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BIOMASS AND CARBON STOCK ESTIMATION OF MANGROVE FORESTS USING REMOTE SENSING AND FIELD INVESTIGATION - BASED DATA ON HAI PHONG COAST

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Abstract. Carbon stocks estimation has received the attention of many countries around the world. With the aim of reducing emissions, mitigating the impacts of climate change, and improving the livelihoods of local people in coastal areas, the current solutions of afforestation and protection of coastal mangrove forests are being considered. This study was conducted to provide the scientific basis for a carbon credit scheme on the coast of Hai Phong by estimating above ground carbon stocks (AGC) and soil organic carbon (SOC). There were 20 plots set up and evenly distributed across Bang La and Dai Hop (only 17 plots for mangrove structure investigation, 20 plots for SOC study). The results showed that AGC stocks were significantly lower than SOC, normally ranging from 9.9 to 29.55 tons ha^{-1}. Using the Walkley-Black method, the total SOC was estimated at the range of 81.76 to 323.83 tons ha^{-1} (with an average of 161.47±15.85 tons ha^{-1}), which indicated a strong relationship between tree density and SOC. In addition, using the IDW interpolation method, this study estimated that the total CO_2 absorbed by mangrove forests was 1,631,834 tons in Bang La and Dai Hop, including 170,462 tons of CO_2 accumulated in the tree biomass and 1,461,372 tons of CO_2 in the soil, which provided a strong evidence for the potential application of C-PFES and the development of a carbon credit scheme in Vietnam.

Keywords: Biomass, carbon stocks, Hai Phong coast, mangrove forests, soil organic carbon.

Classification numbers: 3.5.1; 3.8.2

1. INTRODUCTION

Mangrove forests play an important role in carbon sequestration and are identified as one of the most carbon-rich ecosystems [1, 2, 3], acting as a powerful sink for atmospheric carbon. Continued pressures on mangrove ecosystems, such as increasing demand for timber and firewood, and the expansion of aquaculture and agriculture has exacerbated the problem of global climate change [4]. Mangrove loss is responsible for 10% of the total deforestation-derived emissions worldwide [1]. Climate change is now a global challenge, regardless of national borders [5, 6]. Humans have been experiencing significant impacts of climate change, which include changing weather patterns, rising sea level, and extreme weather events [7]. The greenhouse gas emissions caused by human activities are the key influential factors of climate change and continue to rise to the highest level in history [8]. During the pre-industrial period, the carbon dioxide concentration in the atmosphere increased from about 280 ppm at the beginning of the period to approximately 390 ppm in 2012 [9]. Consequently, solutions must be found within an international framework [10]. The introduction of REDD+ has eliminated global greenhouse gas emissions by building a carbon footprint in which developed countries would meet their carbon reduction goals by buying carbon credits from developing countries like Viet Nam [11].

There are many studies about the roles of terrestrial forests as a source and sink of greenhouse gases, but recently, attention has focused on high annual rates of carbon sequestration in coastal vegetated ecosystems, such as mangrove ecosystems. Indeed, the carbon sequestration in mangrove forests is strong and sustainable in above-ground and underground carbon sinks. It is reported that annual carbon sequestration in coastal mangrove forests is much higher than in tropical forests of the same latitude [12]. However, carbon sequestration is significantly different between live biomass and sediments. By measuring organic carbon in soils in the Indo-Pacific region, the scientists found that organic-rich soils ranged from 0.5 m to more than 3 m deep and accounted for 49 to 98 % of carbon storage in these systems [1]. Moreover, coastal mangrove forests are highly productive ecosystems that provide a wide range of goods and services, both to the marine environment and to coastal populations, as (1) their nursery function, (2) coastal shoreline protection, and (3) their land-building capacity [1, 13].

Hai Phong is a coastal city in the North East of Viet Nam with 4742 ha of mangrove areas (in 2012) and 125 km of coastline [14]. Rising sea level and tropical cyclones associated with climate change are forecasted to become more severe due to increasing impacts of climate change not only in Hai Phong City, but also in Viet Nam [15, 16]. With its natural conditions, Hai Phong City is considered to have great potential for planning, restoring and developing mangrove forests, thereby promoting local people's livelihoods. However, due to complex coastal features, a few comprehensive studies and information about mangrove forests in relation with carbon stocks in Bang La and Dai Hop in particular have been well-documented.

Recently, remote sensing technology has been considered as a powerful application in forest change investigation and carbon sequestration assessment of mangroves. Previous studies have shown that the accumulation of carbon estimates is the most accurate when performed on forest plantation [17], based on local conditions, which was very difficult to do because regenerated species were intermingled. The potential contribution to GHG fixation and storage by these ecosystems becomes obviously, but the comprehensive study on the exact amount of stored carbon is limited and still an attractive area of research, especially in Viet Nam. Moreover, the administration has no practical and scientific significance for the development, protection and management of mangrove resources. Therefore, this study was conducted mainly with the aim of estimating the accumulation of AGC and SOC stocks of *Sonneratia caseolaris* and *Kandelia obovata* in mixed mangrove plantations along the coast of Hai Phong.

2. MATERIALS AND METHODS

2.1. Study site and materials

2.1.1. Study site

Hai Phong is a coastal city in the Red River Delta region of Viet Nam that covers an area of 1519 km². The total population of Hai Phong in 2019 was around 2,028,514 people [18]. This study selected Dai Hop Commune in Kien Thuy District and Bang La Ward in Do Son Township as study sites due to mainly spatial distribution of mangrove forests. As shown in Fig. 1, Hai Phong is located from 20.30'N to 20.01'N latitude and from 106.23'N to 107.08'N longitude. A large area of northern Vietnam's mangrove plantation forests are distributed along the 120 km coastline of Hai Phong [19]. Coastal mangrove forests in Hai Phong are consisting mainly of *Sonneratia caseolaris* and *Kandelia obovata* [17]. However, the mangrove plantation forests in Bang La and Dai Hop are threatened by over-expansion of shrimp farms, other aquaculture activities, and extreme weather patterns (Fig. 1).

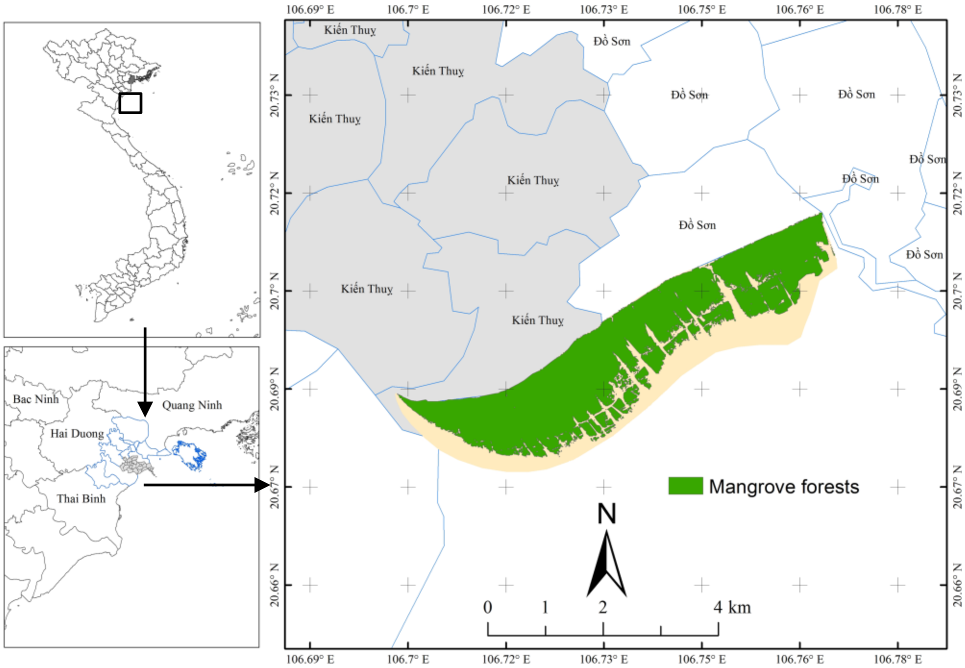

Figure 1. Study sites, including: Geographic location of Viet Nam, Bang La Ward (Do Son Township) and Dai Hop Commune (Kien Thuy District) in Hai Phong City.

On the basis of geographic features, results of field survey and remote sensing, Phan Nguyen Hong (1991) [20] divided mangrove ecosystems into 4 main zones, in which mangrove ecosystems at study sites belong to zone II in Vietnam. These areas have typical characteristics of estuaries and low tidal of storm intensity [20]. However, the salinity in the study areas is low, especially in the rainy season due to the flow of water from upstream rivers.

2.1.2. Materials

In this study, 2018 Sentinel-2A with spatial resolution of 10mx10m was used to detect land use and land cover, including mangrove forests (Table 1).

Table 1. Sentinel-2A data used for classifying mangrove forests.

ID	Image code	Date	Spatial resolution (m)
1	S2A_MSIL1C_20180705T031541[a,b]	05 July 2018	10
2	Land use/cover map[c]	2015	1:50000

Sources:[a]https://earthexplorer.usgs.gov; [b]https://scihub.copernicus.eu/dhus; [c]Hai Phong DARD: Hai Phong Department of Agriculture and Rural Development.

2.2. Methods

2.2.1. Current status of mangrove forests in Bang La and Dai Hop

Data preprocessing

2018 Sentinel-2A image (level 1C) was downloaded from the European Space Agency's Sentinel Scientific Data Hub (Table 1), which was already orthorectified and top atmospheric data. A further process to level 2A product was applied to get bottom-of-atmosphere corrected reflectance Sentinel-2A image by the Semi-Automatic Classification Plugin in QGIS version 3.10.2 [21, 22]. The mask was created and then used to define the areas of mangrove forests in the pre-processed 2018 Sentinel-2A image. This mask was used only to extract areas where mangrove forests were more likely to be present (e.g. intertidal and low-lying areas), and to exclude large coastal areas where mangrove forests did not exist (e.g. far inland and open ocean) prior to Sentinel-2A classification.

Mangrove forests classification and mapping

Land use and land cover classification by NDVI (Normalised Difference Vegetation Index): To create a thematic land use and land cover map, including mangrove forests, this study mainly used NDVI together with visual interpretation approach. The thresholds of NDVI for each land use/cover (mangrove forests, non-mangrove forests, water bodies) were determined and then applied to classify land use/covers and create the thematic map of land use/cover in 2018 with the support of ground survey reference data. NDVI has been widely used for vegetation research, such as crop yield estimation, land cover conversion, and it is directly related to parameters, such as surface soil layer, plant photosynthesis and biomass calculation [23, 24].

The calculated NDVI values, ranging from -1.0 to +1.0, show a clear distribution of vegetation covers in the study areas [23, 25]. The values of NDVI are usually divided into different levels: from the negative value to 0 refers to water cover; NDVI values less than 0.1 usually correspond to areas without vegetation, such as soil, rocks, sand or snow; NDVI values from 0.2 to 0.5 represent to bushes, grass or dry fields; NDVI values from 0.6 to 0.9 or close to 1.0 indicate dense vegetation structure, like forests or crops [26, 27]. Therefore, NDVI was considered as a useful tool and selected for determining the presence of mangrove forests in this study. NDVI was calculated as the following formula:

$$\text{NDVI} = \frac{\text{Band}_{\text{NIR}} - \text{Band}_{\text{RED}}}{\text{Band}_{\text{NIR}} + \text{Band}_{\text{RED}}} \quad [28] \qquad (1)$$

where $Band_{NIR}$ is the near-infrared band with wavelengths from 0.7 µm to 1.0 µm (Band-8), while $Band_{RED}$ is the red band with wavelengths from 0.4 µm to 0.7 µm (Band-4) [29].

Visual interpretation: In this study, the visual interpretation approach refers to using the knowledge and experience of remote sensing experts to separate the areas of mangrove forests from other classes [30]. This approach was used to support land use/cover classification by NDVI in terms of identifying NDVI thresholds for each land use/cover within the consultation of higher spatial resolution image, like Google Earth etc. [31, 32].

Accuracy assessments: Land use/cover map was derived with classification according to NDVI values in 2018. Accuracy assessments were conducted by comparing classification results with reference data that was believed to accurately reflect actual land use/covers [33]. To evaluate the accuracies of Sentinel-2A image classified and assess the accuracy of NDVI approach in 2018, user, producer and overall accuracy with Kappa coefficient were derived from the error matrix. Kappa value is categorised into different groups where kappa values are less than zero, it then indicates no agreement; from 0 - 0.20 refer to a slight agreement; 0.21 - 0.40 represent as a fair agreement, from 0.41 - 0.60 are considered as a moderate agreement, whereas 0.61 - 0.80 are regarded as substantial, and 0.81 - 1.00 refer to an almost perfect agreement [32, 33]. A total of 510 GPS points collected by Garmin GPS map78s was selected using a stratified random sampling approach, which randomly distributed over Bang La and Dai Hop for three main land use/cover classes (300 GPS points for mangrove forests, 160 GPS points for non-mangrove forests, and 50 GPS points for water bodies). Validation points were collected from the field survey and the availability of Google Earth. A number of 306 GPS points (equivalent to 60 % of total field GPS points) were used for classification purposes and 40 % of GPS points (equivalent to 204 GPS points) were used for accuracy assessments. The social interviews with forest rangers and local people who have been in charge of mangrove management were also conducted to identify the challenges and opportunities for C-PFES implementation. This intended to have a better understanding of the status and management scheme of coastal mangrove forests.

2.2.2. Estimation of mangrove biomass, carbon stocks and soil organic carbon

Plots establishment and investigation

Soil samplings were taken at the same time as 17 measuring plots of mangrove forest inventory together with 3 additional plots for soil samples only were set up and carried out. Sampling plots were evenly distributed over three land use/cover classes in Bang La and Dai Hop. In particular, sampling plots 1 to 9 were numbered and established in Bang La Ward, while sampling plots 10 to 17 were allocated in Dai Hop Commune as shown in Fig. 2.

The study established 17 plots with the size of 900 m^2 (30 m × 30 m) and divided into 5 sub-plots of 100 m^2 (10 m × 10 m) as shown in Figs. 2 and 3. Mangrove forests were investigated in sub-plots A, B, C and D, while soil sampling was conducted only in subplot E. For mangrove structure inventory, species name, DBH (the diameter at the breast height, 1.3 m), tree height (total height), and tree density were collected in sub-plots A, B, C and D. The soil sample in the central plot (sub-plot E) was taken at a depth of 0 - 100 cm from the soil surface. Each soil sample was equally divided into five layers by the defined depths (0 - 20 cm, 20 - 40 cm, 40 - 60 cm, 60 - 80 cm, and 80 - 100 cm). The soil samples were then numbered, covered by plastic bags and preserved under the suitable conditions until they were sent to the laboratory in the Vietnam National University of Forestry.

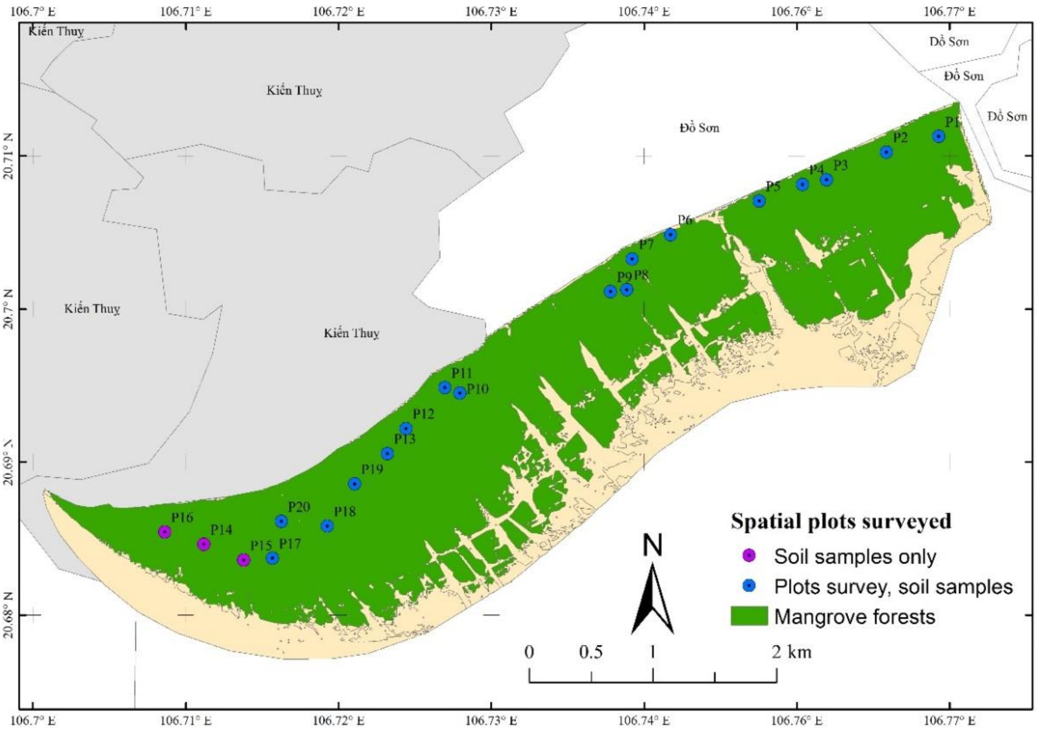

Figure 2. Spatial distribution of sampling plots in Bang La and Dai Hop on the coast of Hai Phong: 20 sampling plots (17 plots for AGC and SOC study + 3 plots for SOC study only).

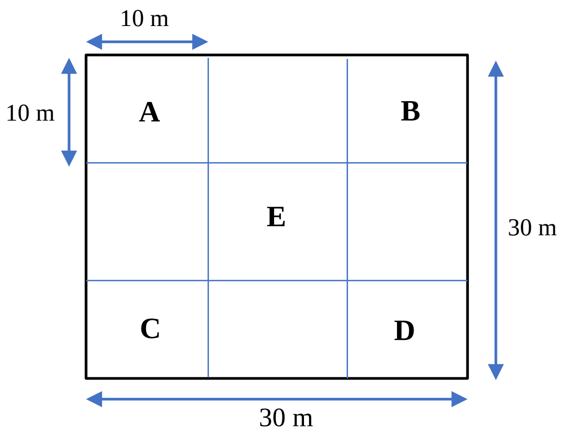

Figure 3. Layouts of sampling plots and subplots (100 m^2) in Bang La and Dai Hop.

Above ground biomass (AGB) and carbon stocks (AGC) estimation

There is a specific equation to calculate the AGB of mangrove forests based on the relationship with the stem diameter of each species [34]. In 2016, Nguyen *et al.*, [35] proposed a allometric equation to estimate the AGB of mangrove species in the coastal zone of the Red River Delta by measuring 101 *K. obovata* trees and 84 *S. caseolaris* trees. Due to the similarity in the coastal region and species composition, this study used their published allometric equations to calculate the AGB and AGC stocks of mangrove species in Bang La and Dai Hop as shown in Table 2.

Table 2. Above ground biomass allometric equations used for Bang La and Dai Hop.

Species	Biomass allometric equations	Sources
Sonneratia caseolaris	Biomass = 0.000596 * $D^{4.04876}$	[35] (2)
Kandelia obovata	Biomass = 0.10316 * $D^{1.85845}$	[35] (3)

where: Biomass is above ground biomass (AGB) of mangrove species, D is the diameter at the breast height. To convert AGB of mangrove forests into AGC stocks, a conversion ratio of 0.47 was applied as AGC = AGB*0.47 [36].

Soil organic carbon (SOC) estimation

The method used to determine total soil organic carbon (SOC) was adapted according to Vietnam National Standard TCVN 9294: 2012. This standard is based on the Walkley-Black method, which was used to determine the organic carbon content in marine sediments [37, 38]. In this process, the organic matter was oxidised using an excess amount of potassium dichromate solution in a sulfuric acid medium, using heat by dissolving the concentrated sulfuric acid into a dichromate solution, then titrating the redundant of dichromate with an iron (II) solution, thus deducting the organic carbon content. To calculate the amount of carbon in the soil sample, the following formula was used:

$$C = \text{Soil organic carbon (\%)} = \frac{(V_0 - V_1) * C_N * 0{,}003 * 1{,}724 * 100 * k}{W} \text{[35, 37, 38]} \quad (4)$$

where V_0 (ml) is the volume of Morh used for the titration, V_1 (ml) is the volume of Mohr used to titrate the environment; C_N is equivalent concentrations of Mohr; k is coefficient of dryness (conversion from dry air to dry soil); 1,742 is experiment coefficient(conversion coefficient from carbon content to organic matter content); W (g) is the weight of soil at the beginning. By using the specific bulk density of the soil sample, the underground carbon stock in a specific area was calculated as follows:

$$A(H) = a(h) \times dh \quad (5)$$

$$a(h) = c(h) \times T(h)/100 \quad (6)$$

$$C(H) = A(H) \times 100 \text{ [36, 38]} \quad (7)$$

where dh (cm) is the depth of a soil layer; H [cm] is the soil depth; c(h) (%) is the carbon content at depth h; T(h) (g/cm^3) is the density of the soil or the volume of soil at depth h; a(h) (g/cm^3) is the accumulation of carbon in the soil at depth h; A(H) (g/cm^2) is the accumulation of carbon in the soil at depth H; C(H) (ton ha^{-1}) is the accumulation of carbon in the forest soil at depth h.

2.2.3. Estimation of above ground biomass, carbon stocks and SOC based on IDW approach

The inverse distance weighted (IDW) method, a deterministic spatial interpolation approach, is one of the most common approaches adopted by geoscientists and geographers, and has been employed in various GIS packages, such as QGIS and ArcGIS [39, 40]. The general premise of IDW is that the attribute values of any given two points are closely related to each other, but they are similarly inversely related to the distance between the two locations [41]. IDW is known as a mapping technique, an exact and convex interpolation method that fits only the continuous model of spatial variation. IDW allows to derive the value of a variable at some new locations using values obtained from known locations [42]. However, the disadvantage of using the IDW method in processing large datasets will be the computation time [40].

The values of unknown points were determined by computing the weighted average of the accurate values in the neighborhood of each pixel. The formula is as follows [43, 44]:

$$Z_j = \frac{\sum_{i=1}^{N} W_{ij} Z_i}{\sum_{i=1}^{N} W_{ij}} \quad (8)$$

where Zj is the estimated value at grid location J; Zi is the known value at control point location i, and Wij is the weight that controls the effect of control points on the calculation of Zj.

This IDW method can be optimised by selecting the nearest points during the interpolation process, known as the growing radius. As the plots were evenly distributed over the study areas, the IDW method was a feasible interpolation method for estimating biomass and carbon stocks as well as SOC at the study sites.

2.2.4. Estimation of the total carbon stocks

Adapting the carbon stocks classification of Bay [45], there would be 5 levels of carbon stocks classified for mangroves forests in this study as shown in Table 3.

Table 3. Categories of carbon stocks.

Carbon stocks categories	Carbon stocks (ton ha^{-1})
Very high	>150
High	101÷149
Average	50÷100
Low	20÷49
Very low	1÷19

Adapted from [45].

To propose for C-PFES, this study calculated the total CO_2 absorbed by mangrove forests using the formula: CO_2 = carbon stocks (ton ha^{-1}) × 44/12 [46].

3. RESULTS AND DISCUSSION

3.1. Land use/covers, mangrove forests mapping in Bang La and Dai Hop

Assessments of mapping accuracies

As a result of NDVI calculated and evaluated, the NDVI threshold for each land use and land cover was defined. The NDVI thresholds for mangrove forests, non-mangrove forests and water bodies were determined to be greater than 0.2, from 0.2 to 0.02, and less than 0.02, respectively. These threshold values were then used to create a map of land use and land cover in 2018 (Fig. 4) [15]. To assess the accuracy of the selected NDVI thresholds, 204 GPS points collected from the field survey (equivalent to 40% of the total 510 GPS points) were used for three main land use/covers (120 points for mangrove forests, 64 points for non-mangrove forests, such as mudflats, sand, bare and wet soil, non-mangrove plants, residential areas; 20 points for water bodies). The total accuracy of NDVI assessments was 88.2% with a Kappa coefficient of 0.79 (Table 4). This accuracy of the NDVI assessments is consistent with that previously reported by Hai-Hoa *et al.* [15].

Table 4. Accuracy assessments of land use/cover classified by NDVI in 2018.

GPS / Sentinel classified	Man	Non-man	Water	Total	User's Accuracy (%)
Man	105	13	2	120	87.5
Non-man	5	57	2	64	89.1
Water	1	1	18	20	90.0
Total	111	71	23	**204**	
Producer's Accuracy (%)	94.6	80.3	81.8		
Overall accuracy (%): 88.2; Kappa coefficient is 0.79					

Man (Mangrove forests); Non-man (Non-mangrove forests); Water (Water bodies)

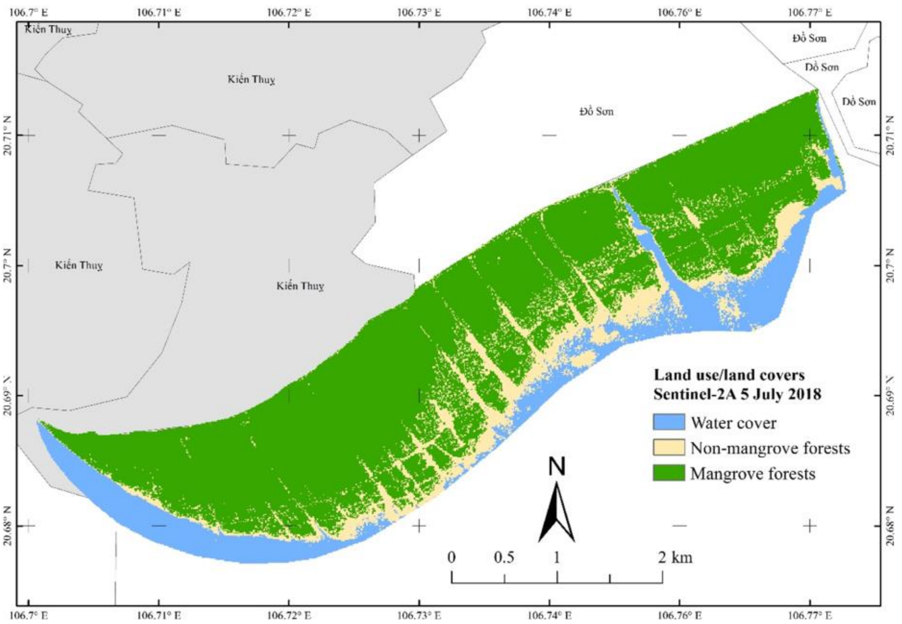

Figure 4. Land use, covers, mangrove forests in Bang La and Dai Hop Communes, Hai Phong Coast.

3.2. Estimation of above ground biomass and carbon stocks in Bang La and Dai Hop

Estimation of AGB and AGC stocks-based field investigation

Field surveys and interviews showed that the dominant species were *K. obovata* and *S. caseolaris*. The age of mangrove forests is mainly from 10 to 19 years. A summary of mangrove structure surveyed, AGB, and AGC is presented in Table 5.

Table 5. Estimation of AGB and AGC stocks from 17 plots in Bang La and Dai Hop along the coast of Hai Phong.

Plots	**Species**	**Longitude**	**Latitude**	**Density (tree ha^{-1})**	**$D_{1.3}$ (cm)**	**H (m)**	**CD (m)**	**AGB (ton ha^{-1})**	**AGC (ton ha^{-1})**
1	*Ko*	106.7659	20.7125	7208	6.53	3.12	0.9	25.07	12.42
2	*Ko, Sc*	106.7621	20.7114	4807	7.87	2.24	1.3	35.94	17.80
3	*Ko*	106.7577	20.7094	5565	6.11	2.34	1.0	22.39	11.09
4	*Ko*	106.7561	20.7091	9275	7.14	2.32	0.9	46.78	23.18
5	*Ko*	106.7528	20.7078	9895	6.45	2.31	1.1	40.26	19.95
6	*Ko, Sc*	106.7464	20.7054	6360	7.83	2.28	1.5	32.40	16.05
7	*Sc*	106.7436	20.7036	1325	8.08	4.48	1.4	26.66	13.21
8	*Ko*	106.7432	20.7014	8109	6.64	2.45	1.3	19.76	9.79
9	*Ko*	106.7421	20.7013	10205	5.87	2.25	1.6	31.45	15.58
10	*Ko, Sc*	106.7311	20.6939	8533	9.19	2.65	1.3	55.64	27.57
11	*Ko*	106.7301	20.6943	6434	7.39	2.31	1.1	22.23	11.01
12	*Ko*	106.7271	20.6913	6699	6.47	2.37	1.2	20.64	10.23
13	*Ko*	106.7258	20.6895	8268	6.24	2.36	0.9	32.68	16.19
14	*Ko, Sc*	106.7174	20.6819	3180	9.19	2.94	1.2	47.97	23.77
15	*Ko, Sc*	106.7214	20.6842	2385	9.41	3.03	1.3	59.64	29.55
16	*Ko, Sc*	106.7234	20.6873	2226	9.62	7.22	1.5	49.74	24.65
17	*Sc, Ko*	106.7181	20.6846	2120	11.08	6.78	1.7	40.56	20.10
			Mean	6034.9	7.7	3.1	1.2	35.9	17.8
			Max	10205.0	11.1	7.2	1.7	59.6	29.6
			Min	1325.0	5.87	2.24	0.9	19.76	9.79

Note: Ko: K. obovata; Sc: S.caseolaris; Ko, Sc: Ko is more dominant; Sc, Ko: Sc is more dominant, CD (Canopy diameter); H (Tree height); $D_{1.3}$ (Diameter at the breast height).

As shown in Table 5, $D_{1.3}$ varies from 5.87 to 11.1 cm, this large variation is due to the species composition of the surveyed plots. The average DBH of the dominant *K. obovata* plots and the *S. caseolaris* plots were 8.9 cm and 11.08 cm, respectively. The main influencing factors on AGB and AGC of mangrove forests are DBH of mangrove species and density [17]. The values of AGB and AGC range from 19.76 to 59.64 (tons ha^{-1}) and from 9.79 to 29.6 (tons ha^{-1}), respectively. The lowest AGB was found in a *K. obovata* plantation plot (Plot 8), and the highest AGB was recorded in plot 17 which is dominated by *S. caseolaris* species. Nguyen *et al*. [35] estimated that the AGC accumulated in *S. caseolaris* at the age of 13 was 43.37 tons ha^{-1} and the age of 10 was 32.96 tons ha^{-1} [17]. For comparison, the AGC stocks at the sites of this study were lower than those reported in a previous study by Hanh [17] in Tien Lang District. A study by Phan Nguyen Hong (1996) showed that in general, the carbon storage in *S. caseolaris* was significantly higher than in *K. obovata*. As a result, *S. caseolaris* has demonstrated a better capacity to accumulate carbon than *K. obovata* and thus contributes more significantly to the reduction of greenhouse gas effect.

The DBH of mangrove species is significantly correlated with the total AGB of mangrove forests, which increases with mangrove growth [35]. At the study site, AGB and mangrove density are inversely related, the higher the tree density, the lower the AGB due to the species composition as confirmed in previous studies by Scrosati *et al.* [47] and Njana *et al*. [48]. Indeed, a high density of *K. obovata* plantations is an important factor for carbon accumulation in mangrove soil [49].

AGB estimation-based IDW interpolation

AGB was estimated by spatial IDW interpolation based on DBH values in Bang La and Dai Hop as shown in Fig 5.

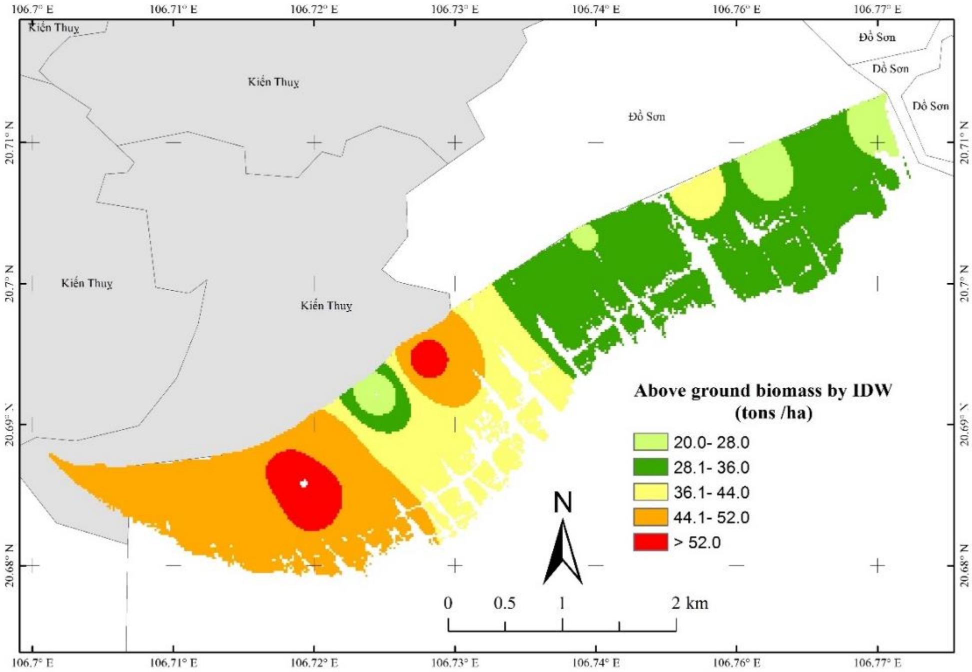

Figure 5. Estimation of AGB by spatial IDW interpolation in Bang La and Dai Hop.

There were 12 plots (equivalent to 70 % of total plots) used for interpolating the AGB of mangrove forests at the study sites as showed in Fig. 5. Five plots were used to evaluate the accuracy of the estimated AGB by spatial IDW interpolation (equivalent to 30 % of total plots, plots 4, 8, 11, 13 and plot 20). As a result, the average accuracy of spatial IDW interpolation results was 81.5 %. The interpolated AGB results indicated 3 distinct categories, the first ranging from 36.0 to 52.0 tons ha^{-1} in Bang La Commune, the second from 36 to 44 tons ha^{-1} in both Bang La and Dai Hop Communes, and the highest biomass region ranged from 44 to 52 tons ha^{-1} in Dai Hop Commune. In general, AGB gradually increased from Bang La to Dai Hop along with the development of two main mangrove species. The highest AGB was recorded in the mixed mangrove forests in Dai Hop with a range of 52 - 60 tons ha^{-1}, while the lowest AGB was observed in the dominant *K. obovata* plantation in Bang La from 20 to 28 tons ha^{-1}.

AGC stocks estimation-based IDW interpolation

AGB stocks were estimated by spatial IDW interpolation based on DBH and AGB in Bang La and Dai Hop as shown in Fig. 6.

There were 12 plots (similar to AGB plots) used to interpolate the AGC of mangrove forests at the study sites as shown in Fig. 6. Plots 4, 8, 11, 13 and plot 20 were used to evaluate the accuracy of the estimated AGC by IDW interpolation (equivalent to 30% of 17 plots). As a result, the overall accuracy assessment of IDW interpolation reached 81.5%. In general, according to Pham Ngoc Bay's carbon stock classification [45], the AGC mangrove stocks at the study sites were below 50 tons ha^{-1}, classified as low and very low carbon stocks [45]. There were 2 main categories of carbon stocks found at the study sites. The first category of carbon stocks ranged from 10 to 19 tons ha^{-1} and the second from 20 to 49 tons ha^{1} across Bang La and Dai Hop, whereas AGC of above 27.5 tons ha^{-1} was found in small areas of Dai Hop Commune (Fig. 6).

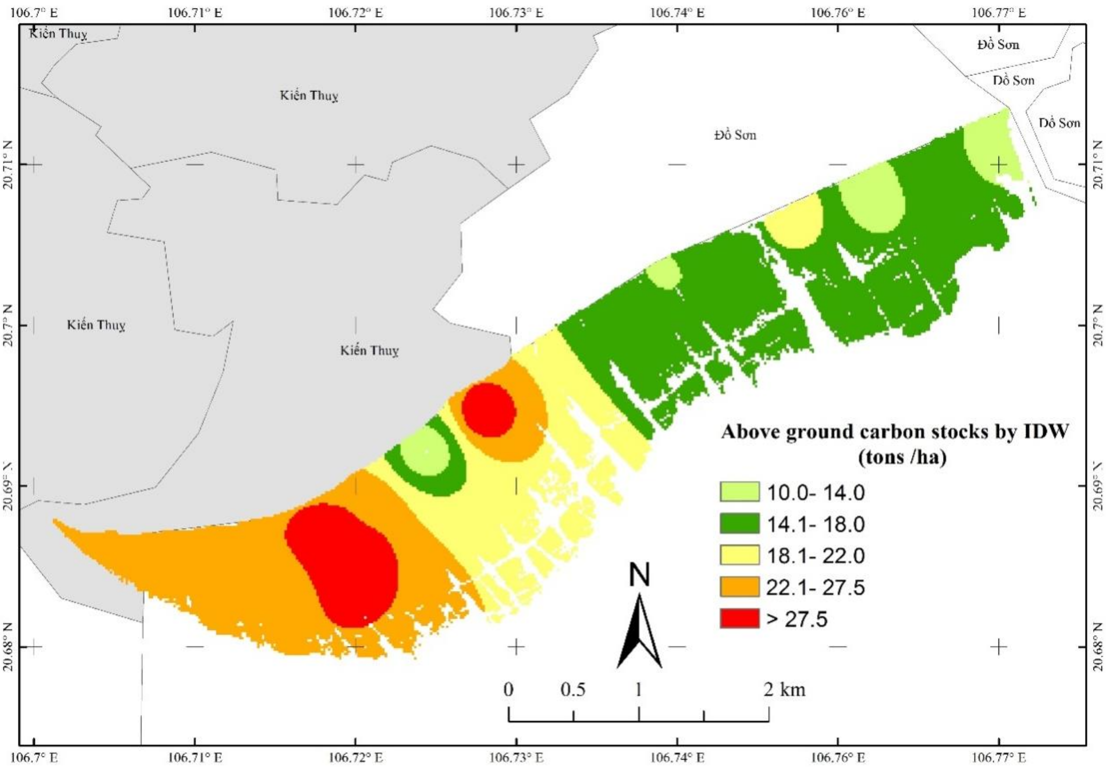

Figure 6. Estimation of above ground carbon stocks by spatial IDW interpolation in Bang La and Dai Hop Communes.

In general, it can be seen that the AGC of mangrove forests is highly dependent on the AGB of mangroves. Mangrove forests with very high AGC stocks were found in the mixed forests of *K. obovata* and *S. caseolaris*. *K. obovata* plantations had low carbon storage due to their small stem diameters, making them susceptible to external influences, such as anthropogenic deforestation and degradation, and impacts of climate change.

3.3. Estimation of soil organic carbon stocks in Bang La and Dai Hop

Soil organic carbon-based Walkley-Black method

According to the results of SOC analysis by the Walkley-Black method (Table 6), the total SOC ranged from 81.76 to 323.83 tons ha^{-1} (an average of 161.48 tons ha^{-1}). The large fluctuations in SOC stocks of 9 plots (plots 1 - 9) in Bang La were recorded, which ranged from 81.76 (plot 1) to 323.83 (plot 4) tons ha^{-1}.This variation can be explained by the large difference in age, density as well as species composition in survey plots. Conversely, there was not a significant variation in the SOC stocks in Dai Hop commune, the average SOC was recorded at 152.9 tons ha^{-1} with a standard deviation of 21.96 tons ha^{-1}.

Table 6. SOC contents in different layers by Walkley-Black method (cm, ton ha^{-1}).

Plots	**Density (tree ha^{-1})**	**Longitude**	**Latitude**	**SOC in different layers (cm)**					**Total**
				0 - 20	20 - 40	40 - 60	60 - 80	80 - 100	
P1	7208	106.7659	20.7125	12.80	23.52	20.35	10.91	14.18	81.76
P2	4807	106.7621	20.7114	15.70	24.18	19.29	34.69	22.30	116.16
P3	5565	106.7577	20.7094	51.79	17.03	30.87	29.00	15.92	144.62
P4	9275	106.7561	20.7091	59.06	57.43	76.91	66.72	63.71	323.83
P5	9895	106.7528	20.7078	65.54	35.72	64.19	57.67	69.48	292.60
P6	6360	106.7464	20.7054	16.15	16.32	19.71	27.88	13.53	93.59
P7	1325	106.7436	20.7036	30.98	23.00	26.54	19.40	10.73	110.66
P8	8109	106.7432	20.7014	8.05	34.83	27.62	34.48	27.99	132.97
P9	10205	106.7421	20.7013	45.98	48.34	25.77	54.82	50.73	225.63
P10	8533	106.7311	20.6939	35.99	24.42	49.93	34.95	30.15	175.44
P11	6434	106.7301	20.6943	22.59	24.72	23.34	17.01	22.20	109.87
P12	6699	106.7271	20.6913	25.82	33.08	28.89	34.50	24.17	146.46
P13	8268	106.7258	20.6895	21.39	35.68	26.97	42.06	33.53	159.64
P17	3180	106.7174	20.6819	29.89	41.77	32.81	31.73	34.70	170.91
P18	2385	106.7214	20.6842	20.71	30.14	30.00	26.77	27.47	135.09
P19	2226	106.7234	20.6873	31.80	35.37	36.05	30.64	35.66	169.51
P20	2120	106.7181	20.6846	21.42	29.31	30.87	39.68	35.06	156.34
			Mean	30.33	31.46	33.54	34.88	31.27	161.48
			Max	65.54	57.43	76.91	66.72	69.48	323.83
			Min	8.05	16.32	19.29	10.91	10.73	81.76

The SOC accumulation in mangrove forests at the study sites was lower than in mangroves (*Rhizophora apiculata*) in Ca Mau and Can Gio, southern Vietnam. The SOC in Ca Mau and Can Gio at depths of 0 -100 cm ranged from 258.51 to 479.29 tons ha^{-1}and from 245.2 to 309.9 tons ha^{-1}, respectively [50]. The main cause is due to the difference in climatic characteristics among Hai Phong (Bang La and Dai Hop), Ca Mau and Can Gio. Moreover, the mangrove forests in southern Viet Namare older than those of the study sites. In addition, the type of mangrove forest is also an important factor affecting the SOC. This study found that there were two kinds of mangrove forests classified based on species composition as shown in Table 7.

The SOC stocks in various soil layers were not much different, but the SOC in mangrove plantations was significantly higher than in mixed mangrove forests. This finding has also been confirmed by previous studies, where mangrove density was identified as a major determinant of SOC intensity [51]. A recent study by Nguyen [49] under the same environmental conditions as the study areas has shown that mangrove plantations have a great influence on SOC accumulation, which depends on tree age, tidal inundation, mangrove species, tree density and natural conditions [17, 38, 52]. As the carbon sequestration of forests was a cumulative process over time, it tends to increase with the growth of forest trees. It is evident that high carbon deposition in soils was facilitated by the slow decomposition of organic matter in the soil (main roots). In 1976, Albright proved that 90% of leaves decomposed within 7 months after falling, but 50 ÷ 88% of root tissues remains in the soil over the years [53]. The leaves were quickly decomposed or carried away by the tide, whereas the roots decayed slowly and accumulated over a long period of time. Therefore, roots play an important role in the accumulation of SOC in mangrove forests.

Table 7. SOC categories by mangrove species composition in Bang La and Dai Hop (tons ha^{-1}).

	Soil depths (cm)				
	0 - 20	20 - 40	40 - 60	60 - 80	80 -100
Mangrove plantation (Dominant *K. obovata*)	34.4	33.34	35.15	36.66	33.26
Mixed mangrove forests	25.21	29.21	30.04	30.95	27.54

Soil organic carbon-based IDW interpolation

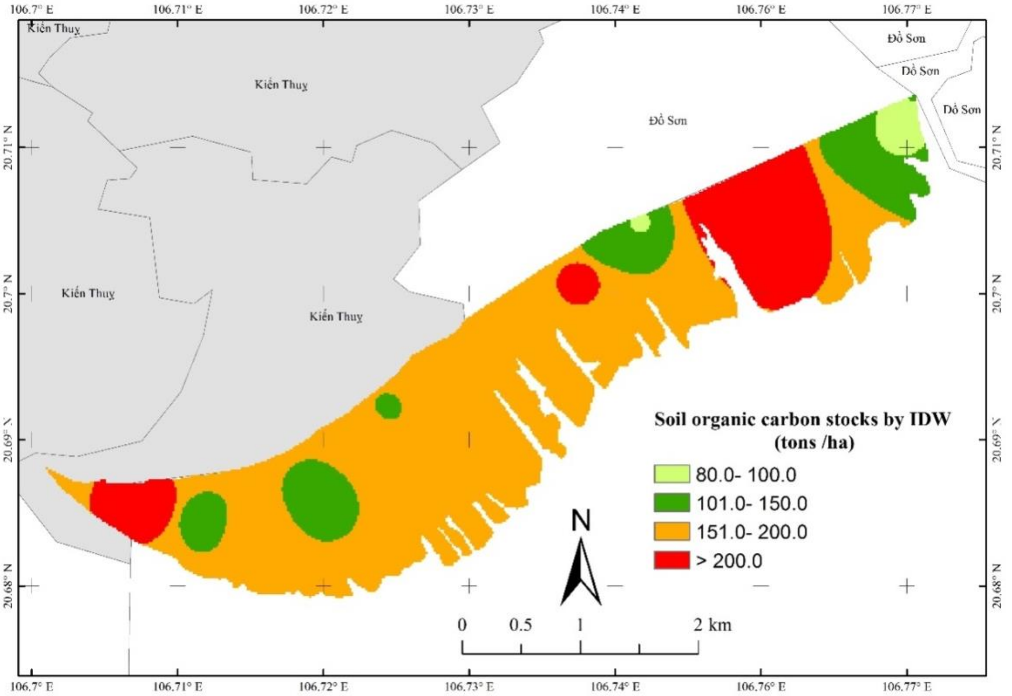

Figure 7. Estimation of SOC stocks by spatial IDW interpolation in Bang La and Dai Hop, Hai Phong coast (min SOC: 81.8 tons ha^{-1}, max SOC: 323.8 tons ha^{-1}).

To create a map of SOC over Bang La and Dai Hop, the study calculated carbon stocks based on soil analysis and computation data, and then used spatial IDW interpolation to generate the SOC map. The map of SOC was expressed in unit of tons ha^{-1} (Fig. 7). 15 out of total 20 plots were used to interpolate the SOC of mangrove forests at the study sites as shown in Fig. 8.

Plots 4, 8, 11, 13 and plot 20 (5 of total 20 plots) were used to evaluate the accuracy of the estimated SOC by IDW interpolation. As a result, the overall accuracy assessment of SOC by IDW interpolation reached 76.0 %.

As shown in Fig. 7, SOC accumulated at various soil depths of 0 - 100 cm was very high, from 80.0 to 323.8 tons ha^{-1}. Most of the plots have a high level of carbon accumulation, reaching over 150 tons ha^{-1} with an area covering about 75.0 % of the study sites. The study area mainly had higher SOC content in the range of 150 to 200 tons ha^{-1}, because *K. obovata* grew very densely, leading to a large number of the fallen matters of mangrove species. Especially, regenerated mangrove trees can resist the impact of wave attacks and prevent the tide from removing organic matters from the soil surface, thereby increasing organic carbon accumulation in sediment samples of mangrove forests.

3.4. Estimation of total carbon stocks in study sites

From the field measurements, the study calculated the amount of absorbed carbon dioxide and the commercial values of mangrove forests in Bang La and Dai Hop as shown in Table 8.

Table 8. Absorbed carbon dioxide by mangrove forests and commercial values at the study sites.

	Absorbed CO_2	**Accumulated CO_2 in the soil**
Total absorbed CO_2	170,462 (tons)	1,461,372 (tons)
Price	\$5USD ton^{-1} [54]	
Conversion(up to 08/07/2021)	1USD = 22,900.00 VND*	
Total proceeds	\$852,310 USD 19,517,899,000 (VND)	\$7,306,860 USD 167,327,094,000 (VND)

*https://portal.vietcombank.com.vn/Pages/Home.aspx

The total CO_2 of mangrove forests in Bang La and Dai Hop was estimated at 1,631,834 tons, including 170,462 tons of accumulated CO_2 in the tree biomass and 1,461,372 tons of CO_2 in the soil, which has provided strong evidence for the possibility of registration of payment for forest environmental services and carbon credit mechanism (C-PFES). The higher the value of carbon stocks, the greater the commercial value that mangrove forests are likely to bring to local people, which is the basis for the application of the C-PFES policy at the study sites [54].

4. CONCLUSIONS

Mangrove protection is one of the most effective ways to mitigate and prevent the negative impacts of climate change in Vietnam. However, to date there has not been much research in this area. This study estimated the stocks of AGC and SOC using field survey data combined with remote sensing data in Bang La and Dai Hop on the coast of Hai Phong. The study set up and investigated 20 plots for mangrove forests (17 of 20 plots for mangrove investigation) and soil organic carbon. The results showed that the SOC was significantly higher than that in mangrove forests, which was consistent with previous studies under similar environmental conditions. Total carbon stocks in Bang La and Dai Hop varied significantly among plots and ranged from 9.9 to 29.55 tons ha^{-1} with the highest AGC of 29.55 tons ha^{-1} in mixed *K. Obovata* and S.

caseolaris forests and the lowest AGC of 9.79 tons ha^{-1} in *K. obovata*. The SOC analysis results based on the Walkley-Black method showed that the SOC content was in the range of 81.76 - 323.83 tons ha^{-1}, in which the highest content of SOC was recorded in plot 4 (approximately 324 tons ha^{-1}) and the smallest one was in plot 1 (81.76 tons ha^{-1}) in Bang La Commune. Our study showed that the ability to accumulate SOC in *K. Obovata* plantations was higher than in mixed forests. According to the results of the IDW interpolation method, this study estimated the total amount of CO_2 absorbed by mangrove forests in Bang La and Dai Hop to be 1,631,834 tons (including 170,462 tons of CO_2 accumulated in tree biomass and 1,461,372 tons of CO_2 in soil), providing strong evidence for the possibility of enrollment in C-PFES and carbon credit mechanism. These findings have provided an important basis for proposing the application of carbon credits as well as the basis for further research in this area in Vietnam.

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Declaration of competing interest. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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