem carbon stock (t C ha^{-1})
ASP	-	118.25^a	118.25^a
MF3	9.51^a	128.19^a	137.70^a
MF14	102.54^c	185.89^b	288.43^b
PMF	64.94^b	301.43^c	366.38^c
F-value	62.40**	324.23**	374.29**

Note: **: significantly different at p<0.01, with the letters a, b, and c in the same column indicating significant differences at p<0.01, as determined by Tukey HSD. ASP: abandoned shrimp pond; MF3: 3-year-old mangrove restoration; MF14: 14-year-old mangrove restoration; PMF: protected mangrove forest

Moreover, soil carbon stock may be influenced by tidal waves, resulting in sediment and soil carbon accumulations (Alongi 2014). Additionally, the organic carbon accumulation of a mangrove forest is regulated by site conditions (Zakaria et al. 2021). However, for the MF3 and MF14, the tidal influence may have had a low impact on the soil carbon stock because the embankments constructed around the shrimp pond would act as a barrier for sediment deposition and distribution.

Ecosystem carbon stock

The land use change from a mangrove forest to shrimp aquaculture significantly increased the loss of carbon. In this study, the ecosystem carbon stock of ASP was lower than that of MP3, MP14, and PMF. The conversion of mangrove forest into aquaculture resulted in a dramatic losses of carbon stock, which significantly affected the CO_2 emissions. Elwin et al. (2019) indicated that the ecosystem carbon stock of an abandoned shrimp pond was disturbed by forest-clearing and soil excavation. In the present study, we estimate that the vegetation and soil carbon stocks removed in the ASP were approximately 64 t C ha^{-1} and 183 t C ha^{-1}, respectively, compared to the PMF. However, an increase in ecosystem carbon stock can also be a result of planting mangrove species. Therefore, *Rhizophora* stand is an effective way for increasing the ecosystem carbon stock in the abandoned shrimp pond as the natural succession of mangrove species was very slow in the abandoned shrimp pond.

The estimated ecosystem carbon stock of ASP, MF3, and MF14 was 118.25, 137.70, and 288.43 t C ha^{-1}, respectively. The changes in vegetation structure in the MF3 and MF14 led to a significant increase in the biomass carbon stock. In addition, the soil properties of restored mangrove forest were improved after the mangrove restoration (Salmo et al. 2013). Ecosystem carbon stocks are strongly influenced by soil properties, forest structure, hydrogeomorphic settings, and changes in land use (Elwin et al. 2019; Sasmito et al. 2020). Globally, the average ecosystem carbon stock of mangrove forest has been estimated at 956 t C ha^{-1} (Alongi 2014). Additionally, the ecosystem carbon stock of mangrove forests can vary at a regional scale (Kauffman et al. 2020). Kauffman et al. (2020) indicated that the ecosystem carbon stock of mangrove forests in Southeast Asia was 1,016.50 t C ha^{-1}. A high ecosystem carbon stock was reported for a mangrove forest in Indonesia (Murdiyarso et al. 2015). In this study, the ecosystem carbon stock of MF3, MF14 and PMF was relatively low (168.58, 301.79, and 322.92 t C ha^{-1}, respectively).

In addition, soil carbon accumulation rate (R_{SC}) in the MF3 and MF14 through mangrove restoration in abandoned shrimp pond was 3.31 and 4.93 t C ha^{-1} year^{-1}, respectively. R_{SC} in the MF3 and MF14 was relatively high compared to that of 15-year-old mangrove restoration at abandoned shrimp pond in southern Thailand (2.70 t C ha^{-1} year^{-1}) (Sakai et al. 2023). The carbon accumulation rate of planted mangrove was higher than global mean soil carbon accumulation rate (1.74 t C ha^{-1}) (Alongi 2014). This result indicated that mangrove reforestation has an important role in increasing soil carbon stock.

Rhizophora spp. are an important species for the local people with multiple uses, such as for making of fisheries tools, construction poles, charcoal, and fuelwood. A high tree density of *R. mucronata* was observed in the MF14 and we suggest management strategies such as thinning in this area. The aboveground carbon stock of MF14 was approximately 15% of ecosystem carbon stock, while the belowground carbon (soil and root) was the 85% stock. Therefore, thinning is likely only has a slight impact on the ecosystem carbon stock. Murdiyarso et al. (2021) indicated that the soil carbon stock of newly logged 10-year-old and 15-year-old stands was not different, as the to soil surface sediment was undisturbed. Therefore, sustainable stand management can be applied in the MF14. The vegetation carbon stock may be affected slightly, while soil carbon pool may remain unchanged. Thinning practice promotes tree growth of the remaining trees, especially in terms of stem growth (Beadle et al. 2013). The growth increment of the remaining trees can be compensated by an increase in the vegetation carbon stock. In addition, canopy gap creation in mangrove stand can accelerate the establishment of seedlings, resulting in long term growth and improvement in forest structure dynamics (Amir and Duke 2019).

The *Rhizophora* spp. stand has the potential to become a significant source of carbon pool during and after the restoration of abandoned shrimp ponds. However, the conservation of mangrove forest appears to be the most effective strategy for maintaining the mangrove carbon stock. The findings of this study could be useful in providing the basic information to estimate the carbon emissions and carbon stock from shrimp aquaculture and restored shrimp ponds. In addition, the variations in carbon stock of root and soil was driven by the zonation of the mangrove species. The current understanding can be significantly important in the estimation of carbon stock in a mangrove forest as a climate change mitigation strategy in Thailand and other such tropical regions.

In conclusion, an assessment of the carbon stock in a restored mangrove forest at the International Mangrove Botanical Garden Rama IX indicated that planting of the *Rhizophora* spp. stand was an effective restoration strategy in reclaiming the abandoned shrimp pond. Apart from good growth and high biomass, we estimated that the root component of the young *Rhizophora* stand in MF3 was a major contributor to the biomass pool and vegetation carbon stock. Interestingly, vegetation biomass and carbon stock in the MF14 were higher than those in the PMF. *Rhizophora* spp. is a suitable species for restoration of abandoned shrimp pond plagued by mud flat condition. The development of vegetation structure in a restored mangrove stand was observed to increase with age, affectingly increasing the vegetation carbon stock and species diversity. However, the natural succession of mangrove species was relatively low and was restricted by the embankment constructed around the shrimp pond. As such, the removal of embankment should be considered for promoting the mangrove distribution and natural succession process. The conservation of mangrove forest can play a significant role in reducing the carbon emission from shrimp aquiculture and maintaining the ecological function. Our results demonstrated that the ecosystem carbon stock of PMF was the highest with value of 366.38 t C ha^{-1}. In contrast, shrimp farming reduced the carbon pool of the mangrove forest. Therefore, mangrove restoration of the abandoned shrimp farming should be considered for increasing the carbon pool.

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