

Determining thresholds of vegetation indexes for mangrove cover mapping and change detection in Ha Tinh province

Chu Quỳnh Anh¹, Nguyen Hai Hoa^{1*}, Nguyen Ngoc Linh¹, Vu Van Truong¹, Nguyen Thi Hai Van²

¹Vietnam National University of Forestry

²F-School, Vietnam National University of Forestry

Xác định ngưỡng các chỉ số thực vật xây dựng bản đồ lớp phủ rừng ngập mặn và phát hiện thay đổi tại tỉnh Hà Tĩnh

Chu Quỳnh Anh¹, Nguyễn Hải Hòa^{1*}, Nguyễn Ngọc Linh¹, Vũ Văn Trường¹, Nguyễn Thị Hải Vân²

¹Trường Đại học Lâm nghiệp

²Trường Phổ thông Trung học Lâm Nghiệp (F-School), Trường Đại học Lâm nghiệp

*Corresponding author: hoan@vnuf.edu.vn

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ABSTRACT

Accurate monitoring of mangrove ecosystems is crucial for coastal zone management, yet region-specific methodologies remain underdeveloped for many vulnerable coastlines. This study developed optimized vegetation index thresholds from Sentinel-2 imagery for accurate mapping of mangrove cover changes in Ha Tinh province, Vietnam. Eight vegetation indices were calculated and evaluated using field survey data combined with remote sensing data. Through threshold analysis and accuracy assessment, the Combined Mangrove Recognition Index (CMRI ≥ 0.15) was identified as the most effective index for mangrove detection in the study area. The mangrove classification for 2025 achieved high accuracy (Overall Accuracy = 95%, Kappa = 0.91). Change detection analysis between 2020 and 2025 revealed a net increase in mangrove area by 27.86% (from 687.97 ha to 879.65 ha). This expansion is attributed to active government-led restoration programs and supporting initiatives. However, persistent threats from illegal logging, aquaculture expansion, and climate-induced hazards highlight ongoing challenges. This study proposes a practical and transferable remote sensing approach to mangrove monitoring. It underscores the need to integrate robust spectral thresholding with effective policy enforcement to ensure long-term mangrove conservation in the vulnerable coastal areas of central Vietnam.

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TÓM TẮT

Giám sát chính xác hệ sinh thái rừng ngập mặn là rất quan trọng đối với công tác quản lý vùng ven biển, tuy nhiên, các phương pháp luận đặc thù cho từng khu vực vẫn chưa được phát triển đầy đủ đối với nhiều đường bờ biển dễ bị tổn thương. Nghiên cứu này đã phát triển các ngưỡng chỉ số thực vật tối ưu từ ảnh vệ tinh Sentinel-2 để lập bản đồ chính xác sự thay đổi độ che phủ rừng ngập mặn tại tỉnh Hà Tĩnh, Việt Nam. Tám chỉ số thực vật đã được tính toán và đánh giá bằng cách sử dụng dữ liệu khảo sát thực địa kết hợp với dữ liệu viễn thám. Thông qua phân tích ngưỡng và đánh giá độ chính xác, chỉ số Nhận dạng Rừng ngập mặn Tổng hợp (CMRI $\geq 0,15$) được xác định là chỉ số hiệu quả nhất để phát hiện rừng ngập mặn trong khu vực nghiên cứu. Phân loại rừng ngập mặn năm 2025 đạt độ chính xác cao (độ chính xác tổng thể = 95%, Kappa = 0,91). Phân tích phát hiện sự thay đổi giữa năm 2020 và 2025 cho thấy diện tích rừng ngập mặn tăng ròng 27,86% (từ 687,97 ha lên 879,65 ha). Sự mở rộng này là do các chương trình phục hồi do chính phủ chủ trì và các sáng kiến hỗ trợ tích cực. Tuy nhiên, các mối đe dọa dai dẳng từ nạn khai thác gỗ trái phép, mở rộng nuôi trồng thủy sản và các hiểm họa do biến đổi khí hậu gây ra đang làm nổi bật những thách thức hiện hữu. Nghiên cứu này đề xuất một phương pháp viễn thám thực tiễn và có thể ứng dụng để giám sát rừng ngập mặn. Nghiên cứu nhấn mạnh sự cần thiết phải tích hợp việc phân ngưỡng quang phổ mạnh mẽ với việc thực thi chính sách hiệu quả để đảm bảo bảo tồn rừng ngập mặn lâu dài tại các khu vực ven biển dễ bị tổn thương ở miền Trung Việt Nam.

Từ khóa:

Chỉ số thực vật, Hà Tĩnh, lập bản đồ rừng ngập mặn, quản lý ven biển, phân tích ngưỡng, Sentinel-2.

1. INTRODUCTION

Mangroves are one of the most biologically productive and critically important ecosystems, commonly found in tropical and subtropical coastal areas [1]. These forests provide many valuable ecosystem services, such as protecting coastlines from storms and erosion, conserving

biodiversity by serving as breeding and nursery grounds for many aquatic species, maintaining water quality, and especially contributing to climate change mitigation through their enormous capacity to absorb and store carbon, often referred to as “blue carbon” [2, 3]. Despite their importance, the global mangrove

area has been severely reduced over the past few decades. It is estimated that the world has lost more than 30% of its mangrove forests since the 1980s, mainly due to human pressures such as the expansion of aquaculture (especially shrimp farming), urbanization, land conversion for agriculture and pollution, combined with the increasing impacts of climate change such as sea level rise and extreme weather events [4, 5].

Vietnam, with a coastline of more than 3,260 km, has extensive mangrove forests, which are important for the livelihoods of coastal communities and national environmental security. The area of mangrove forests in Vietnam has declined significantly over the past century. It was estimated that the mangrove area was 408,500 ha in 1943, but was destroyed by about 40% as a result of the Second Indochina War [6]. By 2020, this area had decreased to about 155,000 ha nationwide, of which Ha Tinh province contributed 687.97 ha [7]. This degradation highlights the long-term pressure on Vietnam's coastal ecosystems. This loss is particularly severe in the central coastal provinces, where the ecosystem is already fragmented and vulnerable. Ha Tinh province, located in the North Central region, is a typical example. The mangrove forests here, concentrated mainly in river mouths in Nghi Xuan, Loc Ha, Thach Ha and Ky Anh, are facing serious threats from both natural disasters (storms, floods, coastal erosion) and human economic activities (conversion to aquaculture ponds, infrastructure development, sand mining).

Remote sensing technology has significantly enhanced the monitoring and management of natural resources, offering a powerful, cost-effective, and repeatable tool for mapping and assessing changes in mangrove ecosystems over large and often inaccessible areas [8]. The advent of medium to high resolution satellite sensors, such as the European Space Agency (ESA) Sentinel-2 (MSI) and PlanetScope, has marked a significant leap forward. Sentinel-2 provides imagery with high spatial resolution (10-20 m for most bands), high data collection frequency and rich spectral information (13 bands), including important red-edge bands, making it particularly suitable for vegetation studies [9]. Its open and free data policy further increases its applicability for studies in

developing countries.

A popular and effective method for remotely sensed mangrove mapping is the use of Vegetation Indices (VI). These indices, calculated by combining different spectral bands, help to highlight the spectral signature of vegetation and assist in distinguishing mangroves from other land cover types (water, bare land, urban areas, and other vegetation types). Indices such as the Normalized Difference Vegetation Index (NDVI) are widely used to assess vegetation greenness and density, while the Two-Band Enhanced Vegetation Index (EVI2) a modified version designed to minimize the effects of canopy background and atmospheric aerosols – provides improved accuracy in densely vegetated areas [10, 11]. The Normalized Difference Water Index (NDWI) is also commonly used to separate water bodies. Furthermore, indices specifically designed for mangrove identification, such as the Combined Mangrove Recognition Index (CMRI), have also been developed and shown to be highly accurate in many areas [12].

However, the effectiveness of these indices depends largely on determining the optimal thresholds to best separate mangrove from non-mangrove pixels in a specific geographical context. These thresholds can vary considerably due to differences in species composition, canopy structure, tidal conditions, and surrounding landscapes. Although there have been several successful studies in the Mekong Delta (Ca Mau, Kien Giang) and the North (Quang Ninh) [12, 13], there remains a significant research gap for the North Central region, especially Ha Tinh province. There has been a lack of systematic, comprehensive studies that have assessed a range of vegetation indices, determined their optimal classification thresholds, and applied them to quantify changes in mangrove area and their drivers in this vulnerable region.

This study aims to fill this important gap. The objective is to determine the optimal thresholds of key vegetation indices derived from Sentinel-2 imagery to accurately map and detect changes in mangrove area in Ha Tinh province during the period from 2020 to 2025. The results of the study will provide a solid scientific basis for local authorities and policymakers in implementing targeted conservation, restoration, and

sustainable management strategies for these invaluable coastal ecosystems.

2. RESEARCH METHODS

2.1. Study site

Ha Tinh is a province in the North Central region of Vietnam, with coordinates from 17°54' to 18°37' North latitude and 105°15' to 106°30' East longitude. With a coastline of about 137 km, the diverse terrain includes estuaries, lagoons, and sandbanks, creating favorable conditions for the development of mangrove forests [14] (Fig. 1). The climate is

tropical monsoon, with a rainy season from September to December and a dry season from April to August. The province is regularly affected by storms and floods, causing coastal erosion and environmental degradation.

Mangrove forests in Ha Tinh are not distributed continuously, but are mainly concentrated in estuary areas of Nghi Xuan, Loc Ha, Thach Ha, and Ky Anh. The main mangrove species include *Sonneratia caseolaris*, *Kandelia obovata*, and *Rhizophora stylosa*, which are well adapted to local salinity and hydrological conditions.

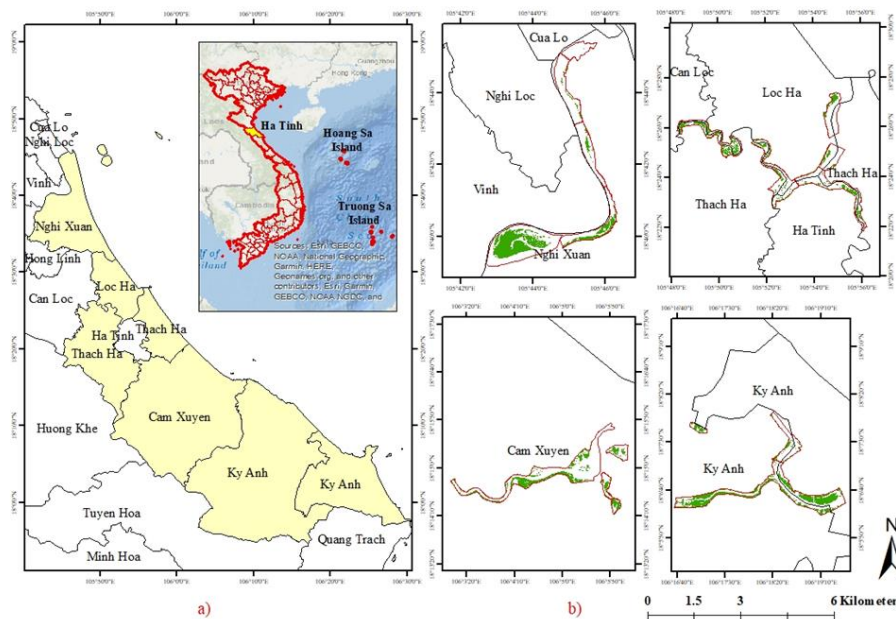


Fig. 1. Study site

(a) Geographical location of Ha Tinh province in Vietnam;
(b) Mangrove forests distributed along the coast of Ha Tinh province.

Despite their important roles, mangrove forests in Ha Tinh are under many pressures from both nature and humans. The expansion of aquaculture, agricultural development and infrastructure construction has reduced forest areas, while natural processes, such as erosion and sedimentation, have also caused serious impacts. Therefore, Ha Tinh is an important and typical area for studying mangrove changes in Central Vietnam.

2.2. Methods

This study employed an integrated methodology combining remote sensing analysis, geographic information systems (GIS), and field validation to map mangrove cover and detect changes from 2020 to 2025.

Data collection and pre-processing

Remote Sensing Data: This study used Sentinel-2 satellite images recorded in 2025. The Sentinel-2 satellite has a multispectral

imager with 13 spectral bands, which is very useful for observing land and vegetation. The bands with 10 m spatial resolution in the visible and near infrared regions were used to study mangrove canopy density. The images were downloaded from the official Copernicus Data Space Ecosystem website at: <https://browser.dataspace.copernicus.eu/>. The study employed selected images from the dry season (March to August) with less than 10% cloud cover to ensure good quality for analysis.

Field Data: A field survey was conducted in June 2025. Survey lines were set up 150 m apart from each other (Fig. 2). On each survey line, two circular sample plots (with a radius of 7 m) were established, also spaced 150 m apart. A Garmin 76cs GPS device (with an accuracy of ± 3 m) was used to record the coordinates of the center point of each sample

plot. The survey lines ran from the shore toward the sea. For each plot, we measured important mangrove forest characteristics like: tree height (H), canopy diameter (CD),

diameter at breast height (DBH, measured at 1.3 m above the ground), diameter at 30 cm above the root system (D30, mainly for Rhizophora species), and tree density (N).

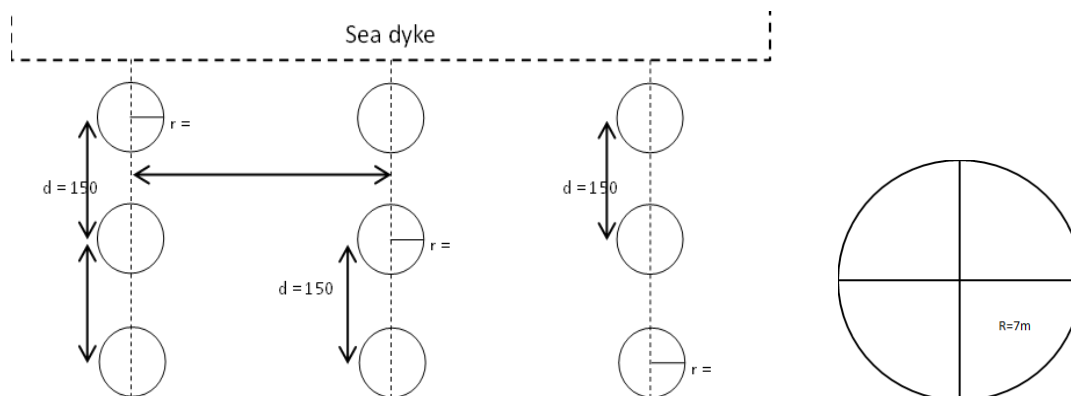


Fig. 2. Layout of circular standard plots (OTC) for surveying mangrove forest structure

Ancillary Data: The study also collected other supporting data for our analysis, including administrative boundary maps, land use/land cover maps, and statistics on aquaculture expansion.

Calculation of vegetation indices

A total of eight vegetation indices (VIs) were selected for calculation in this study

based on the literature review on remote sensing of mangrove forests [12]. These indices, along with their formulas and ecological significance, are detailed in Table 1. The indices were calculated for both 2020 and 2025 images using the Raster Calculator tool in ArcGIS 10.4 by applying the respective formulas for each index.

Table 1. Vegetation indices applied for mangrove mapping in this study

No	Index	Formula	Description	Sources
1	NDVI (Normalized Difference Vegetation Index)	$\frac{NIR - RED}{NIR + RED}$	Vegetation vigor and density.	[15]
2	NDWI (Normalized Difference Water Index)	$\frac{GREEN - NIR}{GREEN + NIR}$	Water detection and monitoring.	[16]
3	SAVI (Soil Adjusted Vegetation Index)	$\frac{(NIR - RED)}{(NIR + RED + L)} \times (1 + L)$ L = 0.5	Vegetation index adjusted for soil background effects.	[17]
4	EVI2 (Two-Band Enhanced Vegetation Index)	$2.5 \times \frac{(NIR - RED)}{(NIR + 2.4 \times RED + 1)}$	Enhanced vegetation index for dense vegetation.	[10]
5	CMRI (Combined Mangrove Recognition Index)	NDVI - NDWI	Combined index for mangrove detection	[18]
6	OSAVI (Optimized SAVI)	$\frac{(NIR - RED)}{(NIR + RED + 0.16)}$	Optimized soil-adjusted vegetation index.	[19]
7	GNDVI (Green NDVI)	$\frac{(NIR - GREEN)}{(NIR + GREEN)}$	Chlorophyll content and vegetation health.	[20]
8	SR (Simple Ratio)	$\frac{NIR}{RED}$	Simple vegetation index.	[21]

Accuracy Assessments

The accuracy was assessed with 400 randomly selected points, including 250 points on the mangrove, 80 points on non-mangrove, and 70 points on water. These points were analyzed visually in high-resolution images

from Sentinel-2, then exported to Google Earth images for verification as ground truth. Overall accuracy (OA), User Accuracy (UA), Producer Accuracy (PA), and kappa coefficient index (KC) were calculated as formulas from Congalton’s equation [22, 23].

$$OA = \frac{\text{Total number of Correctly Classified Pixels (Diagonal)}}{\text{Total Number of Reference Pixels (TS} \times \text{TCS)} - \sum(\text{Column Total} \times \text{Row Total})} \times 100$$

$$KC = \frac{\text{Number of Correctly Classified Pixels in each category}}{\text{TS}^2 - \sum(\text{Column Total} \times \text{Row Total})} \times 100$$

$$PA = \frac{\text{Number of Correctly Classified Pixels in that category (The Column Total)}}{\text{Total Number of Reference Pixels in that category (The Column Total)}} \times 100$$

$$UA = \frac{\text{Number of Correctly Classified Pixels in each category}}{\text{Total Number of Classified Pixels in that category (The Row Total)}} \times 100$$

Determination of thresholds for mangrove cover

The classification thresholds for the vegetation indices were determined by comparing spectral values with field survey data. Specifically, pixel values of the indices were extracted at the locations of the field survey plots. The optimal threshold for each index was identified as the value that yielded the highest overall accuracy when compared against the reference data from the field plots, using the Confusion Matrix function in ArcGIS 10.4 for validation. This process was carried out iteratively using the Reclassify tool until the

classification result matched the actual mangrove boundaries observed in the field and on high-resolution Planet Scope imagery.

3. RESULTS AND DISCUSSION

3.1. Mangrove cover mapping

Accuracy assessments

The accuracy test results from 400 randomly sampled points showed that the mangrove forest classification map was highly reliable. The overall accuracy (OA) reached 95%, far exceeding the basic requirement for studies of this type (Table 2).

Table 2. Confusion matrix and accuracy assessment for the 2025 mangrove cover classification

		Non-	Water	Total	User's Accuracy (%)
Mangrove	250	0	0	250	97
Non- Mangrove	7	60	13	80	100
Water	0	0	70	70	84
Total	257	60	83	400	
Producer's Accuracy (%)	100	75	100	Overall Accuracy = 95% Kappa = 0.91	

The mangrove forest layer gave the best results: 100% of forest points in the field were correctly classified (PA = 100%), and 97% of points classified as forest on the map were actually forest (UA = 97%). The results for the water surface layer were somewhat similar, with PA reaching 100% but UA reaching only 84% due to some shallow water areas being confused with other layers. The non-mangrove class had UA reaching 100% but PA reaching only 75%, mainly due to confusion with

shallow water and sparse forest areas. The Kappa coefficient of 0.91 showed a very high agreement between the map and reality, proving that the classification method had good reliability. Although there is still some confusion in the boundary areas between layers, this result still confirms the feasibility of using Sentinel-2 images to monitor mangrove forests in the study area.

Thresholds for detecting mangrove areas

Table 3. Thresholds defined for mangrove cover using vegetation indices

No.	Indices	Thresholds for mangrove mapping
1	NDVI	≥ 0.10
2	NDWI	≤ 0.20
3	SAVI	≥ 0.15
4	OSAVI	≥ 0.12
5	GNDVI	≥ 0.08
6	SR	≥ 1.20
7	EVI2	≥ 0.10
8	CMRI	≥ 0.15

Determining appropriate spectral thresholds is crucial for accurate mangrove classification. The analysis results showed that the optimal thresholds were all relatively low (NDVI ≥ 0.10 , EVI2 ≥ 0.10 , SAVI ≥ 0.15) (Table 3). This reflects the typical physiological characteristics of mangrove vegetation in saline environments, where canopy greenness is generally lower than that of terrestrial forests. The NDWI threshold (≤ 0.20) indicates a strong water absorption capacity of the vegetation and saturated soil.

Among the evaluated indices, CMRI (≥ 0.15) was proven to be the most effective due to its combination of several spectral characteristics, including vegetation greenness, water stress, and interactions between the forest canopy and soil moisture. The difference in this threshold compared to other forest types confirms the need to establish specific parameters for each study area.

Mangrove extent mapping

Mangrove forests distribution of Ha Tinh Province in 2025

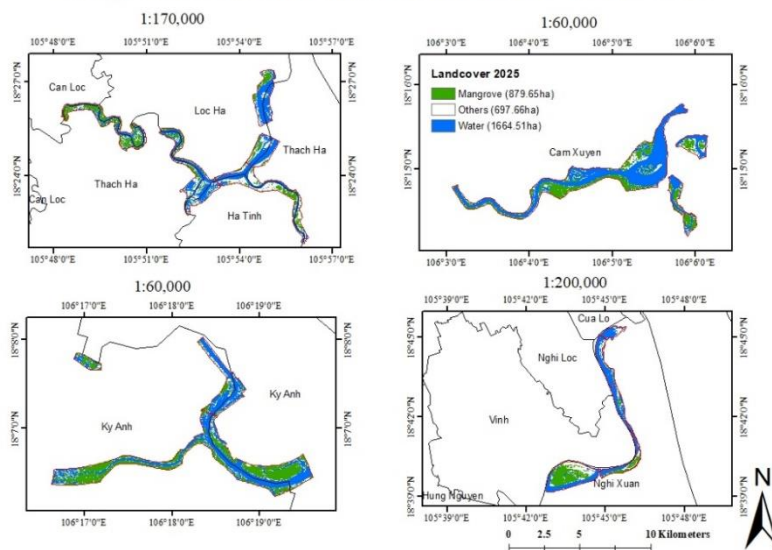


Fig. 3. Mangrove cover in Ha Tinh province in 2025 by CMRI threshold

Based on Sentinel-2 satellite images, the study used CMRI (≥ 0.15) and NDVI (≥ 0.10) thresholds to determine the mangrove area in Ha Tinh in 2025 to reach 879.65 ha, which showed an increase of 27.86% compared to 2020 [7]. This result was achieved thanks to mangrove planting and restoration projects implemented by the provincial Department of Agriculture and Environment, in coordination with the Vietnam Forest Protection and Development Fund, REDD+, and organizations

such as the Red Cross, the Center for Nature Conservation and Development, and the World Bank. The main activities include additional planting, fencing, and improving community management capacity. However, some mangrove areas, especially near aquaculture ponds, are still under pressure from illegal logging and land use conversion. Extreme weather events such as storms, floods and saltwater intrusion also continue to threaten the stability of this ecosystem.

3.2. Change detection of mangrove extent during 2020 - 2025

Changes in mangrove extents

During the period 2020-2025, the area of mangrove forests in Ha Tinh has increased significantly, from approximately 687.97 hectares in 2020 to an estimated 879.65 ha in 2025, an increase of about 27.86% (Fig. 3). This upward trend is consistent with the province's genuine restoration efforts in the early years of the period. In 2020, Ha Tinh planted nearly 66 hectares of new mangrove forests along coastal areas, contributing to an increase in overall forest cover right from the start of the period [24]. By 2022, the province continued to implement activities to plant an additional 44.09 hectares along river mouths and coastal areas to strengthen coastal protection [25]. These reforestation projects, combined with natural regeneration, clearly explain why the area of mangrove forests has increased over the past five years, especially when compared to previous periods when the area declined due to human impact and environmental pressure.

Drivers of changes in mangrove extents

The combination of proactive restoration policies and favorable coastal conditions was the main driver of mangrove forest expansion in Ha Tinh from 2020 to 2025. Throughout this period, the province implemented a series of large-scale planting and restoration programs along coastal and estuarine areas, laying a solid foundation for new restored areas to develop and expand over time [24, 25]. These efforts were supported by improved coastal management, including tighter control of aquaculture expansion and protection of degraded mudflats, allowing planted and naturally regenerated mangrove forests to develop more effectively [7]. These factors formed the main driving force behind the steady increase in mangrove forest area, complementing the gains already achieved from restoration activities carried out in previous years. However, mapping results show that mangrove forests remain under considerable pressure. Illegal logging and conversion of land for aquaculture remain common, especially near fish ponds. In addition, climate change, such as coastal erosion and more severe storms, also threatens the stability and regeneration of forests [26]. Therefore, the future of these mangrove forests will depend on the sustainable effectiveness of conservation

efforts against the combined pressures from humans and climate.

Implications for mangrove sustainable management

This study offers key management implications for sustainable mangrove forest management in Ha Tinh. The validation of the CMRI threshold (≥ 0.15) provides a Sentinel-2 image-based monitoring tool that is both cost-effective and practical. The results also show that proactive restoration programmes are key to expanding forest area. However, persistent threats from illegal logging and law conversion to aquaculture require enhanced law enforcement and stricter spatial planning. Furthermore, mangrove protection needs to be integrated into climate change adaptation strategies to mitigate risks from coastal erosion and natural disasters. Several practical lessons can be drawn from this. Low-cost remote sensing technology, with specialised indices such as CMRI, is indeed a powerful tool, opening up the possibility of proactive monitoring for localities [12]. Investment in forest restoration is necessary and has shown initial successes [24, 25], but without accompanying protection measures, these achievements are easily wiped out by immediate economic pressures a reality that has been observed in many places [5]. In the end, an integrated, adaptable strategy that incorporates technological monitoring, focused restoration, stringent protection regulations, and long-term climate change adaptation plans is required for efficient management [26]. Therefore, a successful management framework needs to be built on a combination of these four elements.

4. CONCLUSION

This research successfully developed a practical framework for mapping mangrove ecosystems in Central Vietnam by determining robust spectral thresholds for Sentinel-2-derived vegetation indices. The Combined Mangrove Recognition Index ($\text{CMRI} \geq 0.15$) is identified as the most reliable indicator, enabling accurate extraction of mangrove areas with an overall accuracy of 95%. Application of this methodology revealed a promising 27.86% expansion of mangrove cover in Ha Tinh province between 2020 and 2025, reflecting the effectiveness of recent conservation initiatives. However, spatial analysis concurrently highlighted persistent vulnerability to localised threats, including illegal exploitation,

aquaculture encroachment, and climate stressors. The validated thresholds provide coastal managers with an efficient monitoring tool, while the findings emphasise the necessity of complementing remote sensing with targeted protection policies to ensure long-term mangrove sustainability in the region.

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