Estimation of mangrove carbon stocks from remote sensing and field survey-based data in Nghe An province

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Ước tính trữ lượng các-bon rừng ngập mặn từ dữ liệu viễn thám và thực địa tại tỉnh Nghệ An

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ABSTRACT

Mangrove forests mainly grow in tropical and subtropical regions, including Southeast Asia, coastal Africa, Latin America, and parts of Australia, which provide critical ecosystem services, including coastal protection from storms, shoreline stabilization, and carbon sequestration. This study determined the locations of mangrove cover, then estimated the biomass and carbon stocks of mangrove forests in Nghe An by integrating multi-source satellite imageries and field measurements. Sentinel-2A and PlanetScope multispectral images were used in combination with field inventory to characterize mangrove structures and their extent. The findings revealed that the total of AGB and BGB of mangrove forest was estimated at 109,824 tons and 31,849 tons, while the total of AGC and BGC of mangrove forests was calculated at 51,617 tons and 14,967 tons in 2025 by Sentinel-2, respectively. The total of ACS across the surveyed area sums up to 51,998 tons in 2025. The study highlights the need for nature-based solutions to mitigate climate change, including Carbon Payment for Forest Environmental Services (C-PFES), Reducing Emissions from Deforestation and Forest Degradation (REDD+). Besides fighting back climate changes, these approaches can also create financial incentives for local stakeholders to maintain and restore mangrove forests. Furthermore, it is essential to strengthen existing policies as well as revise policy frameworks that recognize the ecological and economic values of mangrove in Nghe An province.

***Từ khóa**:*

Các-bon dưới mặt đất (BGC), các-bon trên mặt đất (AGC), Nghệ An, PlanetScope, Sentinel-2A.

TÓM TẮT

Rừng ngập mặn phân bố chủ yếu ở các vùng nhiệt đới và cận nhiệt đới, bao gồm Đông Nam Á, ven biển Châu Phi, Mỹ Latinh và một số vùng của Úc, chúng cung cấp các dịch vụ hệ sinh thái quan trọng, bao gồm bảo vệ bờ biển khỏi bão, ổn định bờ biển và hấp thụ carbon. Nghiên cứu này được thực hiện để xác định phân bố rừng ngập mặn, sau đó ước tính sinh khối và trữ lượng carbon của rừng ngập mặn tại tỉnh Nghệ An bằng cách tích hợp ảnh vệ tinh đa nguồn và số liệu đo đạc thực địa. Ảnh đa phổ Sentinel-2A và PlanetScope được sử dụng kết hợp với dữ liệu thực địa để mô tả cấu trúc rừng ngập mặn và phạm vi phân bố của chúng. Kết quả cho thấy tổng giá trị AGB và BGB của rừng ngập mặn ước tính lần lượt là 109.824 tấn và 31.849 tấn, trong khi tổng trữ lượng AGC và BGC của rừng ngập mặn từ Sentinel-2 tính toán lần lượt là 51.617 tấn và 14.967 tấn vào năm 2025. Tổng lượng tích lũy quá trình cô lập CO2 (ACS) trên toàn khu vực ước tính là 51.998 tấn năm 2025. Nghiên cứu *nhấn mạnh nhu cầu về các giải pháp dựa vào thiên nhiên để giảm thiểu biến đổi khí hậu, bao gồm chi trả carbon cho dịch vụ môi trường rừng (C-PFES), giảm phát thải từ mất rừng và suy thoái rừng (REDD+). Bên cạnh việc ứng phó với biến đổi khí hậu, các giải pháp này có thể tạo ra động lực tài chính cho các bên liên quan tại địa phương trong việc duy trì và phục hồi rừng ngập mặn. Ngoài ra, việc củng cố các chính sách hiện tại cũng như sửa đổi các khuôn khổ chính sách công nhận các giá trị sinh thái và kinh tế của rừng ngập mặn tại tỉnh Nghệ An là rất cần thiết.*

1. INTRODUCTION

Mangrove forests are uniquely adapted intertidal ecosystems that provide a suite of vital ecological functions. They buffer coastlines against waves and storm surges, reduce erosion, and support high biodiversity, including fish and bird species [1, 2]. Importantly, mangrove forests are among the most carbon-rich forests on a per-area basis, storing large amounts of carbon in their biomass and soils [3, 4]. By sequestering carbon, they significantly contribute to climate change mitigation, and their removal can release significant greenhouse gases into the atmosphere [5]. Vietnam is the country with the 6th largest mangrove forest area in Southeast Asia, and the 22nd in the world [6]. With a coastline of 3,260 km, the mangrove ecosystem is important for ecology and livelihoods, playing a crucial role in environmental protection [7]. Although mangroves bring many benefits, this ecosystem is being significantly degraded. The total area of mangrove forests in Vietnam was more than 400,000 ha before the Vietnam War (Maurand, 1943) and is estimated to have decreased by 62% (155,000 ha) by 2021 [8]. The causes of mangrove loss are blamed for impacts of climate change, such as an increase in sea levels and the change in rainfall patterns; human activities like urban development, aquaculture, mining, overexploitation of timber, fish, crustaceans, and shellfish; and coastal infrastructure development, conversion to agricultural and other types of aquaculture, and harvesting of timber that is to be utilized in construction and charcoal manufacturing [9,10]. Vietnam is remarkable in the Mekong Delta with mangrove extent of 81,979.21 ha and the Central region (2,293.44 ha) for mangrove resources [8]. The government's reforestation programs have partially reversed past losses, but challenges remain. In Nghe An province (Central Vietnam), mangroves have been recognised both ecologically and socio-economically , yet data on their extent and carbon stocks remains limited. Accurate estimation of mangrove covers and carbon stocks in Nghe An has been constrained by the lack of integrated field surveys and high-resolution mapping [11, 12]. This research addresses that gap by integrating field surveys and high-resolution mapping to provide comprehensive data on mangrove distribution, biomass, and carbon in Nghe An province.

Remote sensing technologies have been known as powerful tools for monitoring mangrove ecosystems over large areas. Spectroscopy in remote sensing is a significant contribution as it enables one to differentiate and identify the various aspects of matter on the ground. This is the most outstanding benefit. It may determine what objects are based on the reflectance or emission spectrum of the objects. The multispectral images provide various spectral bands or portions of the electromagnetic spectrum. Multispectral satellites like Sentinel-2A (operational since 2015) and PlanetScope (launched in 2016) offer fine spatial resolutions (10 m for Sentinel-2, 3 m for PlanetScope) and frequent revisit times [13, 14]. The strength of this method is the spectroscopy, since various surface materials such as vegetation, soil, and water reflect and absorb energy differently across the electromagnetic spectrum, resulting in distinct spectral signatures [15]. Vegetation indices (VIs), including the Normalized Difference Vegetation Index (NDVI), are mathematical combinations of these spectral bands, designed to emphasize the spectral signature of healthy vegetation, which reflects strongly in near-infrared (NIR) and absorbs red light [16, 17]. VIs are widely used as proxies for biophysical variables such as canopy density, vegetation health, and biomass due to their ability to quantify these spectral characteristics and provide robust ecosystem analysis [18, 19]. This study examined the mangrove forest ecosystem in the coastal area of Nghe An province with three primary dimensions. Firstly, the study determined the spatial distribution of mangrove forests by using Sentinel-2A and PlanetScope data. Secondly, the key mangrove structures, their species composition were investigated in the field. Thirdly, the study estimated the mangrove biomass and carbon stock accumulated in the mangrove forest through field measurement, and used remote sensing data. Based on a detailed examination, the study is expected to give a high-quality scientific foundation to developing and implementing effective and sustainable blue carbon conservation policies in the study area, with a contribution to resource management and climate change adaptation.

The application of remote sensing and field methods to estimate mangrove biomass had both benefits and difficulties. Field-based method represents one of the most basic and reliable methods to estimate biomass and carbon stock representative of mangrove forests. The parameters including a diameter at breast height (DBH), tree height, tree density, and species composition can be measured directly to give highly reliable values in biomass and carbon quantities, in addition to constituting a baseline data to calibrate and validate the remote sensing or modeling outputs [20, 21]. Besides, field surveys are used to identify small modifications to the structure of the forest as well as significant long-term carbon monitoring programs, especially REDD+ [22]. But various challenges also extend to this approach due to muddy substrates, tidal fluctuations, and complex aerial root systems. Additionally, field surveys are labour-intensive, time and cost-consuming, and can only be carried about in sample plots, where inaccuracy could arise during generalisation to the forests as a whole [23].

However, remote sensing is increasingly considered an important tool in estimating biomass and carbon stocks of mangrove forests due to its ability to cover large areas and provide multi-temporal data with high accuracy. With muddy terrain and tides making field surveys difficult, remote sensing helps save a lot of time, manpower, and costs, while reducing risks when working in harsh environments [24]. In addition, remote sensing data allows monitoring forest changes over time, serving resource management, assessing deforestation or forest regeneration, and supporting the correction of field data, thereby improving the reliability of research results [25]. Integrating remote sensing with GIS systems also helps to build maps of mangrove distribution and carbon stocks, providing necessary information for forest restoration programs and greenhouse gas emission reduction policy planning. Thus, in order to enhance efficiency, this study tends to incorporate new methods of fieldwork with remote sensing analysis and biomass simulation in order to have a high level of accuracy as well as efficient resource utilization.

2. STUDY SITE AND METHODOLOGY

2.1. Study site

Nghe An province has a natural area of 16,490.25 km^2 (Fig. 1). It occupies a central position in the North Central Region of Vietnam, borders the sea to the east and Thanh Hoa province to the south, sharing a boundary with Ha Tinh province to the North and a 468 km land border with the Lao People's Democratic Republic to the West. Nghe An consists of 17 districts, 21 administrative units at district level (01 city, 03 towns, and 17 districts), and a total of 480 administrative units at the commune level [26]. The population of Nghe An Province was 3,441,971 people in 2023, with a population density of 207 people per km^2 [27]. Nghe An province is situated in the central part of Vietnam's North Central region and occupies a strategic position along the east-west transport corridor, including seaports, airports, railways, and road networks, facilitating access to neighboring provinces and countries like Laos. Rich in natural resources, such as forests, marine ecosystems, and minerals, Nghe An also benefits from diverse topography that supports robust agricultural development.

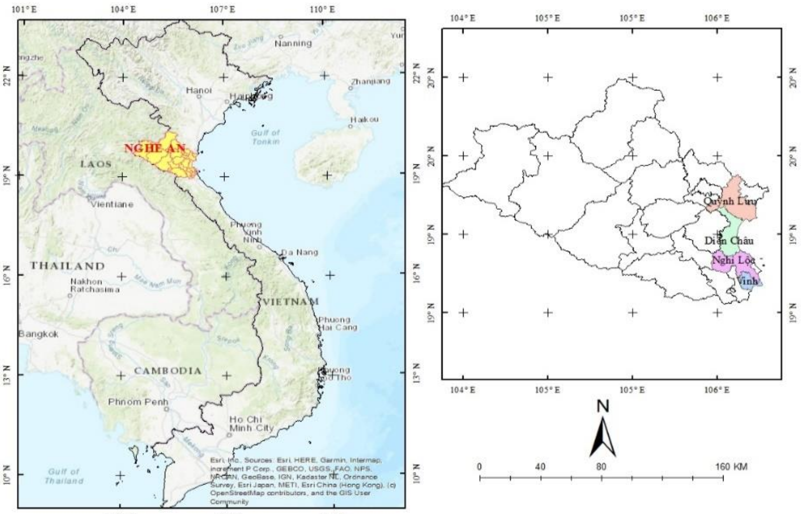

Fig. 1. Geographical location of Nghe An Province, Vietnam

Nghe An province is located within the tropical monsoon climate zone with hot and dry summer and cold and humid winters. The average annual temperature ranges between 23°C and 24°C. The highest temperature can reach 42–43°C and the lowest temperature may fall to nearly 0°C. Nghe An is divided into 6 sub-Eco geomorphology [28] with three distinct ecological regions: mountainous, midland, and coastal plain.

2.2. Study methods

Mangrove cover mapping

The study combined remote sensing analysis with field measurements. High-resolution optical imagery and ground-truth data were processed. Sentinel-2A and PlanetScope images were acquired for the study period. All imageries were required to be processed using ArcGIS, including atmospheric correction, radiometric calibration, geometric correction, and cloud/shadow masking. Terrain effects were addressed by using a digital elevation model (DEM).

Table 1. Remote sensing data used in this study

ID	Image codes	Date of capture	Spatial Resolution (m)	Sensors
1	20250422_035039_80_2511_3B_AnalyticMS	22/04/2025	3	PlanetScope[1]
2	20250422_035042_05_2511_3B_AnalyticMS	22/04/2025	3	PlanetScope[1]
3	20250422_035044_31_2511_3B_AnalyticMS	22/04/2025	3	PlanetScope[1]
4	20250422_035046_56_2511_3B_AnalyticMS	22/04/2025	3	PlanetScope[1]
5	20250422_035048_81_2511_3B_AnalyticMS	22/04/2025	3	PlanetScope[1]
6	20250422_035908_42_2531_3B_AnalyticMS	22/04/2025	3	PlanetScope[1]
7	20250422_035910_81_2531_3B_AnalyticMS	22/04/2025	3	PlanetScope[1]
8	20250422_035915_58_2531_3B_AnalyticMS	22/04/2025	3	PlanetScope[1]
9	20250422_035917_97_2531_3B_AnalyticMS	22/04/2025	3	PlanetScope[1]
10	S2A_MSIL1C_20250112T033111_N0511_R018	12/01/2025	10	Sentinel-2A[2]

[1]https://www.planet.com; [2]https://browser.dataspace.copernicus.eu/

Vegetation indices

Multi-index approach was used to correctly differentiate mangrove forests and other land cover types. The reason behind the choice of each index is the following:

The Normalized Difference Vegetation Index (NDVI) was selected because it has been established that it has good capability in measuring the health and density of the vegetation [29, 30]. It was also a significant predictor variable in the biomass estimation models used in this study [31].

Open water bodies were detected and masked using the Normalized Difference Water Index (NDWI) [30, 32]. This is important in minimizing misclassification in coastal settings where mangroves are in close contact with water.

CMRI was chosen as it is a combination of NDWI and NDVI, which are calculated by subtracting NDWI and NDVI, respectively [33, 34]. CMRI was chosen due to its specific ability to increase the spectral signature of the mangrove canopies and reduce the contribution of soil and water moisture in the background, which enhances mapping accuracy in a tidal environment [33, 34].

A thematic map of mangrove cover was developed in detail using the thresholds obtained using these indices. Quantitative evaluation of the accuracy of this map was then determined by comparing it to field verified validation points by creating an error matrix to determine overall accuracy and Kappa coefficient using standard remote sensing procedures [35, 36].

Table 2. Equations of vegetation indices used for mangrove cover mapping

ID	Vegetation indices	Equations	References
1	Normalized Difference Vegetation Index (NDVI)	$\frac{Band_{NIR} - Band_{RED}}{Band_{NIR} + Band_{RED}}$	[29, 37]
2	Normalized Difference Water Index (NDWI)	$\frac{Band_{GREEN} - Band_{NIR}}{Band_{GREEN} + Band_{NIR}}$	[30, 32]
3	Combined Mangrove Recognition Index (CMRI)	(NDVI–NDWI)	[33, 34]

Where: $Band_{NIR}$ is Near Infrared Band (Band 4); $Band_{RED}$ is RED Band (Band 3); $Band_{GREEN}$ is GREEN Band (Band 2).

Field inventory of mangrove species and key structures

To measure the structure of mangrove forests, the study established from 3 to 5 circular plots depending on how long the width of mangrove forests is on each transect. The distance from the sea dike to the first plot was set at 100 m. On each transect, circular plots were set up, with a fixed radius of 5.64 m (equivalent to 100 m²). Plots along the same transect were spaced from 100 to 150 m apart, depending on the total width of the forest stand. This layout ensures representative sampling across the land-sea gradient and within each mangrove patch.

At each surveyed plot, species composition and tree parameters, including diameter at the breast height (DBH), total tree height, and crown diameter were measured using standard forestry tools. DBH was measured at 1.3m ($D_{1.3}$) of most mangrove species except for *Aegicera corniculatum* due to its growth as multiple tiny stems. The study opted for D_{30} instead of $D_{1.3}$ for *Rhizophora apiculate* species because this species develops prominent stilt roots that interfere with the accuracy and consistency of DBH measurements. Measuring at 30 cm above the highest stilt root provides a more stable and standardized reference point for biomass estimation, ensuring that the diameter reflects true stem growth rather than irregular root structures [20]. GPS coordinates were used to record each plot to match satellite imagery with field data.

Remote sensing-based biomass estimation: This study used Sentinel-2 data for estimating above-ground biomass (AGB) and below-ground biomass (BGB) of mangrove forests for Nghe An province.

Above-ground biomass (AGB): The NDVI values ranged from -0.1 to 1.0 and were classified into different classes [29, 37]. We adopted a model developed by Hoa and Hien (2021) [31] in Nghe An province, which offered a high correlation coefficient (R^2 = 0.98), p-value < 0.0001.

$$AGB = -179.1 + 13243.6 \times NDVI \; (Mg/ha)$$

Below-ground biomass (BGB): To figure out the BGB based on the AGB, the following formula was used [38]:

$$BGB = AGB \times 0.29 \; (Mg/ha)$$

Total biomass of mangrove forests: The total of biomass of mangrove forests in Nghe An is a sum of AGB and BGB [39]:

$$\text{Total biomass} = AGB + BGB \; (Mg/ha)$$

Above-ground carbon stock (AGC): AGC was calculated by using conversion factors that involve the amount of carbon to the amount of biomass [21]:

$$AGC = \text{Total biomass} \times 0.47 \; (Mg/ha)$$

Accumulation of CO_2 sequestration (ACS): To estimate the CO_2 absorption capacity of mangrove forests, the formula below was used [40, 41]:

$$ACS = AGC \times 3.67$$

The AGB measurement for each mangrove species in the field surveys followed a species-specific allometric equation, as shown in Table 3.

Table 3. Mangrove species biomass estimation allometric equations

No	Mangrove species	AGB (kg)	Key structures used	Sources
1	*Sonneratia caseolaris*	$AGB = 0.251 \times \rho \times DBH^{2.46}$ (ρ= 0.34±0.054)	DBH	[39]
2	*Aegicera corniculatum*	$AGB = 3.1253 \times CD^2 \times H$ (R^2=0.99)	CD, H	[42]
3	*Rhizophora stylosa*	$AGB = 0.251 \times \rho \times DBH^{2.46}$ (ρ= 1.050)	DBH	[33]
4	*Kandelia candle*	$AGB = 2.5904 \times CD^2 \times H$ (R^2=0.84) $AGB = 0.251 \times \rho \times DBH^{2.46}$ (R^2=0.98, ρ= 0.0776)	CD, H ($D_{1.3} \leq 5$ cm) DBH, H ($D_{1.3} > 5$ cm)	[33, 42]
5	*Avicennia marina*	$1.8247 \times CD^2 \times H$ (R^2=0.97)	CD, H	[42]
6	*Bruguiera gymnorrhiza*	$0.251 \times \rho \times (DBH)^{2.46}$ (ρ=0.741) General equation: $AGB = 0.0464 \times (DBH^2 \times H)^{0.94275} \times \rho$	DBH, H	[43]

Mangrove mapping accuracy assessments

For accuracy assessment, 330 sample points were collected, with 200 sample points for mangrove forests, 80 points for non-mangrove forests, and 50 points for water. Selection of sampling points were performed through visual interpretation of high-resolution imageries (PlanetScope and Google Earth) in combination with field survey. Overall accuracy (OA) and kappa coefficient index were calculated as formular from Congalton's equation [31, 32]:

3. RESULTS AND DISCUSSION

Accuracy assessments

The results on Sentinel-2 imagery showed that the mangrove mapping reached an accuracy of 93.0% with kappa coefficient of 0.88, indicating substantial agreement between the classified results and reference data. In comparison, the PlanetScope-based analysis achieved overall accuracy up to 97.0% and improved result of kappa coefficient as 0.96, indicating a higher truth in classification precision. The high accuracy values and kappa coefficients for both imagery sources showed the reliability of the classification approach in effectively distinguishing between mangrove forests, non-mangrove forests, and water classes.

Table 4. Accuracy of mangrove mapping by Sentinel-2A in Nghe An

		Class				
		Mangrove	**Non-Mangrove**	**Water**	**Total**	**User's Accuracy (%)**
Sentinel-2 classified	**Mangrove**	190	10	0	200	95
	Non-Mangrove	0	74	6	80	93
	Water	0	7	43	50	86
	Total	190	91	49	330	
	Producer's Accuracy (%)	100	81	88	Overall accuracy 93%	
					Kappa index = 0.88	

Table 5. Accuracy of mangrove mapping by PlanetScope in Nghe An

		Class				
		Mangrove	**Non-Mangrove**	**Water**	**Total**	**User's Accuracy (%)**
PlanetScope classified	**Mangrove**	200	0	0	200	100
	Non-Mangrove	0	77	3	80	96
	Water	0	4	46	50	92
	Total	200	81	49	330	
	Producer's Accuracy (%)	100	95	94	Overall accuracy: 97.8%	
					Kappa index = 0.96	

Threshold of CMRI values for mangrove cover mapping:

The study determined the threshold of CMRI for mangrove is greater than 0.208; for non-mangrove forest is between 0.001 and 0.208, while the threshold for water is less than 0.001. As for PlanetScope, the threshold of CMRI for mangrove is greater than 0.935, while that of non-mangrove forest is between 0.305 and 0.935, with the threshold for water is less than 0.305. In Nghe An province, remaining mangrove areas are affected by the spread of shrimp farming and changes in land use near urban areas, all within the context of locally specific coastal management practices. Therefore, in order to generate detailed biomass maps and assess the total carbon storage potential of mangroves, it is crucial to combine Sentinel-2A data with high-resolution PlanetScope while utilizing vegetation indices like NDVI, CMRI, and red-edge bands calibrated with field-based allometric biomass measurements.

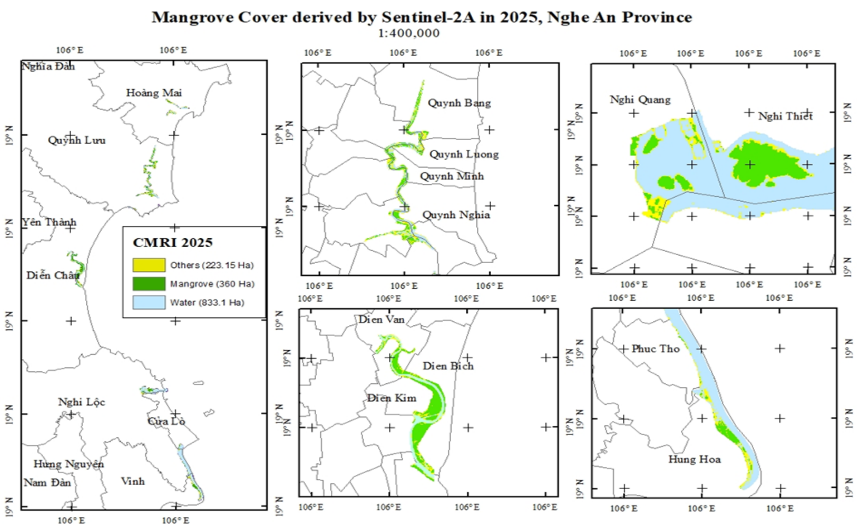

Fig. 2. Mangrove cover by Sentinel-2A in Nghe An Province

The total area of mangrove forests derived from the PlanetScope is estimated at 354 ha. Similarly, the extent of mangrove forest calculated from Sentinel-2A is nearly similar to

PlanetScope, estimated at 360 ha (Fig. 2). This slight difference could be due to the lower resolution of Sentinel-2A since it cannot capture small and narrow patches of mangrove areas where they distribute along coastlines or riverside in Nghe An. It is more likely to miss thin strips and isolated mangrove trees while using Sentinel-2A. On the contrary, higher resolution PlanetScope imagery can detect boundaries more precisely, especially fragmented mangrove forests. Besides, there may be misclassification of partial mangrove pixels where they could be classified as non-mangrove cover by mistake. Therefore, it is suggested that Sentinel-2 require more robust training datasets and post-processing to achieve a similar level of accuracy with PlanetScope.

Field inventory of mangrove species and key structures:

Based on mangrove inventory, it is found that mangrove forests are diverse in Nghe An province, comprising various tree species. Dien Chau district exhibits the highest species richness, with five species recorded in Plot 3 of Dien Bich commune. In Nghi Loc district, the forest is primarily dominated by *Kandelia candel* and *Sonneratia caseolaris*. In contrast, *Rhizophora apiculata* and *Bruguiera gymnorhiza* are the dominant species in Quynh Luu district.

The mangrove plots in Quynh Luu district exhibit the most favorable combination of tree height, diameter at breast height ($D_{1.3}$), and crown diameter, particularly in Quynh Bang and Quynh Nghia communes. In these locations, the average tree height reaches up to 10.6 m, and canopy diameters range from 3.4 to 4.71 m. These plots, primarily dominated by R. *apiculata* and B. *gymnorhiza*, reflect well-established mangrove stands with substantial vertical development.

In Nghi Loc district, several plots (Plot 1, Plot 2, and Plot 3) show a high number of individual trees. *Kandelia candel* is the most common species in this district. However, its average height is relatively short: the overall tree height in Nghi Loc is lower compared to the other districts, ranging from 2.1 meters in Phuc Tho commune to 5.9 meters in Nghi Thiet commune. Despite the shorter stature, the district exhibits considerable stem diameter growth. These plots are occupied mainly by S. *caseolaris* and K. *candel*, where S. *caseolaris* is typically planted in systematic rows, while K. *candel* is scattered more irregularly beneath the canopy.

Biomass and carbon estimation of mangrove based on field survey:

The results indicate that the AGB, AGC, and ACS values vary among different districts (Table 6). Although the trees in Nghi Loc are generally shorter, ranging from 2.1 m to 5.9 m, the high carbon storage can be attributed to the high stem density of *Kandelia candel*.

Table 6. Summary of mangrove biomass and carbon stocks in Nghe An province

Study sites	AGB (kg)	AGC (kg)	ACS (kg)
Dien Chau	13,814.4	6,492.8	23,828.4
Nghi Loc	17,933.7	7,956.4	30,934.0
Quynh Luu	13,448.4	6,320.7	23,196.8

Estimation of biomass and carbon stocks of mangrove forests from Sentinel-2:

The AGB ranges from a minimum of 1.45 tons to a maximum of 5.75 tons, with an average value of 3.1 tons. This variation suggests a moderate to high biomass density, with certain areas supporting particularly mature or dense mangrove stands. A standard deviation value of 0.965 tons shows typical heterogeneity in aboveground biomass distribution that characterizes natural ecosystems. Above-ground biomass calculations in Nghe An province amount to 109,824 tons, which demonstrates mangroves' essential role in carbon sequestration and ecosystem productivity. The below-ground biomass also presents measurable variability. The relatively low standard deviation of 0.28 tons implies a more uniform distribution of BGB compared to AGB. The total of BGB is calculated at 31,849 tons. The total of (AGB, BGB) mangrove biomass is 141,673 tons in 2025.

The total carbon stocks of mangrove forests are estimated at 66,586 tons in Nghe An by 2025, encompassing both above- and below-ground components. The highest concentrations of total mangrove carbon are observed in Dien Kim and Dien Bich communes (Dien Chau district). In contrast, the green and yellow areas, which dominate parts of Quynh Bang, Quynh Nghia, and scattered regions of Nghi Loc, reflect lower carbon values. Total carbon values vary between 0.9 and 3.5 tons per site with a mean of 1.87 tons. The standard deviation of 0.58 indicates noticeable variation in carbon storage.

Estimation of accumulation of carbon dioxide sequestration of mangrove forests:

The ACS values in the studied mangrove area range from a minimum of 6.99 tons to a maximum of 27.2 tons. On average, the ACS is 14.6 tons, with a standard deviation of 4.57 tons, indicating a moderate level of variability around the mean. The total accumulated carbon sequestration across the surveyed area sums up to 519,938 tons. The mean and total values provide a general overview of the carbon storage potential of these mangroves.

Promoting mangrove carbon conservation and blue carbon management

To advance sustainable mangrove management and carbon sequestration in Nghe An province, it is imperative to set up the establishment of a province-wide, satellite-based monitoring system. By integrating Sentinel-2 and PlanetScope imagery with ground-based forest inventory data, this system would enable timely detection of degradation, accurate quantification of biomass changes, and assessment of management effectiveness. In parallel, the province should pilot community-based Payment for Ecosystem Services (PES) and REDD+ initiatives aimed at incentivizing local stewardship of high carbon-density mangrove ecosystems. These mechanisms must be underpinned by transparent benefit-sharing arrangements, local capacity development, and participatory monitoring frameworks. Institutional frameworks should be reinforced through the formal recognition of mangrove carbon stocks within provincial climate strategies and be incorporated into marine protected area (MPA) networks. A strategic focus should include: legal protection of mature and diverse mangrove stands, the formation of accountable community management bodies, and partnerships with private-sector actors, such as carbon credit buyers and eco-tourism enterprises. Finally, restoration efforts should prioritize primary, species-rich mangrove forests over secondary or monospecific stands, by employing adaptive, site-specific reforestation designs to enhance ecological resilience and long-term carbon storage.

4. CONCLUSION

The study investigated the structure as well as estimation of biomass and carbon stocks of mangrove forests in Nghe An province by using multi-sources of remote sensing (Sentinel-2A and high-resolution PlanetScope) and field survey-based data. The findings show significant variability in AGB and BGB across different mangrove sites, highlighting the need for appropriate management strategies that consider local ecological conditions and species diversity. To enhance conservation efforts and ensure the sustainability of mangrove ecosystems, it is important to establish a province-wide, satellite-supported monitoring system that provides regular updates on the extent, structure, and carbon stocks of mangroves. In addition, promoting community-based conservation initiatives, such as C-PFES and REDD+ implementation, can incentivize local stakeholders to maintain and restore carbon-dense mangrove populations. It is also essential to strengthen formal policy frameworks to emphasize the importance of ecological and economic values of mangroves in Nghe An's climate action plans.

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REFERENCES

[1]. Holguin, G., Vazquez, P. & Bashan, Y. (2001). The role of sediment microorganisms in productivity, conservation, and rehabilitation of mangrove ecosystems: An overview. Biology and Fertility of Soils. 33: 265–278.

[2]. Duke, N. (1992). Mangrove floristics and biogeography. In A. Robertson (Ed.), Tropical Mangrove Ecosystems (63–100). American Geophysical Union.

[3]. Patil, V., Singh, A., Naik, N. & Unnikrishnan S. (2015). Estimation of mangrove carbon stocks by applying remote sensing and GIS techniques. Wetlands. 35: 695–707. DOI: 10.1007/s13157-015-0660-4

[4]. Li, Z., Zan, Q., Yang, Q., Zhu, D., Chen, Y. & Yu, S. (2019). Remote estimation of mangrove aboveground carbon stock at the species level using a low-cost unmanned aerial vehicle system. Remote Sensing. 11(9): 1018.

[5]. Thomas, N., Lucas, R., Bunting, P., Hardy, A., Rosenqvist, A. & Simard, M. (2017). Distribution and drivers of global mangrove forest change. 1996–2010. PLoS ONE, 12(6), e0179302.

[6]. Bunting, P., Rosenqvist, A., Hilarides, L., Lucas, R.M., Thomas, N., Tadono, T., Worthington, T.A., Spalding, M., Murray, N.J. & Rebelo, L.M. (2022). Global mangrove extent change 1996–2020: global mangrove watch version 3.0. Remote Sens. 14 : 3657. DOI: 10.3390/rs14153657.

[7]. Le, L.T. (2008). Effect of Hydrology on the Structure and Function of Mangrove Ecosystems in the Can Gio Mangrove Biosphere Reserve, Vietnam. PhD Dissertation. Louisiana State University, US. 208.

[8]. Ministry of Agriculture and Rural Development. (2021). Decision No. 1558/QĐ-BNN-TCLN dated April 13, 2021, on the announcement of the national forest status in 2020. Ministry of Agriculture and Rural Development of Vietnam.

[9]. Gilman, E., Ellison, J., Duke, N. & Field, C. (2008). Threats to mangroves from climate change and adaptation options: a review. Aquat. Bot. 89 : 237–250.

[10]. Ellison, J.C. & Zouh, I. (2012). Vulnerability to Climate Change of Mangroves: Assessment from Cameroon. Cent. Afr. Biol. 1 : 617–638.

[11]. Nong, N.B., Ha, V.H. T. & Le, H.N. (2024). Understanding about mangrove forest management in Vietnam. In V. Padmakumar & M. Shanthakumar (Eds.), Mangroves in a Changing World: Adaptation and Resilience.

[12]. Nguyen, H.T.T., Hardy, G. E. S., Le, T.V., Nguyen, H.Q., Nguyen, H. H. & Nguyen, T. V. (2021). Mangrove forest landcover changes in coastal Vietnam: A case study from 1973 to 2020 in Thanh Hoa and Nghe An provinces. Forests. 12(5): 637.

[13]. Drusch, M., Del Bello, U., Carlier, S., Colin, O., Fedele, A., Gascon, F. & Bargellini, P. (2012). Sentinel-2: ESA's optical high-resolution mission for GMES operational services. Remote Sensing of Environment. 120: 25–36.

[14]. Krishnamoorthy, R., Tanaka, K.& Begum, M.A. (2025). Integrating GIS-Remote Sensing: A comprehensive approach to predict oceanographic health and coastal dynamics. Remote Sensing of Environment. 8: 200–212.

[15]. Campbell, J.B., Wynne, R.H., Shao, Y. & Phan, S.V. (2019). Drought and Human Impacts on Land Use and Land Cover Change in a Vietnamese Coastal Area. Remote Sensing. 11(3): 333.
DOI : 10.3390/rs11030333

[16]. Rouse, J.W., Hass, R.H., Schell, J.A. & Deering, D.W. (1974). Monitoring vegetation systems in the GreatPlains with ERTS. 3rd ERTS Symposium , NASA SP-351, Washington DC, 10-14 December 1973, 309-317.

[17]. Hai-Hoa, N., D., Quang, V., Dai Nguyen, V.K., Linh, V.K. & Manh, N.K. (2020). Estimation of mangrove carbon stocks using Sentinel-2A and field-based data in Tien Lang district, Hai Phong city. Journal of Forestry Science and Technology. 10: 048–058.

[18]. Jaelani, L.M., Safitri, D.S., Kristian, N.E., Alina, A.N., Syariz, M.A., Sanjaya, H. & Rasam, A.R.A. (2025). Mapping mangrove species distribution and density using Sentinel-2 satellite imagery and spectral analysis. Journal of Human Earth and Future. 6(1) : 1–11. DOI : 10.28991/hef-2025-06-01-01

[19]. Ghorbanian, A., Zaghian, S., Asiyabi, R.M., Amani, M., Mohammadzadeh, A. & Jamali, S. (2021). Mangrove Ecosystem Mapping Using Sentinel-1 and Sentinel-2 Satellite Images and Random Forest Algorithm in Google Earth Engine. Remote Sensing. 13(13): 2565. DOI : 10.3390/rs13132565

[20]. Komiyama, A., Poungparn, S. & Kato, S. (2005). Common allometric equations for estimating the tree weight of mangroves. Journal of Tropical Ecology. 21(4): 471-477. DOI: 10.1017/S0266467405002476

[21]. IPCC (2003). Good Practice Guidance for Land Use, Land-Use Change and Forestry. Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R.,

Buendia, L., Miwa, K., Ngara, T., Tanabe, K. and Wagner, F., Eds., Institute for Global Environmental Strategies (IGES), Kanagawa.

[22]. Donato, D.C., Kauffman, J.B., Murdiyarso, D., Kurnianto, S., Stidham, M. & Kanninen, M. (2011). Mangroves among the most carbon-rich forests in the tropics. Nature Geoscience. 4(5): 293-297.

[23]. Alongi, D.M. (2012). Carbon sequestration in mangrove forests. Carbon Management. 3(3): 313–322.

[24]. Fatoyinbo, T. E. & Simard, M. (2013). Height and biomass of mangroves in Africa from ICESat/GLAS and SRTM. International Journal of Remote Sensing. 34(2): 668-681.

[25]. Giri, C., Ochieng, E., Tieszen, L.L., Zhu, Z., Singh, A., Loveland, T., Masek, J. & Duke, N. (2011). Status and distribution of mangrove forests of the world using earth observation satellite data. Global Ecology and Biogeography. 20(1): 154–159.

[26]. World Bank (2019). Ethnic Minorities Development Plan for Nghe An province. Vietnam Improved Land Governance and Database Project (VILG). https://documents1.worldbank.org/curated/en/797501568634562160/pdf/Ethnic-Minorities-Development-Plan-for-Nghe-An-province.pdf [Accessed 4 May 2025]

[27]. Statistics Office of Nghe An (2024). Summary report of the social-economics of Nghe An province in 2023.

[28]. Tuan, T.P. (2014). Ecological Geomorphological Zoning Study for Sustainable Land Use Planning in Nghe An Province. PhD thesis, Vietnam Academy of Science and Technology. Available at: https://www.slideshare.net/slideshow/luan-an-nghien-cuu-dia-mao-sinh-thai-lanh-tho-tinh-nghe-an-hay/229852484 [Accessed 4 May 2025].

[29]. Thu, P.M. & Populus, J. (2007). Status and changes of mangrove forest in Mekong Delta: Case study in Tra Vinh, Vietnam. Estuarine, Coastal and Shelf Science. 71(1-2): 98-109. DOI: 10.1016/j.ecss.2006.08.007

[30]. Du, Y., Zhang, Y., Ling, F., Wang, Q., Li, W. & Li X. (2016). Water Bodies' Mapping from Sentinel-2 Imagery with Modified Normalized Difference Water Index at 10-m Spatial Resolution Produced by Sharpening the SWIR Band. Remote Sensing. 8(4): 354. DOI: 10.3390/rs8040354

[31]. Hai-Hoa, N. & Hien, N.T.T. (2021). Aboveground biomass estimation models of mangrove forest based-on remote sensing and field-surveyed data: Implication for C-PFES implementation in Quang Ninh province, Vietnam. Regional Studies in Marine Science. 48:101985. DOI: 10.1016/j.rsma.2021.101985

[32]. Kaplan, G. & Avdan, U. (2017). Object-based water body extraction model using Sentinel-2 satellite imagery. European Journal of Remote Sensing. 50(1): 137-143.

[33]. Gupta, K., Mukhopadhyay, A., Giri, S., Chanda, A., Datta Majumdar, S., Samanta, S. & Hazra S. (2018). An Index for discrimination of mangroves from non-mangroves using LANDSAT 8 OLI imagery. MethodsX. DOI: 10.1016/j.mex.2018.09.011

[34]. Jamaluddin, I., Thaipisutikul T., Chen Y.N., Chuang C.H. & Hu C.L. (2021). MDPrePost-Net: A Spatial-Spectral-Temporal Fully Convolutional Network for Mapping of Mangrove Degradation Affected by Hurricane Irma 2017 Using Sentinel-2 Data. Remote Sens. 13: 5042. DOI: 10.3390/rs13245042

[35]. Congalton, R.G. (1991). A Review of Assessing the Accuracy of Classifications of Remotely Sensed Data. Remote Sens. Environ. 37: 35–46.

[36]. Congalton, R.G. & Green, K. (1999) Assessing the Accuracy of Remotely Sensed Data: Principles and Practices; Lewis Publisher: Boca Raton, FL, USA.

[37]. Rouse, J.W., Hass, R.H., Schell, J.A. & Deering D.W. (1974). Monitoring vegetation systems in the Great Plains with ERTS. 3rd ERTS Symposium, NASA SP351, Washington DC, 10-14 December 1973. 309-317.

[38]. Mokany, K., Raison, R.J. & Prokushkin, A.S. (2006). Critical analysis of root: shoot ratios in terrestrial biomes. Global change biology. 12(1): 84-96.

[39]. Komiyama, Akira, Ong, Jin, Poungparn & Sasitorn (2008). Allometry, biomass, and productivity of mangrove forests: A review. Aquatic Botany. 89: 128-137. DOI: 10.1016/j.aquabot.2007.12.006

[40]. Cannell, M. (1999). Growing trees to sequester carbon in the UK: answers to some common questions. Forestry 72(3): 237-247.

[41]. Petersson, H., Holm, S., Ståhl G., Alger, D., Fridman, J., Lehtonen, A., Lundström, A. & Mäkipää, R. (2012). Individual tree biomass equations or biomass expansion factors for assessment of carbon stock changes in living biomass–A comparative study. Forest Ecology and Management. 270: 78-84.

[42]. Weiguo., Fu. & Yanyou, Wu. (2011). Estimation of aboveground biomass of different mangrove trees based on canopy diameter and tree height, Procedia Environmental Sciences. 10C: 2189-2194. ISSN 1878-0296. DOI: 10.1016/j.proenv.2011.09.343

[43]. Simpson, W.T. (1996). Method to estimate drykiln schedules and species groupings: Tropical and temperate hardwoods. RPL-RP-548. USDA Forest Service, Forest Products Laboratory, Madison, USA.