CARBON STORAGE POTENTIAL OF NATURAL AND PLANTED MANGALS IN TRANG, THAILAND

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Abstract. This study aims to investigate the carbon storage potential for 25 year-old (planted) and >50 year-old (natural) mangrove stands and mangrove sediment, in three districts of Trang province, Thailand. The results show a lower carbon content in the aboveground biomass of 10-25-year-old (planted) stands than in the >50-year old (natural) stands. However, we found more organic carbon in sediments in planted sites than in natural sites, which could be partly due to the higher tree densities in the former. The derived organic carbon in particulate matter was lower in the planted forest than in the natural forest, which could be due to allochthonous inputs of organic matter from rivers and creeks, and to a higher number of species in the natural forests. This study demonstrated that the amount of carbon stored in mangroves increases with age, but the amount of carbon stored in mangrove soils could vary with mangrove density, sediment size, allochthonous inputs, and inundation. This study suggested that planted and natural mangrove forests can capture and store a substantial amount of carbon. Such information could motivate policymakers and local communities to conserve the last remaining mangrove forests, rehabilitate degraded ones, and replant abandoned fish and shrimp ponds.

Keywords: *carbon content, organic matter, carbon sink, reforested mangroves, mangrove ecosystem*

Introduction

Coastal ecosystems such as mangrove forests, saltmarshes, and seagrass meadows have a significant role in mitigating climate change impacts through carbon sequestration. McLeod et al. (2011), reported that fifty-five percent of the carbon can be sequestered in the vegetated coastal ecosystem (mangrove forest, seagrass beds, and salt marshes), because of their ability to store “blue C” in deep organic soils. “The blue C” refers to all the carbon captured from the ocean, including mangrove forests, seagrasses, meadows, and tidal saltmarshes (Thomas, 2014).

Mangroves are known as a diverse group of plants that grow in tropical to subtropical marine intertidal and estuarine areas (Tomlinson, 1986). The unique characteristics of the root systems of mangroves slow down the incoming tidal waters and allow organic and inorganic materials to settle on top of the sediment (Hutchings and Saenger, 1987) and thereby they mitigate siltation (Thampanya et al., 2006). These roots can also act as nursery grounds (Beaumont et al., 2014). The big trees act as buffer against waves (Horstman et al., 2012), and most importantly mangrove litter

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is a source of nutrients (Boullion et al., 2008). However, these functions are often overlooked and mangroves are valued by humans for the goods they provide, such as charcoal and firewood, tannin, medicines, and as source of fishery products such as shellfish, crabs and shrimps (Aksornkoae, 1993). Mangroves are also often considered an “open access” resource for the local people. As such, mangroves remain among the most threatened ecosystems in the world, cut and cleared at an alarming rate (Valiela et al., 2001). The global estimates were as high as 15,642,673 (FAO, 2007) to 17,000,000 ha of mangroves in 5 countries of the world (Saenger et al., 1983) and trimmed down to 10,354,335 ha in 15 countries (Giri et al., 2011) during the 80’s to 90’s. The losses were rated at 1-2 percent per year by UNEP (2004), and particularly high in Asia due to massive aquaculture activities, urban settlements, and industrialization (Lewis, 2005; Primavera and Esteban, 2008; Romanach et al., 2018).

In Thailand, the mangrove area was recorded as 367,900 ha in 1961 (Aksornkoae, 1993; Havanond, 1997) and were reduced to 245,533 ha by 2015 (DMCR, 2015). Mangrove deterioration occurred especially during the 80’s when intensive shrimp farming and commercialization converted 5,700 ha of mangrove (Boromthanarat et al., 1991; Bantoon, 1994; Yee, 2010), causing major attention because some converted shrimp pond areas were left abandoned or unattended after the economic crises of the shrimp farming industry. The Government of Thailand conducted massive rehabilitation and conservation programs (Fast and Menasvita, 2003) backed-up with legislation and enforcement of laws and regulations on mangrove uses (Aksornkoae, 2012). The significant value of restoring mangrove areas was fully recognized after the Indian Ocean tsunami hit the Andaman areas of Thailand in 2004 (Barbier, 2008). Massive rehabilitation and reforestation spread out in various provinces, particularly in areas with land use change from shrimp farming activities. However, there was lack of monitoring whether these rehabilitation programs are ecologically sound and beneficial to restore degraded mangrove ecosystems, in particular with land use in shrimp farming. In Trang, land-use changes consisted by 2 percent of aquaculture land, by 47 percent of pararubber plantations, and by 17 percent of mangrove forest/evergreen forests and others classified as institutional land development, cities, paddy field, water bodies etc. (Land Use Development, 2013). Thus, this study is significant to Thailand’s marine resources, particularly mangroves that are still threatened by land-use changes.

Overall, increasing awareness of the carbon storage potential of mangrove ecosystems remains a prerequisite for alleviating climate change issues. This study addresses the community structure and carbon capture potential of mangrove with land-use changes from shrimp farming activities and natural stands of mangroves in Trang, Southern Thailand. Two aged group of mangrove forests, the 10-25-years old (YO) planted in mangrove areas with land-use change from shrimp farming activities and >50-YO natural stands, were measured and monitored in the study. The research findings provide information on the community structure of mangroves in Trang, Southern Thailand, and the carbon data obtained will serve as baseline information for future climate change impact studies. Overall this study helps recommend management strategies in promoting the functional role of mangrove as a source and sink of carbon for better management, protection, and conservation of mangrove forests in Southern Thailand.

Materials and Methods

Description of the Study Site

The study sites were located in Sikao (7.478961° N, 99.335952° E), Kantang (7.376096° N, 99.57253° E) and Palian (7.125833° N, 99.622948° E) districts of Trang, Southern Thailand (*Fig. 1*) where both 10-25-year old planted mangrove forest and >50-YO natural mangrove forest are found. In Trang, mangroves cover 249,331.25 ha of which 35,665.00 ha are designated as economic zone and 26,425.00 ha as preservation zone (Aksornkoae, 1993). Most of the mangroves in these districts are still pristine, except for some areas that have been excavated for shrimp farming 3-4 decades ago. These characteristics are common in these three districts: the areas have abandoned shrimp ponds, with some that have been reverted back into mangrove areas. The plantings of mangrove were mostly initiated by the Department of Marine and Coastal Resources (DMCR) and Thai Royal Department of Forestry (Havanond, 1997).

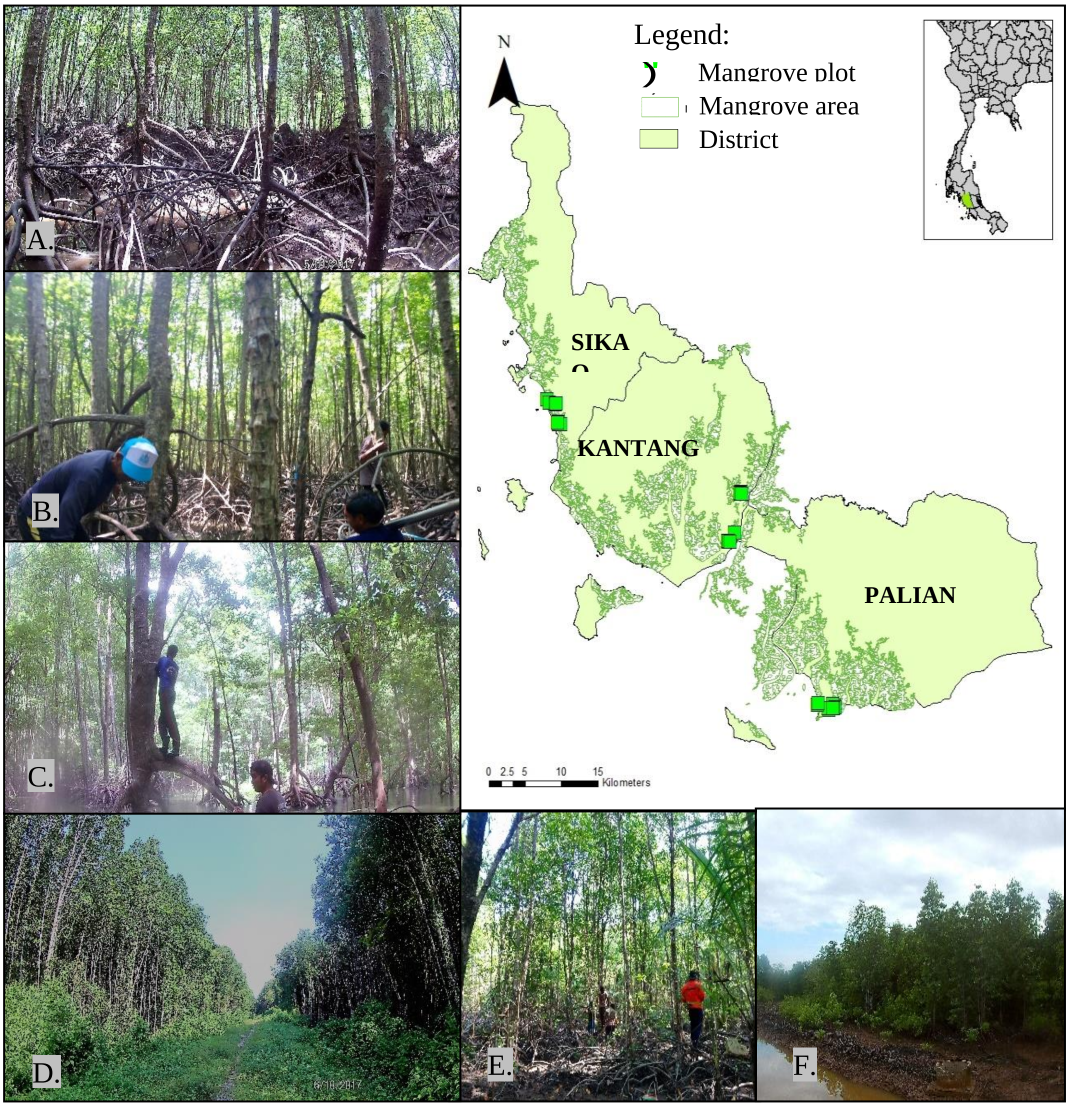

Figure 1. *Map of the study sites showing the 3 districts, mangrove areas and permanent plots (green box) in Trang. A, D, and E are planted mangrove forest. B, C, and F are natural mangrove forest. Inset: Map of Thailand*

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There were ten permanent sampling plots (measuring 10x10 m) established in each district (*Fig. 1*). The sampling plots for the natural forest established in Sikao (SD) were located near a creek, bordered by Pakmeng Beach on the seaward side, while plots for the planted forest were located further southward. In Palian (PD), the plots were established along Palian estuary. The PD estuary is a junction between two big rivers of Klong Lak Khan and Khlong Rae (Horstman et al., 2013). In Kantang (KD), the plots were established inland, with an abandoned shrimp pond adjacent to the rubber plantation that has been replanted (*Fig. 1D*), while plots for the natural forest were located along the creeks and tributaries of KD River. The creeks and rivers receive water from adjacent shrimp pond areas and neighboring households. All plots are affected by the ebb and flow of the tides, except in SD where some of the plots established are inundated only during high tide due to large boulder crab mounds. The plots in PD were established near a concession area where most of the planted mangroves are cut for wood and construction materials (*Fig. 1F*).

Carbon in Aboveground Standing Biomass (CAGB)

To determine the age of a forest, secondary information was obtained from the Department of Marine and Coastal Resources (DMCR). The profile and vegetation structure, such as species composition, density, basal areas, and biomass were obtained (Cadiz and Chotikarn, 2018). Profiling of the community structure was only conducted once, in April 2017. The above-ground biomass estimates followed the allometric equations of Komiyana et al. (2008), using diameter at breast height (D), wood density (ρ) and with coefficient of determination (r^2) of 0.979 (*Eq.1*).

$$\text{Aboveground biomass (kg)} = 0.251\rho \mathrm{D}^{2.46} \tag{Eq.1}$$

The AGB in kg was then converted to tonnes per hectare. The carbon content of standing biomass was obtained from tree biomass multiplied by 50 per cent, as shown below (Kauffman and Donato, 2012):

$$\text{C content of each tree (kgC)} = \text{tree biomass (kg)} \times \text{conversion factor (0.5)} \tag{Eq.2}$$

Dry Bulk Density

The protocols for soil organic carbon (OC) were modified from Kaufman and Donato (2012), Schumacher (2012) and Hoyle (2013), where three parameters were considered to quantify soil carbon pool: 1. Soil depth, 2. Soil bulk density, and 3. Organic carbon concentration. In the determination of soil bulk density, the soil samples were taken in a known volume of 98.17 cm^3 with a metal corer, oven dried at 60°C, and weighed. The bulk density was calculated as the ratio of the dry mass of soil sample to its volume:

$$\text{Dry bulk density (g cm}^{-3}\text{)} = \frac{\text{Mass of dry soil (g)}}{\text{Original volume sampled (cm}^{-3}\text{)}} \tag{Eq.3}$$

$$\text{Soil mass}_{\text{at specified depth}}(\text{mg}) = \text{Bulk Density}(\text{mg m}^{-3}) \times 10{,}000\,(\text{m}^2) \times \text{Depth}(\text{m}) \quad (\text{Eq.4})$$

$$\text{Soil C}_{\text{at specified depth}}\,(\text{mg}) = \frac{\text{Soil mass}_{\text{at specified depth}}\,(\text{mg}) \times \%\text{OC}_{\text{at specified depth}}}{100} \quad (\text{Eq.5})$$

Organic Carbon in Soil Sediments and Organic Matter: Field Sampling and Processing of Soil Samples

The fieldwork was carried out quarterly, in May, August, and November of 2017, and in February of 2018, for one year. August and November represent the wet season and May and February represent the dry season. Thirty permanent plots, measuring 10x10 m, were established and quarterly monitored in both 10-25-YO planted and >50-YO natural mangrove stands in the three districts.

Sediment cores were taken from a 100 m^2 plot in each district (n = 5) and extracted for organic carbon (OC-S). The sediments extracted for organic carbon were sampled from the depths of 0-15, 15-30, 30-50 and 50-100 cm. Sediment sampling was done using a locally manufactured stainless soil corer measuring 5 cm in diameter and 175 cm in length. The volume of the cored OC-S totaled 98.17 cm^3. The soil samples collected quarterly were oven dried at 60^{o}C to a constant weight that was recorded. In preparation for CHN Analysis using CN 628 (LECO Corporation), all the quarterly soil subsamples were cleared from any large particles and wood debris, homogenized, and brought to the Faculty of Science, Prince of Songkla University.

The organic carbon derived from particulate organic matter (OC-POM) in soil samples is classified as the organic component of the soil, which is humus formed by the decomposition of leaves and other plant materials. The OC-POM contents were determined from the Loss on Ignition (LOI). The coring of the sediments was performed three times in each plot (n = 3 per plot) and the soil cores were extracted for depths of 0-15 and 15-30 cm, making a total of 15 subsamples (n = 15) for each district. The volume of the soil core was constant at 294 cm^3. Along with the soil classification, volumetric measurements were applied for further soil classification (Braley, 1992) as the soil was passed through a series of sieves, and the organic matter retained by the 1-2 mm mesh size was collected and air dried (Calumpong and Cadiz, 2012). After drying, the collected OM was put in an oven (Memmert UNB 500) at 60^{o}C until constant weight. From the original weight of the OM/humus, a portion of dried OM or subsample was weighed into a crucible. The crucibles were placed in a muffle furnace (Digital Muffle Furnace FX-14) at 450-500^{o}C for 4 to 5 hours. The organic matter content was calculated and converted to Mg C ha^{-1} (Howard et al., 2014) as follows:

$$\%\text{OM} = \frac{\text{Mass of oven dried soil or humus (g) - ashed soil or humus (g)}}{\text{Mass of original volume sampled (g)}} \times 100 \quad (\text{Eq.6})$$

Physicochemical Parameters

Measurements of redox (Eh), pH, and temperature were done *in situ* using a handheld portable ORP and pH meter (WTW 3210). The probe was inserted into the soil at 0-2 cm depth. Three readings were taken during the day between 9:00 am to 3:00 pm within the sampling period. Rainfall data were obtained from the Meteorological Department, Trang.

Statistical Analyses

Multivariate analysis was used to determine significant differences in CAGB and OC-S and other related parameters, by site and by month. Two-way ANOVA was also used to determine significant differences in OC-S by mangrove age and by sampling month. Levene’s test was applied in ANOVA for the equality of variances. When no significant differences were noted, the data were pooled by age and season and analyzed with a T-test. Post-hoc testing was performed to determine the variations by age (10-25-YO planted and >50-YO natural) and by season (wet and dry). Normality was tested with Shapiro–Wilk's test. Regression analysis was performed to find out the relationship between the production of OM and OC-POM, and DBD and OC-POM.

Results

Carbon Captured in Above Ground Biomass (CAGB)

The highest CAGB among all the sites was recorded in KD at 236.42±35.17 t C ha^{-1}, followed by PD at 181.30±23.25 t C ha^{-1}. The lowest was found in SD at 163.15+27.36 t C ha^{-1}. Results on CAGB combined by the two ages (10-25-YO planted and >50-YO natural forests) in all sites showed that the 10-25-YO planted forest had lower CAGB (143.37±19.12 t C ha^{-1}) than >50-YO natural forest (243.88±22.22 t C ha^{-1}) (p<0.001; *Table 1*).

Table 1. *Mean values of the vegetation structure*

Site/ Age	DE (stem ha^{-1})	BA (m^2 ha^{-1})	Height (m)	Biomass (t ha^{-1})	CAGB (t C ha^{-1})	OC-S (Mg C ha^{-1})*	OM (%)
SD 10-25	1650.00 ±583.90	0.72 ±0.05	15.32 ±0.38	283.39 ±100.23	141.70 ±50.12	193.62 ±15.31	18.04 ±2.17
SD >50	1360 ±286.05	1.19 ±0.10	15.41 ±0.19	369.22 ±50.11	184.61 ±25.05	214.35 ±15.91	23.44 ±1.82
KD 10-25	6220.00 ±459.78	0.57 ±0.02	15.71 ±0.20	325.08 ±46.25	162.54 ±23.13	317.75 ±16.18	23.14 ±1.83
KD >50	616.00 ±131.76	2.47 ±0.25	16.27 ±0.35	620.60 ±95.99	310.30 ±47.99	257.98 ±13.04	19.52 ±1.61
PD 10-25	3667.78 ±1364.81	0.30 ±0.02	15.71 ±0.20	251.72 ±50.05	125.86 ±25.02	305.24 ±29.75	16.31 ±14.52
PD >50	560.71 ±103.55	1.19 ±0.13	15.87 ±0.19	473.48 ±32.84	236.74 ±16.42	293.58 ±13.91	44.39 ±14.52

DE-depth, BA-basal area and H-height (Source: Cadiz and Chotikarn, 2018) CAGB-carbon in above-ground biomass, OC-S-organic carbon in soil and OM-organic matter in 10-25-YO and >50-YO mangrove forests in Trang, Thailand. * 1 metric ton = 1 mega gram (Mg) or 1 000 000 grams. Data represents Mean ± S.E.

According to the species with the most biomass was indicated in *Rhizophora apiculata* Bl. in both of the 10-25-YO planted and >50-YO natural forests in KD at 464.25±130.16 t ha^{-1} and 325.08±46.25 t ha^{-1}, respectively (Cadiz and Chotikarn, 2018). The higher biomass of these species also corresponds to the species of higher CAGB found in both 10-25 planted and >50-YO natural mangrove forests in the three sites as well ($p<0.05$; *Tables 1 and 2*). The *R. apiculata* were consistently high in most of the sites, particularly in >50-YO natural forest in KD (213.55±59.88 t C ha^{-1}). Among the species measured, the CAGB of *R. apiculata* were highest in all sites and between planted and natural sites (*Fig. 2*). For some species such as *Avicennia marina* (Forssk.) Vierh. and *Ceriops tagal* (Perr.) CB Rob, the CAGB located in PD >50-YO natural forest ranged from 1.50±1.50 t C ha^{-1} to 45.10±22.41 t C ha^{-1}.

Table 2. *ANOVA test to determine the significant effects of biomass in three different sites, age and sites vs. age at p<0.05*

Source	**df**	**SS**	**F**	***p***
Site	2	139614451.43	25.87	<0.001
Age	1	522219678.84	193.53	<0.001
Site vs. Age	2	180661336.55	33.47	<0.001

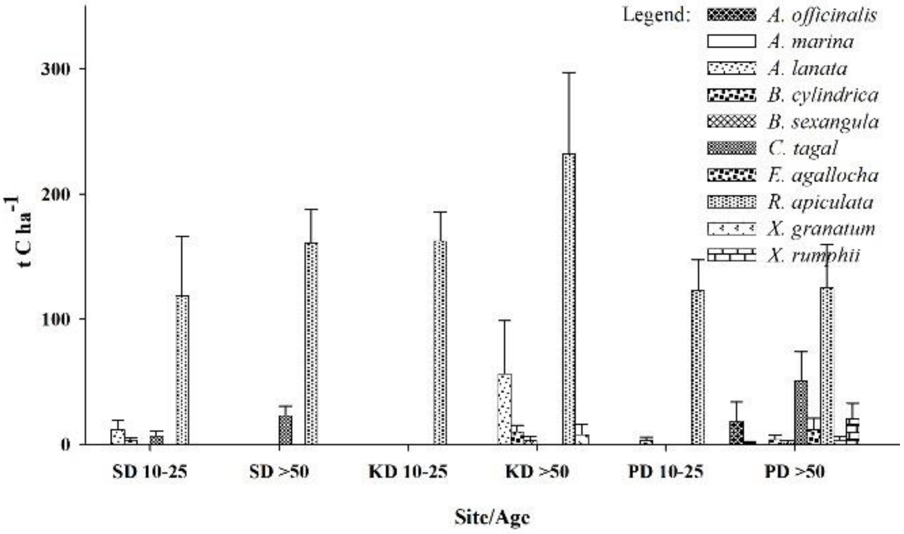

Figure 2. *Carbon content (t C ha^{-1}) of the different species calculated from AGB*

The Organic Carbon Stored Below Ground

Among the various sites, the organic carbon stored in the soil (OC-S) was significantly highest in PD at 299.41±15.60 Mg C ha^{-1}, followed by KD at 288.31±14.07 Mg C ha^{-1} The least was observed in SD at 203.12±10.95 Mg C ha^{-1}. Comparing between planted and natural mangrove, the 10-25-YO planted forest showed higher OC-S (272.49±14.55 Mg C ha^{-1}) than the >50-YO natural mangrove forest (254.73±10.93 Mg C ha^{-1}; $p>0.05$). A three-way ANOVA revealed no significant interaction among the sites, the months, and between planted and natural stands of mangroves (*p>0.05*; *Fig. 3*). The 10-25-YO planted mangrove at KD and PD obtained the OC-S values of 317.75±16.18 Mg C ha $^{-1}$ and 305.24±29.75 Mg C ha $^{-1}$, respectively (*Fig. 3*). Statistically significant variations only showed up in the mean quarterly OC-S in PD >50-YO natural forest, which was highest in August (377.46±14.21 Mg C ha^{-1}), followed by PD 10-25-YO planted forest in November (359.67±27.68 Mg C ha^{-1}). The SD 10-25-YO planted forest had the lowest OC-S at 171.10±22.87 Mg C ha^{-1} in February (*Fig. 3*).

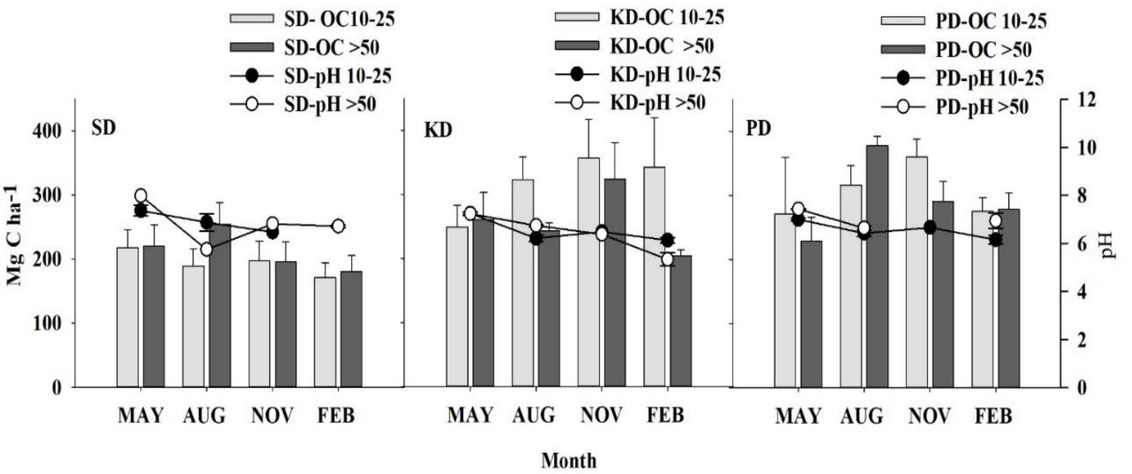

Figure 3. *Organic Carbon stock from soil (OC-S) (Mg-C ha^{-1}) and pH at different sites in 10-25-YO planted and >50-YO natural mangrove forests. Error bars are for S.E.*

Figures 4 and 5 show the overall mean OC-S for wet and dry seasons. The mean OC-S in wet season was significantly higher (285.52±12.49 Mg C ha^{-1}) than in the dry season (241.99±12.71 Mg C ha^{-1}; p<0.05; *Fig. 4*).

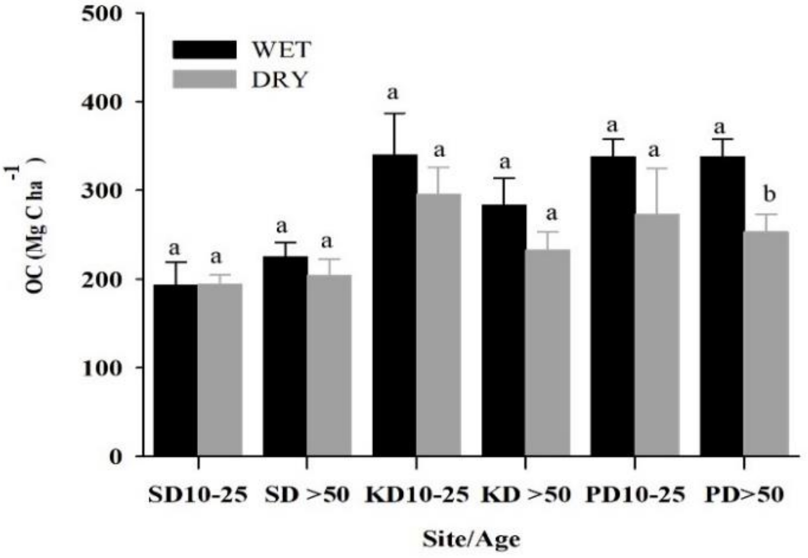

Figure 4. *Overall mean OC-S (Mg C ha^{-1}) in the soil sediments between wet and dry seasons and 10-25-YO planted forest and >50-YO natural mangrove forests. Error bars are for S.E. 'a' on top of the error bar indicates p<0.05 while b indicates p>0.05 in the different sites; n = 5*

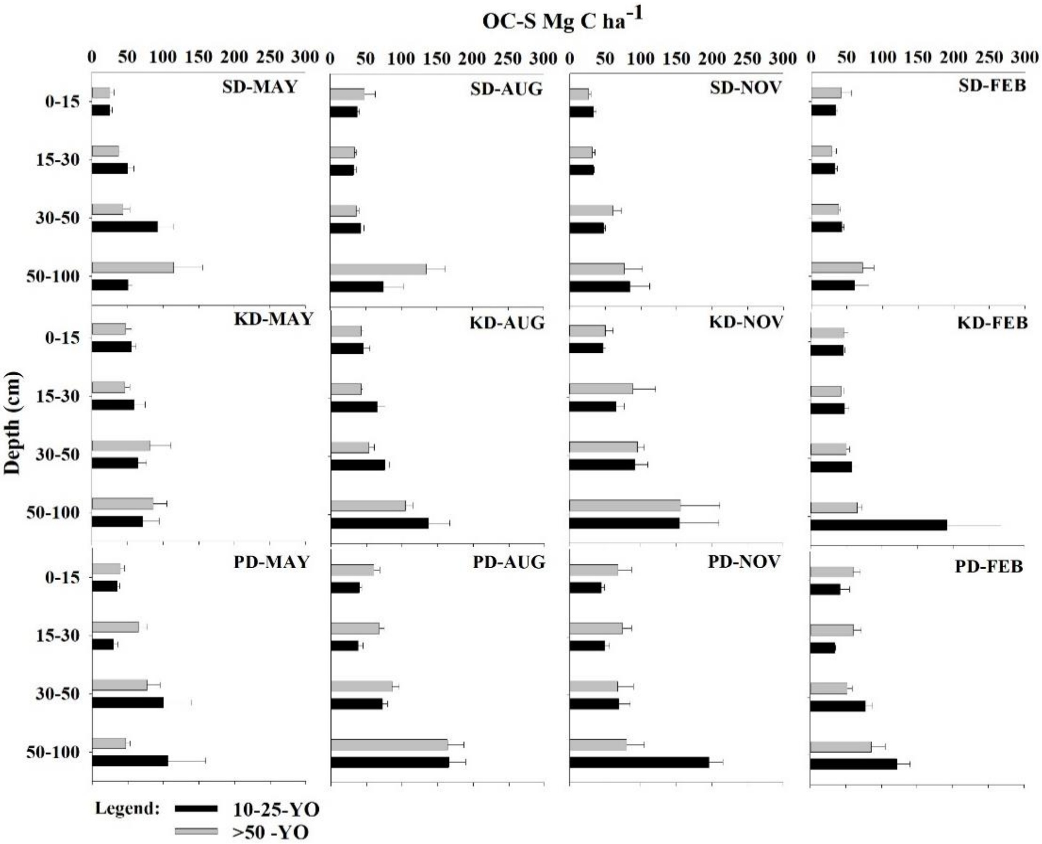

Figure 5. *Organic carbon from soil (Mg C ha^{-1}) stored in various depths in 10-25-YO planted and >50-YO natural mangrove forests in Trang, Thailand, sampled in August 2017 to February 2018. The error bars are for S.E.*

Figure 5 shows a summary of the mean quarterly OC-S and *Figure 6* shows the OC-S in each site and at various depths. The OC-S content varied with depth (0-15, 15-30, 30-50 and 50-100 cm depths). A factorial ANOVA indicated significant differences between 10-25-YO planted and >50-YO natural forests in PD (df=3.32 and 5.96; $p<0.05$) and no significant differences were indicated in SD (df=3.32 and 2.30, $p>0.05$) and KD (df=3.32 and 1.04; $p>0.05$) (*Table 3*). However, the overall trends across various depths in different sites showed higher OC-S at 50-100 cm depth in both 10-25-YO planted and >50-YO natural forest (*Fig. 5*). The values ranged from 27.19±2.25 Mg C ha^{-1} found in 0-15 cm depth in SD 10-25-YO planted forest to 161.17±25.79 Mg C ha^{-1} found in 50-100 cm depth in PD 10-25-YO planted forest (*Fig. 5*).

Dry Bulk Density

The trends in average Dry Bulk Density (DBD) of the sediments followed the same patterns as seen in OC-S. Overall DBD comparison between the two ages showed that 10-25-YO was higher (2.57±0.72 g cm^{-3}) and >50-YO forest was lower (2.34±0.17 g cm^{-3}) (*Fig. 6B*). In terms of the season, the results on DBD are similar to OC-S. It was higher during the wet season (3.10±0.11 mg cm^{-3}) than in the dry season (2.04±0.22 mg cm^{-3}) for both 10-25-YO planted and >50-YO natural (*Fig. 6A*).

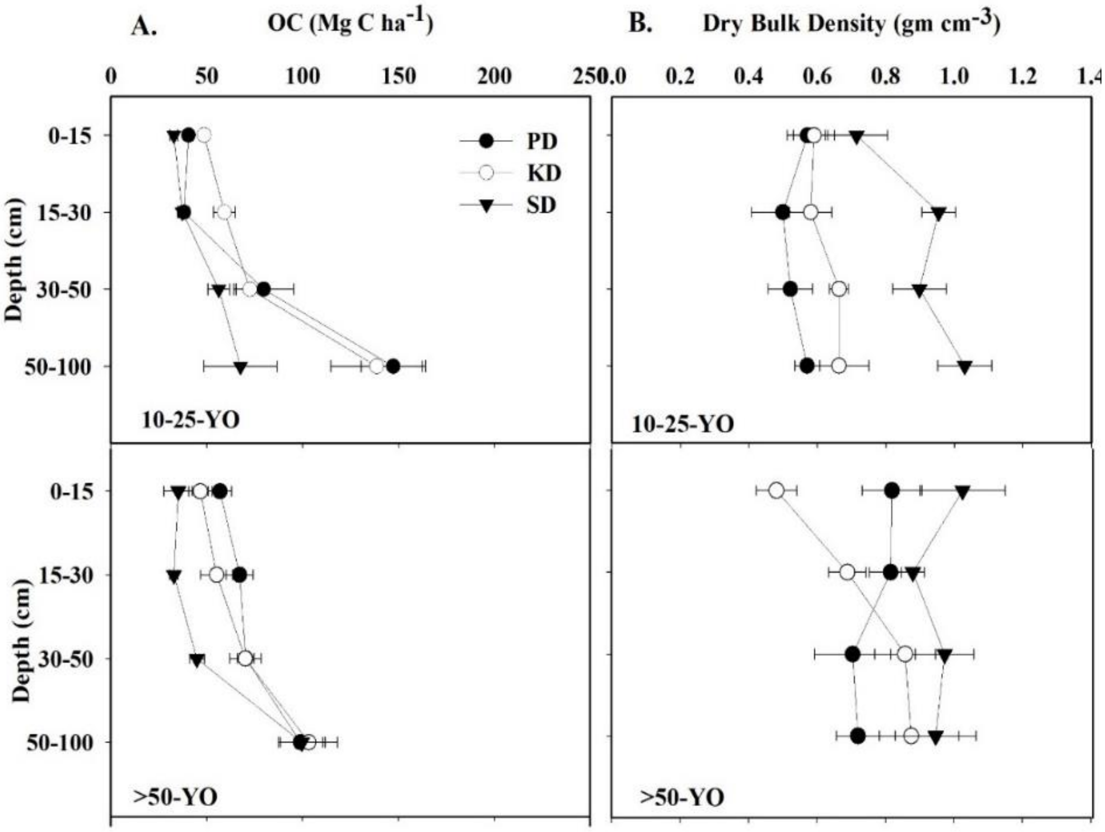

Figure 6. Mean OC-S (Mg C ha^{-1}; A) and Dry Bulk Density (g cm^{-3}; B) at different depths of 10-25-YO planted and >50-YO natural mangrove forests in Trang, Thailand. Error bars are for S.E.

Table 3. *The result of Two-Way ANOVA determining the effects on C of the following factors: Three different sites with 10-25-YO planted and >50-YO natural mangroves at four different depths (n=15)*

Sources of Variation	**Sites**								
	SD			**KD**			**PD**		
	df	**SS**	***p***	**df**	**SS**	***p***	**df**	**SS**	***p***
Age	1	0.18	0.450	1	0.05	0.020	1	0.00	0.680
Depth	3	0.56	<0.001	3	0.60	<0.001	3	0.69	<0.001
Age vs. Depth	3	0.18	0.090	3	0.09	0.390	3	0.36	<0.001

Organic Carbon derived from Organic Particulate Matter (OC-POM)

The organic carbon derived from decayed materials in the mangroves was classified as humus/particulate organic matter (POM) in this study. The OC-POM compared between ages was higher in >50-YO natural forest (74.29±33.57 Mg C ha^{-1}) than in the 10-25-YO planted forest (52.27±9.45 Mg C ha^{-1}; t(25)=2.44; $p<0.05$; *Table 1*; *Fig. 7A*). The peak of OC-POM was in May for both 10-25-YO planted forest (37.42±5.43 Mg C ha^{-1}) and for >5O-YO natural forests (35.01±10.76 Mg C ha^{-1}).

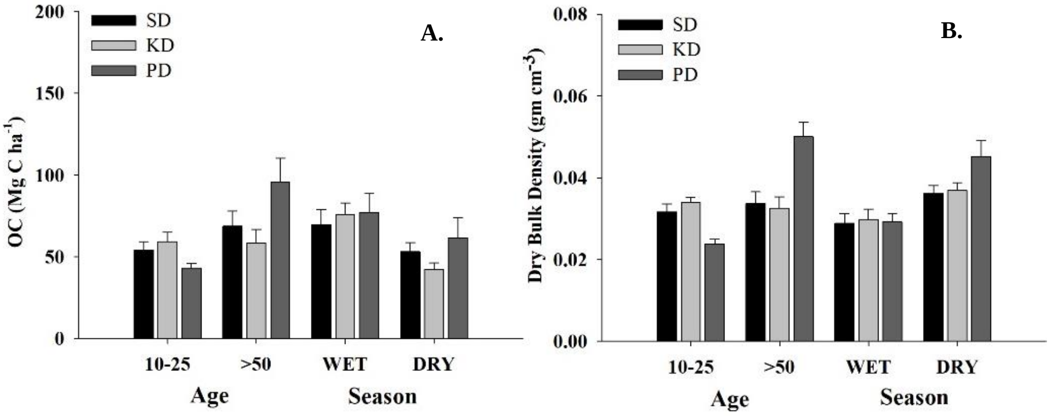

Figure 7. *OC-POM in Mg C ha^{-1} (A) and Dry bulk density in g cm^{-3} (B) from OM/humus in Trang districts. Error bars are for S.E.*

During wet and dry seasons the OC-POM followed the same trend as OC-S, being higher in the wet season (74.15±5.48 Mg C ha^{-1}) than in the dry season (52.41±5.69 Mg C ha^{-1}; p<0.05; *Table 3*; *Fig. 7B*).

Mean quarterly data of OC-POM varied significantly in >50-YO natural forests (Factorial ANOVA, F(3,732.88) = 3.21; p<0.05); and in the three different sites (Factorial ANOVA, F(14,1,750) = 3.21; p<0.05). The 10-25-YO followed the same pattern, (Factorial ANOVA, F(3,1,824) = 3.21; p<0.05 and F(14,86.44) = 1.68; p<0.05). OC-POM in the three sites were highest in August in PD 10-25-YO planted forest (59.23±27.72 Mg C ha^{-1}) and lowest also in PD 10-25-YO planted forest (8.07±0.85 Mg C ha^{-1}; *Fig. 7A*). The DBD followed the same pattern, with PD >50-YO natural forest being the highest at 1.97±0.22 g cm^{-3} (*Fig. 7B*).

In contrast to OC-S, the OC-POM showed variations in the 0-30 cm soil depth. Tested with linear regression, the mean quarterly POM (%) and OC-POM (Mg C ha^{-1}) appear to have no significant relationship (p>0.05) and only have a weak correlation (R^2=0.25) (*Fig. 8A*). DBD and OC-POM were not correlated either (p<0.05 and R^2=0.26) (*Fig. 8B*).

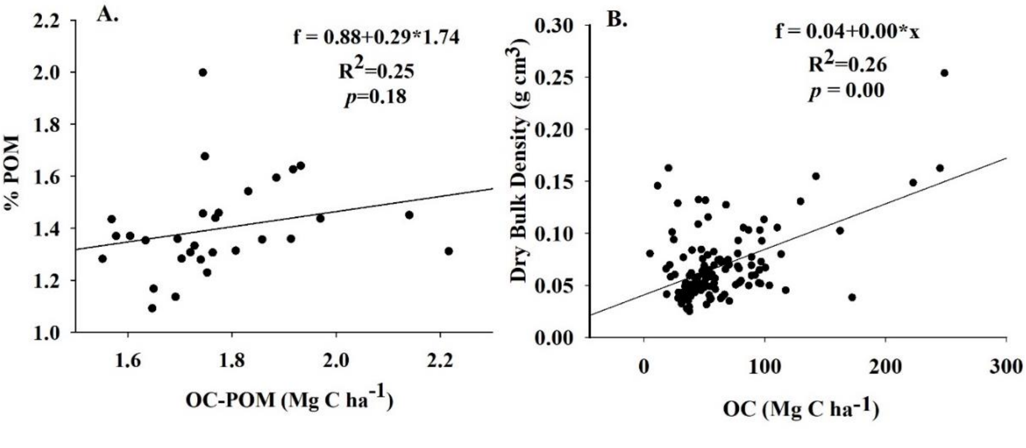

Figure 8. *The log-transformed percent OM and OC (A), and DBD and OC (B). All values are derived from OM*

Soil Characteristics

This study observed that silt/clay was the dominant soil type in both 10-25-YO and >50-YO mangrove forests in Trang (*Fig. 9A-B*). At depths of 0-15 and 15-30 cm, silt/clay dominated in the three sites and was followed by very fine sand and fine sand.

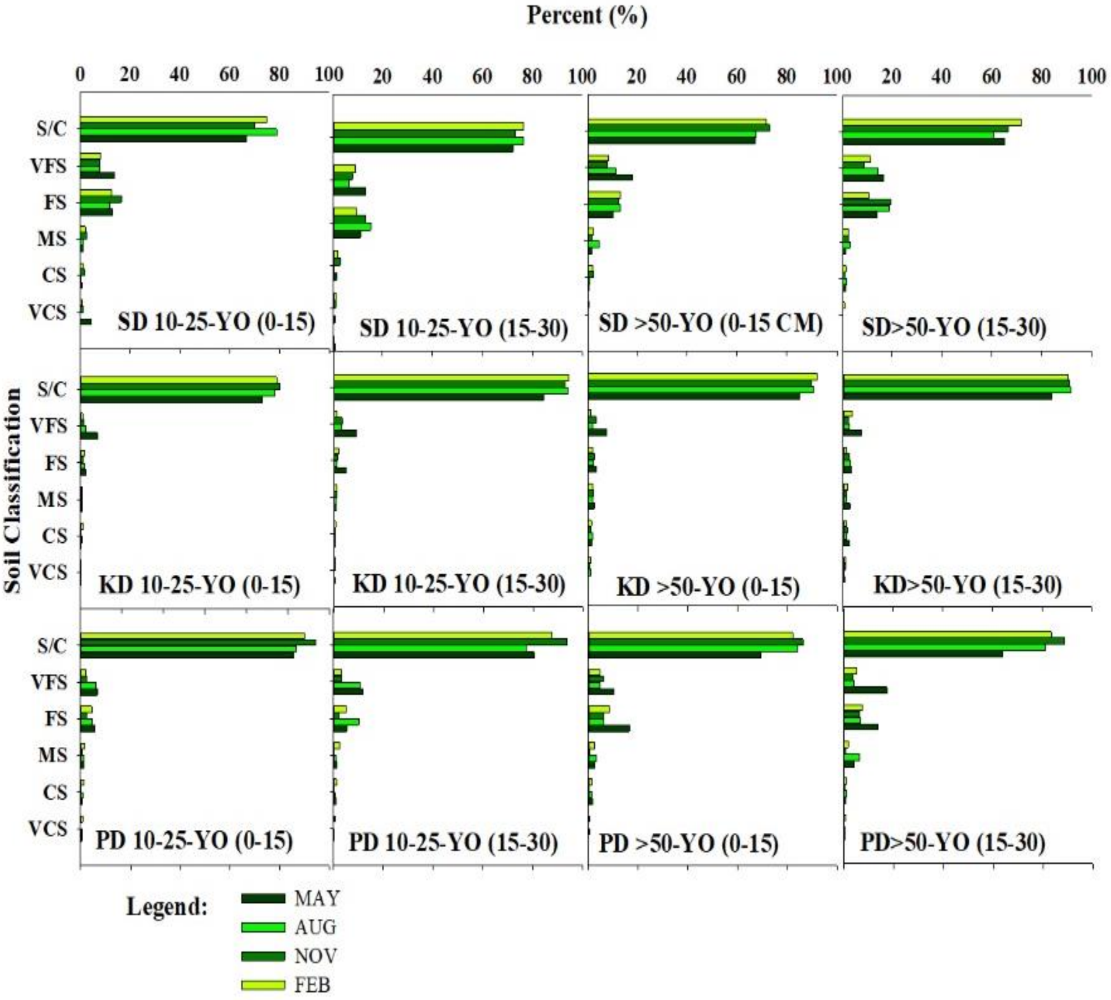

Figure 9. *Dominant characteristics (%) of soil in Trang, Thailand. VCS-very coarse sand, CS-coarse sand, MS-medium sand, FS-fine sand, VFS-very fine sand and S/C-silt/clay*

The Soil Properties

Figure 10 shows the soil temperature for the 10-25-YO planted and >50-YO natural mangrove forests. The mean soil temperature was 27.99±1.11°C in >50-YO forest and 28.08±0.55 in 10-25-YO forest. The mean value was higher in the wet season (M = 28.08±0.14°C) than in the dry season (M = 27.72±0.21°C); but this difference was not statistically significant (*p*>0.05). The average daily rainfall during the sampling period was highest in August (14.90±4.27 mm), followed by May (12.81±3.65 mm) and November 2017 (12.81±3.65 mm/day) (*Figs. 10 and 11*). February 2018 had the lowest rainfall (8.03±2.55 mm).

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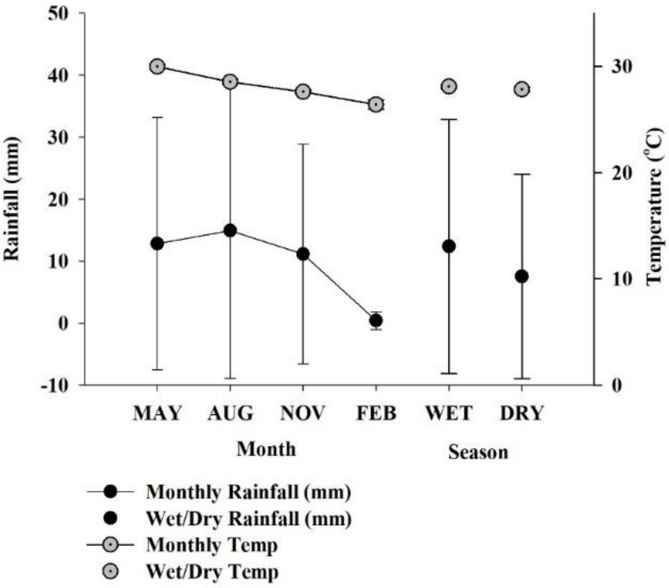

Figure 10. *Mean daily rainfall data (mm) and temperature (°C) during the sampling periods (Source: Meteorological Department, Thailand)*

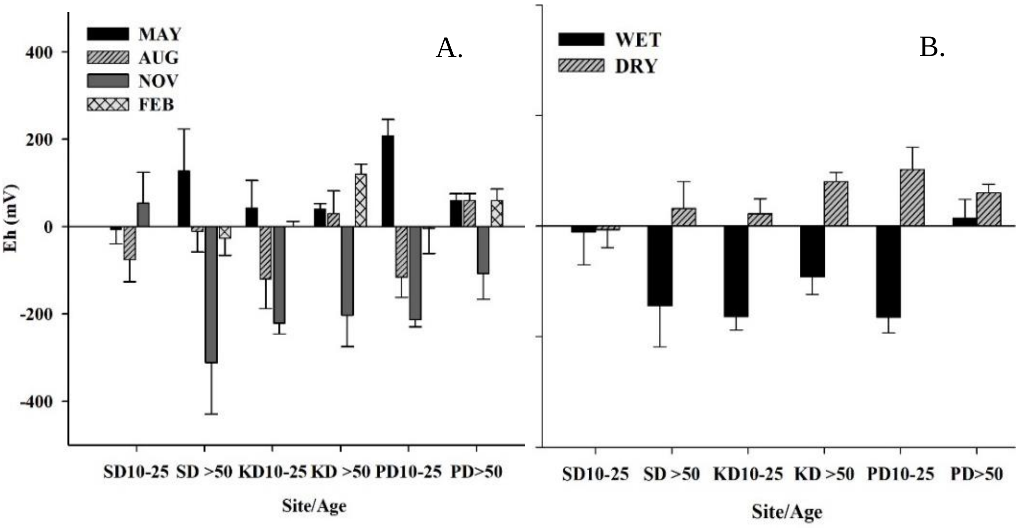

Figure 11. *Eh (mV) quarterly (A) and during the wet and dry seasons (B), in Trang, Thailand*

The pH of the soil had lower values in KD for both 10-25-YO planted (6.45±0.07) and >50-YO natural forest (6.45±0.04), while the highest pH (6.91±0.09) was observed in PD for the >50-YO natural forest (*Fig. 3*). The results were higher in the wet season (6.77±0.08) than in the dry season (6.59±0.04; $p<0.05$). Eh potential of the soil is characteristically anoxic ranging in -9.40±36.36 mV in SD 10-25-YO planted and in -62.40±19.00 mV in KD 10-25-YO planted forests (*Fig. 11*). The comparison between two seasons showed -93.62±21.59 mV during the wet season with the most anoxic soil found in PD 10-25-YO planted forest (-163.72±24.34 mV). Variation of Eh between the two seasons was statistically significant ($p<0.05$; *Fig. 11*).

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Discussion

Above and Below Ground Carbon, Dry Bulk Density and Organic Carbon from Particulate Organic Matter

This study investigated and monitored the organic carbon content in the 10-25-YO planted and >50-YO natural mangrove forests in the Southern part of Thailand. The findings showed that the variation of CAGB differed due to dense growth of *R. apiculata* in the 10-25-YO planted forest; while the >50-YO natural forests had mixed old stands of *Avicennia* spp*.*, *Rhizophora, Bruguiera* spp, *Ceriops,* and *Xylocarpus* spp. (*Fig. 2*). The composition of 11 species in >50-YO natural forest gave taller plants and a wider range of sizes (i.e. diameter at breast height of trees) and densities (*Fig. 2*) compared to the 10-25-YO planted with only 3 species, and dominated by *R. apiculata*. In particular, the dense and mono-stand vegetation in KD 10-25-YO planted in unutilized shrimp pond area (Cadiz and Chotikarn, 2018) confirmed these species as the main contributors to CAGB (*Figs. 1 and 2*).

The estimates of CAGB at three sites show trends comparable to the estimates obtained by Komiyama et al. (2008), and Ong et al. (1995). Ranges of CAGB values around Asia were studied (*Table 3*), and Malaysia showed 116.79 t C ha^{-1} (Chandra et al., 2011) and 305.46 t C ha^{-1} for natural and 122.78 t C ha^{-1} in degraded areas (Zhila et al., 2014). Putz and Chan (1986) reported 409 t C ha^{-1} in 30-YO and Ong et al. (1995) reported 114 t C ha^{-1} in a 20-year old dominantly *R. apiculata* in Matang Mangrove Reserve. The Philippines were in the range from 291.0 to 1578.6 t C ha^{-1} (Abino et al., 2014) in natural areas and 282.64 t ha^{-1} in 27-YO planted areas (Castillio and Breva, 2012). The 10-years old *Rhizophora mucronata* Lamk. and *Bruguira cylindrica* (L.) Blume planted in excavated shrimp pond areas in Khanom, Nakorn Sri Thammarat, Thailand, had 98.7 t C ha^{-1} and 28.8 t C ha^{-1} (Matsuie et al., 2012). It was also established in Ao Sawi, Thailand, that the above-ground biomass in old forest stands tends to have a higher capacity of carbon (about 27%) (Alongi et al., 2001); while this study had a similar trend of higher CAGB in >50-YO natural forest (243.88±22.24 t C ha^{-1}) than in the 10-25-YO planted forest (143.37±19.13 t C ha^{-1}; $p<0.05$). This is caused by more species in the natural stands than in planted stands, highlighting that the species diversity affects the production of CAGB (MacKenzie et. al., 2016).

Soil in mangroves is known as the largest source of organic carbon pool (Alongi et al., 2016), and carbon stored in the soil is the best indicator of productivity in the mangrove ecosystem (Boullion et al., 2008). The distribution and content of carbon stored in the soil are most likely dependent in geographic characteristics of the entire mangrove ecosystem, since all the established plots of the studied sites were directly connected with runoffs from tributaries of rivers, creeks/canals and adjacent shrimp ponds (*Fig. 1*) for ease and accessibility of sampling. However, we found that the similarities of OC-S content in both KD and PD have topographic influence as well. Unlike SD with lower OC-S because of the elevated topography characterized by the high boulders of crab mounds in both 10-25-YO planted and >50-YO natural mangrove forests (*Fig. 1A-B*). We observed that the large boulder crab mounds affect the consistency in coring the soil sediments. The crab mounds once covered the forest floor of the mangroves, and there is a high tendency to core the crab mounted areas instead of coring the forest floor; thus affecting the production of OC-S. These inconsistencies in sampling mangrove carbon affect the OC-S values obtained.

Between planted and natural stands of mangroves, this study observed that OC-S stored in the10-25-YO planted (272.49±19.16 Mg C ha^{-1}) is higher than in the >50-YO natural forest (254.73±11.74 Mg C ha^{-1}). Categorically higher values of OC-S in the 10-25-YO planted forests were due to the higher density of trees (*Table 1*). This characteristic was observed in the 10-25-YO planted forest in KD with the highest OC-S of 317.75±16.18 Mg C ha^{-1}. The compacted soil in the pond perhaps has a tendency and high ability to hold and store sediments and organic matter for a certain period of time, facilitating growth of these 10-25-YO planted forests (*Fig. 1A,B and D*). Another contributing factor in OC-S production is the possibility of higher turn-over rate of defoliation from younger trees apart from dense cover (as closely planted in the shrimp pond areas).

However, the overall mean OC-S obtained in this study was below the global value of 749 Mg C ha $^{-1}$) (Kauffman et al., 2018) but still comparable to observations in Singapore, Vietnam, Philippines, India, Africa, Palau and Micronesia and Brazil.

The temporal (dry and wet season) variations contributed to the variation of OC-S in the mangrove ecosystem. The higher OC-S during the wet season indicates that carbon buried in the soil favored by the right amount of rainfall and temperature (*Fig. 10*). Such that rainfall allows more water flow the movement (i.e., like density stratification and vertical circulation) (Mazda et al., 2007) which enhance the biotic activity of the mangrove soil and potentially contributing the OC-S production.

The overall trends in OC-S was to have more OC-S in deeper soil (50-100 cm depth) and this was particularly observed in the 10-25-YO planted forests in KD and PD (*Figs. 5 and 6*) where the OC-S increased with depth. Similar trend has been observed in the northeastern Brazilian mangroves (Kauffman et al., 2017) and Central-Western Region of Venezuela (Barreto et al., 2016). However, some studies have revealed the opposite trend with the concentration of carbon tending to decrease with depth (Ceron-Breton et al., 2014), because carbon also tends to be influenced by the rate of production of organic matter and not only the rate of decay (Alongi et al., 2016).

The derived OC-POM taken only at 0-30 cm depth is of primary concern in this study since rich POM is mostly found on surface of the forest floor. The result suggests no direct relationship between percent organic matter and OC-POM production (*Fig. 8A*). This indicates that OC-POM settled deeper while the OM settled more at the surface layer (0-30 cm depth) of the soil. The settled OM on soil surface allows more time to reach deeper prior to the integration of the OC-POM. The ingtegration of organic matter in the forest floor and soil profile will only come after the integration and mineralization process (Salmo et al., 2013). While this increases the production of OM in the surface layer, there is also a presence of new litter (Punwong et al., 2018) and then this gradually decreases in the deeper part of the soil. This study indicates that the source of organic matter was mainly the shrimp ponds channeled through canals and rivers (*Figs. 1 and 2*). Hence, the topography at a site influenced the flows and transport of OM in the mangrove stands. Apart from the allochthonous material deposits in the mangrove ecosystem, the presence of different species, tidal range, topography, sediment chemistry, community structure, and substrate characterisitcs (Dittmar and Lara, 2001; Chaikaew and Chavanich, 2017) therefore affect the derived OC-POM.

Overall, the variation and range of OC in mangroves is affected by how sampling is done, along with plot size, precision, and accuracy of allometric models (Rodriguez et al., 2014), species diversity (MacKenzie et al., 2016), hydrogeomorphology, climate and seasons (Ceron-Breton et al., 2014), while this study also considered soil depth induced variations in carbon measurements.

Soil Properties

The significance of soil characteristics such as soil type and composition are most influential in a mangrove ecosystem. The different mangrove species have different affinities to soil types (Calumpong and Cadiz, 1997) that influence the growth and survival of planted mangroves (Salmo et al., 2013). In this study, the results indicate that the soil type in most of the studied areas was muddy with typical silt/clay characteristics exhibited in the mangroves. As described regarding the study site, the deposition of fine particles that are carried with overflow from the big canals and rivers influenced stored carbon in mangroves. Since all the plots assessed were close to rivers, creeks or canals for ease and accessibility of working (*Figs. 1 and 2*), they had fine sand deposits and dense mangrove growth (Punwong et al., 2018), with silt/clay soil. Although the coring of the sediment for soil profile in this study was limited to 0-30 cm depth, the results suggest that silty/clay characteristics in both 10-25-YO planted and >50-YO natural forests tend to hold more carbon as one samples deeper (*Fig. 6A*). This characteristic contributes to the potential to retain organic carbon in the soil to influence DBD (Barreto et al., 2016; Phang et al., 2017). The soil profile in mangroves is generally dominated by silt/clay (*Fig. 9*) which is rich in organic clay and humus due to the biotic activity in the soil (Mazda et al., 2007). This is good for storing OC. This characteristic of soil is also found in Ao Nam Bor, Phuket, Thailand (Kristensen et al., 1995), following also the physical attributes in all the mangrove soils worldwide (Hossain and Nuruddin, 2016). However, the fact that mangroves exist in a wide range of soil types, even potentially within a single study area, contributes to large variability in reported soil C stocks.

Mangroves thrive well in tropical climate. The higher OC-S during wet season was enhanced by rainfall. In the process, the hydrological characteristics attributed by rainfall enhanced the biotic activity of the soil, thus influenced carbon stored in the mangrove soil. On May 2017 during the onset of rainy season, the second highest rainfall took place (*Fig. 8*), while February 2018 was the peak of the dry season, and rain occurred during sampling. However, the soil temperature averages over wet and dry seasons were considerably high, ranging within 24.76-30.02^{o}C compared to 26.99-27.69^{o}C in Phetchaburi (Jitthaisong et al., 2012) or 25.8 to 28.9^{o}C in Tungka Bay, Chumpon, Thailand (Matsuie et al., 2015). Temperature and precipitation are known to influence the survival and growth of mangroves (Numbere and Camilo, 2017), as well as carbon densities.

Evidence of low pH and high redox was observed in KD during the wet season. The 10-25-YO planted area in KD located nearby a rubber plantation, and a former site with land-use change from shrimp farming activities. Perhaps this activity had left nutrients to influence Eh. Categorically, all sites for both stands had highly anoxic soil during the wet season (*Fig. 11A*). Anoxic soil causes faster decomposition of organic matter as revealed by the higher OC-POM during the wet season (*Fig. 7A*). What made Eh high in KD was that the planted mangroves were in an intact abandoned shrimp pond. The infiltration of rainfall in the pond took longer time, while allowing organic matter to settle in the pond. Further, the OC is highly correlated with pH and Eh because of its relation to transport in the mangrove ecosystem. Also the mobilities of phosphorus and magnesium depend on pH and Eh (Matsui et al., 2015). In addition, disturbing mangrove areas triggered the formation of pyrite (a feature of mangrove sediments), which also influenced pH and Eh. This oxidation process occurs typically after a mangrove forest is cleared for aquaculture purposes, like shrimp ponds (Kristensen et al., 1995). Overall, however, neutral soil characteristics were observed in this study.

Conclusions

1) Based on this study, the knowledge gaps on the carbon storage potential of restored mangrove (mostly planted in abandoned shrimp ponds) and mangrove on natural stands were addressed. Sources and sinks of carbon in both types of stands were found in CAGB, OC-S and PO-POM, and their differences were influenced by the community structure and vegetation. The observed large variations in CAGB were likely due to the complexity of species; such as in >50-YO natural forests had 11 species while the 10-25-YO planted mangrove only had 3 species and was dominated by *R. apiculata*, in contrast to higher densities in planted stands than natural stands. Therefore, this study suggests that conservation of mangroves in natural stands remains the first and foremost source and sink of C.
2) While the soil samples cored in crab mounted areas such as in SD showed lower OC-S densities it is best to recommend that further study should be conducted at other sites with the same crab mounted characteristics. This is to ensure that a well-defined inventory approach in assessing ecosystem C stocks is necessary to better account for the heterogeneity in topographic characteristics.
3) This study also demonstrated that both stands of mangroves act as carbon sinks, and therefore planted stands are also carbon sinks similar to the natural stands, provided similar geomorphic and topographic characteristics. The significance of restored mangroves is that even relatively young stands of mangrove forest can sequester a substantial amount of carbon, stored either aboveground in biomass or below ground in the soil. These findings provide additional information for developing strategies for the management of carbon in relation to land-use change (Donato et al., 2012), particularly on reverted shrimp pond areas.
4) Furthermore, all restoration activities need to be well maintained and sustained by the local people, who should appreciate the indirect values of mangroves, specifically as carbon sinks. Since only little is known and no particular research has been done on the active involvement (i.e., experiences and motivations) of the local community towards blue carbon governance (Thomas et al., 2014), and for better management, trainings of the local people for blue carbon initiatives and governance should also be initiated.
5) Overall, this study showed the potential of natural as well as planted stands of mangrove in storing carbon in order to encourage and pursue local sectors of Trang, Thailand and policy makers in both local and national agencies to continue the efforts in mangrove restoration, particularly in areas abandoned from aquaculture activities.

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