Estimation of above-ground carbon of mangrove forest using Sentinel-1 (SAR) and field inventory data: a case study in Quang Yen, Quang Ninh province

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Ước tính trữ lượng các bon trên mặt đất rừng ngập mặn từ ảnh Sentinel-1 (SAR) và điều tra thực địa: nghiên cứu điểm tại Quảng Yên, tỉnh Quảng Ninh

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ABSTRACT

*Tide-dominated mangroves are found along shallow shorelines with modest slope where they receive freshwater runoff and nutrients from rainfall. They have been globally recognized as they play a vital role in preventing coastal erosion, mitigating effects of wave actions, and protecting coastal habitats and adjacent shoreline land-uses from extreme coastal events. By using Sentinel-1A data, the study has constructed the spatial distribution of mangrove cover compared to PlanetScope image in Quang Yen. In fact, this study used the Sentinel-1A-derived VV/VH polarizations for mangrove cover mapping with thresholds of -12.8<VH<-3.8 and -16.65<VV<-3.3. 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 Quang Yen with overall accuracy over 92.0% and Kappa coefficient greater than 0.80 in 2022. This study also developed mangrove AGB models based on the field survey data and SAR data for estimating AGB and AGC of mangrove forests in Quang Yen. Overall, selected AGB models (AGB = 288.17 + 21.57*VV, R^2=0.553, p-value<0.001) have provided promising options for carbon estimation and monitoring to the coastal areas where the cloudy cover is mostly present and optical remote sensing data is usable. To have more accurate AGB models based on SAR data, this study also suggests that further study should be carried out using more advanced machine learning models based on Sentinel-1A and Sentinel-1B for carbon estimation of mangrove forests in Quang Yen.*

Từ khóa:
các-bon trên mặt đất, phân cựcVV/VH, Quảng Yên, rừng ngập mặn, Sentinel-1A

TÓM TẮT

*Rừng ngập mặn phân bố dọc bờ ven biển với độ dốc vừa phải, đây là nơi chúng nhận được nguồn nước ngọt và chất dinh dưỡng từ trong đất liền. Vai trò của rừng ngập mặn đã được biết đến như là trong việc ngăn chặn xói mòn bờ biển, giảm thiểu tác động của sóng biển và bảo vệ môi trường sống ven biển khỏi các hiện tượng thời tiết cực đoan. Nghiên cứu đã sử dụng dữ liệu Sentinel-1A để xây dựng bản đồ phân bố rừng ngập mặn so sánh với kết quả giải đoán trên ảnh PlanetScope tại Quảng Yên. Kết quả nghiên cứu cho thấy có thể sử dụng giá trị phân cực VV/VH từ Sentinel-1A để xác định phân bố rừng ngập mặn với các ngưỡng -12,8<VH<-3,8 và -16,65<VV<-3,3. Việc sử dụng ngưỡng giá trị phân cực VV và VH để xây dựng bản đồ phân bố rừng ngập mặn đối chiếu dữ liệu PlanetScope ở cùng thời điểm nghiên cứu đã khẳng định rằng việc sử dụng VV và VH là phù hợp cho việc giám sát độ che phủ rừng ngập mặn dọc bờ biển Quảng Yên với độ chính xác tổng thể trên 92,0% và hệ số Kappa lớn hơn 0,80 vào năm 2022. Nghiên cứu cũng đã xây dựng mô hình ước tính AGB rừng ngập mặn dựa trên số liệu điều tra thực địa và dữ liệu ảnh SAR để ước tính AGB và AGC của rừng ngập mặn tại Quảng Yên. Nhìn chung, mô hình ước tính AGB được chọn (AGB = 288,17 + 21,57*VV, R^2=0,553, giá trị p-value<0,001) là một sự lựa chọn đầy hứa hẹn để ước tính và giám sát trữ lượng các-bon rừng ngập mặn ven biển, đặc biệt ở nơi mà hầu hết có mây che phủ trong năm và việc sử dụng dữ liệu viễn* *thám quang học là không khả thi. Để có các mô hình ước tính AGB có độ chính xác hơn khi sử dụng dữ liệu SAR, cần có các nghiên cứu xây dựng mô hình ước tính AGB dựa trên cách tiếp cận học máy tiên tiến trên dữ liệu Sentinel-1A và Sentinel-1B khi ước tính lượng carbon rừng ngập mặn cho khu vực nghiên cứu.*

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. For example, aquatic and terrestrial insects, fish, reptilian, amphibian, and vertebrate species or plants prefer wetlands and salts, typically sea grasses [3]. Despite their recognized importance of mangrove forests, they are being globally degraded and deforested at an alarming rate [2, 4]. The primary drivers of mangrove loss that have been identified include aquaculture expansion and conversion of other land use [5-7]. Similarly, mangrove ecosystems have been known as highly valuable resources for local people, who are living nearby the coastal regions in Vietnam [4, 8]. Their ecosystems have offered the local people good opportunities and stable coastal livelihoods [6]. 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, 5, 6].

To pursue sustainable mangrove management, remote sensing has been applied to monitor and assess mangrove ecosystems and their dynamics over the last decades [7, 8]. Synthetic aperture radar (SAR) sensors are effective for monitoring forest biomass due to their independence of cloud cover and weather conditions [8] and ability to penetrate the forest canopy [10, 11]. SAR sensors apply various wavelengths which could penetrate the forest in different ways [11]. The launch of Sentinel-1A and Sentinel-1B offer very frequent SAR data acquisitions with a free data policy [12]. The X-band and C-band of Sentinel-1 are sensitive to leaves and needles [13]. These bands are also suitable for monitoring the young growth stages of mangrove forests [14]. 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 [15]. 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 (Stahl *et al.* 2011) [16]. Therefore, model-based inference is based on assumptions of the model [17]. 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 Quang Yen coast of Quang Ninh province [18, 19].

This study aimed to quantify the extent of mangrove cover along the coast of Quang Yen town, Quang Ninh province using Sentinel-1A-derived polarization thresholds, then developed the models of mangrove AGB and AGC based on the Sentinel-1A and field-derived data for Quang Yen. These findings are hoped to provide a scientific foundation for using Sentinel-1 for mangrove carbon monitoring and change detection in Quang Ninh province, thus contributing to further studies on the same focus but with the scale of the whole Vietnam in general.

2. RESEARCH METHODOLOGY

2.1. Study site

Quang Yen is a coastal town, located in the Southwest of Quang Ninh province (Fig. 1). It is geographically situated away 40 km from Ha Long city to the Southwest, 18 km from Uong Bi city to the southeast, and about 20 km from Hai Phong port city to the east [20]. Terrestrial forests in Quang Yen occupy a small area and distribute mainly in the high mountainous area in the North bordering Hoanh Bo, however, it is worth noting that they play an important role in the economic development of the town, especially in regulating water resources of the Yen Lap reservoir. Furthermore, they also offer diverse ecological landscapes for tourism development [18].

Significantly, Quang Yen town also has more than 30-km coastlines with many estuaries and tidal flats. The sea area with the enclosed bay is known as a home of many sea creatures with high economic values which provide a rich source of aquatic resources both in saltwater and brackish water. Despite the mounting benefits they bring up, mangrove forests along the coast of Quang Yen have been under great pressure from urbanization and economic development; land use/cover conversion; and shrimp farming activities [7, 20].

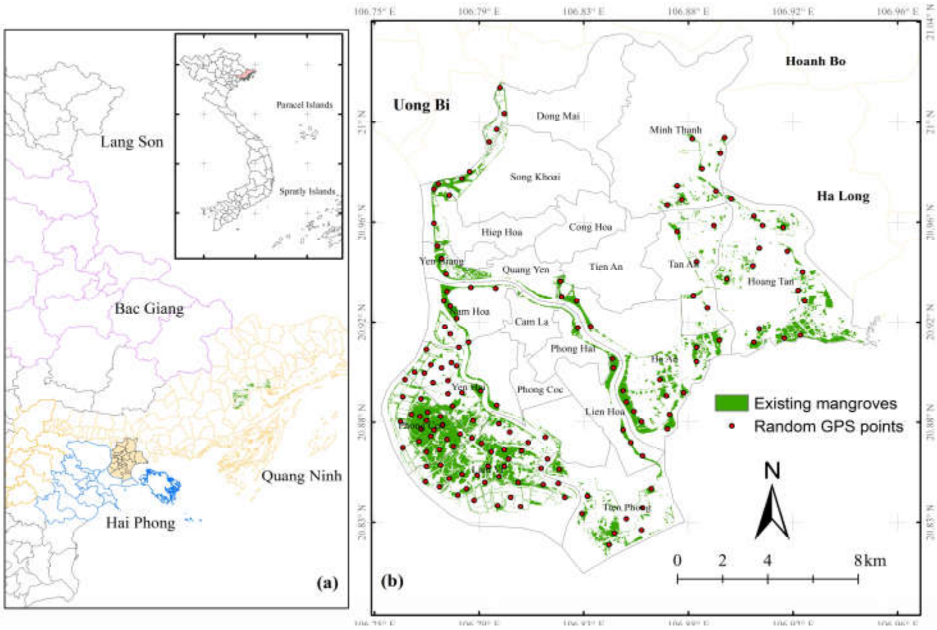

Figure 1. Study location
(a) Quang Ninh province in Vietnam,
(b) Mangrove forests distributing in Quang Yen town, Quang Ninh province

2.1. Remote sensing data collection

Sentinel-1 image captured in 2022 was used to classify the extent of mangrove forests together with 2023 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_20220725T225111_20220725T225136_044263_054873_E6F3	25/07/2022	10
2[b]	20230531_030857_74_2473_3B_AnalyticMS_SR	31/05/2023	3
	20230531_030859_93_2473_3B_AnalyticMS_SR		
	20230531_030902_13_2473_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 (closed and open canopy) for above-ground biomass (AGB) and above-ground carbon estimation (AGC). This study intended to focus on mangrove covers for AGB and AGC model development. Therefore, circular plots were established for mangrove survey. Besides, the circular plots were taken randomly for biomass measurements across the Quang 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) [8, 22, 23]. There were two or three plots in each transect, spaced 30 m apart each plot [8]. At each circular plot, mangrove measurements (DBD and CD) were conducted to determine the biomass using the methods developed by Kauffman and Donato [22]. Within each plot, geographic coordinates were recorded by the GPS 76cs. A total of 30 circular plots were set up in this study (Fig. 1), of which 20 plots were used for mangrove biomass model development, while 10 plots were used for the model validation. In 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 [8]. The main species along the Quang Yen coast include *Sonneratia caseolaris*, *Aegiceras corniculatum*, *Avicennia*, and *Bruguiera gymnorrhiza* [18].

Above-ground biomass (AGB):

Allometric equation was used to estimate for the mangrove AGB of each individual mangrove species. The species-species wood density of mangrove forests is adopted from Komiyama [24].

$$AGB\ (kg) = 0.251*\rho * D^{2.46}$$

Where ρ is species-species wood density. Total AGB 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 [22].

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:

$$AGC = AGB*0.475$$

Sentinel-1 pre-processing: In this study, to quantify the extent of mangrove forests in Quang 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, accuracy assessments of mangrove extent mapping with the assistance of the field data survey and PlanetScope data; (3) Models of Sentinel-1 and field data-based mangrove AGC were set up using R statistics Version 3.6.

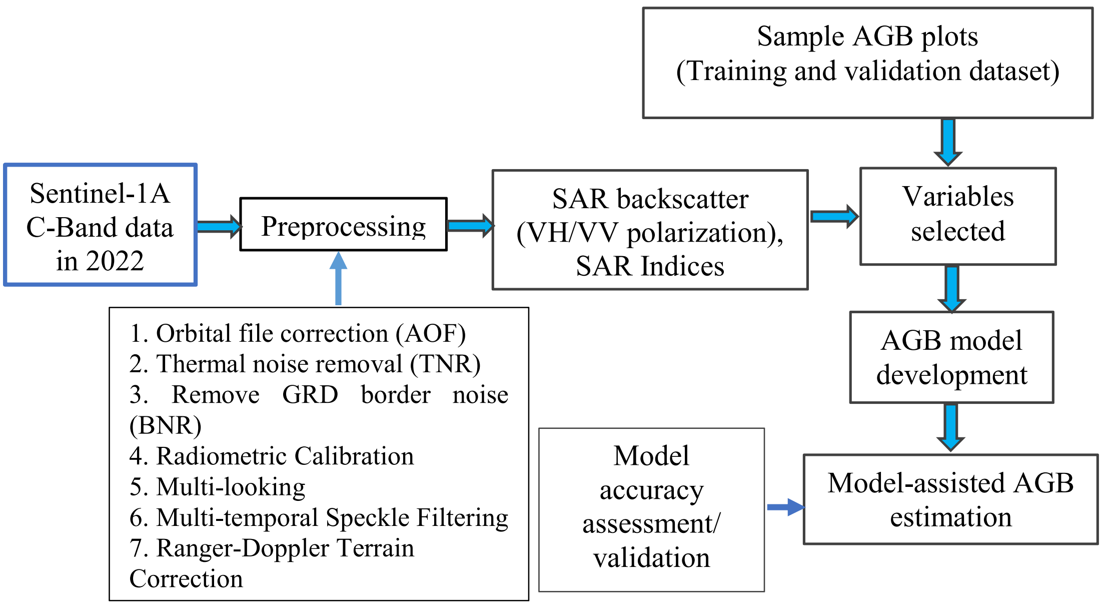

Figure 2. Flow chart of Sentinel-1A preprocessing and model development

Mangrove cover extraction:

This study used the Combined Mangrove Recognition Index (CMRI) for mangrove cover mapping from PlanetScope in 2023, which is created by a combination of 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 [20] 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 0.846 (CMRI> 0.846), while CMRI with value less than 0.846 (CMRI< 0.846) is identified as non-mangrove cover [20].

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.

Mean backscatter values from the Sentinel-1A, including VV and VH polarizations were computed and used to mask to both include areas where mangrove forests are more likely to distribute, such as low-lying areas and intertidal zones excluding areas where mangrove forests do not naturally occur as far inland, highlands and open area [19, 21, 25].

Accuracy assessments of classified images: For image accuracy assessments, this study used high-resolution PlanetScope image captured in 2023 in combination with GPS points collected from the field investigation in 2022 and 2023. The quantitative validation was then performed to evaluate the classification accuracies of mangrove cover derived from thresholds and referenced data. There are 200 GPS sampling points in total, including 150 GPS points for mangrove cover and 50 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 combined 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 [26], which is a measure of the consistency between two maps, considering all the elements of the error matrix [27]. A Kappa with value of 0 is inconsistent: from 0.41 to 0.6 refers as moderately consistent; 0.61–0.8 is remarkably homogeneous; and 0.81–1.0 is almost perfect homogeneity [28, 29]. 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 [30].

Calculation of polarization indices of Sentinel-1A:

To select the most suitable AGB models of mangrove forests, Sentinel-1 indices that were selected as AGB model inputs have 8 polarization indices (Table 2). The first indices were generated from Sentinel-1A, known as derived polarization indices that were used to model development (Table 2).

Table 2. Equations of VV/VH polarizations of Sentinel-1A used for mangrove cover mapping

VV/VH polarizations	Equations	References
Single VV	VV	
Single VH	VH	
CR Cross-Ratio	VH/VV, VV/VH	[31]
DR (dB) Depolarization Ratio	VH - VV) VV - VH)	[32]
Multiplication polarization	VV*VH	
Addition polarization	VV+VH	

where,

VV is polarization VV of Sentinel-1A;

VH is polarization VH of Sentinel-1A.

Modelling estimation of mangrove AGB development:

This study used eight polarization variables shown in Table 2. Each polarization index was calculated based on its formula presented in Table 2, followed by modeling the relationship of Sentinel-1 data and field AGB-based measurement was carried out. All modelling tasks were conducted by R statistics version 3.6.3. The AGB models were then developed, which was based on 20 circular plots and polarization indices using 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 [8].

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 10 validation plots located outside the training plots (20 plots) that serve the purpose of model development. The correlation between measured AGB from validation plots and the predicted AGB generated from Sentinel-1 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. FINDINGS AND DISCUSSION

3.1. Mangrove cover and accuracy assessments in Quang Yen

Accuracy assessments of mangrove cover mapping:

The Sentinel-1A image was used to produce the polarization value-based mangrove cover maps (VH and VV polarizations) for the whole coast of Quang Yen. The error matrices showed that accuracy assessments of VH and VV polarization-based mangrove cover classification in 2022 have a high level of accuracy compared to user's accuracy. To be more specific, mangrove cover detected by VH and VV polarizations are 90.7% and 91.3%, respectively, as opposed to 96.4% of accuracy by PlanetScope data. As for that of non-mangrove cover, the figure for VH and VV polarizations both stands at 96.0%, giving overall accuracies of 92.0% (VH polarizations) and 92.5% (VV polarizations) in 2022 (Table 3).

Table 3. Summary of accuracy assessments of mangrove cover in Quang Yen

VV polarizations-based classified image-

	Reference data in 2022 (Data collected from field survey)			
	Man	**Non-**	**Total**	**User's Accuracy (%)**
Man	**137**	13	150	91.3
Non-	2	**48**	50	96.0
Total	*95*	*62*	200	
Producer's Accuracy (%)	98.6	78.7	Overall Accuracy: 92.5% Kappa Coefficient = 0.81	

Note: 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	**136**	14	150	90.7
Non-	2	**48**	50	96.0
Total	*95*	*62*	200	
Producer's Accuracy (%)	98.6	77.4	Overall Accuracy: 92.0% Kappa Coefficient = 0.80	

RI-based classified PlanetScope

	Reference data in 2022 (Data collected from field survey)			
	Man	**Non-**	**Total**	**User's Accuracy (%)**
Man	**144**	6	150	96.4
Non-	0	**50**	50	100.0
Total	*95*	*62*	200	
Producer's Accuracy (%)	100.0	89.3	Overall Accuracy: 96.5% Kappa coefficient = 0.91	

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

The results of accuracy assessment based on verified data show that the CMRI-based PlanetScope is a good classifier with overall classification accuracy at >96.5% and Kappa coefficient at 0.91. More importantly, overall accuracy assessments and Kappa coefficients of VH and VH backscatters in comparison with PlanetScope data confirm that it is reliable to use both VH and VV polarizations for mangrove cover discrimination from other non-mangrove covers, which 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 in Quang Ninh province.

Mangrove cover-based VH and VV polarizations

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.

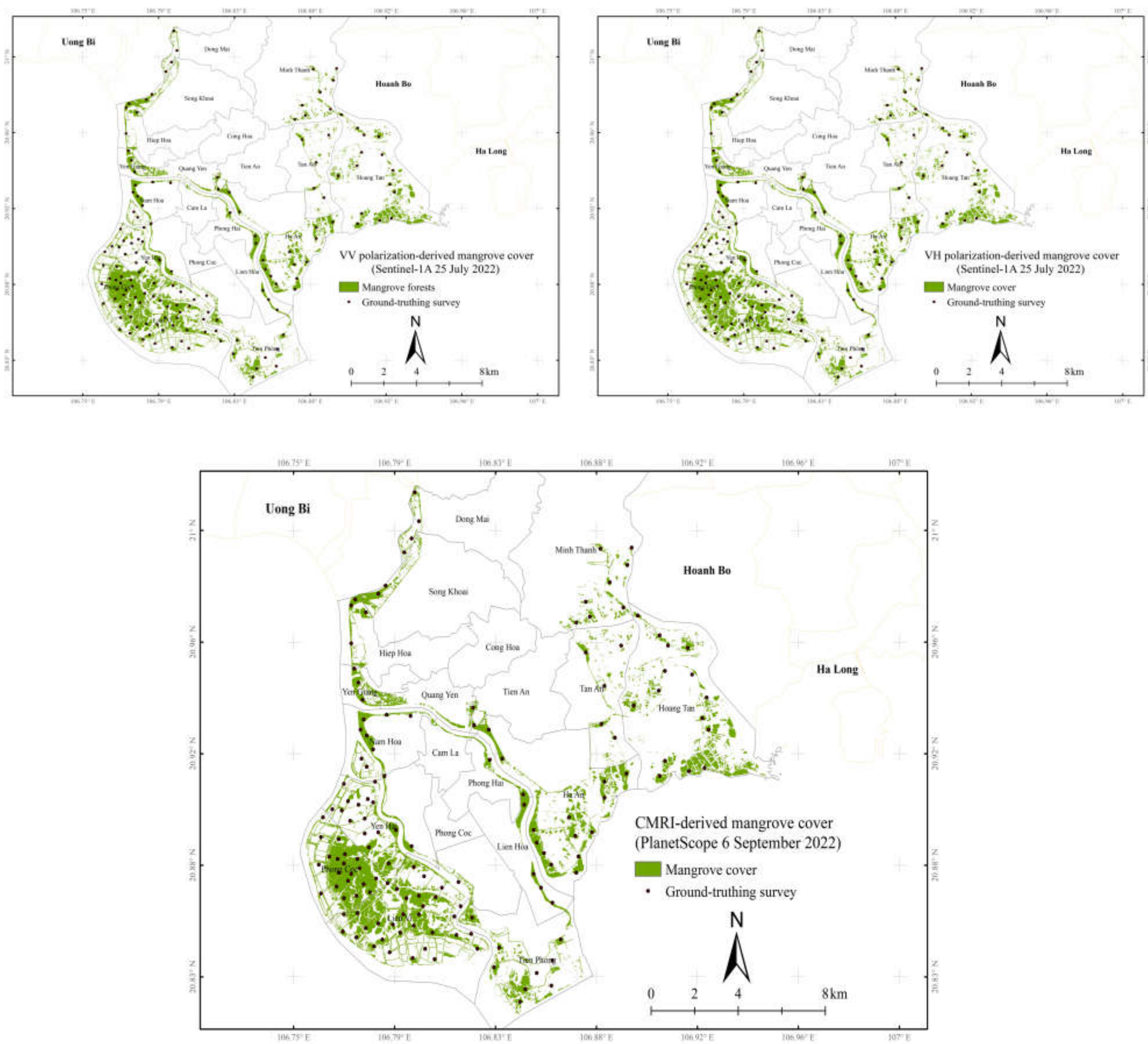

Figure 3. Sentinel-1 VH and VV polarizations-derived mangrove cover compared to PlanetScope data in Quang Yen

It is found out that for the whole coast of Quang Yen, there is 2,753.8 ha and 2753.6 ha of mangrove forests estimated from VH (-12.8<VH<-3.8) and VV polarizations (-16.65<VV<-3.3), respectively, as compared to 2750.0 ha from PlanetScope data (CMRI>0.846). Remarkably, in terms of total extent of mangrove cover, there is a slight difference between VH/VH polarizations-derived Sentinel-1A and CRMI-derived PlanetScope data, a gap of about 0.14%. This small difference indicates that VH and VV polarizations with the thresholds defined are reliable for mangrove cover mapping in Quang Yen (Fig. 3).

3.2. Models of mangrove AGB and AGC estimtion

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 0.446 to 0.554, indicating a moderate correlation based on step-wise linear regression models. Regresion models were having values of $R^2>0.550$, including Model 1, 2, and 3 as summarised in Table 4.

Table 4. RMSE test results, the AGB estimation models based on VV and VH polarizations

Models	Variables	AGB estimation models	Data used
1	VV	AGB ~ VV, r^2=0.553, p-value<0.001, RMSE=35.15	Sentinel-1A
2	VV^2	AGB ~ VV^2, r^2=0.554, p-value<0.001, RMSE=35.83	Sentinel-1A
3	VV*VH	AGB ~ VV*VH, r^2=0.446, p-value<0.001, RMSE=33.94	Sentinel-1A
4	VV/VH	AGB ~ VV/VH, r^2=0.476, p-value<0.001, RMSE=30.43	Sentinel-1A
6	VH/VV	AGB ~ VH/VV, r^2=0.472, p-value<0.001, RMSE=31.15	Sentinel-1A

As shown in Table 4, model that was derived from backscatters of Sentinel-1A offered the best models with VV (Model 1 and Model 2) with R^2 greater than 0.550 and p-value<0.001. In this study, the best AGB model is the one with lowest RMSE and highest R^2 (the coefficient of determination, Model 1). It was selected and used to estimate and map the AGB of mangrove forests in Quang Yen (Fig. 4).

Table 5. Model accuracy assessments by comparing predicted and measured AGB values

Validation plots	Longitute	Latitude	Measured plots	Models			
				Model 2		Model 1	
				Predicted values	RMSE	Predicted values	RMSE
QY9	106.77715	20.93788	155.3	153.5	39.2	153.6	43.4
QY10	106.77759	20.93715	151.6	157.5	43.2	158.2	39.6
QY11	106.77838	20.93638	100.4	132.1	43.1	130.4	39.6
QY12	106.77851	20.93741	106.3	151.8	42.2	151.5	38.7
QY13	106.77832	20.92702	105.0	151.1	40.1	150.7	36.4
QY14	106.77783	20.92677	96.0	144.7	39.2	143.6	34.5
QY15	106.77723	20.92672	182.2	92.5	39.0	94.9	33.0
QY17	106.77813	20.92605	107.9	159.3	35.8	160.5	27.2
QY18	106.77855	20.92632	115.4	149.2	35.2	148.5	25.9
QY33	106.77624	20.94249	145.8	144.1	41.7	142.9	33.0
Difference between predicted and measured AGB values			Max		43.2		43.4
			Min		35.2		25.9
			Mean		39.9		35.1

As can be seen in Table 5, the RMSE (Root Mean Square Error) values of Model 1 and Model 2 are similar. Moreover, a difference can be spotted between predicted and observed mangrove AGB values ranging from -2.0% to 49.6%. This study selected Model 1 (AGB = 288.17 + 21.57*VV, R^2=0.553, p-value<0.001) for mangrove AGB and AGC calculation in Quang Yen.

Models of mangrove AGC estimation

In Fig. 4, the majority of AGC of mangrove in Quang Yen is categorized into a group of 50.00 to 100 kg carbon per pixel, while smaller areas of carbon amount classified into a group of less than 50 kg per pixel distribute over Quang Yen (Fig. 4). It indicates that enhancement of mangrove quality should be prioritized for carbon conservation purposes.

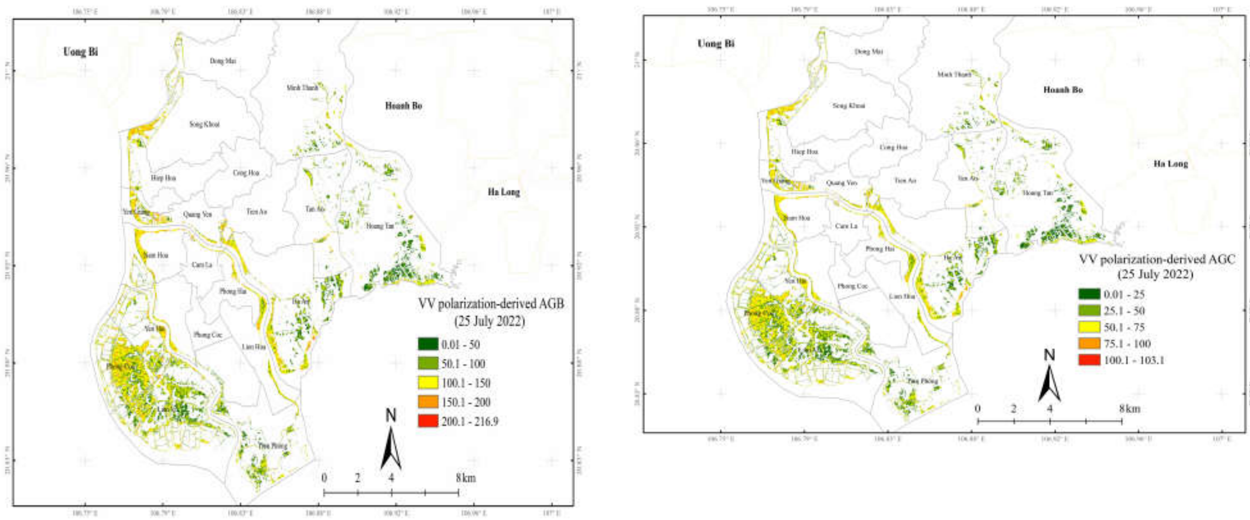

Figure 4. Mangrove AGB and AGC estimation based on Sentinel 1- VH and VV polarizations-derived model in Quang Yen

Study implications for mangrove monitoring

In Vietnam, few studies have examined the development of AGB estimation model based on Sentinel-1 (SAR) and field-survey data, in particular in Quang Yen (Quang Ninh). More importantly, this is the first study that develops AGB models of mangrove and estimates AGB and AGC of mangrove forests that can be used for assessing mangrove environmental services under the recently issued policy regarding carbon payment-based voluntary trading credits. This study investigated the mangrove conditions by setting up sampling plots in Quang 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). This study also aimed to examine the relationship between AGB calculated from the field and AGB estimated from backscatters of Sentinel-1A collected thanks to the developed AGB models. It is hoped that the findings can be used for C-PFES over the Quang Ninh province and other relevant coastal regions with the cloudy coverage in Vietnam. Our study suggests that other machine learning-based models should be tested to develop the AGB estimation of mangrove forests in Quang Yen from Sentinel-1A and Sentinel-1B.

4. CONCLUSION

It is evident that remote sensing technology can offer an effective tool to monitor and detect changes in coastal land covers and mangrove cover over time. Therefore, this study used the Sentinel-1A-derived VV/VH polarizations for mangrove cover mapping with thresholds of -12.8<VH<-3.8 and -16.65<VV<-3.3. It is confirmed that data collected using VV and VH polarizations for mangrove cover mapping, when compared to PlanetScope data, are suitable for mangrove cover monitoring along the coast of Quang Yen, with overall accuracy over 92.0% and Kappa coefficient greater than 0.80 in 2022. Our study also developed mangrove AGB models based on the field survey data and SAR data for estimating AGC of mangrove forests in Quang Yen. Overall, selected AGB models have provided promising options for carbon estimation and monitoring to the coastal areas where the cloudy cover is mostly present and optical remote sensing data is usable. The study also suggests that advanced machine learning models based on Sentinel-1A and Sentinel-1B for carbon estimation of mangrove forests should be tested in Quang Yen.

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