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ESTIMATION OF CHANGES IN ABOVE-GROUND BIOMASS AND CARBON STOCKS OF MANGROVE FORESTS USING SENTINEL-2A IN THAI THUY DISTRICT, THAI BINH PROVINCE DURING 2015 - 2019

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Abstract. Mangrove forests are found along shallow shorelines with modest slopes where they receive freshwater runoff and nutrients from rainfall. They have been globally recognised as having a vital function in preventing coastal erosion, mitigating wave actions, and protecting coastal habitats and adjacent shoreline land-uses from extreme coastal events. Using Sentinel-2A, the spatial distribution of mangrove forests was constructed over three years. The accuracy assessment showed that the overall accuracy of the 2019 Sentinel-2A classification was 93.6 % with a Kappa coefficient of 0.90, and the accuracy of the Sentinel-2A in 2015 and 2017 was also more than 90.0 % with a Kappa coefficient of 0.87. There were 2327.9 ha of mangrove forests in 2019; 2007.9 ha in 2017; and 1881.3 ha in 2015. The AGB of mangrove forests in Thai Thuy has increased over time. In 2015, the area of mangrove forests with AGB higher than 7.3 tons ha^{-1} and AGC more than 3.42 tons ha^{-1} was estimated at about 877.2 ha, the area of mangrove forests with AGB and AGC greater than 7.3 and 3.42 tons ha^{-1}, respectively, increased to 1067.6 ha in 2017, and there were 1241.1 ha with AGB over 7.3 tons ha^{-1} and AGC greater than 3.42 ton ha^{-1} in 2019. There were small variations of AGB and AGC of mangrove forests between field measurements and Sentinel-based estimation in 2019. Therefore, using Sentinel-2A to estimate AGB and AGC of mangrove forests is reliable and applicable to the Thai Binh coast and it needs to be tested in other similar coastal areas in Viet Nam.

Keywords: Biomass, carbon stocks, mangrove forests, Sentinel-2A, Thai Thuy.

Classification numbers: 3.5.1; 3.8.2

1. INTRODUCTION

Mangroves or tide-dominated mangroves are found along shallow shorelines with modest slopes where they receive freshwater runoff and nutrients from rainfall and have a high salinity concentration [1, 2, 3, 4, 5, 6]. They are also subjected to wave actions and storm surges [7], and are flushed by regular tides [5]. Significantly, mangrove forests have been globally recognised as having a vital function in preventing coastal erosion, mitigating effects of wave actions, currents and storm surges, and protecting coastal habitats and adjacent shoreline land-uses from extreme coastal events [8, 9, 10, 11]. Although their significantly functional values are well-recognised, they are still being deforested and degraded for coastal settlement, and aquaculture, resulting in a loss of ecosystem services and associated economic benefits [12, 13]. Consequently, a rapid reduction of mangrove extents together with the associated impacts of increased severity of storms has the potential to impact catastrophically on coastal communities.

In Viet Nam, mangrove forests are recently recognised as a highly valuable resource [14, 15]. These unique coastal forests provide multiple ecosystem services, including carbon storage, wood production for building, fish trap construction and firewood, habitat for aquatic food resources, and most importantly shoreline stability and erosion control [8, 16]. However, the area of mangrove forests has rapidly declined over time; from an estimated 408,500 ha in 1943 to 290,000 ha in 1962, to 252,000 ha in 1982; and to 155,290 ha in 2000 [17, 18]. Remarkably, recent evidence has shown that the area of mangrove forests increased to 210,000 ha in 2008 thanks to a National Action Plan for Mangrove Protection and Development, and other international mangrove restoration and rehabilitation programs [17, 18, 19]. Despite this national increase, some areas are now still experiencing a decline of mangrove covers [19]. In Thai Binh province, increased fragmentation of mangroves has reduced their capacity to withstand coastal processes, such as coastal currents, wave actions, semi-exposed coastline locations [2, 20, 21]. In addition, the underestimation of the value of mangrove forests and weak management and protection have also led to severe degradation of mangroves over the years. This is resulting in the loss of key mangrove resources and associated ecosystem services, also threatening the local livelihoods by increased vulnerability of coastal communities to storm surges with large storms and typhoons. Therefore, an integrated approaches, including payments for carbon sequestration of mangrove forests should be adopted to restore and re-establish mangroves in Thai Binh province.

Currently, climate change has been affecting negatively the world-wide environment and Viet Nam is one of the most severely affected countries, including Thai Binh province [22, 23, 24]. Therefore, to reduce carbon emissions by enhancing mangrove restoration and rehabilitation activities, and monitoring mangrove emissions is extremely essential due to main carbon storage sources in the world from mangrove forests [25, 26].

In order to estimate mangrove ecosystem services, including carbon sequestration and storage, it is necessary to first assess trends of mangrove dynamics associated with biomass and carbon stocks in Thai Binh province. Various remote sensing technologies and techniques have extensively applied to monitor mangrove forest dynamics and estimate carbon stocks due to their large spatial-temporal coverage, cost effectiveness, ready availability and applicability [1, 27, 28, 29, 30, 31, 32, 33, 34]. Despite the global extensive application of remote sensing and GIS technologies and techniques to monitor the spatial-temporal dynamics of mangrove forests, such as mangrove extents, biomass and carbon stocks, accurate and reliable information on estimates of mangrove biomass and carbon stocks based on remote sensing data in Thai Binh and Viet Nam is very limited.

The aim of this study was to quantify spatial-temporal extents of mangrove forests in Thai Thuy district, Thai Binh province from 2015 to 2019 by using Sentinel-2A imageries. The AGB and AGC of mangrove forests, and their changes in selected periods were estimated. The findings obtained were then used to inform coastal management planning and policy development, particularly related to the sustainable management of mangrove forests in connection with C-PFES, and likelihood improvements in the face of a changing climate in Viet Nam.

2. MATERIALS AND METHODS

2.1. Study site and materials

2.1.1. Study site

Thai Thuy is a coastal district of Thai Binh province in the Red River Delta region of Viet Nam that covers an area of 268,44 km² [35, 36]. This district has a population of 250,222 in 2019 [35, 36]. The district centre is located in Diem Dien town. This study selected Thai Thuy district as a study site due to mainly spatial distribution of mangrove forests with dominant species, known as *Kandelia obovata*, *Sonneratia caseolaris*, *Rhizophora stylosa*, and *Aegiceras corniculatum* (Fig. 1).

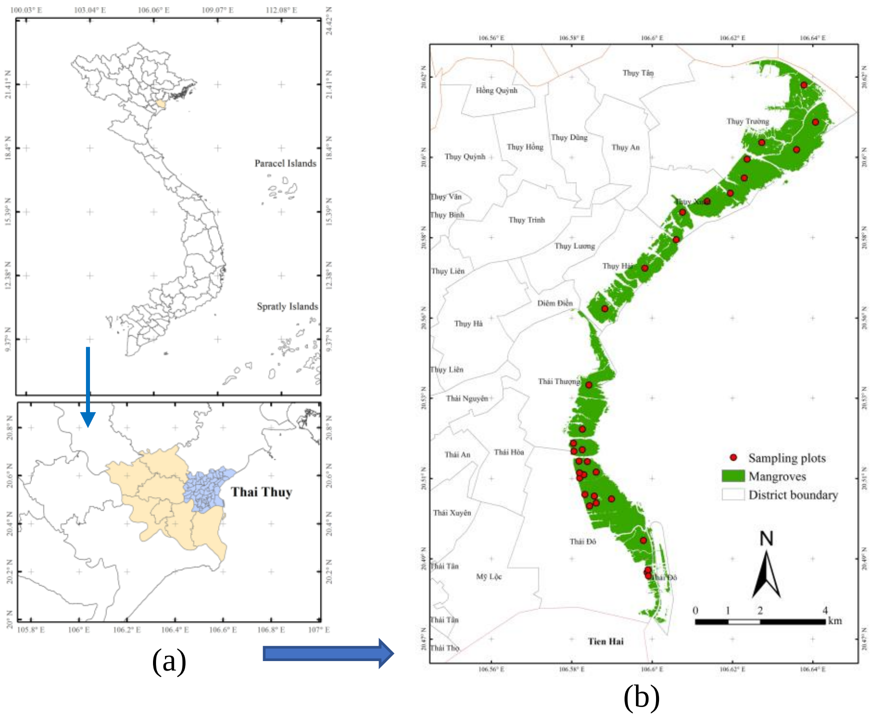

Figure 1. Study site: (a) Geographical location of Thai Binh province in Viet Nam; (b) Thai Thuy district in Thai Binh province.

2.1.2. Materials

In this study, the multi-temporal Sentinel-2A imageries (2015-2019) were used to detect mangrove covers, and then to calculate AGB (Above-ground biomass) and AGC (Above-ground carbon stocks) of mangrove forests (Table 1). In addition, the PlanetScope images in 2017 were used for accuracy assessments of the 2017 Sentinel-2A images in combination with the field survey conducted in 2019 and Google Earth data because the 2017 PlanetScope images offer a higher spatial resolution (3 m × 3 m) than the Sentinel-2A images (10 m × 10 m), but it is only available for 2017.

Table 1. Remotely sensed satellite imageries used in this study.

ID	Image codes	Date	Resolution (m)	Remarks
1[a]	S2A_MSIL1C_20190928T031650	28/9/2019	10 × 10	Sentinel 2A
3[a]	S2A_MSIL1C_20171217T033108	17/12/2017	10 × 10	Sentinel 2A
4[a]	S2A_MSIL2C_20150810T0331200	10/8/2015	10 × 10	Sentinel 2A
5[b]	20170529_023943_1027_3B_AnalyticMS	03/6/2017	3 × 3	PlanetScope
	20170605_062510_0c43_3B_AnalyticMS	05/6/2017	3 × 3	PlanetScope
	20170605_062509_0c43_3B_AnalyticMS	05/6/2017	3 × 3	PlanetScope
	20170603_023945_1006_3B_AnalyticMS	03/6/2017	3 × 3	PlanetScope
6[a]	DEM	2011	30 × 30	

Sources: [a]http://earthexplorer.usgs.gov;[b]https://www.planet.com/explorer

2.2. Methods

Field data collection

Data were gathered from three types of coastal land use and cover in 2019, including mangrove forests (closed and open canopy), non-mangrove land use (abandoned aquaculture pond, bare and wet land, other non-mangrove plants, and others), and water bodies. This study intended to focus on mangrove forests for the calculation of above-ground biomass (AGB) and above-ground carbon (AGC) rather than other land covers. Therefore, plots were set up only for mangrove survey. Sites for plot establishment were randomly taken for biomass measurements, which were across over the Thai Thuy coast (Fig. 1). Linear circular plots with a radius of 7 m along the transects were set up to collect data required for the estimation of mangrove biomass (Fig 1). Each transect has up to three circular plots, spaced 30 m apart [37, 38]. At each plot, all measurements (mangrove diameter at the breast height, $D_{1.3}$) necessary to determine the biomass were conducted, according to Kauffman and Donato's method of calculating mangrove biomass stocks [38]. Within each mangrove plot, geographic coordinates were recorded using a Garmin 76cs GPS. A total of 32 plots were set up in this study, which were used for mangrove biomass and carbon calculation. In addition, there were 250 GPS points in 2015, 250 points in 2017 and 250 points in 2019 collected for three classes (mangrove forests, waters, and others including non-mangrove forest plants, built-up areas, bare and wet land and others) across over the Thai Thuy coast for accuracy assessments.

Image analysis

Sentinel-2A images were already geo-referenced. In order to obtain a pixel-to-pixel match between two images, Sentinel-2A in 2019 was used to register 2017 PlanetScope images to improve geometric accuracies. This geometric correction was required to improve the geolocation to a root mean square error of less than a pixel and the accuracy of subsequent change analysis. All images were geo-referenced to UTM WGS 1984 Zone 48N projection and datum.

Masking possible mangrove areas was conducted to reduce unnecessary data volume and increase overall classification accuracy. In order to mask possible mangrove areas accurately, higher spatial resolution images in this study, including PlanetScope (3 m x 3 m) and Google Earth images were used to delineate the boundary of possible mangrove areas from other land use and land cover types. The delineated boundary was then checked with the field survey to ensure that every possible mangrove areas were included within the boundary. Remarkably, mangrove forests in the study site are separated from other land use and land cover types by the dyke system. Therefore, there was no difficulty in delineating the boundary of possible mangrove areas at the study sites. In addition, the 30-m SRTM DEM data, their derived slope and elevation were also employed to mask out the regions of high elevation and steep-slope where mangrove forests are not likely to occur [39]. The mask was then used to define the mangrove areas in the pre-processed Sentinel-2A images (2015, 2017 and 2019). These images were clipped to extract only areas where mangrove forests were more likely to be present (e.g. low-lying areas and inter-tidal zones), and to exclude large coastal areas where mangrove forests did not occur (e.g. far inland, highlands and open ocean) before the image classification was undertaken [40].

Image classification

In this study, Normalised Difference Vegetation Index (NDVI) was used for image classification [41]. NDVI calculation is defined as follows:

$$NDVI = (\rho 8 - \rho 4)/(\rho 8 + \rho 4) \quad (1)$$

where $\rho 4$ and $\rho 8$ are known as the reflectance values from Band-4 (RED) and Band-8 (NIR) of a Sentinel-2A image, respectively. NDVI has been extensively and intensively used to estimate vegetation properties, despite being prone to noise from variations in atmospheric and soil conditions, and tending to saturate with increasing vegetation density [42, 43]. NDVI values range from −1.0 to 1.0, but are between 0 and 1.0 for vegetation because $\rho 8$ is typically larger than $\rho 4$ [43].

Raster Calculator in Spatial Analyst Tools in ArcGIS (Version 10.4.1) was then used to calculate NDVI values, AGB and AGC of mangrove forests. In this study, images were classified according to the NDVI values with the ground truthing. These training samples were selected as points to represent distinct sample areas of various land cover types to be classified as mangroves (named mangrove forests), water bodies and others (non-mangrove plants, bare and wet soil, built-up areas, and others).

Post classification and accuracy assessments

In post-classification process, the filtering process was also applied to remove isolated pixels or noise from the classification output. The filtered classified image was then used as the final mangrove cover map for each year. The spectral classes were visually compared with the reference data derived from the sample plots, ground truthing, Google Earth and LULC map sheet (1/50,000) to verity land cover classification accuracy. The 2017 PlanetScope images (3 m x 3 m) provide a higher spatial resolution reference data set that is suitable for assessing the classification accuracy of the Sentinel-2A in 2017. Therefore, the accuracy matrix was conducted based on comparison of the 2017 PlanetScope and 2017 Sentinel-2A images, while the 2019 and 2015 Sentinel-2A images were assessed based on Google Earth images in 2015 and field survey in 2019.

Estimation of changes in AGB and AGC of mangrove forests from remote sensing data

In order to calculate the above-ground biomass (AGB) of mangrove forests, this study used the regression model developed from the independent variable Normalized Difference Vegetation Index (NDVI) by Bindu *et al*., [44] instead of developing calculation formula for Thai Binh mangroves. The reason is that the study aimed to test whether how applicable and reliable the AGB's formula of Bindu *et al*., [44] compared to the field-based data can be used to Thai Binh mangrove forests. In other words, it is necessary whether to develop the AGB and AGC calculation for Thai Binh mangrove forests. Therefore, AGB was calculated using NDVI data from Sentinel-2A images as shown in the following formula:

$$AGB = 0.507 * e^{(NDVI * 9.933)} [44] \tag{2}$$

carbon stocks were then obtained by multiplying the total AGB with a conversion factor of 0.47 (47.0 % of biomass) known as Above-ground carbon (AGC) [45]. Changes in AGB and AGC of mangrove forests were estimated using Spatial Analyst Tools in ArcGIS 10.4.1.

$$\text{AGC (Above-ground carbon)} = \text{AGB} * \text{C organic (0.47 is a conversion factor)} \tag{3}$$

$$\text{ACS (Amount of } CO_2 \text{ sequestration from AGB)} = 3.67 * \text{AGC [46]} \tag{4}$$

Estimation of changes in AGB and AGC of mangrove forests from field survey data

In this study, allometric equations for Above-ground biomass (AGB) developed by Komiyama *et al*., [47] were used to calculate the AGB of mangrove forests in Thai Thuy coast as shown in the formula below:

$$AGB = 0.251 * \rho * DBH^{2.46} [47] \tag{5}$$

where ρ is species-specific wood density. The AGB was calculated separately for each species and average value was taken. AGC and ACS of field-plot survey were calculated the same as AGC and ACS estimated from remote sensing data.

3. RESULTS AND DISCUSSION

3.1. Mangrove extents in Thai Thuy district

Accuracy assessments of Sentinel-2A classification

The accuracy evaluation showed that the overall accuracy of the 2019 Sentinel-2A classification was 93.6 % with user accuracy of 93.2 % and producer accuracy of 95.9 % for mangrove extents, and a Kappa coefficient of 0.90 (Appendix 1). It was therefore assumed that the use of Sentinel-2A images was adequate for mapping temporal changes in mangrove forests [48, 49]. The accuracy assessments of 2017 and 2015 Sentinel-2A images also indicated that there were all more than 90.0 % of the overall accuracy with a Kappa coefficient of 0.87, while user accuracy assessments were high for all classes (Appendix 2 and 3).

Spatial mangrove extents in Thai Thuy district

From the classified images, it was shown that there were 1881.3 ha, 2007.9 ha, and 2327.9 ha of mangrove forests in 2015, 2017 and 2019, respectively (Fig. 2). Our study revealed that mangrove forests in Thai Thuy have been distributing over 5 coastal communes, including Thuy Hai, Thuy Xuan, Thuy Truong, Thai Do, and Thai Thuong. However, the field survey indicated that mangrove forests have mostly distributed in Thuy Truong and Thuy Xuan communes with dominant species as *Sonneratia caseolaris*, while most of the remaining mangroves in Thai Thuy district are mixed plantations of *Kandelia obovata*, *Sonneratia caseolaris* and *Rhizophora stylosa*.

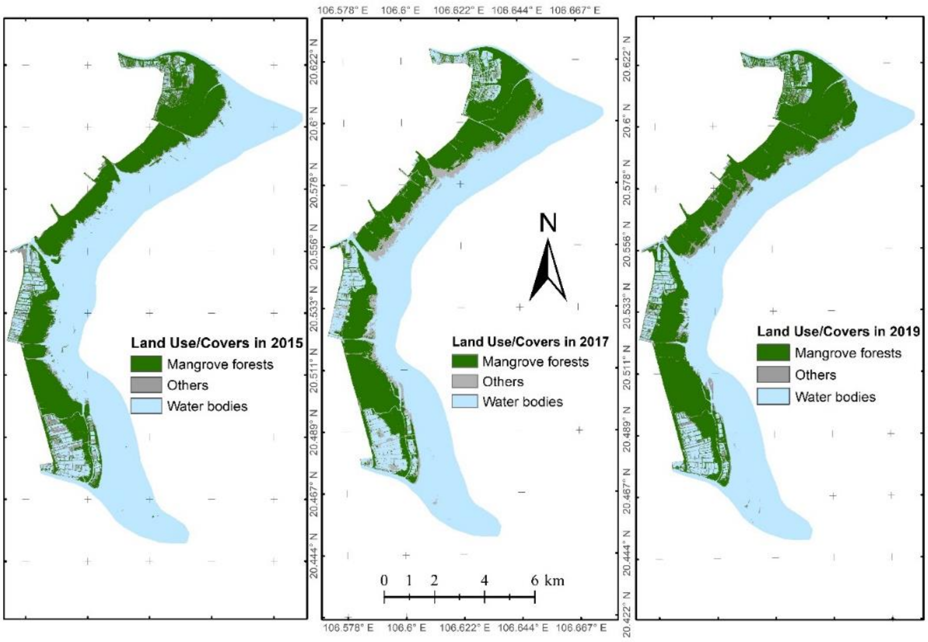

Figure 2. Spatial distribution of mangrove forests in Thai Thuy district, Thai Binh province (Sentinel-2A: 28/9/2019, 17/12/2017 and 10/8/2015).

As can be seen from Fig. 2, there were 3 classes classified from 2015, 2017 and 2019 Sentinel-2A images, including mangrove forests (NDVI > 0.158); others (0.001< NDVI ≤ 0.158, including bare and wet soils; non-mangrove plants; built-up areas; and others); and water bodies (NDVI ≤ 0.001 to negative values). In this study, mangrove forests were the main object. Therefore, from the status map of land use and covers, mangrove forests were separated from others and water bodies for estimating mangrove AGB and AGC based on the threshold of NDVI values and formula of Bindu *et al*., [44].

3.2. Estimation of mangrove AGB and AGC

3.2.1. AGB and AGC of mangrove forests

In this study, the formula of Bindu *et al*., [44] was adopted to estimate above-ground biomass (AGB) of mangrove forests in 2015, 2017 and 2019 for Thai Thuy district, then above-ground carbon (AGC) of mangrove forests across those three years was estimated. The results are shown in Fig. 3 and Fig. 4.

Spatial distribution of AGC of mangrove forests in Thai Thuy

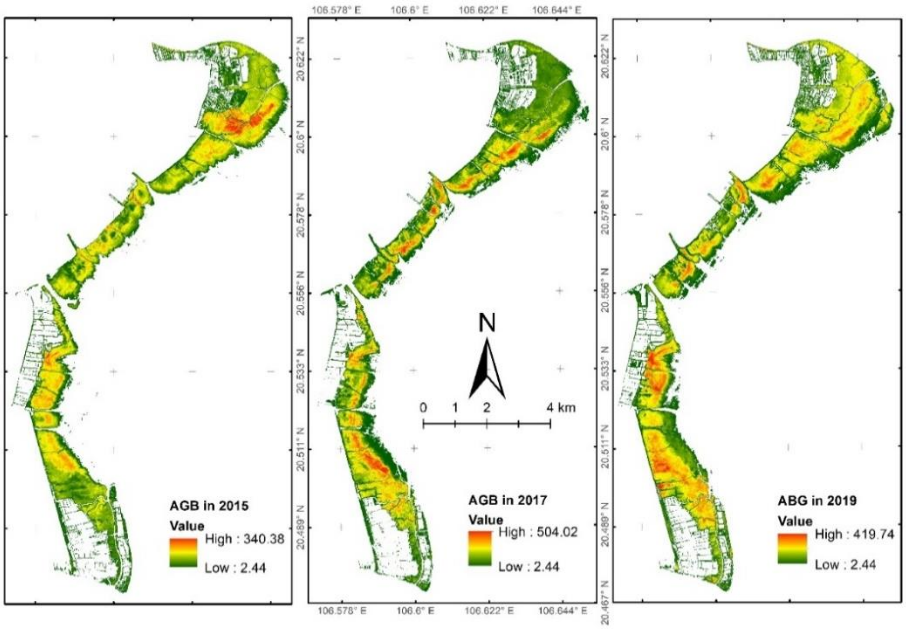

Figure 3. Spatial distribution of AGB of mangrove forests in 2015, 2017 and 2019.

As shown in Fig. 3, AGB of mangrove forests in Thai Thuy district has been fluctuated over time, from 2015 to 2019. In particular, a maximum value of mangrove AGB was estimated at 340.38 kg pixel^{-1} (equivalent to 34.04 ton ha^{-1}) with an average value of 69.8 kg pixel^{-1} in 2015 (equal to 6.98 ton ha^{-1}), then increased to 504.02 kg pixel^{-1} in 2017 (equivalent to 50.4 ton ha^{-1}, an average value of 106.7 kg pixel^{-1}), but decreased to 419.74 kg pixel^{-1} in 2019 (equivalent to 41.97 ton ha^{-1}, an average value of 82.0 kg pixel^{-1}). To categorise mangrove ABG into three classes, namely low (NDVI: 0.158 ÷ 0.3), medium (NDVI: 0.3 ÷ 0.5) and high values (NDVI > 0.5), the study used the threshold of mangrove NDVI values and classified them into three groups with adaptation from Bindu *et al*. [44] and Hernina *et al*. [50].

Table 2. Changes of AGB and AGC according to mangrove areas across three years (ha).

Mangrove NDVI values	**AGB** (ton ha^{-1})	**AGC** (ton ha^{-1})	**Areas of mangrove forests** (ha)		
			2015	**2017**	**2019**
≤ 0.3	0.23 ÷ 1.0	0.11 ÷ 0.47	320.5	395.9	415.4
0.3÷ 0.5	1.0 ÷ 7.3	0.47 ÷ 3.42	683.7	544.1	671.4
> 0.5	> 7.3	> 3.42	877.2	1067.6	1241.1
Areas (ha)			**1881.4**	**2007.9**	**2327.9**

As shown in Table 2, there is a generally increasing trend of both mangrove AGB and AGC experiencing in three groups of mangrove NDVI values. In particular, the area of mangrove forests with AGB ranging from 2.26 to 9.98 kg pixel^{-1} (equivalent to 0.23 ÷ 1.0 ton ha^{-1}) was estimated at 320.5 ha, 395.9 ha and 415.4 ha in 2015, 2017 and 2019, respectively (Table 3). Remarkably, the mangrove area with AGB greater than 72.77 kg pixel^{-1} (equivalent to 7.3 ton ha^{-1}) increased by 190.7 ha during the period 2015 - 2017 and by 173.5 ha during the period 2017 - 2019, whereas there was an reduction of 139 ha of the mangrove areas observed during the period 2015 - 2017, but increased again by 127 ha during the period 2017-2019. More interestingly, increased mangrove areas have been mainly found in Thuy Do, Thai Truong and Thuy Xuan communes.

Spatial distribution of AGC of mangrove forests in Thai Thuy district

The results of AGC of mangrove forests estimated in Fig. 4 showed that there were changes in AGC of mangrove forests over three years. In particular, the mangrove AGC reached a maximum value in 2015, estimated at 159.98 kg pixel^{-1} (equivalent to 16.0 tons ha^{-1}, an average value of 32.8 kg pixel^{-1}), then increased to 236.89 kg pixel^{-1} in 2017 (equivalent to 23.7 tons ha^{-1}, average value is 50.2 kg pixel^{-1}), but decreased to 197.28 kg pixel^{-1} in 2019 (equal to 19.73 tons ha^{-1}, average value is 38.5 kg pixel^{-1}).

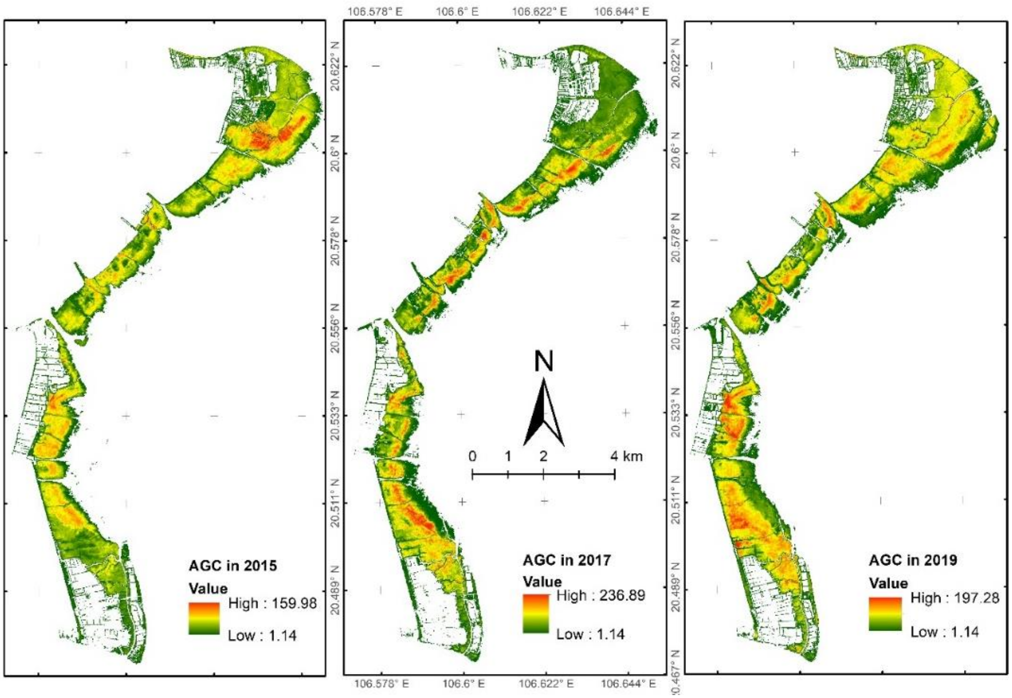

Figure 4. Spatial distribution of AGC of mangrove forests in 2015 (a), 2017 (b) and 2019 (c).

Similarly, Table 3 shows that the most of mangrove areas (877.2 ha) experienced with mangrove AGC greater than 3.4 tons ha^{-1} in 2015, but there was a significant increase in the area of mangrove forests, up to 1037.6 ha in 2017 and 1241.1 ha in 2019. In contrast, there was a reduction of mangrove forests with AGC of 0.47 ÷ 3.4 tons ha^{-1} during 2015-2017.

Table 3. Estimation of mangrove AGB and AGC accumulation in over 3 years of study.

Year	2015	2017	2019
∑AGB (tons)	1,312,339.3	2,143,196.5	1,908,841.9
∑AGC (tons)	616,799.5	1,007,302.4	897,155.6
∑ ACS (tons)	2,263,654.2	3,696,799.7	3,292,561.1

AGB: Above-ground biomass; AGC: Above-ground carbon stocks; ACS (Amount of CO_2 sequestration).

Table 3 indicated that a range of AGC changed over the three years. Similarly, the total of AGC accumulated tended to increase during this period. Specifically, in 2015 a total AGC of 616,799.5 tons were recorded, but in 2017 it nearly doubled, estimated at 1,007,302.4 tons. Interestingly, the highest amount of AGC accumulated was found in Thai Do, Thai Thuong and Thuy Xuan communes, while the lowest amount of AGC was identified in Thuy Truong commune due to young mangrove forests with small trunks and diameters, and low density.

3.2.2. Variations of mangrove AGB and AGC estimated from field survey and Sentinel-2A data

To assess the variations of AGB and AGC of mangrove forests estimated between field measurement and Sentinel-2A data, the mangrove AGB and AGC were calculated from 32 sample plots from March to May 2019 (Table 4). The study then compared the correlation between the field-calculated AGB and AGC and the Sentinel-estimated AGB and AGC in 2019 according to the formula of Bindu *et al*., [44]. The results are shown in Table 4.

Table 4. Field- and Sentinel-based estimation of AGB and AGC in 2019.

Plots	Latitude	Longitude	Field-based estimation (tons ha^{-1})		Sentinel-based estimation (tons ha^{-1})		Variations between field and Sentinel estimation	
			AGB	AGC	AGB	AGC	AGC (tons ha^{-1})	%
1	20.4851	106.5986	78.1	37.1	55.6	26.4	10.7	28.8
2	20.4841	106.5990	13.5	6.4	16.2	7.7	1.3	19.6
3	20.4859	106.5989	35.3	16.8	41.3	19.6	2.8	16.9
4	20.5035	106.5827	32.8	15.6	36.1	17.1	1.6	10.2
5	20.5043	106.5845	74.7	35.5	50.7	24.1	11.4	32.1
6	20.5063	106.5840	18.1	8.6	19.8	9.4	0.8	9.6
7	20.5067	106.5814	6.6	3.1	8.9	4.2	1.1	35.1
8	20.5772	106.6067	49.5	23.5	53.2	25.3	1.8	7.5
9	20.5878	106.6152	40.4	19.2	46.5	22.1	2.9	15.0
10	20.5901	106.6217	15.7	7.5	18.5	8.8	1.3	17.7
11	20.5995	106.6263	80.7	38.3	55.7	26.5	11.9	31.0

12	20.5581	106.5869	65.5	31.1	55.3	26.3	4.8	15.5
13	20.5209	106.5783	23.3	11.0	26.5	12.6	1.5	13.9
14	20.5191	106.5807	28.7	13.6	25.3	12.0	1.6	11.8
15	20.5186	106.5784	29.3	13.9	35.2	16.7	2.8	20.2
16	20.5158	106.5821	37.1	17.6	44.2	21.0	3.4	19.1
17	20.5159	106.5798	14.4	6.8	17.2	8.2	1.4	19.9
18	20.5112	106.5799	31.4	14.9	27.6	13.1	1.8	12.2
19	20.5122	106.5811	26.2	12.4	29.7	14.1	1.7	13.4
20	20.5127	106.5799	21.9	10.4	19.65	9.3	1.0	10.1
21	20.5701	106.5982	70.5	33.5	84.1	39.9	6.5	19.3
22	20.5848	106.6088	86.6	41.1	120	57.0	15.9	38.6
23	20.5959	106.6262	89.3	42.4	123	58.4	16.0	37.7
24	20.6039	106.6307	87.4	41.5	100	47.5	6.0	14.4
25	20.6023	106.6401	80.5	38.2	115	54.6	16.4	42.9
26	20.6110	106.6454	60.7	28.8	48.9	23.2	5.6	19.4
27	20.6206	106.6403	95.4	45.3	74.6	35.4	9.9	21.8
28	20.5365	106.5823	70.2	33.3	90.4	42.9	9.6	28.8
29	20.5249	106.5810	75.3	35.8	95.3	45.3	9.5	26.6
30	20.5134	106.5842	85.8	40.8	98.2	46.6	5.9	14.5
31	20.5051	106.5886	65.3	31.0	85.7	40.7	9.7	31.2
32	20.4938	106.5972	75.7	36.0	97.1	46.1	10.2	28.3

AGB (Above-ground biomass); AGC (Above-ground carbon stocks).

As can be seen from Table 4, there were variations of AGB and AGC of mangrove forests between field measurements and Sentinel-2A data-based estimation in 2019. More specifically, the variations of AGB and AGC of mangrove forests ranged at 1.73 ÷ 34.5 tons ha^{-1} and 0.8 ÷ 16.4 tons ha^{-1}, respectively. The results of AGC estimation based on the model of Bindu *et al*., [44] in comparison with plot-based measurement also showed that the percentage of AGC difference ranged from 7.5 to 42.9 % (Table 4). In particular, the number of plots with the estimated difference in AGC below 30.0 % were 25 plots (equivalent to 78.2 %), whereas there was only one plot with a difference in AGC greater than 40.0 %. This finding implied that the formula of Bindu *et al*., [44] can be used to estimate AGB and AGC of mangrove forests in Thai Binh coast with an accuracy of 78.2 %, 25 plots out of 32 plots have differences in AGB and AGC between the plot survey and remote sensing-based data less than 30 %. This model should be applied to other coastal sites similar to the Thai Binh coast. This finding is also confirmed by other studies by Pham *et al*., [49] and Wang *et al*., [48].

3.4. Changes in AGB and AGC of mangrove forests

Changes in AGB of mangrove forests

Changes in AGB of mangrove forests in the periods 2015 - 2017, 2017 - 2019 and 2015 - 2019 were summarised in Table 5.

Table 5. Mangrove areas experiencing changes in AGB in selected periods.

Periods / Changes	2015 - 2017		2017 - 2019		2015 - 2019	
	ha	**%**	**ha**	**%**	**ha**	**%**
Decreased (-)	515.5	27.4	891.9	44.4	437.9	18.8
Increased (+)	1195.5	63.5	1071.2	53.3	1331.9	57.2
Unchanged	170.5	9.1	44.8	2.2	558.1	24.0
Total	***1881.4***	***100***	***2007.9***	***100***	***2327.9***	***100***

(+) refers to areas experiencing increased AGB, (-) refers to areas experiencing decreased AGB.

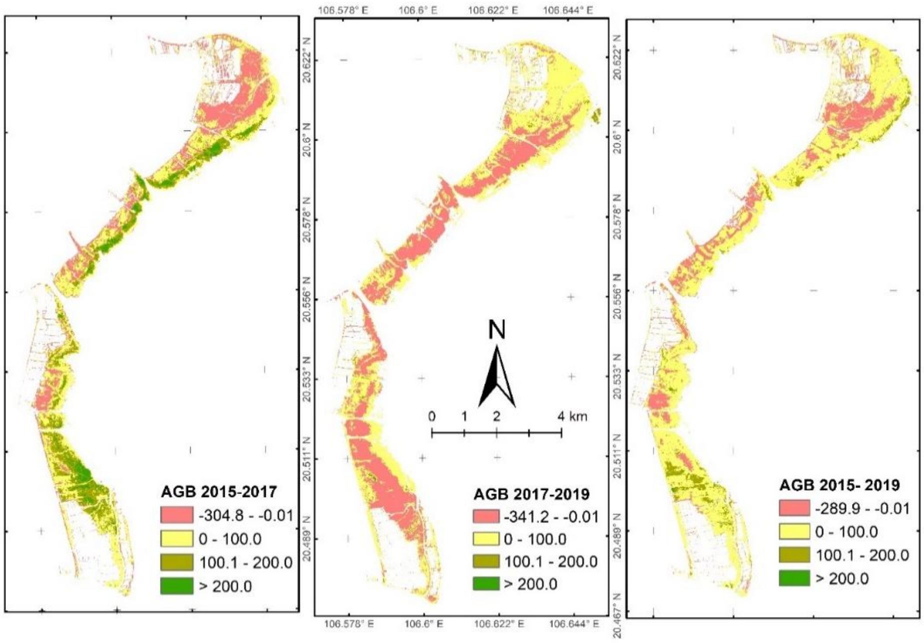

Figure 5. Changes in AGB of mangrove forests in the periods 2015 - 2017; 2017 - 2019; and 2015 - 2019 (kg pixel^{-1}).

It can be seen from Table 5 and Fig. 5 that there was a large fluctuation in AGB of mangrove forests in the periods 2015 - 2017, 2017 - 2019 and 2015 - 2019. There was nearly 57.2 % of the total area of mangrove forests experiencing an increase in AGB (up to 200 kg pixel^{-1} or up to 2.0 tons ha^{-1}), while a smaller percentage (18.8 %) of the mangrove area experienced a decrease of up to 29.0 tons ha^{-1} during the period 2015 - 2019. Specifically, Thuy Truong commune experienced the largest decrease in AGB due to illegal shrimp farming expansion and conversion of mangroves to other land uses [35] despite successful restoration and sustainable development through mangrove ecosystem programs across coastal districts of

Thai Binh province, including the programs of the Korean Government the Vietnamese Government at that time [35]. As a result, there was an increase of 446.4 ha of mangrove forests during the period 2015 - 2019.

Changes in AGC of mangrove forests

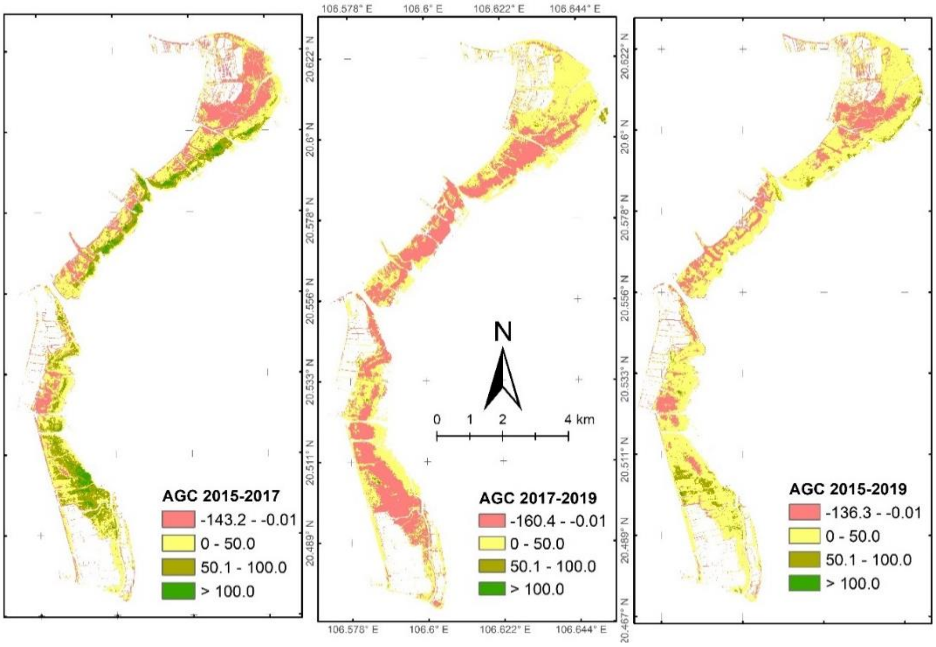

Figure 6. Changes in AGC of mangrove forests in the periods: 2015 - 2017; 2017 - 2019; and 2015 - 2019 (kg pixel^{-1}).

As shown in Fig. 6, AGC of mangrove forests in Thai Thuy district has been fluctuated with the variations of AGB. The study results showed that there was a wide range of fluctuations in the AGC in various communes of Thai Thuy district. During the period 2015 - 2017, some places experienced a loss of AGC of 14.3 tons ha^{-1}, an increase of AGC of more than 10.0 tons ha^{-1}, an average increase of 22.8 tons ha^{-1}. Similarly, during the period 2017 - 2019, changes in AGC were recorded with a loss of AGC of 16.0 tons ha^{-1}, an increase of AGC of 13.6 tons ha^{-1}, but an average AGC during this period was -0.65 tons ha^{-1}, showing that AGC decreased over this period. However, the overall mangrove AGC in the whole period 2015 - 2019 generally increased by 12.9 tons ha^{-1} (Fig. 6). This can be explained by successful mangrove restoration and rehabilitation programs. Particularly, it is suggested that the increase in mangrove age classes, structures, canopy and their species composition over time are the main factors affecting the amount of AGC (above-ground carbon stocks) accumulated in mangrove forests [51].

4. CONCLUSIONS

By using Sentinel-2A images, the study has constructed the spatial distribution of mangrove forests over three years. The accuracy evaluation showed that the overall accuracy of the 2019 Sentinel-2A classification was 93.6 %, and other accuracy assessments of the 2015 and 2017 Sentinel-2A images also were more than 90.0 %. It was therefore assumed that the use of Sentinel-2A images was adequate for mapping temporal changes in mangrove forests. The study showed that there were 2327.9 ha of mangrove forests in 2019, 2007.9 ha in 2017, and 1881.3 ha in 2015. Most of the mangrove area (877.2 ha) had mangrove AGB and AGC greater than 7.3 and 3.4 tons ha^{-1} in 2015, respectively, but there was a significant increase in the area of mangrove forests observed in 2017 (1037.6 ha) and in 2019 (1241.1 ha). However, there was a reduction of mangrove forests with AGB and AGC ranging from 1.0 to 7.3 and from 0.47 to 3.42 tons ha^{-1} during the period 2015-2017, respectively.

There was nearly 57.2 % of the total area of mangrove forests experiencing an increase of AGB (up to 2.0 tons ha^{-1}), while 18.8 % of the mangrove forest area experienced a decrease (up to 29.0 tons ha^{-1}) during the period 2015 - 2019. There were small variations of AGB and AGC between field measurements and Sentinel-based estimation in 2019. Therefore, our study suggests that the use of Sentinel-2A images to estimate AGB and AGC of mangrove forests is reliable and applicable to the Thai Binh coast and should be tested in other similar coastal areas in Viet Nam.

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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.

REFERENCES

1. Aschbacher J., Ofren R., Delsol J.P., Suselo T.B., Vibulsresth S. and Charrupat T. - An integrated comparative approach to mangrove vegetation mapping using advanced remote sensing and GIS technologies: preliminary results, Hydrobiologia **295** (1995) 285-294. https://doi.org/10.1007/BF00029135.
2. Gilman E.L., Ellison J., Duke N.C. and Field C. - Threats to mangroves from climate change and adaptation options: a review. Aquatic Botany **89** (2008) 237-250. https://doi.org/10.1016/j.aquabot.2007.12.009.
3. Liang S., Zhou R., Dong S. and Shi S. - Adaptation to salinity in mangroves: Implication on the evolution of salt-tolerance, Chinese Science Bulletin **53** (2008) 1708-1715. https://doi.org/10.1007/s11434-008-0221-9.
4. Lovelock C.E., Ball M.C., Feller I.C., Engelbrecht B.M. and Ling Ewe M. - Variation in hydraulic conductivity of mangroves: Influence of species, salinity, and nitrogen and phosphorus availability, Physiologia Plantarum **127** (2006) 457-464. https://doi.org/10.1111/j.1399-3054.2006.00723.x.
5. Lugo A. E. and Snedaker S. C. - The Ecology of mangrove, Annual Review of Ecology **5** (1974) 39- 64. https://doi.org/10.1146/annurev.es.05.110174.000351.
6. Rivera-Monroy V., Twilley R., Medina E., Moser E. B., Botero L., Francisco A. M., and Bullard E. - Spatial variability of soil nutrients in disturbed riverine mangrove forests at different stages of regeneration in the San Juan River Estuary, Venezuela, Estuaries **27** (2004) 44-57. https://doi.org/10.1007/BF02803559.

7. Baldwin A., Egnotovich M., Ford M., and Platt W. - Regeneration in fringe mangrove forests damaged by Hurricane Andrew, Plant Ecology **157** (2001) 151-164. https://doi.org/10.1023/A:1013941304875.

8. Lee S.Y., Primavera J. H., Dahdouh-Guebas F., McKee K., Bosire J. O., Cannicci S., Diele K., Fromard F., Koedam N., Marchnd C., et al. - Ecological role and services of tropical mangrove ecosystems: A reassessment. Global Ecology and Biogeography **23** (2014) 726-743. https://doi.org/10.1111/geb.12155.

9. Mazda Y., Magi M., Kogo M., and Hong P. N. - Mangroves as a coastal protection from waves in the Tong Kong delta: Viet Nam, Mangroves and Salt Marshes **1** (1997) 127-135.https://doi.org/10.1023/A:1009928003700.

10. Tamin N. M., Zakainah R., Hashim R., and Yin Y. - Establishment of *Avicennia marina* mangroves on accreting coastline at Sungai Haji Dorani, Selangor, Malaysia, Estuarine, Coastal and Shelf Science **94** (2011) 98- 109.https://doi.org/10.1016/j.ecss.2011.07.009.

11. Zhang K., Liu H., Li Y., Xu H., Shen J., Rhome J., and Smith III T. J. - The role of mangroves in attenuating storm surges, Estuarine, Coastal and Shelf Science **102-103** (2012) 11-23. https://doi.org/10.1016/j.ecss.2012.02.021.

12. Giri C., Zhu Z., Tieszen L. L., Singh A., Gillette S., and Kelmelis J. A. - Mangrove forest distributions and dynamics (1975–2005) of the tsunami-affected region of Asia, Journal of Biogeography **35** (2008) 519-528. https://doi.org/10.1111/j.1365-2699.2007.01806.x.

13. Thampanya U., Vermaat J., Sinsakul S., and Panapitukkul P. - Coastal erosion and mangrove propagation of Southern Thailand, Estuarine, Coastal and Shelf Science **68** (2006) 75-85. https://doi.org/10.1016/j.ecss.2006.01.011.

14. Boateng I. - GIS assessment of coastal vulnerability to climate change and coastal adaption planning in Viet Nam, Journal of Coastal Conservation**16** (2012) 25-36. https://doi.org/10.1007/s11852-011-0165-0.

15. Hanh P. T. T. and Furukawa M. - Impact of sea level rise on coastal zone of Viet Nam, Bulletin of College of Science, University of the Ryukyus **84** (2007) 45-59.

16. Spalding M. D., Ruffo S., Lacambra C., Meliane I., Hale L. Z., Shepard C. C., and Beck M. W. - The role of ecosystems in coastal protection: Adapting to climate change and coastal hazards, Ocean and Coastal Management **90** (2014) 50-57. https://doi.org/10.1016/j.ocecoaman.2013.09.007.

17. Sam D. D., Binh N. N., Que N. D., Phuong V. T. - Overview of Viet Nam Mangrove Forest. Agriculture Publisher House, Ha Noi, Viet Nam (2005) pp.136 (in Vietnamese),

18. Sam D. D. and Phuong V. T. - NationalAction Plan for the Protection and Development Vietnam's Mangrove Forest till 2015 (2005) pp.12.

    http://www.mekonginfo.org/assets/midocs/0002531-environment-national-action-plan-for-protection-and-development-of-vietnam-s-mangrove-forest-till-2015.pdf

19. Hai-Hoa N. - The relation of coastal mangrove changes and adjacent land-use: A review in Southeast Asia and Kien Giang, Viet Nam, Ocean and Coastal Management **90** (2014) 1-10. http://dx.doi.org/10.1016/j.ocecoaman.2013.12.016.

20. Hai-Hoa N., McAlpine C., Pullar D., Johansen K., and Duke N. C. - The relationship of spatial-temporal changes in fringe mangrove extent and adjacent land-use: Case study of Kien Giang coast, Viet Nam, Ocean and Coastal Management **76** (2013) 12- 32. https://doi.org/10.1016/j.ocecoaman.2013.01.003.

21. Willemsen P. W.J. M., Horstman E. M., Borsje B. W., Friess D. A., and Dohmen-Janssen C. M. - Sensitivity of sediment trapping capacity of esturine mangrove forests, Geomorphology **273** (2016) 189-201. https://doi.org/10.1016/j.geomorph.2016.07.038.
22. Kauffman J. B. and Donato D. C. - Protocols for the measurements, monitoring and reporting of structure, biomass and carbon stocks in mangrove forests. Working Paper **86**. CIFOR, Borgor, Indonesia (2012) pp.50.https://doi.org/10.17528/cifor/003749.
23. Tri N. H., Adger W. N., and Kelly P. M. - Natural Resource Management in Mitigating Climate Impacts: The Example of Mangrove Restoration in Viet Nam, Global Environmental Change **8** (1998) 49-61.https://doi.org/10.1016/S0959-3780(97)00023-X.
24. Ward R. D., Friess D. A., Day R. H., and Mackenzie R. A. - Impacts of climate change on mangrove ecosystems: a region by region overview, Ecosystem Health and Sustainability **4** (2016) 1-25.https://doi.org/10.1002/ehs2.1211
25. Dittmar T., Hertkorn N., Kattner G., and Lara R. J. - Mangroves, a major source of dissolved organic carbon to the oceans, Global biogeochemical cycles **20** (2006) 1-7. https://doi.org/10.1029/2005GB002570.
26. Tue N. T., Dung L. V., Nhuan M. T., and Omori K. - Carbon storage of a tropical mangrove forest in Mui Ca Mau National Park, Viet Nam, Catena **121** (2014) 119-126. https://doi.org/10.1016/j.catena.2014.05.008.
27. Akumu C. E., Pathirana S., Baban S., and Bucher D. - Monitoring coastal wetland communities in north-eastern NSW using Aster and Landsat satellite data, Wetlands Ecology and Management **18** (2010) 357-365.https://doi.org/10.1007/s11273-010-9176-0.
28. Myeong S., Nowak D. J., and Duggin M. J. - A temporal analysis of urban forest carbon storage using remote sensing, Remote Sensing of Environment **101** (2006) 277-282. https://doi.org/10.1016/j.rse.2005.12.001.
29. Rajitha K., Mukherjee C. K., and Chandran R. V. - Applications of remote sensing and GIS for sustainable management of shrimp culture in India, Aquacultural Engineering **36** (2007) 1-17. https://doi.org/10.1016/j.aquaeng.2006.05.003.
30. Rozenstein O. and Karnieli A. - Comparison of methods for land-use classification incorporating remote sensing and GIS inputs, Applied Geography **31** (2011) 533-544. https://doi.org/10.1016/j.apgeog.2010.11.006.
31. Stoms D.M. and Estes J.E. - A remote sensing research agenda for mapping and monitoring biodiversity, International Journal of Remote Sensing **14** (1993) 1839-1860. https://doi.org/10.1080/01431169308954007.
32. Tuxen K., Schile L., Stralberg D., Siegel S., Pakker T., Vasey M., Callaway J., and Kelly M. - Mapping changes in tidal wetland vegetation composition and pattern across a salinity gradient using high spatial resolution imagery, Wetlands Ecology and Management **19** (2011) 141-157.https://doi.org/10.1007/s11273-010-9207-x.
33. Zhang K., Thapa B., Michael R., and Gann D. - Remote sensing of seasonal changes and disturbance in mangrove forest: A case study from South Florida, Ecosphere **7** (2016) 1-23. https://doi.org/10.1002/ecs2.1366.
34. Zhu Z., Woodcock C.E. and Olofsson P. - Continuous monitoring of forest disturbance using all available Landsat imagery, Remote Sensing of Environment **122** (2012) 75-91.https://doi.org/10.1016/j.rse.2011.10.030.

35. Hai-Hoa N. and Binh T. D. - Using Landsat imagery and vegetation indices differencing to detect mangrove change: A case in Thai Thuy district, Thai Binh province, Journal of Forest Science and Technology **5** (2016) 59 -66.
36. Thai Thuy Bureau of Statistics - Thai Thuy economic and commercial developement, http://thongkethaibinh.gov.vn/index.php/Tin-tuc/huyen-thai-thuy-phat-trien-thuong-mai-dich-vu-483.html, 2021 (accessed by 08/05/2021) (in Vietnamese).
37. Castillo J. A. A., Apan A. A., Maraseni T. N., and Salmo S. G. - Estimation and mapping of above-ground biomass of mangrove forests and their replacement land uses in the Philippines using Sentinel imagery, ISPRS Journal of Photogrammetry and Remote Sensing**134** (2017) 70-85.https://doi.org/10.1016/j.isprsjprs.2017.10.016.
38. Krauss K. W., McKee K. L., Lovelock C. E., Cahoon D. R., Saintilan N., Reef R., and Chen L. - How mangrove forests adjust to rising sea level, New Phytologist **202** (2014) 19-34.https://doi.org/10.1111/nph.12605.
39. Chen B., Xiao X., Li X., Pan X., Doughty R., Ma J., Dong J., Qin Y., Zhao B., Wu Z., et al. - A mangrove forest map of China in 2015: Analysis of time series Landsat 7/8 and Sentinel 1A imagery in Google Earth Engine cloud computing platform, ISPRS Journal of Photogrammetry and Remote Sensing **131** (2017) 104- 210.

    https://doi.org/10.1016/j.isprsjprs.2017.07.011.
40. Long J. B. and Giri C. - Mapping the Philippines' mangrove forests using Landsat imagery, Sensors **11** (2011) 2972-2981. https://doi.org/10.3390/s110302972.
41. Rakotomavo A. and Fromard F. - Dynamics of mangrove forests in the Mangoky River delta, Madagascar, under the influence of natural and human factors, Forest Ecology and Management **259** (2010) 1161-1169. https://doi.org/10.1016/j.foreco.2010.01.002.
42. Alsaaideh B., Al-Hanbali A., Tateishi R., Kobayashi T., and Nguyen T. H. - Mangrove forests mapping in the southern part of Japan using Landsat ETM+ with DEM, Journal o f Geographic Information System **5** (2013) 269-377. doi:10.4236/jgis.2013.54035.
43. Gao B. C. - NDWI: a normalized difference water index for remote sensing of vegetation liquid water from space, Remote Sensing of Environment **58** (1996) 257-266. https://doi.org/10.1016/S0034-4257(96)00067-3.
44. Bindu G., Rajan P., Jish E. S., and Joseph K. A. - Carbon stocks assessment of mangroves using remote sensing and geographic information system, The Egyptian Journal of Remote Sensing and Space Sciences **23** (2018) 1-9.

    https://doi.org/10.1016/j.ejrs.2018.04.006.
45. Eggleston H. S., Buendia L., Miwa, K., Ngara T., and Tanabe K. - IPCC Guidelines for National Greenhouse Gas Inventories. Japan: N. p., 2006 pp.7. http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.htm, 2021 (accessed by 7/8/2021).
46. IPCC (Intergovernmental Panel on Climate Change). - Climate Change 2001. Intergovernmental Panel on Climate Change National Greenhouse Gas Inventories Programme (2001). (accessed by 15 April 2021). http://www.ipcc.ch/ipccreports/tar/wg3/index.php?idp=477S.
47. Komiyama A., Poungparn S., and Kato S. - Common allometric equations for estimating the tree weight of mangroves, Journal of Tropical Ecology **21**(2005) 471-477. https://doi.org/10.1017/S0266467405002476.

48. Wang D., Wan B., Qiu P., Zuo Z., Wang R., and Wu X. - Mapping height and aboveground biomass of mangrove forests on Hainan Island using UAV-LiDAR sampling, Remote Sensing **11** (2019) 2156. https://doi.org/10.3390/rs11182156.

49. Pham T. D., Yoshino K., Le N. N., and Bui D. T. - Estimating abovegrround biomass of a mangrove plantation on the Northern coast of Viet Nam using machine learning technique with an integration of ALOS-2 PALSAR2 and Sentinel 2A data, International Journal of Remote Sensing **39** (2019) 7761- 7788. https://doi.org/10.1080/01431161.2018.1471544.

50. Hernina R., Juhans. and Waryono T. - Carbon stock and carbon emission estimation in Java's North coast National road (Jalur Pantura) within Karawang Regency using high resolution satellite image, IOP Conf. Series: Earth and Environmental Science **338** (2019) 012038.https://doi.org/10.1088/1755-1315/338/1/012038.

51. Rahman M. M., Khan M. N. I., Hoque A. K. F., and Ahmed I. - Carbon stock in the Subdarbans mangrove forest: Spatial variations in vegetation types and salinity zones, Wetlands Ecol Manage **23** (2015) 269-283. https://doi.org/10.1007/s11273-014-9379-x.

APPENDICES

Appendix 1. Accuracy assessments of Sentinel classification in 2019.

		Reference data from the field-based survey in 2019				
Sentinel image classified		**Man**	**Others**	**Waters**	**Total**	**User's Accuracy (%)**
	Man	**70**	3	2	75	93.2
	Others	3	**101**	6	110	91.8
	Waters	0	2	**63**	65	96.9
	Total	*73*	*106*	*71*	*250*	
	Producer's Accuracy (%)	95.9	95.3	88.7		

Man (Mangrove forests); Waters (Water bodies); Others (including non-mangrove plants, built-up areas, bare, wet land, and others). Overall Accuracy Assessment: 93.6 %, Kappa coefficient = 0.90.

Appendix 2. Accuracy assessments of Sentinel classification in 2017.

		Reference data from the field-based survey, Google Earth in 2017				
Sentinel image classified		**Man**	**Others**	**Waters**	**Total**	**User's Accuracy (%)**
	Man	**52**	4	4	60	86.7
	Others	2	**115**	3	120	95.8
	Waters	2	5	**63**	70	90.0
	Total	*56*	*124*	*70*	*250*	
	Producer's Accuracy (%)	92.9	92.7	90.0		

Man (Mangrove forests); Waters (Water bodies); Others (including non-mangrove plants, built-up areas, bare, wet land, and others). Overall Accuracy Assessment: 92.0 %, Kappa coefficient = 0.87

Appendix 3. Accuracy assessments of Sentinel classification in 2015.

		Reference data from the field-based survey, Google Earth in 2015				
Sentinel image classified		**Man**	**Others**	**Waters**	**Total**	**User's Accuracy (%)**
	Man	**55**	8	2	65	84.6
	Others	2	**124**	4	130	95.4
	Waters	1	3	**51**	55	92.7
	Total	*58*	*135*	*57*	*250*	
	Producer's Accuracy (%)	94.8	91.9	89.5		

Man (Mangrove forests); Waters (Water bodies); Others (including non-mangrove plants, built-up areas, bare, wet land, and others). Overall Accuracy Assessment: 92.0 %, Kappa coefficient = 0.87.