USING SENTINEL IMAGE DATA AND PLOT SURVEY FOR THE ASSESSMENT OF BIOMASS AND CARBON STOCK IN COASTAL FORESTS OF THAI BINH PROVINCE, VIETNAM

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Abstract. Quantitative evaluation of biomass and carbon stored in coastal forests of Thai Binh province (Vietnam) does not only contribute to coast protection, but is also required for emphasizing the forest's importance in local socio-economic development when participating in the carbon market. This estimation is primarily based on field data (diameter at breast height, height and quantity of tree in 14 surveyed plots), anatomical data (above ground biomass, total biomass and carbon content of 31 sampled trees) and an NDVI map calculated from Sentinel imagery. Mathematical models are used for expressing the relationships: above ground biomass vs. diameter at breast height, height; biomass vs. above-ground biomass; biomass vs. carbon; and above-ground biomass vs. NDVI. The results show the same behavior of above ground biomass, total biomass and carbon stock, they increase with the growth of tree. The exponential model is acceptable for correlating above ground biomass and NDVI, showing higher values in long planted areas and the lower ones in newly formed lands with recently planted mangroves. Biomass and carbon stock in the study area have average productivities of 38.8 t/ha and 19.4 t/ha, respectively. Overall estimations are ca. 292 kilotons of biomass and ca. 146 kilotons of carbon, roughly valuated of US$ 5.9 million.
Keywords: *AGB, NDVI, mangrove, remote sensing data, CO_2 valuation, Vietnam*

Introduction

Forests play a critical role in the Earth's climate system, in a number of different ways. Most importantly concerning global climate change, they capture CO_2 from the atmosphere, convert it into living biomass (stems, roots, branches and leaves) through photosynthesis and store large amounts of carbon in forest soils, absorbed through leaf litter, wood debris and roots (Brack, 2019). The estimates of carbon stored in forest ecosystems in the world vary significantly. In 2000, the Intergovernmental Panel on Climate Change estimated the total amount to be 1,100 gigatons (Gt) (Watson et al., 2000), which is 1.3 times greater than the carbon stored in fossil fuels (estimated at 800 Gt) and much larger than carbon released into the atmosphere from human activity since 1870 (about 600 Gt) (Federici et al., 2018). FAO (2010) yielded lower value of about 652 Gt, including 44%, 5%, 6% and 45% in live biomass, dry biomass, garbage and forest soils respectively. Therefore, a large amount of CO_2 will be released into the atmosphere from global deforestation. At the United Nations Climate Change Conference in Indonesia in December 2007, 187 member countries signed the Bali Agreement which outlined the program "Reducing Emissions from Deforestation and Forest Degradation" (REDD), with the aim to limit the destruction of tropical forests. Many countries will meet some of their emission reduction targets through the purchase

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of carbon credits of developing countries made available by absorption of CO_2 by forests (United Nations Framework Convention on Climate Change - UNFCCC, 2007). So far, the carbon trading market has been divided into two types: the regulatory compliance and the voluntary markets. The regulatory compliance is the market in which carbon trading is based on the commitment of states in the UNFCCC to achieve the goal of reducing greenhouse gases. It is regulated by mandatory, mainly for Clean Development Mechanism (CDM) or Joint Implementation (JI) projects. The voluntary carbon market, outside the Kyoto Protocol framework, is based on bilateral or multilateral cooperation agreements between organizations, companies or countries. Thus, the problem posed here is to quantify the amount of CO_2 stored by forest ecosystems in developing countries, including Vietnam. This work, first of all, requires identifying the biomass and carbon accumulated in these forests.

Forest biomass could be estimated by allometric functions relating biomass and dimensions of tree or its components such as Diameter at Breast Height (DBH), tree height (H), trunk circumference, branches, roots, leaves, etc. (Clough and Scott, 1989; Comley and McGuinness, 2005; Basuki et al., 2009; Chave et al., 2014; Bao et al., 2016; Kebede and Soromessa, 2018). The CO_2 absorption of forest ecosystems is generally determined by direct measurement of physiological processes controlling carbon balance (Botkin et al., 1970; Woodwell, 1970), analyzing eddy correlation for quantifying net ecosystem exchanges of CO_2 (Wofsy et al., 1993), mathematical functions presenting the relationship between biomass, carbon stock and tree dimensions (Grier et al., 1989; Hunter et al., 2013; Ostadhashemi et al., 2014). Remote sensing data, including optical imagery (aerial photography, multispectral, and hyperspectral), Synthetic Aperture Radar (SAR) and Light Detection And Ranging (LiDAR) combined with field measurements, allometric equations, supported by GIS techniques are also used for estimating spatiotemporal variation of biomass and carbon stock in vegetation (Patenaude et al., 2004; Myeong et al., 2006; Jeyanny et al., 2011; Santoro and Cartus, 2018; Hirata et al., 2018; Pham et al., 2019). For the optical imagery, these estimations are usually based on regression models correlating Above Ground Biomass (AGB) and vegetation indices such as Normalized Difference Vegetation Index (NDVI), Green NDVI, Soil Adjusted Vegetation Index, Simple ratio, Red-edge simple ratio (Baloloy et al., 2018; Punalekar et al., 2018).

In Vietnam, biomass and forest productivity have also been studied for specific populations such as Rhizophora (Tri, 1986; Tan, 2001), *Pinus kesiya* (Phuc, 1996), *Acacia auriculiformis* (Thong, 1998), increased and diversified since the adoption of CDM (Lung and Van, 2004; Phuong, 2006; Hai et al., 2009; Trieu, 2010). Carbon stored in forest is also estimated and valuated (Ty, 2004; Nam, 2009; Tin and Loi, 2015). Recently remote sensing is applied for estimating biomass and carbon stock in mangrove (Vu et al., 2014; Pham and Yoshino, 2017; Quang and Hoa, 2018; Luong et al., 2019). For carbon trade within framework of Kyoto Protocol, there are numerous limitations impeding investments in Vietnam such as: inadequacies in approval process, lack of openness and transparency in mechanisms of financial allocation, etc. Vietnam currently has several projects towards carbon market (Lung and Van, 2004; Ty, 2004). In general, most of the studies focused on forest ecosystems in hilly and mountainous areas or mangroves in the coastal plain of southern Vietnam.

This study to evaluate the biomass and carbon stocks in coastal forests of Thai Binh province, belonging to the Red River Delta, not only fills up the lacking area but also contributes to the protection and development of these ecosystems, orienting to

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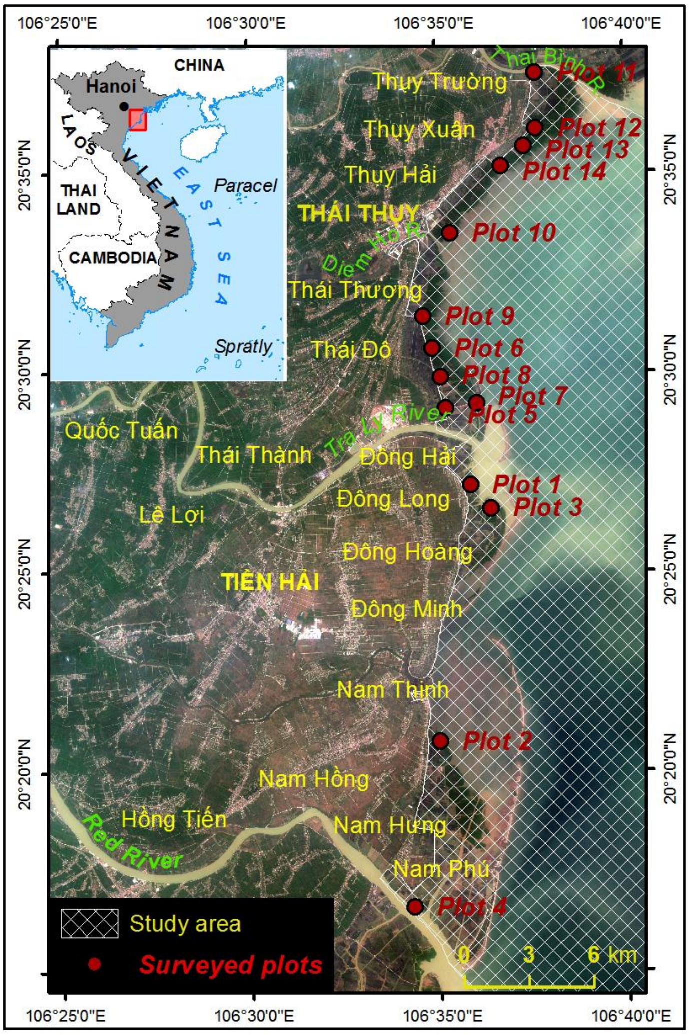
participate into the carbon market, increasing the importance of coastal forest in local socio-economic development, thereby raising awareness of mangrove protection in the strategy dealing with climate change, simultaneously contributes to biodiversity conservation for the Red River Delta Biosphere Reserve.

Materials and methods

Study area

The coastal area of Thai Binh Province, located in Thai Thuy and Tien Hai districts (*Figure 1.*), is considered as one of the areas rich in biodiversity and strongly affected by climate change. Its population is estimated approximately 458,700 people with a density of 917 inhabitants/km^2 (Thai Binh Statistical Office, 2016).



ID	Coordinate
Plot 1	20°27'10.4"N 106°35'52.8"E
Plot 2	20°20'44.9"N 106°35'02.4"E
Plot 3	20°26'34.8"N 106°36'25.2"E
Plot 4	20°16'35.8"N 106°34'19.2"E
Plot 5	20°29'05.3"N 106°35'13.2"E
Plot 6	20°30'36.0"N 106°34'51.6"E
Plot 7	20°29'12.1"N 106°36'03.6"E
Plot 8	20°29'51.7"N 106°35'06.0"E
Plot 9	20°31'23.9"N 106°34'37.2"E
Plot 10	20°33'29.2"N 106°35'24.0"E
Plot 11	20°37'28.9"N 106°37'40.8"E
Plot 12	20°36'05.0"N 106°37'40.8"E
Plot 13	20°35'39.5"N 106°37'22.8"E
Plot 14	20°35'09.2"N 106°36'43.2"E

Figure 1. *Study area and surveyed plots (Image: Sentinel-2A dated 10 Aug 2015)*

This area is in tropical monsoon climate with annual average temperature about 22-24ºC, hottest in July (averagely 29.1ºC) and coldest in January (averagely 16.7ºC). The precipitation of 1,658 mm/year unevenly distributes among the months of the year.

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The rainy season, from May to September, makes up 70 - 80% of annual total. The rest time, from October to April, the monthly rainfall is usually below 100 mm, resulting in water shortage. From May to November, especially in August, the area is hit by typhoons and tropical depressions, coming from the South China Sea with an average frequency of 2.1 times/year (Van et al., 2017).

Four major rivers, namely Thai Binh, Diem Ho, Tra Ly and Red rivers (*Figure 1.*), flowing through the study area to the sea, have complicated hydrological regime due to the influence of both Red and Thai Binh river systems. In general, there are two distinct seasons: the flood season, from June to October, accounts for 75 - 80% of the total annual flow; the dry, from November to May, makes up 20 - 25% of the total (Anh, 2016).

The wave regime, controlled by prevailing wind, has the directions: northeast in offshore area and northeast, east or southeast in coastal area for the winter; south in offshore area and southeast or south in coastal area for the summer. On the coast, winter waves can reach 0.4 - 0.9 m height in average and 3.0 m maximum; the summer waves are 0.7 to 1.2 m of average height and 6m highest. Influenced by storms and tropical cyclones, the large waves in winter are more frequent than in summer. The diurnal tide with high amplitude in relief of gentle slope creates considerably large tidal flats with a width of 4 - 5 km, even 7 - 8 km in Thai Binh estuary, favoring mangrove development for the study area (Anh, 2016).

Developed on Holocene unconsolidated sands, silts and clays, the relief of study area is relatively flat and low. The river-sea interaction produces the following landforms: river channels and floodplains, delta plains, ancient sandy dunes, high and low tidal flats, mouth bars. Among them, high and low tidal flats are the terrain suitable for mangrove development. Statistically, there are 13 soil types of sandy, saline, acid sulfate and alluvial groups in the area. Among them, the high, medium and low saline and tidal flat soils, related to mangrove forest, occupy 22,058.47 ha accounting for 37.23% of the total natural area of Tien Hai and Thai Thuy districts (Anh, 2016).

The total coastal forest of Thai Binh province occupies 3,899.1 ha, including 3,709.1 ha (95%) of mangroves, in 10 communes and towns of the two districts Thai Thuy and Tien Hai (Thai Binh Department of Agriculture and Rural Development - TBDARD, 2016). Mangroves are mainly pure or mixed planted forests with following species in majority *Sonneratia caseolaris*, *Kandelia obovata*, *Aegiceras corniculatum*, *Bruguiera gymnorohiza*, *Avicennia marina*. Communities of *Avicennia marina* and *Kandelia obovata*are commonly distributed in the outermost area with high salinity and deep water. *Sonneratia caseolaris*, *Kandelia obovata*, and *Aegiceras corniculatum* are situated in moderately submerged area. The community with dominance of *Sonneratia caseolaris* and underbrush *Acanthus ilicifolius*is mainly found in the estuarine area (Thuy et al., 2016). In Thai Thuy district, there are more than 2000 hectares of mangroves concentrated in 5 communes: Thuy Truong, Thuy Xuan, Thuy Hai, Thai Phuong and Thai Do. An inventory in Thuy Truong lists 38 plant families with 111 species in which 12 species are true mangrove sand 30 others are mangrove associates (Cuc and Tan, 2004). In Tien Hai district, mangroves are distributed mainly in five communes: Nam Thinh, Nam Hung, Nam Phu, Dong Long and Dong Hoang, in which the first three belong to Tien Hai Wetland Nature Reserve occupying an area of 1450 ha. This Reserve has: 11 species of true mangroves with 1 fern and 10 angiosperms; and 37 species of mangrove associates with 17 monocotyledons and 20 dicotyledons (Tuan and Anh, 2008). Outside of the reserve such as in Dong Long,

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the flora has quite high diversity with 66 species of 33 families, whose 8 species are true mangroves and 19 others are mangrove associates (Tam, 2013). For whole coastal zone of Thai Binh, there are 14 species of true mangrove in the communities of natural forest, planted forest, aquaculture ponds and new-land pioneer as follows (Van et al., 2017):

- 1 fern: *Acrostichum aureum* L.;
- 12 dicotyledons: *Acathus ebracteatus* Vahl, *Acathus ilicifolus* L., *Sensuvium portulacastrum* L, *Avicennia marina* (Forsk) Veirh), *Lumnitzera racemosa* (Gaud.) Presl., *Derris trifoliata* (Benth) Barker, *Excoecaria agallaocha* L, *Aegiceras corniculatum* (L.) Blanco, *Bruguiera gymnorohiza* (L), *Kandelia obovata* Sheue Liu & Yong, *Rhizophora stylosa* Griff.and *Sonneratia caseolaris* (L.) Engl.;
- 1 monocotyledon: *Cyperus stoloniferus* Retz.

Methods

Biomass and carbon evaluation for the study area is firstly based on field data (DBH, H and tree quantity in surveyed plots), anatomical data (AGB, total biomass and carbon content of sampled trees) and NDVI map calculated from Sentinel imagery. From the anatomical data, the mathematical models expressing AGB vs. DBH and H, Biomass vs. AGB, Biomass vs. Carbon relationships are set up. The mean AGB in pixel (100 m^2) and mean NDVI are determined for each surveyed plot, and then expressed in a mathematical model, enabling to map AGB from NDVI for the study area. The biomass map can be produced from AGB map by Biomass vs. AGB expression and then carbon stock from biomass by Biomass vs. Carbon expression.

Field survey

In the study area, 14 key plots with sizes of 100 m^2 (10 m x 10 m), 500 m^2 (25 m x 20 m) or 2,500 m^2 (50 m x 50 m), selected on the basis of topographic features and current status of mangroves, were surveyed in November 2015 (*Figure 1.*). In each plot, survey work was conducted: statistics of the number of trees, measurement of DBH and H of all trees, species identification, abnormal characteristics of trees (banyan tree, buttress tree, diameter of buttress, buttress height, etc.) and weighting of fresh biomass of sampled trees.

A total of 31 trees, representative for key plots, are sampled for laboratory analysis. However, *in situ* identification of sampled trees is carried out and precise measurements are also done for diameter at the stump (position 0.0 m), DBH, stem length (from the stump to the highest), height below the branches (from the position 0.0 m to the main branching point of the tree), trunk length from the base (position 0.0 m) to the point of 10 cm diameter; buttress height and diameter, etc. For the below-ground parts, the coarse roots, greater than 2 mm in diameter, are dug out for biomass estimation; and the fine roots, less than 2 mm in diameter, are ignored in this estimation because of the difficulty in separating them from other organic matter in soil. After the *in situ* measurements, the sampled trees are separated into their parts such as the trunk, branches, leaves, roots and buttress (if present), then weighted for fresh biomass estimation.

Finally, each tree is sampled in stem, branch, leaf and root for laboratory analysis. Stem sample includes 2 - 3 cutting boards or radial cutting boards (if the tree is large) with a mass accounting for 0.2% of fresh stem. Branch is taken with 4 small cutting

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boards, weighted of 0.5 - 1.0 kg in total. All samples are packed in plastic bags and tied tightly to prevent evaporation.

Carbon analysis in tree samples

Samples taken from roots, stems, branches and leaves of mangroves are dried at 70°C for estimating dry mass and moisture content. These dry samples are grinded to the size through 0.2 mm sieve for analysis. The organic carbon content is determined by Walkley Black method specified in Vietnam Standards (TCVN 9294: 2012).

Mathematical modeling

Based on the anatomical data of tree samples and imagery data, the mathematical models are used to quantify the relationship between:

- DHB, H and AGB, i.e. biomass sum of trunk, branches and leave.
- AGB and total biomass, i.e. biomass sum of trunk, branches, leave and root.
- Biomass and accumulated carbon
- AGB and NDVI

The coefficient of determination - R^2 (*Eq. 1*) and the Standard Error of the regression - SEreg (*Eq. 2*) are used for measuring the goodness of fit of the models. F value (*Eq. 3*) for F-test is also used to assess whether any of the independent variables in a multiple linear regression are significant.

$$R^2 = \frac{SSreg}{SStot} = 1 - \frac{SSres}{SStot} = 1 - \frac{\sum_i (y_i - f_i)^2}{\sum_i (y_i - \bar{y})^2} \quad \text{(Eq.1)}$$

$$SEreg = \sqrt{\frac{\sum_i (y_i - f_i)^2}{n-2}} \quad \text{(Eq.2)}$$

$$F = \frac{MSreg}{MSres} = \frac{(\sum_i (f_i - \bar{y})^2)/(p-1)}{(\sum_i (y_i - f_i)^2)/(n-p)} \quad \text{(Eq.3)}$$

where, SSreg is regression sum of squares; SSres is residual sum of squares; SStot is total sum of squares; y_i is the measured value; $\bar{y}$ is the mean of y_i; f_i is mathematically calculated value; n is number of observations; p is number of regression parameters.

The coefficient of determination (R^2) ranges from 0 to 1. In general, the higher the R^2, the better the model fits your data and the model could be acceptable if $R^2 \geq 0.5$.

The standard error of the regression could be used to obtain a rough estimate of the 95% prediction interval. About 95% of the data points are within a range that extends from ±2.SEreg from the fitted line.

In F-test with a significance level α, in these cases α = 0.05, models are accepted if F-value > F-significance and P-value is less than 0.05.

The Microsoft Excel with ANOVA add-in is used for the above-mentioned analyses and mathematical modelling.

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Remote sensing and GIS

The images should be dated around the moment of field survey for synchronizing the data. Given the weather condition and available data, the image of Sentinel 2A, taken at 10:15:36.027 (local time) on 10 August 2015, the best image close to survey time in November, is chosen for analysis (*Figure 1*). Its three bands Green (559.8 nm), Red (664.6 nm) and Near InfraRed - NIR (832.8 nm) with 10 m resolutions are used for calculating NDVI and Normalized Difference Water Index (NDWI):

NDVI = (NIR-Red)/ (NIR+Red) (Rouse *et al.*, 1974) (Eq.4)

NDWI= (Green-NIR)/ (Green+NIR) (McFeeters, 1996) (Eq.5)

The NDVI value, ranging from -1 to +1, increases with increased green biomass as a result of increased red reflectance due to greater absorption of incident red light by plant chlorophylls and decreased near-infrared reflectance associated with radiation scattering by the hydrated wall of leaf cells.

NDWI is used to distinguish land and sea by identifying water body with a value greater or equal to threshold of 0.3 for Landsat (McFeeter, 1996, 2013) or 0.1 for Sentinel (Kaplan and Avdan, 2017).

The GIS with ARCGIS software is applied for integration and production of maps presenting spatial variation of data and for extraction of information.

Results and discussion

Results of plot survey

Detailed surveys are conducted for all 14 plots with total area of 10600 m^2 (*Table 1.*). 700 trees counted in these plots have mean values of 10.69 cm and 4.66 m for DBH and H respectively. Plot 11, forest of *Sonneratia caseolaris* in Thuy Truong commune (Thai Thuy district), is the largest mean DBH (19.19 cm). The smallest mean DBH with value of 5.88 cm is Plot 7, a recently planted forest of *Sonneratia caseolaris - Kandelia obovata - Bruguiera gymnorohiza* in Con Den (Tien Hai district). In terms of average height for each plot, Plot 6 is the highest (9.11 m) and Plot 10 is the lowest (3.11 m). The highest density is Plot 3 (7600 trees/ha) and the lowest is Plot 12 (100 trees/ha). In general, the older forests have mean DHB and height higher than the overall average because they have long time for growing their dimensions. The high density is statistically related to forests having mean DHB and height lower than the overall average. These forests may be planted on a large scale recently.

Biomass and carbon stored in sampled trees

Biomass and carbon storage are determined for 31 sample trees with DBH from 5.41 cm to 14.01 cm and height from 1.5 m to 5.5 m (*Table 2*). The analytical results show that the AGB, total biomass and accumulated carbon range 4.11 - 41.04 kg, 4.34 - 43.65 kg and 2.18 - 21.83 kg, respectively. The same changing behavior with minimum in Tree 8 and maximum of Tree 31 (*Table 2.*) shows a close relationship among AGB, total biomass and accumulated carbon. In general, they increase with the growth of tree, i.e. the increase of DHB and height.

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Table 1. *Plot survey*

Plot number	Dominant species	Length x Width (m)	Area (m^2)	Tree Quantity	Mean of DHB (cm)	Mean of Height (m)	Density (trees/ha)
1	*Son.*	25 x 20	500	92	10.45	5.65	1840
2	*Son., Kan.,Bru.*	25 x 20	500	40	11.24	4.79	800
3	*Son., Kan.,Bru.*	10 x 10	100	76	7.92	3.74	7600
4	*Son.*	25 x 20	500	82	15.62	5.88	1640
5	*Son.*	25 x 20	500	103	8.27	3.83	2060
6	*Son., Kan.,Bru.*	10 x 10	100	9	14.85	9.11	900
7	*Son., Kan.,Bru.*	10 x 10	100	67	5.88	3.90	6700
8	*Kan.*	10 x 10	100	21	9.02	4.71	2100
9	*Son., Kan.,Bru.*	50 x 50	2500	32	11.31	3.96	128
10	*Son., Kan.,Bru.*	10 x 10	100	54	7.96	3.11	5400
11	*Son.*	10 x 10	100	14	19.19	8.64	1400
12	*Son., Kan.,Bru.*	50 x 50	2500	25	16.42	5.72	100
13	*Son., Kan.,Bru.*	50 x 50	2500	36	14.66	5.00	144
14	*Son., Kan.,Bru.*	25 x 20	500	49	12.65	4.29	980
Overall			**10600**	**700**	**10.69**	**4.66**	**660**

Note: Son. - Sonneratia caseolaris; Kan. - Kandelia obovata; Bru. - Bruguiera gymnorohiza

Table 2. *Dry biomass and carbon storage in sampled trees*

Tree	Parameters		Dry biomass (kg)						Total carbon storage(kg)
	DBH (cm)	H (m)	Trunk	Branch	Leaf	Root	AGB	Total	
1	10.98	3.9	9.5	11.03	3.74	1.89	24.27	26.16	13.09
2	11.14	4.2	13.82	10.8	4.5	1.85	29.12	30.97	15.49
3	5.57	1.5	2.93	1.89	1.08	0.95	5.9	6.85	3.44
4	10.98	4.45	15.26	4.32	3.15	1.4	22.73	24.13	12.07
5	8.59	3	4.55	7.34	2.93	1.53	14.82	16.35	8.19
6	6.68	1.8	3.56	4.19	3.02	1.44	10.77	12.21	6.11
7	5.57	1.6	3.24	1.04	0.59	0.5	4.87	5.37	2.69
8	5.41	1.5	2.93	0.68	0.5	0.23	4.11	4.34	2.18
9	10.03	3.5	9	10.35	3.6	1.67	22.95	24.62	12.32
10	11.94	4.1	13.95	11.25	4.95	2.03	30.15	32.18	16.11
11	7.96	2.5	5.85	3.6	1.8	0.77	11.25	12.02	6.02
12	11.62	4.5	15.3	4.5	3.6	1.58	23.4	24.98	12.49
13	8.91	2.9	4.95	7.65	3.15	1.53	15.75	17.28	8.66
14	7	2	4.05	4.5	3.15	1.49	11.7	13.19	6.61
15	6.05	1.9	3.24	1.04	1.04	0.59	5.32	5.91	2.96
16	11.94	4.5	15.98	5.18	3.38	1.62	24.54	26.16	13.08
17	9.87	4	9.9	10.8	3.15	1.53	23.85	25.38	12.7
18	12.73	4.2	15.3	11.25	4.05	2.12	30.6	32.72	16.37
19	6.37	2	3.15	2.25	1.35	0.54	6.75	7.29	3.66
20	10.19	3.7	13.95	3.15	2.25	1.08	19.35	20.43	10.23
21	10.5	3.4	9	7.2	4.95	2.16	21.15	23.31	11.66
22	6.37	1.7	3.56	4.19	3.02	1.49	10.77	12.26	6.14
23	6.68	2.1	4.05	2.25	1.35	0.77	7.65	8.42	4.23
24	10.66	4.6	14.63	11.7	4.5	2.12	30.83	32.95	16.48
25	11.94	4.4	11.25	12.6	4.5	2.07	28.35	30.42	15.22
26	12.57	4.1	13.05	10.35	4.05	1.89	27.45	29.34	14.69
27	8.28	2.6	5.85	3.83	2.25	1.04	11.93	12.97	6.5
28	11.46	4.8	16.16	5.22	4.05	2.03	25.43	27.46	13.74
29	14.01	5.1	9.9	14.85	5.85	2.12	30.6	32.72	16.37
30	9.87	3.8	7.11	8.37	6.03	2.16	21.51	23.67	11.85
31	13.69	5.5	13.5	4.14	23.4	2.61	41.04	43.65	21.83

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Analyzing the correlation of DBH and H with AGB, ABG with total biomass, biomass with carbon storage (*Table 3.*), the following suitable expressions could be chosen:

$$AGB = 2.110606*DBH + 3.302734*H - 11.8674 \quad (Eq.6)$$

$$Biomass= 1.0548*AGB + 0.4502 \quad (Eq.7)$$

$$Carbon = 0.4999*Biomass + 0.0127 \quad (Eq.8)$$

Table 3. *Analysis of DHB, H, AGB, biomass and carbon correlations from anatomical data*

	Coefficients	*SE*	*P-value*	R^2	*SEreg*	*F*	*Significance F*
ABG ~ DBH, H							
Intercept DBH H	-11.8674 2.1106 3.3027	2.4435 0.7472 1.5973	4.1041E-05 8.6232E-03 4.8028E-02	0.9265	2.7342	176.3669	1.35E-16
Total biomass ~ ABG							
Intercept ABG	0.4502 1.0548	0.1111 0.0052	3.48346E-4 2.21622E-47	0.9993	0.2749	41898.9073	2.22E-47
Carbon storage ~ Biomass							
Intercept Biomass	0.0127 0.4999	0.0023 0.0001	7.1E-06 1.54E-87	0.9999	0.0057	24664592	1.54E-87

Correlation between AGB and NDVI

NDVI is produced from Red and NIR bands of Sentinel image (*Eq. 4*). This product is integrated with study area (*Figure 2.a*) and land – sea distribution (*Figure 2.b*), mapped from NDWI (*Eq. 5*) with the threshold of 0.1 (Kaplan and Avdan, 2017), to obtain NDVI map for the study area (*Figure 2.c*). For the study area, NDVI varies from -0.30 to 0.66, its high value is found in Thuy Truong – Thuy Hai, Thai Thuong and south of Nam Thinh, the low value is commonly around the river mouth. The mean values of surveyed plots (*Table 4*) extracted from NDVI map are in range of 0.18 (Plot 12) – 0.50 (Plot 3).

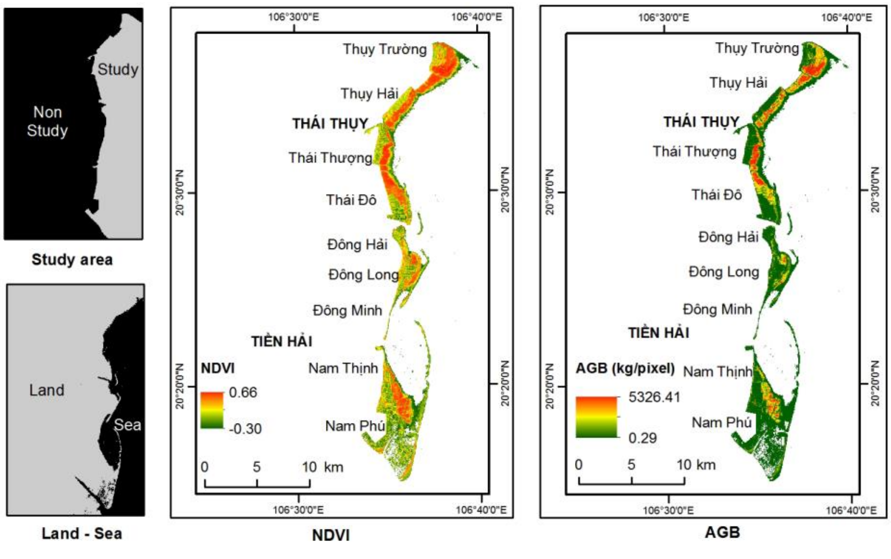

Figure 2. *Study area (a), Land – sea distribution (b), NDVI (c) and AGB (d)*

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Table 4. *Estimation of AGB and IDVI for surveyed plots*

Plot number	**AGB** (kg)	**Area** (m^2)	**AGB productivity** (kg/100m^2)	**Mean NDVI**
1	2666.99	500	533.40	0.42
2	1112.42	500	222.48	0.29
3	1315.14	100	1315.14	0.50
4	3334.79	500	666.96	0.36
5	1888.67	500	377.73	0.31
6	448.20	100	448.20	0.48
7	904.37	100	904.37	0.48
8	479.93	100	479.93	0.46
9	806.21	2500	32.25	0.31
10	826.17	100	826.17	0.43
11	803.49	100	803.49	0.46
12	1045.78	2500	41.83	0.18
13	1285.58	2500	51.42	0.29
14	1426.26	500	285.25	0.34

Note: 100 m^2 = 1 pixel (10 m x 10 m)

The AGB of each plot (*Table 4.*) is estimated from mean values of DBH and H (*Table 1*) by the mathematical model expressing their relationship (*Eq. 6*). AGB values vary from 448 kg (Plot 6) to 3335 kg (Plot 4). However, in term of productivity, AGB in an area unit, 100 m^2 or 1 pixel for Sentinel image with used bands in this case, the minimum and maximum are 32.25 kg/ 100 m^2 (Plot 9) and 1315.14 kg/ 100 m^2 (Plot 3).

The AGB productivity and NDVI of plots (*Table 4.*) could be correlated as follow (*Figure 3.*):

$$AGB = 6.5135\ e^{10.234NDVI} \quad \text{or} \quad \ln(AGB) = 10.234*NDVI + 1.8739 \qquad \text{(Eq.9)}$$

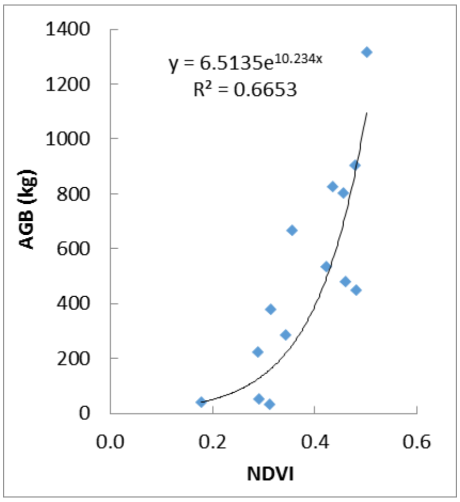

Figure 3. *Graph expressing AGB vs. NDVI*

Using the coefficient of determination R^2 and F-test (*Table 5.*) show that this expression of AGB - NDVI relation (*Eq. 9*) is acceptable.

An AGB map is produced from NDVI by the model expressing their relationship (*Eq. 6*). The AGB in the study area (*Figure 2.d*) ranges from 0.29 kg/pixel to 5326.41 kg/pixel with high value in Thuy Truong – Thuy Hai, Thai Thuong and south of Nam Thinh, where also the NDVI is high.

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Table 5. *Analysis of ln(AGB)~NDVI correlation*

	Coefficients	*SE*	*P-value*	R^2	*SEreg*	*F*	*Significance F*
Intercept	1.8739	0.8183	0.0409	0.6653	0.7246	23.8493	0.0004
NDVI	10.234	2.0955	0.0004				

Biomass and carbon stock in coastal forests

Biomass as well as carbon stored in forest depend heavily on the species, age and density of trees. In Giao Lac commune (Nam Dinh province), next to the study area, the amount of carbon accumulated in *Kandelia obovate* forests of 1, 5, 6, 8 and 9 years increases with the ages (Hanh, 2009). In mixed forests of *Kandelia obovate* and *Sonneratia caseolaris* with 10, 11 and 13 years of Nam Phu commune (Thai Binh province), accumulated carbon in also increases with the age and it in *Kandelia obovate* (1.60 - 2.39 kg/tree) is much lower than in *Sonneratia caseolaris* (23.22 - 37.23 kg/tree); however, due to the tree density, carbon productivity in *Kandelia obovate* (49.31-124.56 t/ha) is higher than in *Sonneratia caseolaris* (12.51 - 32.74 t/ha) (Hanh, 2015).

For the study area, biomass is estimated from AGB (*Eq. 7*) and then carbon storage is from biomass (*Eq. 8*). Biomass and carbon storage (*Figure 4.*) have high value in the region of Thuy Truong – Thu Hai, Thai Thuong – Thai Do, Nam Hung, where mangrove is planted for long time, and low value around the river mouth, the newly formed land with recently planted mangrove. Biomass extracted from its map ranges from 76 kg/ha to 561875 kg/ha with an average of 38796 kg/ha. Carbon storage varies from 39 kg/ha to 280882 kg/ha with an average value of 19395 kg/ha. Overall estimations for whole study area, covering approximately 7527 ha (752690 pixel), are 292,014,265 kg biomass and 145,987,493 kg carbon.

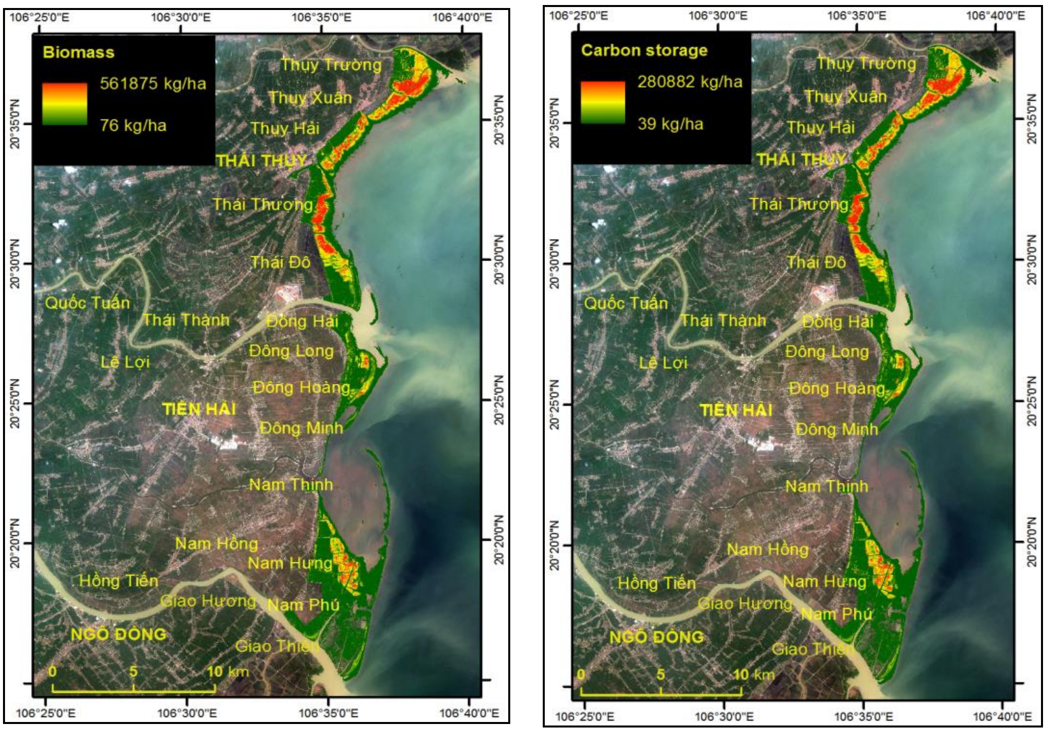

Figure 4. *Total biomass (left) and carbon storage (right)*

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Forest CO_2 valuated through carbon market participation

The carbon market is seen as the main tool to reduce CO_2 emissions, one of the four greenhouse gases. The carbon market activity is supported by four main mechanisms outlined in the Kyoto Protocol, including emissions trading mechanism, CDM, JI and REDD (Höhne et al., 2015). In Vietnam, given the CO_2 price from US$5/t to US$10/t, the carbon stored in production forests is valuated from VND 61 million/ha (restored forest) to VND 119 million/ha (rich forest) for Southern Vietnam, VND 50 - 121 million/ha for the Central Vietnam and VND 46 - 100 million/ha for the Northern Vietnam (Vietnamese Academy of Forest Sciences, 2013).

For the study area, as mentioned above, the total carbon in coastal forest is estimated of 145987.49 tons, so the converted CO_2, as much as 3.6667 times of carbon, is 535287.47 tons. Based on the lowest CO_2 price of US$11/t in carbon market price, the total CO_2 absorbed in coastal forest of Thai Binh province is valuated of US$ 5,888,162. This is a significant value for forest managers, especially for local habitants managing the community forests in Tien Hai and Thai Thuy coastal districts of Thai Binh province.

General remarks

According to TBDARD (2016), coastal forests of Thai Binh province is landward limited by the sea dikes. These dikes are also used as inner limit of study area; the outer is the land - sea boundary, defined by McFeeter (1996) as NDWI = 0.3 (*Figure 2.b*). The study area covers 7527 ha, but the statistics of TBDARD (2016) gave a smaller number, 3,899.1 ha of coastal forest for Thai Binh, in which 3,709.1 ha (95%) is mangroves. This difference is probably due to the study area defined by NDWI takes into account of forests and non-forested area, i.e. lands for residential, garden, crops, public work or other purposes and newly accreted land while the data of TBDARD is only administratively managed forests. Furthermore, the superficies of study area is influenced by imaging time related to tide and weather condition, spatial resolution of image and delineation of outer limit by NDWI. In the case of Fresno city (California, USA), using NDWI to detect swimming pools for Mosquito Abatement has overall classification accuracy of 91.2% and an overall Kappa coefficient of 0.806 (McFeeters, 2013).

All the mathematical models are assessed by coefficient of determination R^2 (*Eq. 1*), Standard error of the regression (*Eq. 2*) and F-test with significance level $\alpha = 0.05$ from F value (*Eq.3*). The F-test and high R^2 show all the chosen mathematical models expressing relationships among DBH, H, AGB, NDVI, biomass and carbon storage, (*Eq. 6*), (*Eq. 7*), (*Eq. 8*) and (*Eq. 9)*, are acceptable. There are close correlations between AGB and DBH and H (*Eq. 6*), biomass and AGB (*Eq. 7*) and carbon and biomass (*Eq. 8*), expressed by $R^2 > 0.9$. Lower correlation between NDVI and AGB, $R^2 = 0.67$, may be due to different time between Sentinel data (Aug 2015) and plot survey (Nov 2015) and also due to few number of sample plots (14 plots).

The study area includes not only mangroves, but also other vegetation in small percentage such as forests of *Casuarina equiselifolia* and trees planted in gardens, residential and public areas.

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Conclusion

The coastal forests of Thai Binh province are largely made up of mangroves with dominant species of *Sonneratia caseolaris, Kandelia obovate, Bruguiera gymnorohiza* and *Aegiceras corniculatum,* planted for a long time up to now. On an area of 10,600 m^2 of 14 plots, there are 700 trees with a mean DBH of 10.69 cm mean height of 4.66 m. Forests with DBH larger than overall average often have the height above overall average due to longtime plantation. Dense forests are often associated with small trees, recently planted on a large scale.

There are close relationships among DHB, H, AGB, total biomass and accumulated carbon. The AGB, total biomass and accumulated carbon change in the same behavior and they increase with the growth of tree, i.e. the increase of DHB and height.

The relationship between AGB and NDVI could be presented in acceptably exponential model. They have higher value Thuy Truong – Thuy Hai, Thai Thuong and south of Nam Thinh and lower value around the river mouths. Biomass and carbon stock do the same with the average productivities of 38.8 t/ha and 19.4 t/ha respectively. Overall estimations for whole study area covering approximately 7527 ha are 292 kilotons biomass and 146 kilotons carbon, worth about US$ 5.9 million. Most of this value is contributed by mangrove, showing its role not only in coastal protection from erosion but also in economic interest of local community.

The forest biomass and carbon stock could be evaluated from satellite data in combination with plot surveys. In future study, the more accurate assessment requires the synchronous data of both imageries and field survey as well as the adequate plots covering all vegetation’s types.

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