Mangrove above-ground carbon estimation from Sentinel-1A (SAR) and field-based data in Tien Yen district, Quang Ninh province

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Ước tính trữ lượng các bon trên mặt đất rừng ngập mặn từ dữ liệu Sentinel-1A (SAR) và điều tra thực địa tại huyện Tiên Yên, tỉnh Quảng Ninh

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ABSTRACT

Mangrove forests have been globally recognized as they play a vital role in preventing coastal erosion, mitigating the effects of wave actions, and protecting coastal habitats and adjacent shoreline land-uses from extreme coastal events. Sentinel-1 (SAR) offers a new opportunity for mangrove cover mapping and biomass estimation, especially in the tropics where mangrove deforestation and degradation are highest and cloud cover is persistent. This study used the Sentinel-1A-derived VV/VH polarizations for mangrove cover mapping with thresholds of -23.5<VH<-9.05 and -17.5<VV<-3.8. Upon using VV and VH polarizations for mangrove cover mapping compared to PlanetScope data, it has been confirmed that these polarizations are suitable for mangrove cover monitoring along the coast of Tien Yen with an overall accuracy of over 90.5% and Kappa coefficient greater than 0.78 in 2022. This study also developed mangrove AGB models based on the field survey data and SAR data for estimating the AGB of mangrove forests in Tien Yen. In fact, we evaluated the capability of using Sentinel-1A for the retrieval and predictive mapping and mangrove AGB through the conventional linear regression models. The findings show that the models based on VV and VH polarization values from Sentinel-1A can be used for mangrove AGB estimation. Overall, selected AGB Model 1 with R^2=0.445 (p-value<0.001) has provided an option for carbon estimation. To have more accurate AGB models based on SAR data, this study also suggests that more research should be carried out using more advanced machine learning models based on Sentinel-1A and Sentinel-1B for carbon estimation of mangrove forests in Tien Yen.

TÓM TẮT

Vai trò của rừng ngập mặn được biết trong việc ngăn chặn xói mòn bờ biển, giảm thiểu tác động của sóng và bảo vệ môi trường sống khỏi các hiện tượng thời tiết cực đoan ven biển. Sentinel-1A (SAR) mang đến cơ hội mới cho việc lập bản đồ độ che phủ và ước tính sinh khối rừng ngập mặn, đặc biệt là ở vùng nhiệt đới nơi mà nạn phá rừng và suy thoái rừng ngập mặn diễn ra nhiều và ở những nơi có mây che phủ thường xuyên. Nghiên cứu đã sử dụng giá trị tán xạ ngược phân cực VV/VH của ảnh Sentinel-1A để lập bản đồ thảm phủ rừng ngập mặn với các ngưỡng xác định là -23,5<VH<-9,05 và -17,5<VV<-3,8. Việc sử dụng phân cực VV/VH để lập bản đồ độ che phủ rừng ngập mặn so với dữ liệu của PlanetScope năm 2022 cho thấy các giá trị tán xạ ngược phân cực VH/VV có thể sử dụng để theo dõi giám sát lớp phủ rừng ngập mặn dọc bờ biển Tiên Yên với độ chính xác tổng thể trên 90,5% và hệ số Kappa lớn hơn 0,78. Nghiên cứu cũng đã xây dựng mô hình AGB rừng ngập mặn dựa trên dữ liệu khảo sát thực địa và dữ liệu SAR, từ đó ước tính AGC của rừng ngập mặn ở Tiên Yên. Trên thực tế, kết quả đánh giá khả năng sử dụng Sentinel-1A để lập bản đồ sinh khối trên mặt đất (AGB) rừng ngập mặn thông qua mô hình hồi quy tuyến tính thông thường cho thấy các mô hình dựa trên giá trị phân cực VV và VH từ

Sentinel-1A có thể sử dụng được để ước tính AGB rừng ngập mặn. Mô hình ước tính AGB (Model 1) được chọn với R^2=0,445 (p-value<0,001) để ước tính lượng sinh khối trên mặt đất rừng ngập mặn. Để có các mô hình ước tính sinh khối trên mặt đất (AGB) chính xác hơn dựa trên dữ liệu SAR, nghiên cứu đề xuất các mô hình học máy tiên tiến nên được thử nghiệm dựa trên Sentinel-1A và Sentinel-1B để ước tính lượng các-bon của rừng ngập mặn ở Tiên Yên.

1. INTRODUCTION

Mangrove forests are a group of salt-tolerant trees and shrubs that mainly distribute in the intertidal regions of the tropical and subtropical coastlines [1, 2]. They are a rich ecosystem with many types of biodiversity and provision of the habitat that allow a wide variety of living things to flourish in. Despite their recognized importance, mangrove forests are being globally degraded and deforested at an alarming rate [2, 3]. The primary drivers of mangrove loss that have been identified include aquaculture expansion and conversion of other land use [4-7]. As for other benefits that mangrove forests could bring forwards, their ecosystems have also offered the local people good opportunities and stable coastal livelihoods [5]. However, the extent of mangrove forests has experienced significant losses in recent decades under the economic development and the pressure from the growth of population to meet the major demand for aquaculture and fishing production [1, 4, 5].

Empirical studies show that quantification of the carbon stocks of mangroves would provide emission estimates based on actual measures of carbon stocks and reduce the uncertainty of the estimate. In addition, climate mitigation programs including Reducing Emissions from Deforestation and Forest Degradation (REDD+) are being proposed to prevent large emissions from deforestation and forest degradation in the tropics. These programs will require accurate assessment and mapping to establish the baseline biomass and C stocks for the changes. Above-ground biomass (AGB) is one of the important carbon pools in mangrove ecosystem. There are a number of literature review on mangrove biomass and their carbon stocks. However, few studies have quantified biomass and carbon stock of mangrove forest using Sentinel-1A (SAR) in Tien Yen District. Estimation of biomass-based field plots can be used to infer the carbon stocks for the whole study site. This approach is feasible when employed in an area of a few hectares, however, it would be costly and require a lots of time if applied in a wider scale. It is also difficult to implement the method in remote and treacherous portions in a larger landscape. The use of satellite remote sensing techniques could be proven to be cost-effective and timesaving when it is implemented in large scale biomass assessment. For this approach, remote sensing-based biomass assessment utilizes the relationships between field-measured biomass data, imagery, and other thematic maps to develop models that predict biomass in different locations of the study site. The outcome of remote sensing-based biomass estimation is a spatially explicit pattern of the total AGB and its variations for the entire area.

Satellite image-based biomass prediction models can be derived from RADAR backscatter polarizations. These models can be developed with or without using ancillary thematic map data (e.g: elevation). In the tropics, however, during the rainy season where clouds are persistent, it would be challenging when trying to use of multispectral image is challenging. In contrast, data from space-borne synthetic aperture radar (SAR) sensors can be put in good use regardless of time and weather conditions, which could be valuable for the monitoring of land cover. Sentinel-1 offers SAR images with a high geometric resolution with HH+HV (Sentinel-1B) or VV+VH (Sentinel-1A) polarizations in the C-band [8]. What's more, it is common to use models in relation to observation of forest attributes measured on the field plots and remotely-sensed data for the same plots as plot-based estimates are not sufficiently precise and there are not enough field plots available [9]. Therefore, model-based inference is based on assumptions of the model [10]. Adversely, despite the globally extensive application of remote sensing for mangrove monitoring, using Sentinel-1 data for mangrove carbon estimation and monitoring is either not well-documented or too limited to monitor and evaluate the success of mangrove deforestation and degradation in some regions of Vietnam, including Tien Yen coast of Quang Ninh province [11, 12]. A new-generation Sentinel-1A (SAR) is expected to provide new capabilities for monitoring and mapping of biomass in the coastal zone of the tropics on the ground that Sentinel-1 allows ones to gather RADAR imagery with HH+HV or VV+VH polarizations in C-band. However, to our knowledge, no report has been submitted on the topic of the retrieval and mapping of the biomass of mangrove forest from data acquired by SAR instruments onboard the Sentinel-1 satellite mission yet. Therefore, pioneering studies are in need to assess these new-generation satellite imagery.

In this study, we evaluated the ability of data from Sentinel-1A (SAR) for the retrieval and predictive mapping of mangrove AGB in Tien Yen district as a case study of Quang Ninh province. The specific objectives of the study included the following points: (1) to determine and model the relationship between field-measured AGB and Sentinel-1 SAR backscatter coefficients from mangrove forest, (2) to evaluate the accuracy of the biomass prediction models, and (3) to evaluate the accuracy of the output predictive biomass maps. We developed and evaluated AGB estimation models derived from Sentinel-1 SAR imagery. The novelty of this paper is the use of Sentinel-1 data for mangrove AGB estimation. It is a pioneering study that utilizes Sentinel-1A (SAR) for biomass modelling and mapping of mangrove forests in Tien Yen district, Quang Ninh province. These findings would provide a scientific foundation for using Sentinel-1A (SAR) for mangrove carbon monitoring and change detection in Quang Ninh province.

2. RESEARCH AND METHODS

2.1. Study site

Tien Yen district is located in the northeast of Quang Ninh province, Vietnam (Fig. 1).

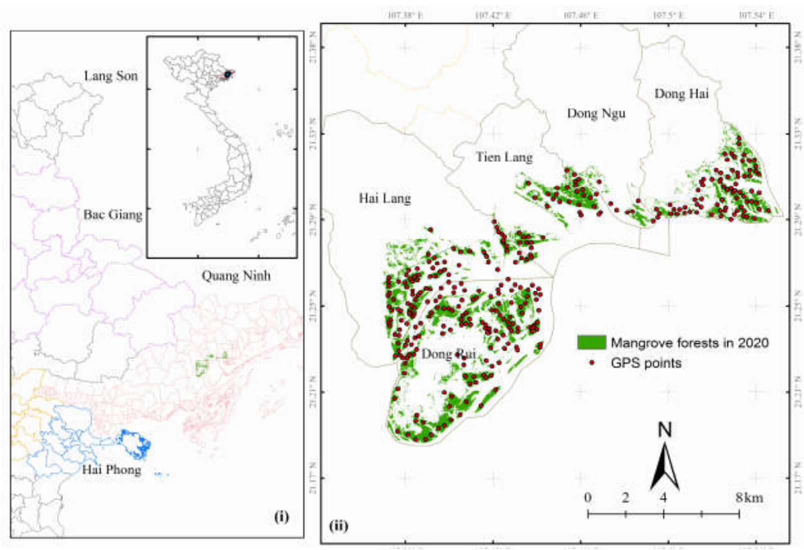

Figure 1. Study site: (i) Quang Ninh province,
(ii) Mangrove forests distributing in Tien Yen district, Quang Ninh province

The district is situated between the Gulf of Tonkin to the east and China to the north. The main economic activities in Tien Yen are agriculture and fishing and many people in the district rely on mangrove forests for additional income. There are a total of 16 communes in the district, 5 of which have mangrove forests, including Hai Lang, Dong Ngu, Dong Hai, Dong Rui, and Tien Lang. Despite the mounting benefits they bring up, mangrove forests along the coast of Tien Yen have been under great pressure from urbanization and economic development, land use/cover conversion, and shrimp farming activities [7, 13].

2.2. Remote sensing data collection

Sentinel-1A image captured in 2022 was used to classify the extent of mangrove forests together with 2022 PlanetScope images for validation purposes (Table 1).

Table 1. Sentinel-1A, PlanetScope data used for mangrove extent and ABG carbon estimation.

ID	Image codes	Date capture	Spatial resolution (m)
1[a]	S1A_IW_GRDH_1SDV_20220723T105805_20220723T105830_044227_054754_695A	Sentinel-1A 23/07/2022	10
	S1A_IW_GRDH_1SDV_20220723T105830_20220723T105855_044227_054754_0458		
2[b]	20220407_022714_32_2463_3B_AnalyticMS_SR	PlanetScope 07/04/2022	3
	20220407_030044_63_2461_3B_AnalyticMS_SR		

Sources: [a]https://scihub.copernicus.eu, [b]https://www.planet.com/explorer

2.3. Study methods

Field data collection:

The field data was collected from areas of mangrove forests (with closed and open canopy) for AGB and above-ground carbon estimation (AGC). This study intended to focus on mangrove covers for AGB model development, therefore, circular plots were established for mangrove survey. Besides, the circular plots were taken randomly for biomass measurements across the Tien Yen Coast. As for measurements, they are linear circular plots with 14 m radius (equivalent to 615.4 m^2 for more than one mangrove species) and 7 m radius (equivalent to 153.9 m^2 for single mangrove species) [7, 14, 15]. There were two or three plots in each transect, spaced 30 m apart each plot [7]. At each circular plot, mangrove measurements (DBH and CD) were conducted to determine the biomass using the methods developed by Kauffman and Donato [14]. Within each plot, geographic coordinates were recorded by the GPS 76cs. A total of 41 circular plots were set up in this study (Fig. 1), 30 of which were used for mangrove biomass model development, while 11 plots were used for the model validation. Within each plot, all individual mangrove trees at the breast height (1.3 m from the ground) or 30 cm above the highest prop root for stilt-rooted species like *Rhizophore* species were measured [7]. The main species along the Tien Yen Coast include *Kandelia obovata*, *Aegicera corniculatum*, *Avicennia marina*, *Rhizophora stylosa* and *Bruguiera gymnorrhiza* [11].

Above-ground biomass (AGB):

Allometric equation was used to estimate the mangrove AGB of each individual mangrove species (Table 2). The species-species wood density of mangrove forests is adopted from Komiyama [16].

Table 2. Above-ground biomass estimation formula for mangrove species

No	Species	Formula of Biomass (kg)	Mangrove structures used	Sources
1	*General*	$0.251 * \rho * D^{2.46}$		[16]
2	*Bruguiera gymnorrhiza*	$0.1681*\rho*DBH^{2.31}$ (R^2=0.99) ρ= 0.801	DBH, H	[17]
3	*Kandelia candle*	$2.5904*CD^2*H$ (R^2=0.84) $0.251*\rho*DBH^{2.46}$ (R^2=0.98) ρ= 0.0776	Canopy diameter, H (DBH <5 cm) DBH, H (DBH > 5 cm)	[16, 18]
4	*Avicennia marina*	$1.8247*CD^2*H$ (R^2=0.97)	Canopy diameter, H	[18]
5	*Aegicera corniculatum*	$3.1253*CD^2*H$ (R^2=0.99)	Canopy diameter, H	[18]
6	*Rhizophora* stylosa	$0.168*D^{2.42}$ + $Biomass_{stilt}$ (kg) = $0.0209 *D^{2.55}$ (R^2=0.99)	D_{30}, H	[17]

Where: ρ is species-species wood density, CD represents canopy diameter (m), and H and DBH are the tree height (m) and the diameter of tree at the height of 1.3 m, respectively [19]. Total AGB of each plot was taken as the sum AGB individual mangrove species. The species-species wood density of mangrove forests is adopted from Kauffman and Donato [14]. AGB is the total above-ground biomass of mangrove individual (kg).

Above-ground carbon stock (AGC):

AGC can be calculated based on AGC using conversion factors that involve the amount of carbon to the amount of biomass:

AGC = AGB*0.475

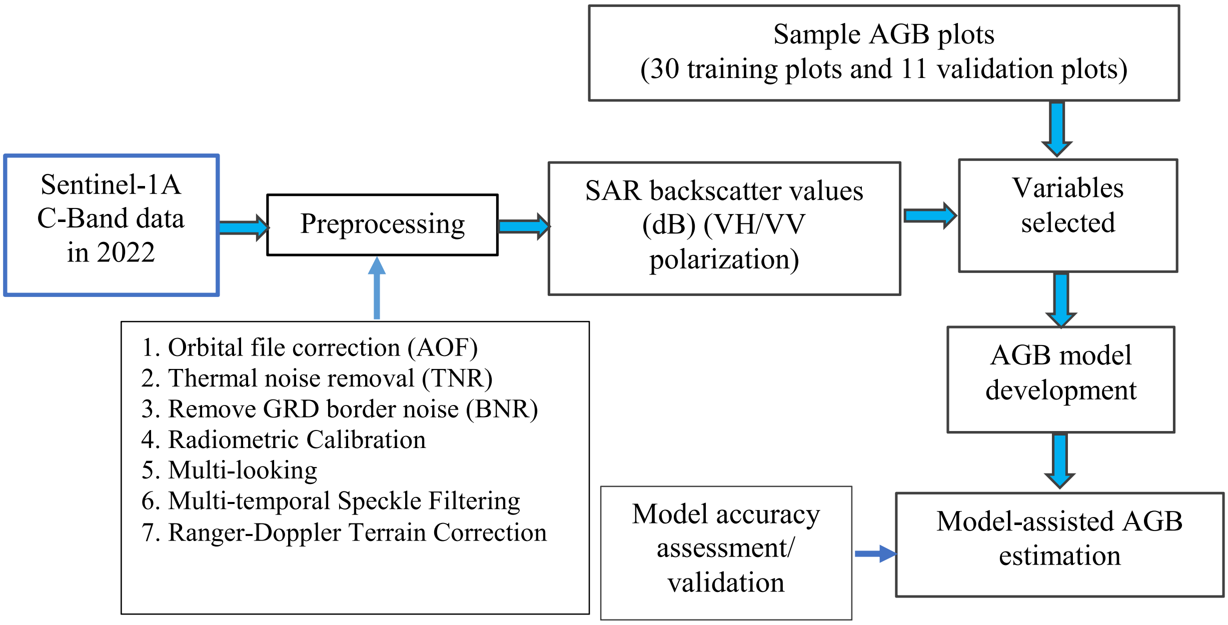

Figure 2. Flow chart of Sentinel-1A preprocessing and AGB model development in Tien Yen

Sentinel-1 pre-processing:

In this study, to quantify the extent of mangrove forests in Tien Yen, the steps were proceeded as follows: (1) Data pre-processing steps were conducted using SNAP 9.0, including Applying Orbit File (AOF), Thermal Noise Removal (TNR), Remove GRD Border Noise (BNR), Calibration; Multi-looking, Multi-temporal Speckle Filtering, Range-Doppler Terrain Correction, dB Conversion (Fig. 2); (2) Determination of thresholds for mangrove forests and non-mangrove forests was conducted, then mangrove cover/extent was estimated using defined thresholds, followed by accuracy assessments of mangrove extent mapping with the assistance of the field data survey and PlanetScope data; (3) Models of Sentinel-1A and field data-based mangrove AGB were set up using R statistics Version 4.3.1.

Mangrove cover extraction:

This study used the Combined Mangrove Recognition Index (CMRI) for mangrove cover mapping from PlanetScope in 2022, which is created by combining NDVI and NDWI for the spectral discrimination of mangrove covers from non-mangrove classes. We also adopted the thresholds of PlanetScope-derived CMRI from the study of Hai-Hoa [13] for distinguishing mangrove cover from other land cover with the field survey-based modification. The thresholds for mangrove cover are identified to be greater than 0.7585 (CMRI> 0.7585), while CMRI with value less than 0.7585 (CMRI< 0.7585) is identified as non-mangrove cover [13].

CMRI (Combined Mangrove Recognition Index) = NDVI - NDWI

NDVI (Normalized Difference Vegetation Index) = (NIR-RED) / (NIR+RED)

NDWI (Normalized Difference Water Index) = (GREEN-NIR) / (GREEN + NIR)

Where GREEN is Band-2; RED is Band-3, and NIR in PlanetScope image is Band-4.

Backscatter mean values from the Sentinel-1A, including VV and VH polarizations were computed and masked to two kinds of areas. One is where mangrove forests are more likely to distribute, such as low-lying areas and intertidal zones excluding. The other is where mangrove forests do not naturally occur as far inland, highlands and open area [12, 13, 20].

Accuracy assessments of classified images: For image accuracy assessments, this study used high-resolution PlanetScope image captured in 2022 in combination with GPS points collected from the field investigation in 2022. The quantitative validation was then performed to evaluate the classification accuracies of mangrove cover derived from thresholds and referenced data. There are 210 GPS sampling points in total, including 150 GPS points for mangrove cover and 60 points for non-mangrove covers. These random points were used for accuracy assessments of mangrove cover map.

For statistical accuracy assessments, independent test samples were included in the process to create a computational matrix. The classification and control matrices were constructed to cross-tabulate the observed data with the reference data using the Kappa coefficient [21], which is a measure of the consistency between two maps, considering all the elements of the error matrix [22]. A Kappa with value of 0 is inconsistent: from 0.41 to 0.6 is referred to be moderately consistent; 0.61–0.8 is remarkably homogeneous; and 0.81–1.0 is almost perfect homogeneity [23, 24]. To use the data correctly, this study considered the minimum level of the overall interpretation accuracy in coastal land covers, in which mangrove cover maps would be at least 85.0% as suggested by previous studies of Foody [25].

Calculation of VV/VH polarization of Sentinel-1A:

To select the most suitable AGB models of mangrove forests, we examined 13 polarization variables of Sentinel-1A that were selected as AGB model inputs (Table 3). The first variables were generated from Sentinel-1A, also known as derived polarization variables that were used for model development (Table 3).

Table 3. VV/VH polarizations of Sentinel-1A used for mangrove cover mapping.

VV/VH polarizations	Variables	References
Single VV	VV	[26]
Single VH	VH	
CR Cross-Ratio	(VH/VV), (VV/VH), Sqrt(VV/VH), sqrt(VH/VV)	
Multiplication polarization	(VV*VH), Ln(VV*VH)	
Addition polarization	(VV+VH)/2	
	VV^2, VH^2, Ln(VH^2), Ln(VV^2)	

where,

VV is VV polarization of Sentinel-1A;

VH is VH polarization of Sentinel-1A.

Modelling estimation of mangrove AGB development:

This study used 13 polarization variables shown in Table 3. Each polarization variable was calculated based on its formula presented in Table 3. After that, we worked on by modelling the relationship of Sentinel-1A data and field AGB-based measurement was carried out. All modelling tasks were conducted by R statistics version 4.3.1. The AGB models were then developed, which was based on 30 circular plots and polarization variables using a step-wise regression approach. This process was conducted by removing the one with the smallest standardized coefficient until no improvement was noticed in the estimate of the error, thereby eliminating collinear variables [7].

To assess the model performance, Root Mean Square Error (RMSE) and the coefficient determination (R^2) between measured AGB and predicted AGB data were used. The accuracy was done using 11 validation plots established in different locations as opposed to the training plots (30 training plots) that serve the purpose of model development. The correlation between measured AGB from validation plots and the predicted AGB generated from Sentinel-1A was examined using the equations as follows:

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i \quad y_i)^2}$$

$$\mathrm{RMSE}\ (\%) = \left(\frac{\mathrm{RMSE}}{\overline{Y}}\right) \quad 100$$

where,

x_i is measured AGB of mangrove forests;

y_i is the predicted AGB of mangrove forests; and $\overline{Y}$ is the mean of mangrove AGB measured.

3. RESULTS AND DISCUSSION

3.1. Mangrove cover derived from S1-SAR backscatter values

Accuracy assessments of mangrove cover from VV and VH polarization values

The Sentinel-1A data was used to produce the VH and VV polarization value-based mangrove cover maps for the whole coast of Tien Yen where mangrove forests are possibly found. The error matrices showed that accuracy assessments of VH and VV polarization-based mangrove classification in 2022 have a high level of accuracy compared to user's accuracy. To be more specific, the index for accuracy assessment of mangrove cover detected by VH and VV polarizations are 88.0% and 88.7%, respectively, as opposed to 98.0% of accuracy by 2022 PlanetScope data. As for that of non-mangrove cover, the figure for VH and VV polarizations both stands at 98.3%, giving overall accuracies of 90.5% for VH polarization and 91.0% for VV polarization in 2022 (Table 4).

Table 4. Accuracy assessments of mangrove cover in Tien Yen District

VV polarization-based classified image	**Reference data in 2022** (Data collected from field survey)				
		Man	**Non-**	**Total**	**User's Accuracy (%)**
	Man	**133**	17	150	88.7
	Non-	2	**58**	60	96.7
	Total	135	75	210	
	Producer's Accuracy (%)	98.5	77.3	Overall Accuracy: 91.0% Kappa coefficient = 0.79	

Man (Mangrove forests); Non- (Non-Mangrove forests).

VH polarization-based classified image	**Reference data in 2022** (Data collected from field survey)				
		Man	**Non-**	**Total**	**User's Accuracy (%)**
	Man	**132**	18	150	88.0
	Non-	2	**48**	60	96.7
	Total	134	76	210	
	Producer's Accuracy (%)	98.5	76.3	Overall Accuracy: 90.5% Kappa coefficient = 0.78	

CMRI-based PlanetScope classification	**Reference data in 2022** (Data collected from field survey)				
		Man	**Non-**	**Total**	**User's Accuracy (%)**
	Man	**147**	3	150	98.0
	Non-	1	**59**	60	98.3
	Total	148	62	210	
	Producer's Accuracy (%)	99.3	95.2	Overall Accuracy: 98.1% Kappa coefficient = 0.95	

Man (Mangrove forests); Non- (Non-Mangrove forests).

The results of accuracy assessment based on verified data show that the PlanetScope-based CMRI is a good classifier with overall classification accuracy at 98.1% and Kappa coefficient at 0.95. More importantly, overall accuracy assessments and Kappa coefficients of VH and VH backscatters compared to PlanetScope data confirm that it is reliable to use both VH and VV polarizations for mangrove cover discrimination from other non-mangrove covers since it offers a great alternative for the cloudy cover areas. The kappa coefficients of VH and VV backscatters also indicate that there are very high agreements between the classified maps and the reference data, thus implying that the Sentinel-1A-derived VH and VV polarizations have a great potential for mangrove cover monitoring and mapping for the whole coast of Quang Ninh Province.

Mangrove cover derived from VV and VH:

As the thresholds of VH and VV polarizations have been determined for discriminating mangrove cover and non-mangrove covers, the thematic maps of mangrove cover are then constructed as indicated in Fig. 3.

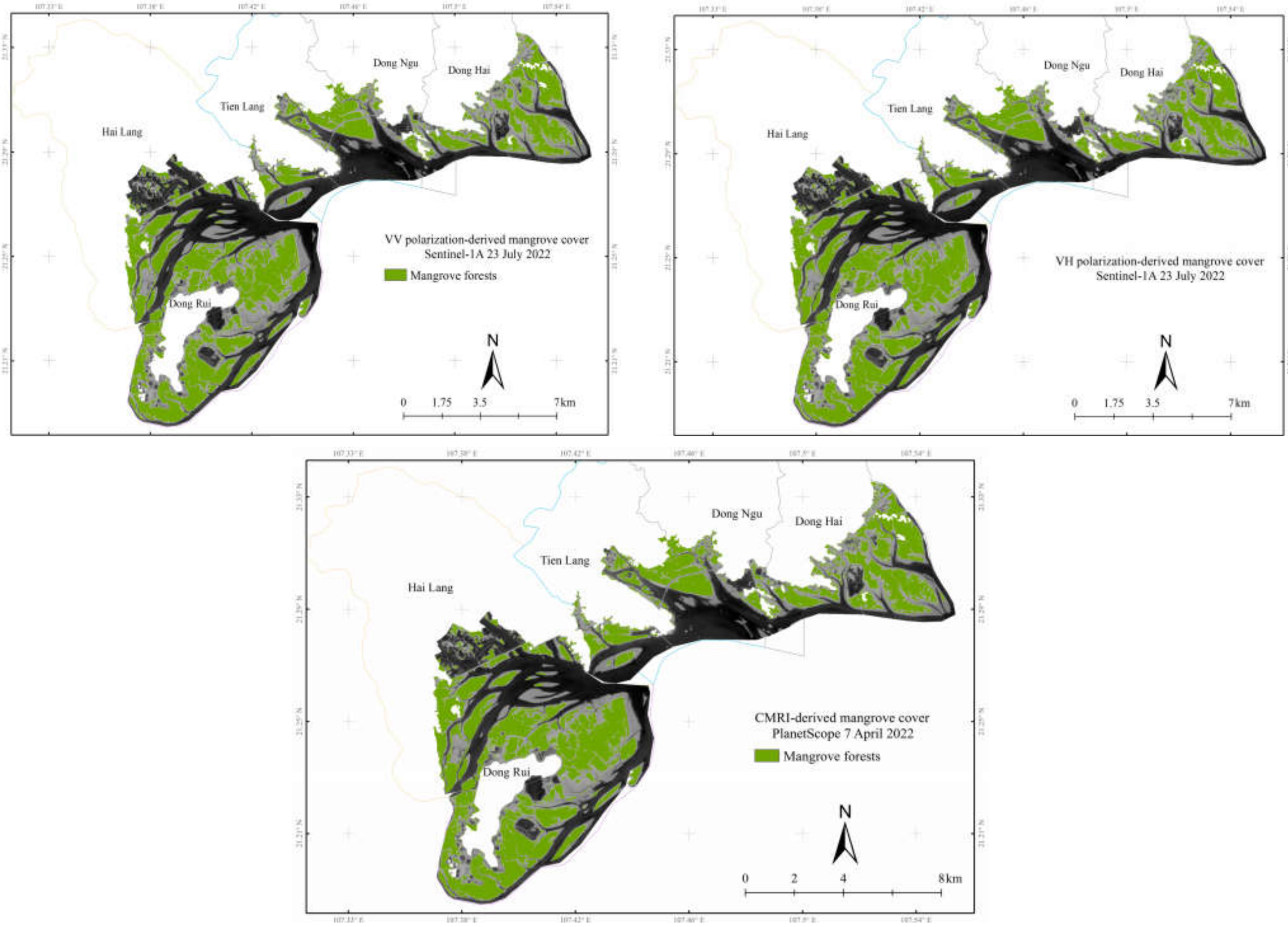

Figure 3. Mangrove cover-derived VH and VV polarizations based on Sentinel-1A compared to 2022 PlanetScope data in Tien Yen

It is found out that for the whole coast of Tien Yen, there is 3,523.0 ha and 3,523.8 ha of mangrove forests estimated from VH (-23.4<VH<-9.05) and VV polarizations (-17.5<VV<-3.8), respectively, as compared to 3,558.2 ha from PlanetScope data (CMRI>0.7585). Notably, in terms of total extent of mangrove cover, there is a slight difference between VH polarization-derived and VV-polarization-derived mangrove extent. A similar pattern is also seen between VH/VV backscatter-derived mangrove cover and CMRI-derived mangrove cover from PlanetScope data, which identified by a gap of about 0.99%. This small difference indicates that VH/VV polarizations with the defined thresholds compared to CMRI-derived mangrove cover are reliable for mangrove cover mapping in Tien Yen (Fig. 3).

Field plots, mangrove AGB and S1 SAR backscatter coefficients:

Mangrove AGB calculated in the survey plots:

As indicated in Fig. 4, the average AGB of mangrove forest calculated is 64.8 kg $pixel^{-1}$ with the dimension (10 m by 10 m, equivalent to 100 m^2) or 64,751.9 kg ha^{-1}.

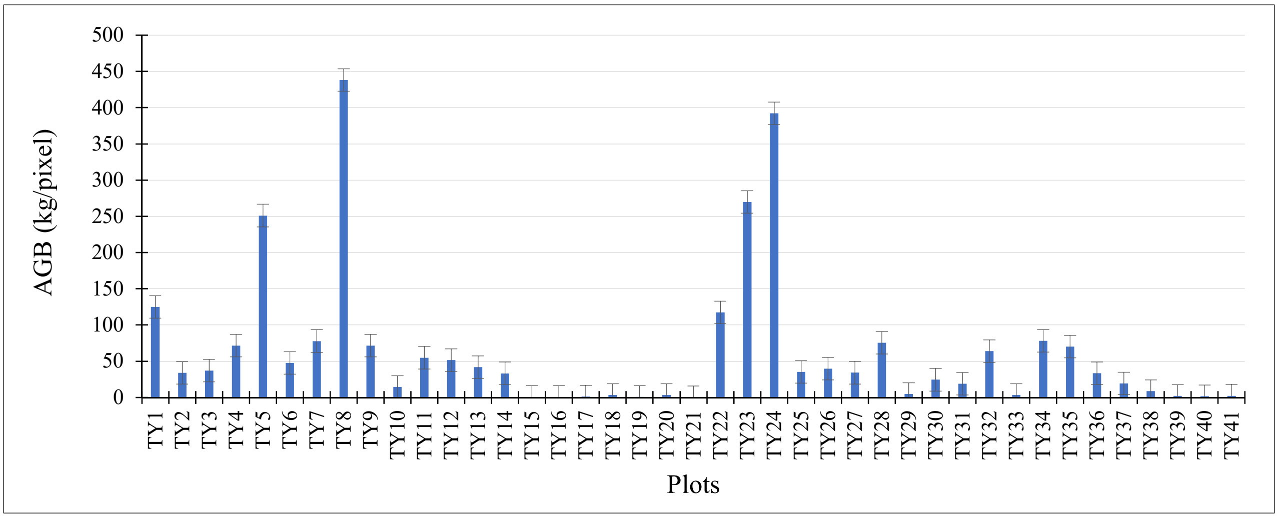

Figure 4. Field plot profile of mangrove AGB in Tien Yen corresponding to plots

Plots (1, 5, 6, 8, 18, 28, 31, 32, 34, 37, 41) used for model validation,

Plots (2-4, 7, 9-17, 19-27, 29, 30, 33, 35, 36, 38, 39, 40) for the model development.

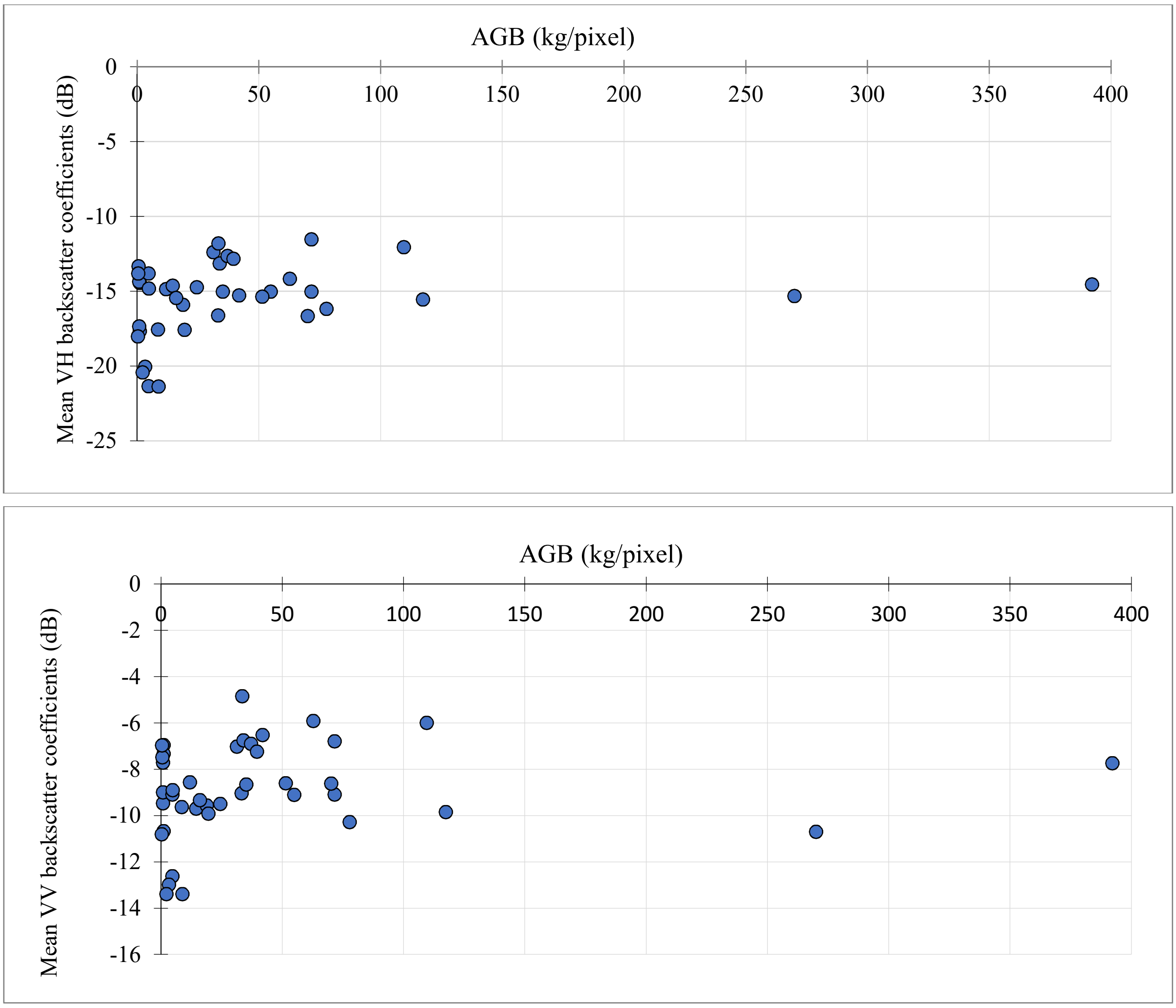

Figure 5. Relationship between observed mangrove AGB and Sentinel-1 SAR backscatter coefficients in the field plots

In addition, there was a growth in backscatter values as the mangrove AGB increases (Fig. 5). In fact, VH and VH backscatter (dB) values corresponding to mangrove AGB were defined from -21.36 (8.81 kg of AGB pixel^{-1}) to -11.51 (71.6 kg of AGB pixel^{-1}) in VH polarization, and from -13.39 (8.81 kg of AGB pixel^{-1}) to -4.84 (33.42 kg of AGB pixel^{-1}) in VV polarization (Fig. 5).

3.2. Development of mangrove AGB models

Development of AGB models:

Models of mangrove AGB estimation:

The overall result of determining regression values between mangrove biomass and VV/VH polarizations has a value of R^2 from 0.307 to 0.445, indicating a moderate correlation based on step-wise linear regression models. Regression models, including model 1 and 2, were reported with the values of R^2>0.410 as summarized in Table 5.

Table 5. AGB estimation models based on VV and VH polarizations

Model	AGB estimation models	Data
1	lm(Ln(AGB) ~ - 531.5645 + 11.1456*VV + 156.782*sqrt(VH/VV) + 408.6425*sqrt(VV/VH) + 0.228*(VV*VH) + 17.2139* Ln(VV*VH) r^2=0.4452, p-value<0.001	S1A
2	lm(formula = Ln(AGB) ~ -361.634+67.7593*VV -50.4833*(VV+VH)/2 -0.4463*VH^2 + 1.2406*VV^2 + 474.6845*sqrt(VV/VH) r^2=0.409, p-value<0.001	S1A
3	lm(Ln(AGB) ~ -219.94054 + 20.56272*VV - 0.22766*VH^2 -35.06271*(VV+VH)/2 + 425.22847*sqrt(VV/VH) -66.373044*Ln(VV^2) r^2=0.384, p-value<0.001	S1A
4	lm(Ln(AGB) ~ -325.61 + 120.47*sqrt(VH/VV) + 222.61*sqrt(VV/VH) r^2=0.307, p-value<0.001	S1A

Note: AGB, VH and VH were taken as average values per pixel (10mx10m, equivalent to 100 m^2). S1A is Sentinel-1A data.

As shown in Table 5, model that was derived from backscatters of Sentinel-1A offered the best model with mean VV and VH backscatters (Model 1) of R^2=0.445 and p-value<0.001, followed by the Model 2. In this study, the best AGB model is the one with lowest RMSE and highest R^2 (the coefficient of determination). Therefore, Model 1 was selected to calculate the mangrove AGB and AGC in Tien Yen in Tien Yen (Tables 6 and 7, Fig. 6).

Table 6. Summary of the statistics of selected AGB model for AGB and AGC estimation.

Residuals:				
Min	**1Q**	**Median**	**3Q**	**Max**
-3.5895	-0.6812	0.1189	0.8256	3.6364
Coefficients	**Estimate**	**Std. Error**	**t value**	**Pr(>|t|)**
(Intercept)	-531.5645	129.6969	-4.099	0.000411 ***
VV	11.1456	4.8683	2.289	0.031150 *
sqrt(VH/VV)	156.7820	37.9202	4.135	0.000375 ***
sqrt(VV/VH)	408.6425	102.2394	3.997	0.000531 ***
VV/VH	0.2280	0.1101	2.071	0.049323 *
Ln(VV*VH)	17.2139	8.0087	2.149	0.041898 *
Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1				
Residual standard error: 1.687 on 24 degrees of freedom Multiple R-squared: 0.4452, Adjusted R-squared: 0.3296 F-statistic: 3.852 on 5 and 24 DF, p-value: 0.01054				

Table 7. Model accuracy assessments by comparing predicted and measured AGB values

Validation plots	Longitude	Latitude	Ln(Measured AGB) (kg/pixel)	Models (kg/pixel)			
				Model 1		Model 2	
				Predicted values	RMSE	Predicted values	RMSE
TY1	107.38656	21.19301	3.4	2.8	0.9	2.2	1.6
TY5	107.40438	21.24192	4.1	4.6	1.0	4.7	1.6
TY6	107.38832	21.24515	2.5	2.2	1.1	1.8	1.7
TY8	107.39171	21.24876	4.2	2.3	1.1	1.9	1.7
TY18	107.37673	21.21529	1.5	2.3	1.0	0.9	1.7
TY28	107.38736	21.19359	2.9	2.1	1.0	1.5	1.7
TY31	107.52671	21.31473	2.4	3.6	1.0	0.8	1.7
TY32	107.52669	21.31292	2.8	2.2	1.0	1.6	1.8
TY34	107.52665	21.31349	3.0	2.2	1.1	0.7	1.8
TY37	107.53029	21.31382	1.6	2.3	1.1	1.8	1.8
TY41	107.52531	21.31672	1.9	2.6	1.2	4.8	2.0
Difference between predicted and measured AGB values		**Max**	**4.2**	**4.6**	**1.2**	**4.8**	**2.0**
		Min	**1.5**	**2.1**	**0.9**	**0.7**	**1.6**
		Mean	**2.8**	**2.6**	**1.0**	**2.1**	**1.7**

As can be seen in Table 7, the mean RMSE (Root Mean Square Error) values of Model 1 and Model 2 are significantly different. In fact, a difference can be spotted between predicted and observed mangrove AGB values. This study selected Model 1 (R^2=0.445, p-value<0.001) for mangrove AGB and AGC estimation in Tien Yen.

Models of mangrove AGB and AGC estimation:

As indicated in Figure 6, the majority of mangrove AGB and AGC in Tien Yen is categorized up to 20 kg and 10 kg per pixel, respectively (Fig. 6). It indicates that mangrove management should be prioritized for the improvement of mangrove carbon conservation.

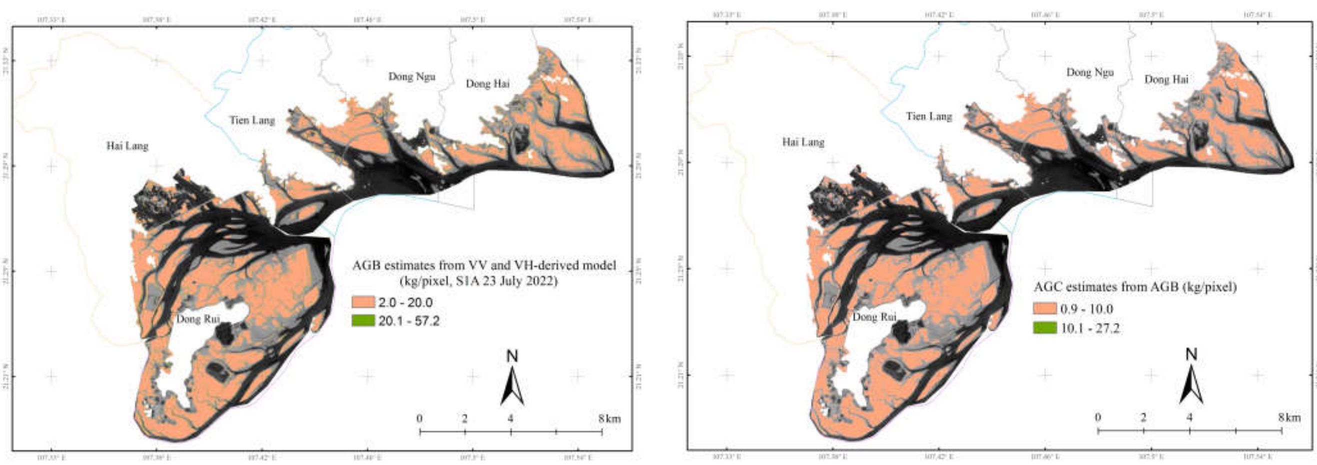

Figure 6. AGB estimates from VV and VH-derived model, AGC calculation from AGB model in Tien Yen

3.3. Implications for mangrove AGB, AGC monitoring in Vietnam

In Vietnam, limited studies have examined the development of AGB estimation model based on Sentinel-1 (SAR) and field-survey data, especially those that are focused in Tien Yen (Quang Ninh). Therefore, we decided to take the initiative and conduct this study with a view to developing AGB models of mangrove and estimates AGB and AGC of mangrove forests. The findings are hoped to be proved useful in assessing mangrove environmental services under the recently issued policy regarding carbon payment-based voluntary trading credits. Moreover, this study investigated the mangrove conditions by setting up sampling plots in Tien Yen as a pilot site, where the researchers measured some key mangrove structures in 30 linear circular plots with 14 radius (equivalent to 615.4 m^2). The study also aimed to examine the relationship between AGB calculated from the field and AGB estimated from backscatters of Sentinel-1A collected by applying the developed AGB models. The findings can be used for C-PFES over the Quang Ninh Province and other relevant coastal regions with the cloudy coverage in Vietnam. However, our study suggests that other machine learning-based models should as well be tested to develop the AGB estimation of mangrove forests in Tien Yen from Sentinel-1A and Sentinel-1B.

4. CONCLUSION

It is evident that Sentinel-1A (SAR) can be used for biomass retrieval and mapping of mangrove cover. It is because the prediction accuracy is compatible to imagery from current conmercial sensors. A moderate correlation (R^2=0.455) between observed AGB and estimated AGB from Sentinel-1A (SAR)-derived VH and VV backscatters was identified by the conventional linear regression models. This finding indicates that using Sentinel-1A for mapping mangrove cover and mangrove AGB is a potential in Tien Yen. Therefore, the free and open-sourced Sentinel-1 data (SAR) shoud be encouraged in conducting mangrove AGB mapping. We recommend that follow-up study should include for Sentinel-1-generated DEM in their future research to test its capability for biomass retrieval mapping in combination with backscatters and multi-spectral data (PlanetScope and Sentinel-2 data). In addition, multi-dated combination of VH and VV polarization or HH and HV in C-band of Sentinel-1A should also be tested for biomass estimation. Besides, the accuracy of the mangrove AGB estimation could be improved with more additional plots distributed strategically in areas far from the current plots. Finally, it is advised that various data transformation techniques as well as nonlinear multiple regression form in machine learning approach should be applied in the methodology so as to to improve accuracy rate of the mangrove AGB.

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