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Research article

Assessment of factors that influence carbon storage: An important ecosystem service provided by mangrove forests

Kanokporn Swangjang [a,*], Kamolchanok Panishkan [b]

[a] Department of Environmental Science, Faculty of Science, Silpakorn University, Nakhonpathom, 73000, Thailand
[b] Department of Statistics, Faculty of Science, Silpakorn University, Nakhonpathom, 73000, Thailand

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ABSTRACT

Mangrove ecosystem services (ES) support the global carbon (C) cycle. This study aimed to assess factors affecting the loss or gain of C stocks in mangrove forests in Thailand. Two fundamental considerations were taken into account, including ES supplied by mangroves from the perspective of C stocks, and the potential for C loss resulting from human activities conducted in mangrove forests. Three different land-use types in mangrove forests were studied: an area encroached upon by the local population (L1), a conservation area (L2), (both of which were dominated by the mangrove species *Avicennia alba*), and a seaside area. Based on their average height and diameter at breast height (DBH), most of the mangrove trees were determined to be young. The highest importance value index (IVI) was seen for *A. alba*, at 224.73 (L1) and 213.79 (L2). Above- and below-ground C levels were 189.97 t-Cha^{-1}, 77.11 t-Cha^{-1} in L1 and 81.73 t-Cha^{-1}, 32.54 t-Cha^{-1} in L2. Soil C stocks were 60.95 t-Cha^{-1} (L1) and 43.71 t-Cha^{-1} (L2). Statistical analysis indicated that nitrogen was the crucial factor influencing soil C in both L1 and L2. Overall, the total mangrove C stocks in L1 were estimated to be 328.64 t-Cha^{-1}, which surprisingly was higher than in L2, at 290.34 t-Cha^{-1}. The potential change in C stocks was then assessed. This showed that demand for mangrove resources resulted in the permanent loss of C stocks, particularly within plant communities, as the major fraction of C was from above-ground C stores. The loss of 1 ha of mangrove vegetation was estimated to result in the loss of 77.71–189.97 t-C/ha^{-1} and 32.54–81.73 t-Cha^{-1} in L1 and L2, respectively. Different approaches to mangrove management based on the differing supply and demand for ES are recommended.

1. Introduction

Ecosystem service (ES) frameworks have been established as a powerful tool with which to facilitate communication between scientists and policymakers and foster the implementation of more sustainable land-use practices (Zoderer et al., 2016). A classification of ES proposed by the Millennium Ecosystem Assessment (MEA, 2005) has been widely adopted, according to the outcomes of supply and demand in a given ecosystem (Balvanera et al., 2016), although many other frameworks have been proposed that aim to make such classification more relevant to decision-makers, economists, and ecologists (Kienast and Helfenstein, 2016).

Mangrove forests are important ecosystems whose wide range of ES support social, economic, and environmental interests (Mangkay et al., 2013; Castillo et al., 2017). Mangrove forests are a specific type of habitat, located between the latitudes of 30° N and 30° S (Teka et al., 2019), and thus can be found in tropical and subtropical regions (Gillerot et al., 2018). Approximately 28% of all mangrove forests are located in Southeast Asia (Brander et al., 2012). Mangrove ecosystems are of particular importance as a pool of stored carbon (C) and their potential for C offsetting schemes (Gillerot et al., 2018). Besides their capacity for C storage, mangroves are one of the most productive ecosystems on the planet, providing human societies with a range of ecosystem goods and services (Barbier et al., 2011). The services provided depend on the specific features of mangrove forests, their structure, and their characteristics. ES provided by mangrove forests include regulatory services, provision services, and cultural services (Uddin et al., 2013). Climate regulation is one of the most important ES and one in which mangrove forests play a key role, as they can have an important impact on C stocks (Vauhkonen and Packalen, 2018).

Unfortunately, mangrove forests are threatened by numerous human activities, especially through being cut down to make way for

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* Corresponding author.
E-mail address: swangjang_k@su.ac.th (K. Swangjang).

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aquaculture, urban development, recreation, and other purposes (Vo et al., 2012). Globally, mangroves have disappeared at a rate of loss of 1–2% each year, with a total loss of 35% during the past 20 years (Carugati et al., 2018; Swann, 2018). Brander et al. (2012) estimated the loss of mangrove forests in Southeast Asia for the period 2000 to 2050 and predicted a decrease from 6,042 to 2,082 ha, a loss in ES worth approximately USD 2.16 billion. The conversion of mangrove forests to other types of land use is a serious problem because of the reduced production of detritus, increased erosion rates, increased oxidation of soil organic carbon (SOC), and the release of stored C (Chhabra et al., 2003; Timilsina et al., 2014). Sanderman et al. (2018) indicated that in the year 2000, mangrove forests held around 6.4 billion metric tons of C in the form of SOC; up to 122 million tons of this C was released between 2000 and 2015, with more than 75% of these C emissions from soil resulting from mangrove deforestation in Southeast Asian countries.

Soils deliver a wide range of ES, including food production, water and climate regulation, energy provision, and biodiversity (Greiner et al., 2017). The provision of soil ES depends on the complex biological, physical, and chemical properties of soil and their interactions with crop management techniques. Soil functions, especially in terms of the C pool and the production of biomass, are closely related to soil quality, which also determines a soil's capacity to deliver ES (Dietze et al., 2019). Soil C stocks (SC stocks), which could be almost double the C pool stored as biomass (Kaul et al., 2010), are regarded as being of major importance for the ES value of mangrove forests. The potential of SC stocks has been proposed as one way to mitigate emissions of the greenhouse gas, CO_2 (Chhabra et al., 2003; Nam et al., 2016).

The loss of mangrove forests affects the functioning of local ecosystems and the provision of ES (Bhomia et al., 2016). Zhao et al. (2004) noted that the actual services provided by ecosystems and the value of these services are site specific, hence it is preferable to determine the nature and value of ES at a small scale. The present study aimed to assess the factors influencing C stocks in mangrove forests. Rigorous impact assessments are required prior to undertaking any mangrove reclamation activities (Zhao et al., 2004). There are two fundamental considerations to take into account: 1) ES supplied by mangrove vegetation and soils from the perspective of C stocks; and 2) the potential for C loss resulting from activities conducted in mangrove forests. Mangrove plant community structure and soil analyses were considered for their impact on C stocks and as important suppliers in mangrove ecosystems (Lunstrum and Chen, 2014). These factors could influence C storage both above- and below-ground; C storage is a crucial ES provided by mangroves that helps to support the global C cycle. Finally, ways to protect ES provided by mangroves, based on local conditions, are recommended.

2. Materials and methods

2.1. Study area

The study area (Figure 1) is located along the western coast of the Gulf of Thailand, between latitude 13°19′-13°27′ N and longitude 99°56′-100°05′ E. The climate is tropical, with an average annual temperature of 33 °C and rainfall 1044 mm yr^{-1} (Thai Meteorological Department, 2020). Mangrove forests in the area have been influenced by human exploitation and activities, particularly aquaculture and ecotourism (Swangjang and Bunpraserth, 2017). An overview of the study framework is shown in Figure 2. Transect lines were set up in two zones of mangrove habitat and designated as land use 1 and 2. Land use 1 (L1) comprised disturbed land, which included land adjacent to areas encroached upon by local people for aquaculture and building purposes. Human activities can directly affect mangrove resources, usually by reducing the number of mangrove trees as well as from the release of polluted water from aquaculture farms. These activities have been increasing continuously in this part of Thailand, which has led to the Thai Government regulating some areas in this region to encourage reforestation through the creation of protected zones. Land use 2 (L2), which acted as a control zone, comprised the original forest, which is an area connecting the encroached forest with the untouched shoreline forest. This area has generally not been directly affected by local human activities. L1 and L2 not only differed in their land use histories but also in their distance to the shoreline, which is also likely to have an impact on the species present, the forest structure, and soil characteristics.

A reforestation policy was initiated in Thailand in 1989, which was a positive development for mangrove recovery (Thai Department of Marine and Coastal Resources (DMCR), 2018). However, there are many government agencies involved, including the Department of Marine and Coastal Resources (DMCR), the Department of Mineral Resources (DMR), the Department of Land Development (DLD), the Department of Lands

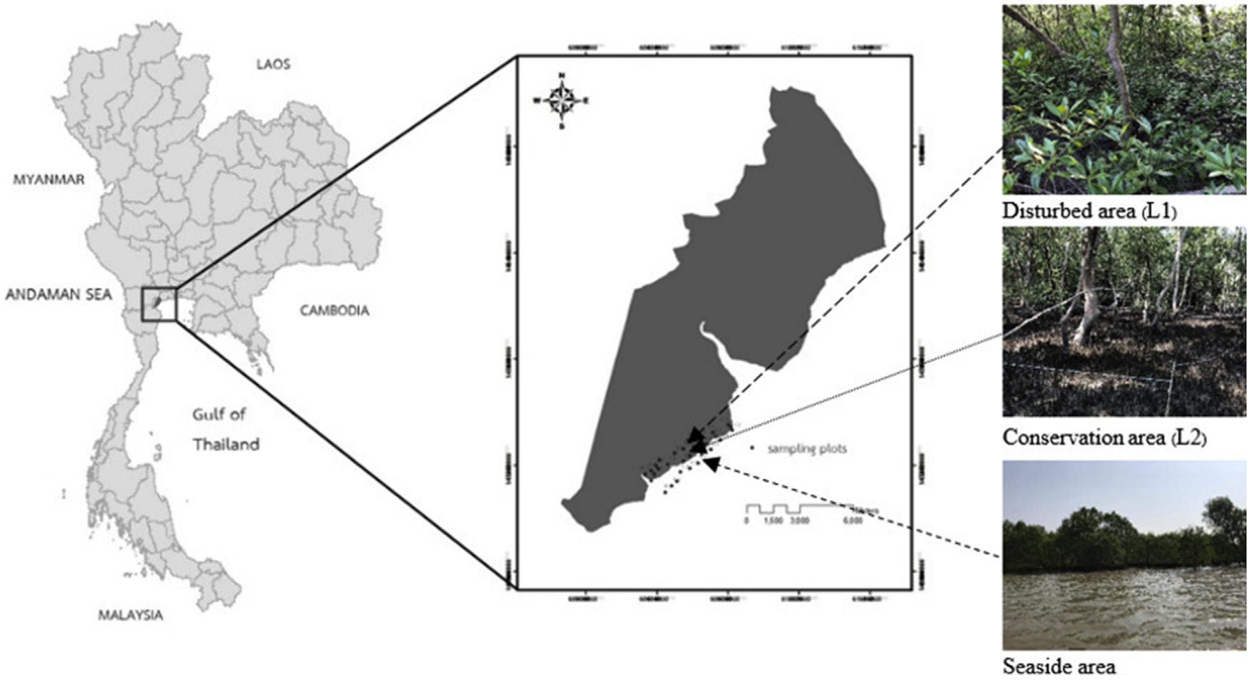


Figure 1. Location of the study area.

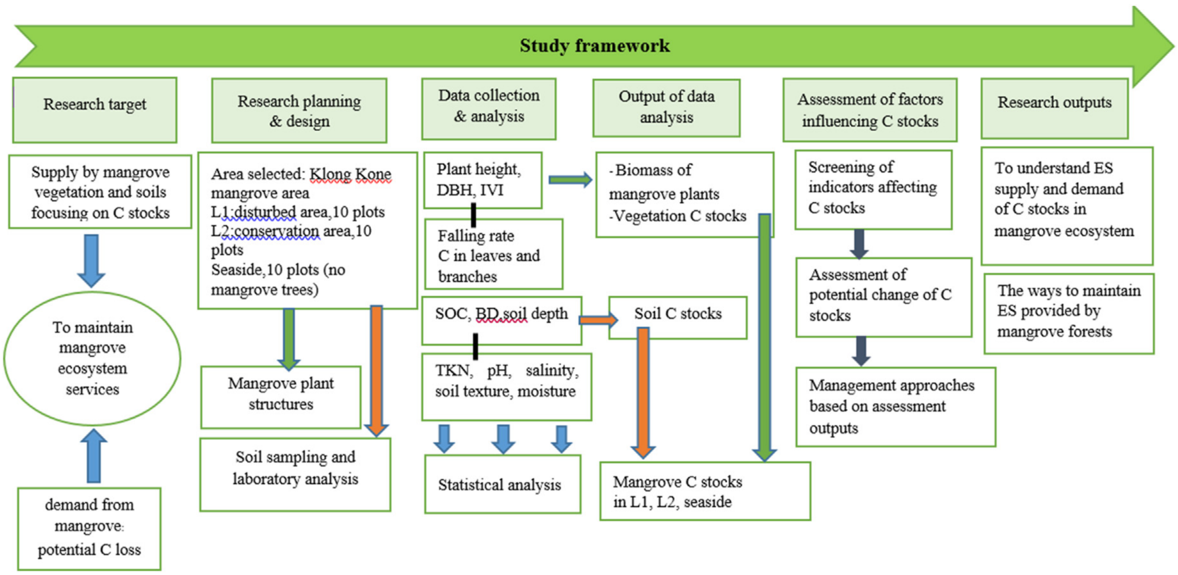


Figure 2. Study framework.

(DL), the Department of Public Works (DPW), and Town and Country Planning (TCP). They each have various responsibilities to undertake in connection with mangroves; as a consequence, some conflicts among policies have emerged, in particular between ways to continue the exploitation of mangroves and efforts to conserve them. For example, DMCR established land-use zones in 2009, which included protected areas and rented areas, mostly for the purposes of aquaculture and ecotourism. However, in 2017, TCP classified these mangrove areas to be used for community purposes.

2.2. Mangrove community structure

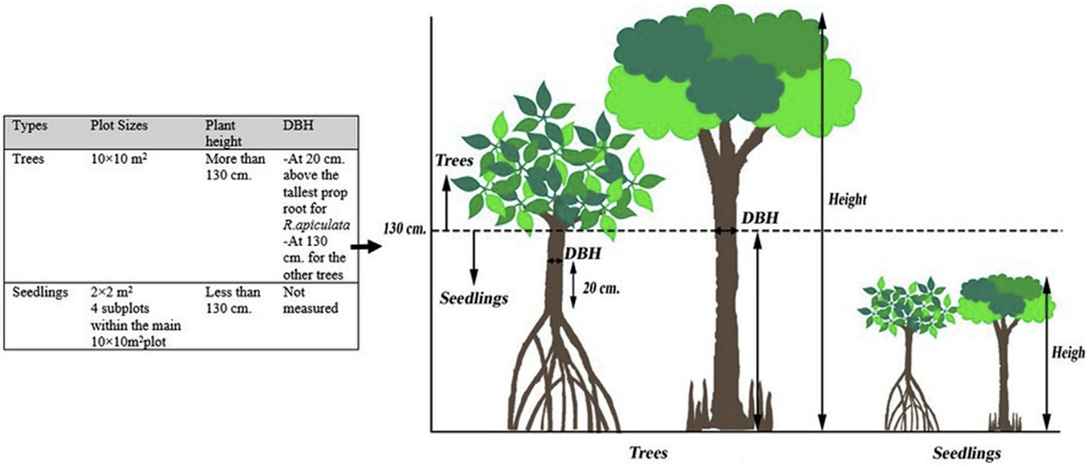
Fieldwork was conducted during February 2019, in Thailand's dry season, which is influenced by the northeast monsoon. Twenty plots were established, ten in disturbed areas (L1) and ten in undisturbed areas (L2); the latter have been classified as conservation areas according to DMCR policy since 1989. Ten plots, with a distance of 1 km between each plot and comprising a line of longitudinal transects, were made using quadrats of 10 × 10 m^2 for trees and 2 × 2 m^2 for seedlings. Plants of height more than 130 cm were classified as trees and less than 130 cm as seedlings. Plants of height less than 50 cm and without branches were excluded from the survey (Bulmer et al., 2016). As the diameter at breast height (DBH) of mangrove plants was generally less than 10 cm, in this study, both saplings and trees were classified in the same group. Data recorded in each quadrat included the number of each individual species, tree height (m), and DBH (cm) at 130 cm for trees, excluding *Rhizophora apiculata*, for which the DBH was measured 20 cm above the tallest prop root (Figure 3). Mangrove plant community composition and structure was calculated to derive mangrove characteristics, including (relative) density (the number of individuals of a species per plot area), (relative) coverage (basal area of each species), and (relative) frequency (the number of a kind plots occupied per the number of whole plots) (Mangkay et al., 2013). The importance value index (IVI) of each species was calculated using the following equations (Curtis and McIntosh, 1950):

$$\text{Relative frequency(RF)} = \frac{100(\text{frequency of occurrence of a species})}{\text{sum of the frequency of all species}} \tag{1}$$

$$\text{Relative density(RD)} = \frac{100(\text{density of current species})}{\text{total density of all species}} \tag{2}$$

$$\text{Relative coverage(RC)} = \frac{100(\text{basal area of current species})}{\text{basal area of all species}} \tag{3}$$

For trees: Importance value index (IVI) = relative frequency + relative density + relative coverage (4)



Types	Plot Sizes	Plant height	DBH
Trees	10×10 m^2	More than 130 cm.	-At 20 cm. above the tallest prop root for *R.apiculata* -At 130 cm. for the other trees
Seedlings	2×2 m^2 4 subplots within the main 10×10m^2plot	Less than 130 cm.	Not measured

Figure 3. Mangrove plants and their classification.

$$\text{For seedlings: IVI} = \text{relative frequency} + \text{relative density} \quad (5)$$

To calculate the biomass of trees, the allometric equations of Komiyama et al. (2005) for the above-ground and below-ground biomass were employed. The coefficients from these equations, developed for Thai mangrove trees and based on Komiyama et al. (2005), were as follows:

$$\text{Above-ground wood biomass} = 0.251\ \rho\ D^{2.46} \quad (6)$$

$$\text{Below-ground root biomass} = 0.199\ \rho^{0.899}\ D^{2.22} \quad (7)$$

The ρ values according to Komiyama et al. (2005) were found to be: *Avicennia alba*, 0.506; *Rhizophora apiculata*, 0.770; *Rhizophora mucronata*, 0.701; and *Xylocarpus granatum*, 0.528. Conversion of tree mass to the equivalent quantity of C was performed by multiplying the biomass by a conversion factor of 0.4633, based on values for mangrove trees in Thailand (Thai Greenhouse Gas Management Organization, 2008).

2.3. *Falling rate*

The amount of litter was determined from the rate of falling leaves and branches, by placing containers that accurately measure the volume of fallen leaves and branches under each mangrove species for 24 h. Ten replications for each individual species were performed in February (dry season) and June (wet season). The start and finish times of each replication were recorded. The specimens were weighed, and the falling rate was calculated ($\text{gm}^{-1}\text{day}^{-1}$). The litter comprising leaves and branches was separated and the samples were air dried. The calculation used to determine the total density of leaves and branches was as follows (Camacho et al., 2011).

$$\text{Total density of leaves and branches} = \text{dry weight (g)/volume (cm}^3\text{)} \quad (8)$$

The average densities of the ten replications for each individual species for both periods were calculated.

2.4. *Carbon in leaves and branches*

Total carbon (TC) in leaves and branches was determined using a CHN Analyzer (LECO 628 series). Organic carbon (OC) content was determined for the leaves of each mangrove species, using the loss of weight on ignition method (LOI%) (Ben-Dor and Banin, 1989). OC content was then calculated using Kauffman and Donato's equation (2012):

$$\text{OC (\%)} = 0.415 \times \text{LOI\%} + 2.89 \quad (9)$$

The results of falling rate and OC content values of leaves and branches will be discussed later in terms of their potential as ES provided by mangroves.

2.5. *Soil sampling and analysis*

Soil sampling was undertaken in three areas, including the L1 and L2 plots used in the mangrove study and from an additional location near the seaside. Soil indicators were selected based on soil functions related to the C pool in soil (European Commission, EC 2006). SOC was the main indicator. Factors that affect SOC include soil texture (Zhong et al., 2018) and bulk density (BD) (Kauffman and Donato, 2012). Soil nitrogen (N) was also selected to enable consideration of the C:N ratio (Bulmer et al., 2016). Soil samples were taken at a depth of 30 cm using a core sampler. In each of the plots, five samples were taken, including a sample from each corner of the quadrat and one from the center. Soil samples were then composited and taken to be representative of each plot. The samples were oven-dried at 60 °C and passed through a 2-mm sieve to analyze BD and texture and a 0.5-mm sieve to analyze the remaining parameters. Soil analyses were performed as follows: soil texture was determined using the hydrometer method (Bouyoucos, 1962), pH was measured using a pH meter, salinity was determined using the conductivity method (Rhoades, 1993), BD was determined by the core method (Culley, 1993), SOC was determined using the Walkley and Black method (Walkley and Black, 1934), and total nitrogen (TKN) was determined using the Kjeldahl method (Sparks et al., 1996). Carbon stock was calculated according to the following equation (Guo and Gifford, 2002):

$$C_{\text{stock}} = \text{SOC} \times \text{BD} \times \text{D} \quad (10)$$

where C_{stock} is carbon stock in soil (t-Cha^{-1}), BD is bulk density (g.soil.m^{-3}), and D is the soil depth (cm).

2.6. *Statistical analyses*

All statistical analyses were performed using the statistical Package for Social Sciences (SPSS) version 23.0 for Windows (IBM Corp., 2015). Pearson's correlation coefficients were calculated to determine statistical correlations between soil properties in each area. Multiple linear regression with a stepwise selection method was used to fit a model describing associations between SOC and the factors influencing SOC. Basic assumptions for the least squares method were checked, which was to ensure the errors in the regression model were independent and normally distributed, with constant variance.

3. Results and discussion

Mangroves in the study area decreased between 1997 and 2007, but then increased slightly between 2007 and 2012 because of a government policy together with increased muddy areas resulting from mangroves being replanted along the coast. By 2017, mangroves covered 7.07% of the total land in the study area. The majority of land use was dedicated to aquaculture, which had increased from 44.57% in 1997 to more than 80% in 2017 (Thai Department of Marine and Coastal Resources, 2018). According to our survey, the aquaculture areas included both active and abandoned ponds, while mangrove areas were also used for some types of aquaculture that do not use pond methods. These findings agreed with those of Barbier et al. (2011), who indicated that aquaculture expansion has been the dominant force behind global mangrove deforestation, in particular the expansion of shrimp farms.

3.1. *Structural attributes of mangroves*

A decline in mangrove forests directly affected the community composition of plants, which are the primary producers of an ecosystem, in the habitat we studied. The results of the plot count shown in Figure 4 illustrate the plant composition within the mangrove forests. In L1, the dominant mangrove species was *Avicennia alba*, with a density of 23.6 stems ha^{-1}. *Rhizophora mucronata*, *Xylocarpus granatum*, and *Nypa fruticans* were also found in the encroached area of L1. In L2, the most

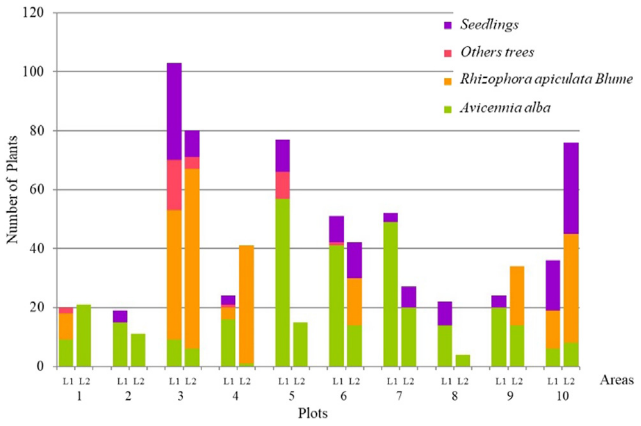


Figure 4. Plant community structures in land-use areas 1 and 2.

Table 1. DBH (cm) and height (m) of mangrove plants by species.

Species	The number of individual trees by DBH range (cm)					The number of individual trees by height range (m)				
	<10	10–20	20–30	30–40	>40	<5	5–10	10–15	15–20	>20
A. alba	56	220	38	8	28	258	35	35	18	4
R. apiculata	223	21	-	-	-	192	31	20	1	-
R. mucronata	26	-	-	-	-	24	2	-		-
X. granatum	8	-	-	-	-	8	-	-	-	-

common mangrove species was *R. apiculata*, with a density of 17.40 stems ha^{-1}. The total plant density in L1 (33.60 stems ha^{-1}) was greater than that in L2 (29.20 stems ha^{-1}). In both land-use types there was a large number of seedlings. Seedlings were prominent despite the areas approaching the encroachment zone. Hence, preventing the invasion of mangrove forests is important for maintaining mangrove ecosystems.

In terms of DBH (Table 1), *A. alba* showed various DBH values, mostly between 10 and 20 cm. For other plant species, the DBH was less than 10 cm. Similarly, for plant height, the height of *A. alba* ranged between 2 and 22 m, while many other plants were less than 5 m tall. According to Muhd-Ekhzarizal et al. (2018), in Malaysia, the average DBH of *A. alba* and *R. apiculata* was 14.24 and 13.70 cm, respectively, and the average height was 11.56 and 11.26 m, respectively. The size of mangrove plants is related to their age, which is also a factor that affects their C stocks (Camacho et al., 2011). Based on the average tree sizes, it was apparent that most of the mangroves in our study area were of a young age.

Regarding plant distribution, the highest density was seen for *A. alba* in plot 5, followed by plots 7 and 6. *R. apiculata* was mostly found in both land use types found of plot 3. The location of plot 3 was close to where ecotourism activities took place (Swangjang and Kornpiphat, 2021). These activities included planting mangrove trees, which mostly comprised *R. apiculata*. Some of these reforestation efforts were questionable and potentially unsustainable. Specifically, reforestation efforts should pay more attention to pioneer species such as *A. Alba*, rather than *R. apiculata.*

A high level of plant diversity is correlated with a high level of ecosystem functioning. The highest IVI was seen for *A. alba*, at 224.73 and 213.79 in L1 and L2, respectively (Table 2). The IVI was seen for *R. apiculata*, at 83.49 and 116.27 in L1 and L2, respectively. As for seedlings, *A. alba* had the highest IVI in L1 (148.37), and *R. apiculata* had the highest IVI in L2 (146.30). Thus, it can be seen that both *A. alba* and *R. apiculata* are important species in the mangrove areas studied. However, compared with other mangrove forests (Camacho et al., 2011; Chaturvedi et al., 2011), there was less species diversity here, because of the disturbance caused by local human activities. This was especially true in LI, where *A. alba* was dominant. Based on plant composition, the above-ground (AG) and below-ground (BG) biomass was calculated (Figure 5). These values affect mangrove C stocks, which are discussed in the following section.

3.2. Carbon in mangrove plants and leaf-fall rates

Soil C content varies depending on several factors. Fallen leaves and branches represent one of the main initial sources of C, through their decomposition in soil. These litter products play an important role in the C cycle in mangrove forests, which further affects the net increase in C in the area. According to Ray et al. (2011), the decomposition of mangrove plant debris results in 1.69 t-C ha^{-1}yr^{-1} being stored in mangrove soils, which is more than that stored in the soil of tropical forests, which is around 0.49 t-C ha^{-1}yr^{-1}. In the present study, *S. caseolaris*, which was rarely found in the study area, exhibited the highest rate of leaf-fall and the greatest leaf density, whereas *A. alba*, which was the dominant species, had the lowest leaf-fall rate (Table 3). These results agreed with those of a study conducted by Poungparn et al. (2009) in a mangrove forest on the upper eastern coast of the Gulf of Thailand.

The highest OC content in leaves was seen in *S. caseolaris* (40.52%). The TC values in leaves were slightly higher than those for OC. This indicates that most of the C in plants occurs in the form of OC. There was more C in branches than in leaves for all species. Ray et al. (2011) found that most C in plants was stored in the roots (43.00%–45.10%), followed by the branches (42.40%–43.05%), and the leaves (42.09%–42.50%). Leaf litter in a tropical forest contains 38.00%–49.00% of the forest's C

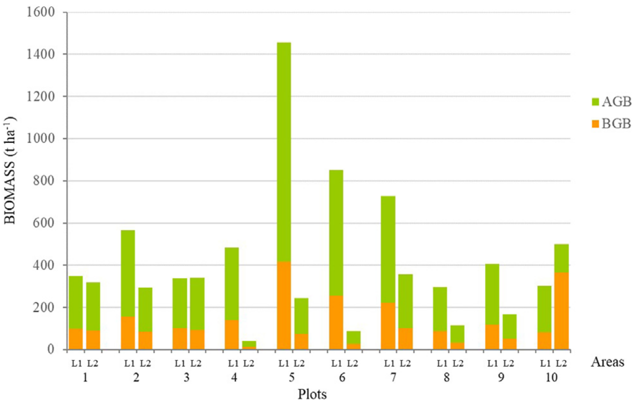


Figure 5. Biomass of mangrove plants.

Table 2. Importance value index (IVI) of mangrove plants.

Species	Relative density (RD) (%)		Relative coverage (RC) (%)		Relative frequency (RF) (%)		Importance value index (IVI)	
	L1	L2	L1	L2	L1	L2	L1	L2
A. alba	74.88	61.51	94.29	93.46	55.56	58.82	224.73	213.79
Seedlings	90.04	100.00	-	-	58.33	33.33	148.37	133.33
R. apiculata	50.08	74.23	20.30	12.63	22.22	29.41	83.49	116.27
Seedlings	90.15	96.30	-	-	33.33	50.00	123.48	146.30
R. mucronata	14.52	6.90	4.75	1.13	11.11	11.76	30.38	19.80
Seedlings	9.09	11.11	-	-	8.33	16.67	17.42	27.78
X. granatum	10.90	-	1.43	-	11.11	-	23.44	-

Note L1 and L2 are mangroves in land-use zones 1 and 2, respectively.

Table 3. Carbon distribution in the leaves and branches of mangrove plants.

Species	OC in leaves (%)		TC (%)		Falling rate ($t.ha^{-1}yr^{-1}$)	Density ($g.cm^{-3}$)	
	June	February	Leaves	Branches		Leaves	Branches
R. mucronata	38.44	39.63	40.80	41.35	1.93	0.2799	0.3351
R. apiculata	35.60	36.07	38.33	43.72	1.63	0.3117	0.3693
A. alba	37.39	36.32	37.55	43.58	1.26	0.2027	0.2568
X. granatum	31.48	37.75	42.00	44.48	1.61	0.2119	0.4366
S. caseolaris	40.52	40.52	40.54	44.43	2.37	0.3585	0.2523

(Kauffman and Donato, 2012). Additionally, Hien et al. (2018) found that the quantity of OC in live roots (33.87% ± 1.98%) was slightly higher than that in dead roots (32.65% ± 1.28%).

3.3. Mangrove soils

Soils are recognized as being the largest terrestrial pool of C (Nam et al., 2016; MacKenzie et al., 2016). The average depth of soil in mangrove forests in Thailand is 40 cm; however, in our study area the average depth was 50 cm (Department of Marine and Coastal Resources, 2018). The soil texture was silty clay in L1 and L2 and clay loam in the seaside area. These were fine-textured soils with a clay content of 49.16%, 47.33%, and 35.87% in L1, L2, and the seaside, respectively. There was a higher sand content in soil from the seaside area, which was located in a coastal mangrove forest. This is an area that regenerates soil as a result of sediments deposition associated with products resulting from plant residues decomposition especially leaves and branches. The rate of decomposition depends on the biotic and abiotic conditions in the area (Kida and Fujitake, 2020). According to the mangrove soil properties shown in Table 4, a high variation in pH (7.25 ± 0.96) was found in soil from L1, which was caused by nearby human activities. There was less variation in pH in soil from L2 (7.92 ± 0.20), while the lowest variation in pH was found in the seaside soils (7.98 ± 0.14). The highest salinity value was found in L1 (11.95 ± 0.15 ppt), which resulted from invasive activities in the area, especially aquaculture. The addition of nutrients is a crucial factor involved in enhancing the salinity of mangrove soil (Chen and Ye, 2014). There were no differences in the BD. A study by Barreto et al. (2016) indicated that BD values were inversely correlated with SOC level. In the present study, the average percentage of SOC in L1 was 2.52 ± 1.11, which was the largest level of variation. The lowest variation in SOC was found in the seaside area, with an average percentage of 1.53 ± 0.40, followed by L2, with an average percentage of 1.71 ± 0.91. A study conducted by Hien et al. (2018) in the north of Vietnam found that the mean value of mangrove SOC was 1.40%, which is in the normal range found in other Asian mangrove forests.

The average C:N ratios in L1, L2, and seaside were 9.81 ± 1.39, 10.37 ± 1.76, and 8.98 ± 3.58, respectively. This ratio affects the rate of microbial metabolic processes involved in the nitrogen cycle (Finn et al., 2015). Nitrogen immobilization is enhanced by a greater C:N ratio (Bimüller et al., 2014). According to Weiss et al. (2016), the C:N ratio of mangrove soil can be high (more than 200), which is not an appropriate condition for decomposition by microorganisms. Relationships between soil properties such as pH, BD, moisture, SOC, and N were investigated, and multiple linear regression models were derived for each area. Multiple linear regression with a stepwise selection method indicated that N was the only factor that influenced SOC. The quantity of SOC was positively correlated with N in L1 and L2. The quantity of SOC showed no correlation with N in the seaside area. The relationship between SOC and N found in LI and L2 was determined using the following equations:

$$\mathrm{SOC\ (L1)} = 0.170 + 8.829\ \mathrm{N},\ R^2 = 0.898 \quad (11)$$

$$\mathrm{SOC\ (L2)} = 0.055 + 9.862\ \mathrm{N},\ R^2 = 0.888 \quad (12)$$

The correlation coefficients of determination were 0.898 and 0.888 for L1 and L2, respectively. These values indicated that 89.80% and 88.80% of the total variance could be explained by the model's equation. The basic assumptions of errors were met. The errors in the regression model were independent and identically normally distributed, with constant variance. Pearson's correlation coefficients illustrated the correlations among overall soil properties in the three land-use zones. A highly significant correlation ($p < 0.01$) between SOC and N was found in L1 ($r = 0.948$) and L2 ($r = 0.942$). BD and pH showed a negative correlation with SOC. These correlations were present in L1 ($r = -0.277, -0.276$) and L2 ($r = -0.301, -0.562$). Average values of C stocks, which were calculated from the SOC and BD for L1, L2, and the seaside area, were 60.95, 43.71, and 37.45 $t\text{-}Cha^{-1}$, respectively (Figure 6). A study conducted by Camacho et al. (2011) in mangrove forests in the Philippines, which are dominated by *R. apiculata*, showed that the average C stock was 140.4 $t\text{-}Cha^{-1}$, whereas we found that the average C stock in L2, which was dominated by *R. apiculata*, was lower than this.

Table 4. Mangrove soil properties.

Mangrove basic soil properties	Areas		
	L1 (average ± SD)	L2 (average ± SD)	Seaside (average ± SD)
pH	7.25 ± 0.96	7.92 ± 0.20	7.98 ± 0.14
Moisture (%)	7.64 ± 3.90	4.83 ± 1.93	4.71 ± 1.41
BD (gcm^{-3})	0.81 ± 0.07	0.86 ± 0.04	0.82 ± 0.02
Salinity (ppt)	11.95 ± 0.15	10.96 ± 0.09	10.03 ± 0.06
N (%)	0.26 ± 0.12	0.17 ± 0.09	0.21 ± 0.14
SOC(%)	2.52 ± 1.11	1.71 ± 0.91	1.53 ± 0.40
OC:N	9.81 ± 1.39	10.37 ± 1.76	8.98 ± 3.58
C_{stocks} ($t\text{-}Cha^{-1}$)	60.95 ± 27.90	43.71 ± 21.69	37.45 ± 9.92
Soil particles proportion			
Sand(%)	5.29 ± 0.02	4.15 ± 0.82	20.62 ± 1.00
Silt(%)	45.55 ± 0.01	48.52 ± 0.82	43.51 ± 1.80
Clay(%)	49.16 ± 0.01	47.33 ± 0.01	35.87 ± 0.80
Soil textures	Silty clay	Silty clay	Clay loam

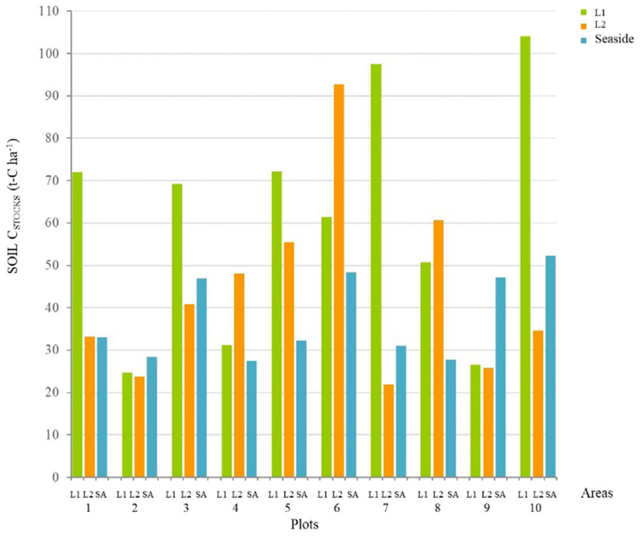


Figure 6. Carbon stocks in mangrove soils.

3.4. Carbon stocks in mangrove ecosystems

This research sought to explore the impacts of threats to mangrove forests on mangrove ES and C stocks; therefore, we considered C from plants both above-ground (AG) and below-ground (BG), together with SC stocks. The results in Table 5 illustrate that average C stocks in L1 (328.64 t-Cha^{-1}) were higher than in L2 (290.34 t-Cha^{-1}). Consequently, AGC was considered to play a major role in this area. Chaturvedi et al. (2011) reported AGC stocks of 62–182 t-Cha^{-1} for tropical mangroves in Thailand, with the variation related to plant community composition. The dominant species in many plots in L1 was *A. alba*. The average SC stock in L1 (60.95 t-Cha^{-1}) was higher than in L2 (43.71 t-Cha^{-1}). A comparison with C stocks in mangrove ecosystems reported by previous studies is shown in Table 6. The mangrove C stocks found in this study were more or less different with the other mangroves in the Asian region. Mangrove structure, land use, and soil properties were the basic factors that influenced mangrove C stocks. Mangrove plant species distribution also played an important role in C stocks in these ecosystems and is directly linked with the supply of C stocks in mangrove ecosystems. Furthermore, soil C also forms an important pool of C stocks in mangrove ecosystems. A study by Chhabara et al. (2003) found that the mean SOC in the top 50-cm of soil in tropical swamp forests was 92.10 t-ha^{-1}. The variation in SC stocks shown in Table 6 was dependent on soil depth (see equation 10) and the soil properties in each study.

Pearson's correlation coefficients between C stocks AG and BG in the mangrove forests in the L1 and L2 areas were 0.996 and 0.997, respectively. A highly significant statistical association ($p < 0.01$) was seen for C between AG and BG in the same line but an opposite correlation was found for the different land use areas. Compared with mangrove plants in L1, many of the mangrove plants in L2 were younger and were dominated by *R. apiculata*. According to Camacho et al. (2011), C storage in mangrove plants increases with their increasing age. The composition of C stocks was more varied in L2 than in L1 (Figure 7). In L1, a large fraction of C was from AG plants, therefore deforestation in this area directly affects the loss of C stock in mangroves.

The importance of mangroves as a potential source of C stocks has been confirmed by many researchers (Poungparn et al., 2009; Barreto et al., 2016; Camacho et al., 2011; Bhomia et al., 2016; Bulmer et al., 2016; Hien et al., 2018). An interesting study by Ray et al. (2011) indicated that, in tropical zones, the sensitivity of mangrove forests was a cause of the decline in C stocks. Attention should be paid to maintaining the existing dominant mangrove species by reducing the impacts from human invasion. The re-consideration of land use could help to control the demand for mangrove resources.

3.5. Assessment of factors influencing carbon stocks in mangrove forests

An assessment to investigate the potential changes in C stocks in mangrove forests was performed to analyze the likely impacts due to human activities that threaten this ecosystem. The steps of the assessment were: indicator screening and evaluation, assessment of possible C stock changes, and ways to control these changes, as follows.

First, a screening of indicators was performed to select the factors that affect C stocks in relation to mangrove ES. Human activities also have an influence, such as land-use change, which can further affect ecosystems and their services (Vo et al., 2012; Timilsina et al., 2014; Liu et al., 2017). Mangrove trees are greatly affected by land-use change (Kauffman and Donato, 2012). These changes may further significantly affect ecosystem processes and the services that they provide. The present study focused on mangrove plants and soils. The impacts on SC stocks were influenced by both human and natural factors. Soil texture was mostly influenced by natural conditions (Jankowski, 2014). The clay content of soil directly affects BD and increases C stocks in an area (Srivastava et al., 2020). As for plants, as the main C sources in mangrove areas (Yong et al., 2011), the plant communities studied were directly affected by human activities. In terms of plant species composition in the study area, *A. alba* was found to have the highest IVI, and this difference was significant. In L2, *R. apiculata* seedlings were dominant as a result of ecotourism reforestation activities at the nearby seaside area. However, this planting activity could not provide a sustainable supply of mangrove plants, since *A. alba* is required in this area as a pioneer species to support other mangrove plants (Barbier et al., 2011). The level of C in leaves, which further supplies the ecosystem, was 37.55% and 38.33% for *A. alba* and *R. apiculata*, respectively, while there was a higher level of C found in

Table 5. Carbon stocks in mangrove ecosystems.

Plot	AGC (t-Cha^{-1})		BGC (t-Cha^{-1})		SC$_{stock}$ (t-Cha^{-1})		Total C $_{stock}$ (t-Cha^{-1})	
	L1	L2	L1	L2	L1	L2	L1	L2
1	115.34	106.22	45.98	41.62	72.00	33.21	233.32	352.3
2	190.84	97.33	71.88	38.93	24.72	23.84	287.43	317.95
3	110.48	114.15	46.54	43.67	69.26	40.79	226.28	381.43
4	159.23	13.55	64.35	5.97	31.13	48.03	254.71	90.15
5	481.95	79.16	192.81	33.94	72.08	55.50	746.84	299.61
6	276.19	27.73	118.27	13.26	61.48	92.71	455.93	181.19
7	234.11	118.52	103.19	46.76	97.46	21.99	434.76	378.73
8	97.06	37.70	40.74	15.35	50.75	60.63	188.55	175.13
9	133.72	53.96	54.88	23.65	26.52	25.82	215.12	193.32
10	100.82	168.97	38.51	62.25	104.12	34.56	243.46	533.63
Average	189.97	81.73	77.71	32.54	60.95	43.71	328.64	290.34

branches, at 43.58% and 43.72% for *A. alba* and *R. apiculata*, respectively. In terms of utilization by humans, branches were more in demand than leaves, for example for use as firewood. This demand further affects the supply of C stocks in mangroves. The decomposition rate is another important factor (Sayer et al., 2011). Branches take longer to decompose than leaves. A study by Swangjang and Bunpraserth (2017) showed that the longest period it took for leaves of *A. alba* and *R. apiculata* to composite was four and six months, respectively, whereas branches took much longer than this to decompose.

Second, the possibility that declining mangrove forests due to human activities could affect C stocks was explored. ES assessment is most effective at the scale of individual ecosystems and their characteristics (Müller et al., 2016). In the present study, involving two land-use types and a seaside area in mangrove forests, the characteristics of plant community structures and mangrove management were evaluated. The risk of impacts came from two factors. At the policy level, any changes in land use are directly enforced by Town and Urban Planning. Unfortunately, the Town and Urban Planning guidelines published in 2017 stated that the entire Klong Kone area should be adopted for community purposes (Rachakitchanubeksa, 2017). This could risk further declines in the mangrove areas in the future. Although conserving the forest is mandatory in L2, the impacts from nearby local activities could subsequently transform the mangrove forest, as the area is located near aquaculture farms that place demands on mangrove resources.

In the study area, the demand for mangrove resources affected losses of C stocks both directly and indirectly. Mangrove forests have declined as a result of aquaculture activities, especially in L1, which is encroached upon by the local community. The conversion of mangrove forests for aquaculture has been responsible for up to 52% of global mangrove losses (Bhomia et al., 2016). A key characteristic of these changes is the permanent loss of the composition of C stocks, especially in plant communities. In the present study, the loss of 1 ha of mangrove trees in L1 led to the loss of 167.74–410.05 tons of biomass (see Figure 5), which in turn directly led to the loss of 77.71–189.97 t-Cha^{-1} (see Table 5). According to MacKenzie et al. (2016), the loss of mangrove forests leads to the permanent loss of BGC.

In the seaside area, ecotourism is the main activity and includes the planting of various mangrove species. However, *R. apiculata* was mainly used for these reforestation activities. A study by Anunsiriwat and Chukwamdee (1997) showed that the survival rate of *A. alba* and *R. apiculata* saplings was 74.40% and 51.20%, respectively. The soil in the seaside area also had a lower clay content. These factors can potentially affect the supply of C stocks in this area.

Table 6. A comparison of carbon stocks in various tropical mangrove forests.

Location	Carbon stocks in mangroves	Source
Present study, Thailand	AGC: 81.73–189.97 t-Cha^{-1}	
	BGC: 32.54–77.71 t-Cha^{-1}	
	SC stock: 43.71–60.95 t-Cha^{-1}	
	Mangrove C stock: 290.34-328.64 t-Cha^{-1}	
Mekong Delta, Vietnam	AGC:61.4–69.0 t-Cha^{-1}	Nam et al. (2016)
	BGC: 8.70–10.80 t-Cha^{-1}	
	SC stock: 696.52–926.91 t-Cha^{-1} (soil depth 300 cm)	
	Mangrove C stock: 766.62-1006.71 t-Cha^{-1}	
Kuala Selangor and Sunjai Haji Dorani, Malaysia	AGC: 48.17–121.82 t-Cha^{-1}	Hong et al. (2017)
	BGC: 3.26–13.12 t-Cha^{-1}	
	SC stock: 69.95–152.95 t-Cha^{-1}	
	Mangrove C stock: 151.40-246.21 t-Cha^{-1}	
Bohol, Philippines	AGC: 98.60–250.60 t-Cha^{-1}	Camacho et al. (2011)
	BGC: 39.30–120.00 t-Cha^{-1}	
	Mangrove C stock: 145.60-370.70 t-Cha^{-1}	
Bintan Island, Indonesia	AGC: 41.01–260.58 t-Cha^{-1}	IDEAS Consultancy Services (2013)
	BGC: 20.86–108.78 t-Cha^{-1}	
	Mangrove C stock: 61.87-369.36 t-Cha^{-1}	
Sundarbans, Bangladesh	AGC: 45.24–152.57 t-Cha^{-1}	Rahman et al. (2015)
	BGC: 11.72–62.37 t-Cha^{-1}	
	SC stock 90.83–196.54 t-Cha^{-1}	
	Mangrove C stock 159.49-360.01 t-Cha^{-1}	
Kerala, India	Vegetation C stock: 28.13–123.28 t-ha^{-1}	Harishma et al. (2020)
	SC stock: 52.04–100.80 t-Cha^{-1}	
	Mangrove C stock: 80.16-214.24 t-Cha^{-1}	
Mahanadi, India	Vegetation C stock: 89.10–90.60 t-Cha^{-1}	Sahu et al. (2016)
	SC stock: 54.30–60.90 t-Cha^{-1}	
	Mangrove C stock: 143.40-151.50 t-Cha^{-1}	

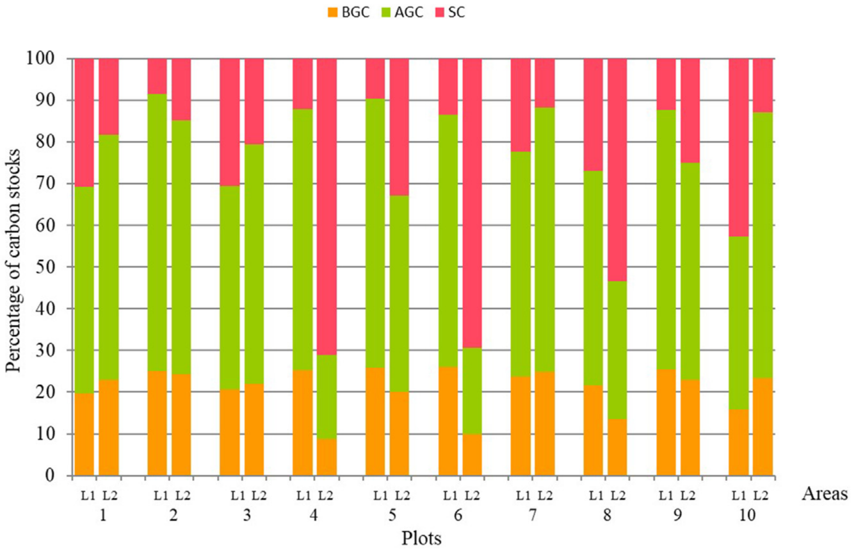


Figure 7. Carbon stock distribution in mangrove ecosystems.

Third, different ES demands require different mangrove forest management approaches. Mangrove habitats were considered at the landscape scale. The factors affecting mangrove forest ES and their potential impacts led to the development of appropriate ways to mitigate each impact that was characterized. The different factors that impact the L1, L2, and seaside areas can affect the potential C storage in these areas. The largest demand on ES in L1 came from local activities from the population living nearby, especially for aquaculture, although higher C stocks were found there compared with the levels in L2. Hence, intensive control of land-use approaches is clearly required in order to prevent harmful activities. This is a widely accepted planning concept and an inherent part of the supply and demand of ES (Brander et al., 2012; Kienast and Helfenstein, 2016; Zoderer et al., 2016).

As for the seaside area, the best management decision would be to recognize pioneer species, stand density, and coastal protection benefits. Reforestation with pioneer species, especially *A. alba*, is required. There were more demands on ES in this area in terms of ecotourism activities (Swangjang and Kornpiphat, 2021) than in L1 and L2. The SC stock of the seaside area was lower than that in L2 due to natural factors relating to the soil texture. This highlights the fact that ecotourism activities were the main source of ES demand. Tourism management is required, both in terms of appropriate activities and in controlling the number of boats. In L2, the conservation area should be strictly controlled. The arguments for this are that the supply of ES depends on both the local site conditions and the interactions among ecosystems and human influences.

4. Conclusion

The integration of an assessment approach with the ES concept provides the opportunity to understand the loss and/or gain of C stocks in mangrove ecosystems. Using this approach led to two key findings. First, Town and Urban Planning supports the possibility of land-use changes; these changes subsequently make demands on mangrove resources due to the expansion of local human activities. These activities can directly affect mangrove forests, decreasing the potential services that are an inherent part of the supply and demand of ES. The results of this study confirm the importance of controlling land use in mangrove areas, especially in areas similar to L1, which is more influenced by community activities, especially aquaculture, than L2, which is a conservation area. Both areas were dominated by *A. alba*; however, the IVI values of *A. alba* were higher in L1 than they were in L2. If the current invasive situation in L1 continues, the loss of C stocks will also continue, at a level of approximately 328.64 t-Cha^{-1}. The size of mangrove trees and their IVI values were crucial factors for C stocks in vegetation. Second, there are ways in which we can maintain ES provided by mangrove forests. Using our assessment approach, we showed that each mangrove area has its own specific characteristics that can impact the risk of C losses. Many of the activities in the mangrove areas we studied were classified as “green” activities, especially ecotourism. However, these activities require ES from mangroves that lead to losses in both the direct and indirect supply of ES. These hidden activities can affect the mechanisms that directly result in C stocks being lost from mangrove forests as a whole.

Declarations

Author contribution statement

Kanokporn Swangjang: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Kamokchanok Panishkan: Analyzed and interpreted the data; Wrote the paper.

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Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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References

Anunsiriwat, A., Chukwamdee, J., 1997. Effect on Mangrove Plantation to Sedimentation on New Mud Flat Area at Samut Songkram. Royal Forest Department, Thailand, p. 23.

Balvanera, P., Quijas, S., Martín-Lόpez, B., Barrios, E., Dee, L., Isbell, D., White, P., Blanchard, R., 2016. The links between biodiversity and ecosystem services. In: Potschin, M., Haines-Young, R., Fish, R., Turner, R.K. (Eds.), Routledge Handbook of Ecosystem Services. Routledge, Oxon, pp. 45–61.

Barbier, E.B., Hacker, S.D., Kennedy, C., Koch, E.W., Steir, A.C., Silliman, B.R., 2011. The value of estuarine and coastal ecosystem services. Ecol. Monogr. Eco. 81, 169–193.

Barreto, M.B., Monaco, S.L., Daz, R., Barreto-Pittol, E., Lopez, L., Peralba, M., 2016. Soil organic carbon of mangrove forests (Rhizophora and Avicennia) of the Venezuelan Caribbean. Coast. Org. Geochem. 100, 51–61.

Ben-Dor, E., Banin, A., 1989. Determination of organic matter content in arid-zone soils using a simple “loss on ignition” method. Commun. Soil Sci. Plant Anal. 20, 1675–1695.

Bhomia, R.K., Kauffman, J.B., McFadden, T.N., 2016. Ecosystem carbon stocks of mangrove forests along the Pacific and Caribbean coasts of Honduras. Wetl. Ecol. Manag. 24, 187–201.

Bimüller, C., Mueller, C.W., von Lützow, M., Kreyling, O., Kölbl, A., Haug, S., Schloter, M., Kögel-knabner, I., 2014. Decoupled carbon and nitrogen mineralization in soil particle size fractions of a forest topsoil. Soil Biol. Biochem. 78, 263–273.

Bouyoucos, G.J., 1962. Hydrometer method improved for making particle size analysis of soils. Agron. J. 54, 464–465.

Brander, L.M., Wagtendonk, A.J., Hussain, S.S., McVittie, A., Verburg, P.H., de Groot, R.S., Ploeg, S., 2012. Ecosystem service values for mangroves in Southeast Asia: a meta-analysis and value transfer application. Ecosyst. Serv. 1, 62–69.

Bulmer, R.H., Schwendenmann, L., Lundquist, C.J., 2016. Carbon and nitrogen stocks and below ground allometry in temperate mangroves. Front. Mar. Sci. 3.

Camacho, L.D., Gevaña, D.T., Carandang, A.P., Camacho, S.C., Combalicer, E.A., Rebugio, L.L., Youn, Y.C., 2011. Tree biomass and carbon stock of a community-managed mangrove forest in Bohol, Philippines. For. Sci. Technol. 7, 161–167.

Carugati, L., Gatto, B., Rastelli, E., Martire, M.L., Coral, C., Greco, S., Danovaro, R., 2018. Impacts of mangrove forests degradation on biodiversity and ecosystem functioning. Sci. Rep.-UK 8, 13298.

Castillo, J.A.A., Apan, A.A., Maraseni, T.N., Salmo, S.G., 2017. Soil C quantities of mangrove forests, their competing land uses, and their spatial distribution in the coast of Honda Bay, Philippines. Geoderma 293, 82–90.

Chaturvedi, R.K., Raghubanshi, A.S., Sigh, J.S., 2011. Carbon density and accumulation in woody species of tropical dry forest in India. For. Ecol. Manag. 262, 1576–1588.

Chen, Y., Ye, Y., 2014. Effects of salinity and nutrient addition on mangrove *Excoecaria agallocha*. PLoS One 9 (4), e93337.

Chhabra, A., Palra, S., Dadhwal, V.K., 2003. Soil organic carbon pool in Indian forests. For. Ecol. Manag. 173, 187–199.

Culley, J.L.B., 1993. Density and compressibility. In: Canter, M.R. (Ed.), Soil Sampling and Methods of Analysis. Lewis Publisher, Boca Raton, pp. 529–549.

Curtis, J.T., McIntosh, R.P., 1950. The interrelations of certain analytic and synthetic of phytosociological characters. Ecology 31, 434–455.

Dietze, V., Hagemann, N., Jürges, N., Bartke, S., Fürst, C., 2019. Farmers consideration of soil ecosystem services in agricultural management- A case study from Saxony Germany. Land Use Pol. 81, 813–824.

European Commission, 2006. Thematic Strategy for Soil Protection. http://eur-lex.Europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52006DC0231from=EN. (Accessed 5 January 2019).

Finn, D., Page, K., Catton, K., Strounina, E., Kienzle, M., Robertson, F., Armstrong, R., Dalal, R., 2015. Effect of added nitrogen on plant litter decomposition depends on initial soil carbon and nitrogen stoichiometry. Soil Biol. Biochem. 91, 160–168.

Gillerot, L., Vlaminck, E., De Ryck, D.J.R., Mwasaru, D.M., Beeckman, H., Koedam, N., 2018. Inter- and intraspecific variation in mangrove carbon fraction and wood specific gravity in Gazi Bay, Kenya. Ecosphere 9 (6), e02306.

Greiner, L., Keller, A., Grêt-Regamey, A., Papritz, A., 2017. Soil function assessment: review of methods for quantifying the contributions of soils to ecosystem services. Land Use Pol. 69, 224–237.

Guo, L.B., Gifford, R.M., 2002. Soil carbon stocks and land use change: a meta analysis. Glob. Change Biol. 8, 345–360.

Harishma, K.M., Sandeep, S., Sreekumar, V.B., 2020. Biomass and carbon stocks in mangrove ecosystems of Kerala, southwest coast India. Ecol. Process 9, 31.

Hien, H.T., Marchad, C., Aime, J., Nhon, D.H., Hongt, P.N., Tung, N.X., Kim Cuc, N.T., 2018. Belowground carbon sequestration in a mature planted mangroves (Northern Viet Nam). For. Ecol. Manage. 407, 191–199.

Hong, L.C., Hemati, Z., Zakaria, R.M., 2017. Carbon stock evaluation of selected mangrove forests in Peninsular Malaysia and its potential market value. J. Environ. Sci. Manag. 20–2, 77–87.

IBM Corp, 2015. IBM SPSS Statistics for Windows, Version 23.0. IBM Corp, Armonk, NY.

IDEAS Consultancy Services, 2013. Preparation of Baseline Data Mangrove Ecosystem Management in Binland Island. Indonesia.

Jankowski, M., 2014. The evidence of lateral podsolization in sandy soils of Northern Poland. Catena 112, 139–147.

Kauffman, J.B., Donato, D.C., 2012. Protocols for the Measurement, Monitoring and Reporting of Structure, Biomass and Carbon Stocks in Mangrove Forests. Working Paper 86. CIFOR, Bogor, Indonesia. View at Google Scholar.

Kaul, M., Mohren, G.M.J., Dadhwal, V.K., 2010. Carbon storage and sequestration potential of selected tree species in India. Mitig. Adapt. Strategies Glob. Change 15, 489–510.

Kida, M., Fujitake, N., 2020. Organic carbon stabilization mechanisms in mangroves soils: a review. Forests 11, 981.

Kienast, F., Helfenstein, J., 2016. Modelling ecosystem services. The links between biodiversity and ecosystem services. In: Potschin, M., Haines-Young, R., Fish, R., Turner, R.K. (Eds.), Routledge Handbook of Ecosystem Services. Routledge, Oxon, pp. 144–156.

Komiyama, A., Poungparn, S., Kato, S., 2005. Common allometric equations for estimating the tree weight of mangroves. J. Trop. Ecol. 21, 471–477.

Liu, J., Li, J., Qin, K., Zhou, Z., Yang, X., Li, T., 2017. Changes in land-uses and ecosystem services under multi-scenarios simulation. Sci. Total Environ. 586, 522–526.

Lunstrum, A., Chen, L., 2014. Soil carbon stocks and accumulation in young mangrove forests. Soil Biol. Biochem. 75, 223–232.

MacKenzie, R.A., Foulk, P.B., Klump, J.V., Weckerly, K., Purbospito, J., Murdiyarso, D., Donato, D.C., Nam, V.N., 2016. Sedimentation and belowground carbon accumulation rates in mangrove forests that differ in diversity and land use: a tale of two mangroves. Wetl. Ecol. Manag. 24, 245–261.

Mangkay, S.D., Harahab, N., Polii, B., 2013. Economic valuation of mangrove forest ecosystem in Tatapaan, South Minahasa, Indonesia. J. Environ. Sci. Toxicol. Food Technol. 5 (6), 51–57.

Millennium Ecosystem Assessment (MEA), 2005. Ecosystems and Human Well-Being: Synthesis. Island Press, Washington DC.

Muhd-Ekhzarizal, M.E., Mohd-Hasmadi, I., Hamdan, O., Mohamad-Roslan, M.K., Noor-Shaila, S., 2018. Estimation of aboveground biomass in mangrove forests using vegetation indices from SPOT-5 image. J. Trop. For. Sci. 30 (2), 224–233.

Müller, F., Burkhard, B., Hou, Y., Kruse, M., Ma, L., Wangai, P., 2016. Indicators for ecosystem services. In: Potschin, M., Haines-Young, R., Fish, R., Turner, R.K. (Eds.), Routledge Handbook of Ecosystem Services. Routledge, Oxon, pp. 157–169.

Nam, V.N., Sasmito, S.D., Murdiyarso, D., Purbopuspito, J., MacKenzie, R.A., 2016. Carbon stocks in artificially and naturally regenerated mangrove ecosystems in the Mekong Delta. Wetl. Ecol. Manag. 24, 231–244.

Poungparn, S., Komiyama, A., Tanaka, A., Sangtiean, T., Maknual, C., Kato, S., Tanapermpool, P., Patanaponpaiboon, P., 2009. Carbon dioxide emission through soil respiration in a secondary mangrove forest of eastern Thailand. J. Trop. Ecol. 25, 393–400.

Rachakitchanubeksa, 2017. Samutsongkram Town and urban planning, 134 (42 ก) on 12 April BD 2560.

Rahman, M., Khan, N.I., Hoque, A.K.F., Ahmed, I., 2015. Carbon stock in the Sundarbans mangrove forest: spatial variations in vegetation types and salinity zones Wetlands Ecol. Manage 23, 269–283.

Ray, R., Ganguly, D., Chowdhury, C., Dey, M., Das, S., Dutta, M.K., Mandal, S.K., Majumder, N., De, T.K., Mukhopadhyay, S.K., Jana, T.K., 2011. Carbon sequestration and annual increase of carbon stock in a mangrove forest. Atmos. Environ. 45, 5016–5024.

Rhoades, JD, 1993. Electrical conductivity methods for measuring and mapping soil salinity. Adv. Agron. 49, 201–251.

Sahu, S.C., Kumar, M., Ravinndranath, N.H., 2016. Carbon stocks in natural and planted mangrove forests of Mahanadi mangrove wetland, East Coast of India. Curr. Sci. 110 (12), 2253–2260.

Sanderman, J., Hengl, T., Fiske, G., Silvik, K., Landis, E., 2018. A global map of mangrove forest soil carbon at 30 m spatial resolution. Environ. Res. Lett. 13 (2018), 055002.

Sayer, E.J., Heard, M.S., Grant, H.K., Marthews, T.R., Tanner, E., 2011. Soil carbon release enhanced by increased tropical forest litter fall. Nat. Clim. Change 6, 304–307.

Sparks, D., Page, A., Helmke, P., Loeppert, R., Soltanpour, P., Tabatabai, M., Sumner, M., 1996. Methods of Soils Analysis Part 3- Chemical Methods, SSSA Book Series. Soil Science Society of America, Madison, pp. 1085–1121.

Srivastava, R., Mohapatra, M., Latare, A., 2020. Impact of land use change on soil quality and species diversity in the Vindhyan dry tropical region of India. J. Trop. Ecol. 36 (2), 72–79.

Swangjang, K., Bunpraserth, W., 2017. Temperature influencing on carbon and nitrogen ratio in mangrove soil. In: The 6th International Conference on Research in Chemical. Agriculture & Biological Sciences, Singapore, pp. 27–28. March 2017.

Swangjang, K., Kornpiphat, P., 2021. Does ecotourism in a Mangrove area at Klong Kone, Thailand, conform to sustainable tourism? A case study using SWOT and DPSIR. Environ. Dev. Sustain. 23, 15960–15985.

Swann, L., 2018. New Study Finds Catastrophic Loss of Mangroves. https://www.leonardodicaprio.org/new-study-finds-catastrophic-loss-of-mangroves/.

Teka, O., Houessou, L.G., Djossa, B.A., Bachmann, Y., Oumoro, M., Sinsin, B., 2019. Mangroves in Benin, West Africa: threats, uses and conservation opportunities. Environ. Dev. Sustain. 21, 1153–1169.

Thai Department of Marine and Coastal Resources, 2018. Mangrove forest. https://www.dmcr.go.th. (Accessed 10 December 2020).

Thai Meteorological Department, 2020. Thailand Weather. https://www.tmd.go.th. (Accessed 10 December 2020).

Thailand Greenhouse Gas Management Organization, 2008. The Guideline for Potential Plant. Auksornsiam, Bangkok. (Accessed 10 December 2020).

Timilsina, N., Escobedo, F.J., Staudhammer, C.L., Brandeis, T., 2014. Analyzing the causal factors of carbon stores in a subtropical urban forest. Ecol. Complex. 20, 23–32.

Uddin, M.S., Steveninck, E.R., Stuip, M., Shah, M.A.R., 2013. Economic valuation of provisioning and cultural services of a protected mangrove ecosystem: a case study on Sundarbans Reserve Forest, Bangladesh. Ecosyst. Serv. 5, e88–e93.

Vauhkonen, J., Packalen, T., 2018. Uncertainties related to climate change and forest management with implications on climate regulation in Finland. Ecosyst. Serv. 33 (part B), 213–224.

Vo, Q.T., Kuenzer, C., Vo, Q.M., Moder, F., Oppelt, N., 2012. Review of valuation methods for mangrove ecosystem services. Ecol. Indicat. 23, 431–446.

Walkley, A., Black, I.A., 1934. Estimation of soil organic carbon by the chromic acid titration method. Soil Sci. 37, 29–38.

Weiss, C., Weiss, J., Boy, J., Iskandar, I., Mikutta, R., Guggenberger, G., 2016. Soil organic carbon stocks in estuarine and marine mangrove ecosystems are driven by nutrient colimitation of P and N. Ecol. Evol. 6 (14), 5043–5056.

Yong, Y., Baipeng, P., Guangcheng, C., Yen, C., 2011. Process of organic carbon in mangrove ecosystems. Acta Ecol. Sin. 31, 169–173.

Zhao, B., Kreuter, U., Li, B., Ma, Z., Chen, J., Nakagoshi, N., 2004. An ecosystem service value assessment of land use change on Chongming Island, China. Land Use Pol. 21, 139–148.

Zhong, Z., Chen, Z., Xu, Y., Ren, C., Yang, G., Han, X., Ren, G., Feng, Y., 2018. Relationship between soil organic carbon stocks and clay content under different climatic conditions in Central China. Forests 9, 598–612.

Zoderer, B.M., Tasser, E., Erb, K.H., Stanghellini, P.S.L.S., Tappeiner, U., 2016. Identifying and mapping the tourists' perception of cultural ecosystem services: a case study from an Alpine region. Land Use Pol. 56, 251–261.