СТРУКТУРА, ФУНКЦИОНИРОВАНИЕ И ДИНАМИКА ЭКОСИСТЕМ

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CHANGES OF THE MANGROVE FOREST AREA IN THANH PHU DISTRICT, BEN TRE PROVINCE DURING 1990–2020 *

Phung Thai Duong[1], Pham Cam Nhung[2], Ngo Thi Ngoc Tu[3], Huynh Thi Sanh[4], Nguyen Quoc Hau[5], Nguyen Van Dung[6]

[1]Dong Thap University, province Dong Thap, Viet Nam,
[2]A. O. Kovalevsky Institute of Biology of the Southern Seas of RAS, Sevastopol, Russian Federation,
[3]My Hiep junior high school, province Dong Thap, Viet Nam,
[4]Tan Hoi Trung junior high school, province Dong Thap, Viet Nam,
[5]Mien Tay Construction University, province Vinh Long, Viet Nam,
[6]People's Police University, Ho Chi Minh City, Viet Nam,
e-mail: ptduong@dthu.edu.vn

Abstract: The complex ecosystem of mangrove forests holds great ecological and economic significance. Unfortunately, in the last half-century, numerous mangrove forests have been lost due to high population growth, rapid urbanization, aquaculture expansion, and other human activities. Asia, in particular, has experienced the most significant decline of mangrove forests, Including Vietnam. However, recent studies indicate that mangroves in Vietnam are either expanding or fragmenting. The objective of the study is to evaluate changes in the area of coastal mangroves in Thanh Phu district, Ben Tre province in the period 1990–2020 by applying remote sensing technology. To plan for management and to improve the role of mangroves in providing ecosystem services and resources, local livelihoods, and global benefits. Based on the research and analysis results, the authors have established a map of changes in mangrove area in Thanh Phu district, Ben Tre province. In general, the area of mangrove forests in Thanh Phu distric has decreased over 30 years. Despite the fact that after 2000 there has been an increase in the area of mangrove forests in the study area. The spatial transformation of coastal mangroves in Thanh Phu district, Ben Tre province over a span of 30 years and the factors responsible for their reduction are investigated in the study. The research also reveals the recovery process of mangroves through various stages, offering valuable insights to government for proposing solutions to regenerate and enhance mangrove ecosystems. This could ultimately aid in the restoration and enrichment of varied coastal ecosystems.

Keywords: mangrove, forest area, remote sensing, Landsat, Vietnam.

Introduction

Vietnam has a rich coastal mangrove vegetation, stretching from Quang Ninh to Ha Tien. However, its area of mangroves has been significantly diminished. Mangrove forests are a complex ecosystem of ecological and economic importance [Huan, Lan, 2019]. They are able to prevent the washing away of soil and the destruction of coastlines by the ebb and flow. The root systems of mangrove forests delay rainfall runoff and strengthen the soil, thereby reducing soil erosion. Mangrove forests weaken the destructive effects of hurricanes and tsunamis, constant erosion. It has been established that such forests protect the soil from natural disasters more effectively than artificial structures [Фан и др., 2021].

Mangrove ecosystems can act as highly efficient carbon sinks in tropical climates [Donato et al., 2011] because they can sequester carbon in both aboveground biomass [Pham et al., 2018] and below-ground biomass [Pham, Yoshino, 2017; Pham, Yoshino, Bui, 2017], as well as in sediments [Alongi, 2012;

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Kauffman et al., 2014]. Despite such benefits, many mangrove forests have been lost in the past 50 years worldwide due to high population growth, rapid urbanization, aquaculture expansion and the impact of other human activities [Alongi, 2002; Chen et al., 2017; Giri et al., 2015]. Among the regions of the world, Asia has suffered the greatest loss (1.9 million hectares) of mangroves [The world's mangroves … , 2007], with more than 100 000 ha being lost from 2000 to 2012 [Richards, Friess, 2015].

Mangroves in Vietnam have either been expanding or fragmenting, according to several recent research papers. Hauser et al. (2017) conducted a study of mangroves in Ca Mau province (Ngoc Hien region) during 2004–2013, and they discovered that the mangrove area was decreased between 2004 and 2009 before stopping in 2009 [Hauser et al., 2017]. An increase in mangrove area due to afforestation was also observed in the Can Gio region from 2000 to 2011 [Pham, Brabyn, 2017]. Pham and Brabin (2017) found that this increase in mangrove area was due to rhizophora colonization, while changes in aboveground biomass caused by avicennia marina and mangrove apples were not consistent in terms of space surface.

Landsat remote sensing imagery provides information about the Earth's surface with its broad coverage, objective and cyclical information. Therefore, this photographic material is widely used in many fields, including monitoring of forest cover changes. Several studies have evaluated changes in forest areas using satellite images, and their conclusions are reasonably accurate and objective [Nardin, Woodcock, Fagherazzi, 2016; Van et al., 2015; Manh et al., 2015; Son et al., 2015; Pham, Yoshino, 2015; Nguyen et al., 2013; Pham et al., 2013; Thu, Populus, 2007; Seto, Fragkias, 2007; Béland et al., 2006; Binh et al., 2005; Thu, Demaine, 1996; Phùng, Tôn, Đánh giá biến … Tiền Giang … , 2021; Phùng, Tôn, Đánh giá biến … Cà Mau … , 2021; Tôn, Phùng, 2020; Quyen, Brunner, 2011; Hauser et al., 2017; Pham, Brabyn, 2017; Vo, Kuenzer, Oppelt, 2015; Kuenzer, Tuan, 2013]. Ton and Phung (2020) used Landsat satellite images and GIS technology to assess changes in mangrove area in Bac Lieu province through the periods 1988–1998, 1998–2013, 2013–2018 and 1988–2018 [Phùng, Tôn, 2020]. Tran and Vien Ngoc Nam (2017) used Landsat remote sensing images, calculated NDVI, RVI, DVI, LAI indexes combined with natural color combinations to conduct image classification over the years 2001, 2004, 2007, 2010, 2013 and 2016. Then they analyzed the formation process of the alluvial flat Con Ngang and mangroves from 2001 to 2016 [Trần, Viên, 2017]. Nguyen and Nguyen (2017) successfully created maps of the state of mangrove areas in 2001, 2008 and 2015 in two buffer zone communes of Xuan Son National Park, Phu Tho province. Based on the results of forest land area, they built maps of changes in forest land area in the period 2001–2008 and 2008–2015 [Mai, Nguyen, 2017].

Stemming from the above facts, using multi-temporal Landsat remote sensing images and GIS technology in assessing changes in coastal mangrove area in Thanh Phu district, Ben Tre province in the period 1990–2020 is an urgent and scientifically meaningful work.

The objective of the study is to evaluate changes in the area of coastal mangroves in Thanh Phu district, Ben Tre province in the period 1990–2020 by applying remote sensing technology. To plan for management and to improve the role of mangroves in providing ecosystem services and resources, local livelihoods, and global benefits.

Materials and methods

Study area

Thanh Phu district is located in the south of Ben Tre province [Trần, 2009] (Figure 1). Thanh Phu's coastal communes, including An Nhon, Giao Thanh, Thanh Phong, and Thanh Hai, specialize in shrimp farming. Notably, there is a wetland nature reserve in Thanh Phu.

Thanh Phu Wetland Nature Reserve has a total natural area of 8825 ha, of which forest land is 4307.1 ha, accounting for 48 %; plantation forest is 3329.9 ha, accounting for 37 % of the total natural area; and natural forest reaches 977.2 ha, accounting for 11 %, with coordinates 9°57'40"–9°50'05"N and 106°32'58"–106°32'56"E [Phạm, 1997].

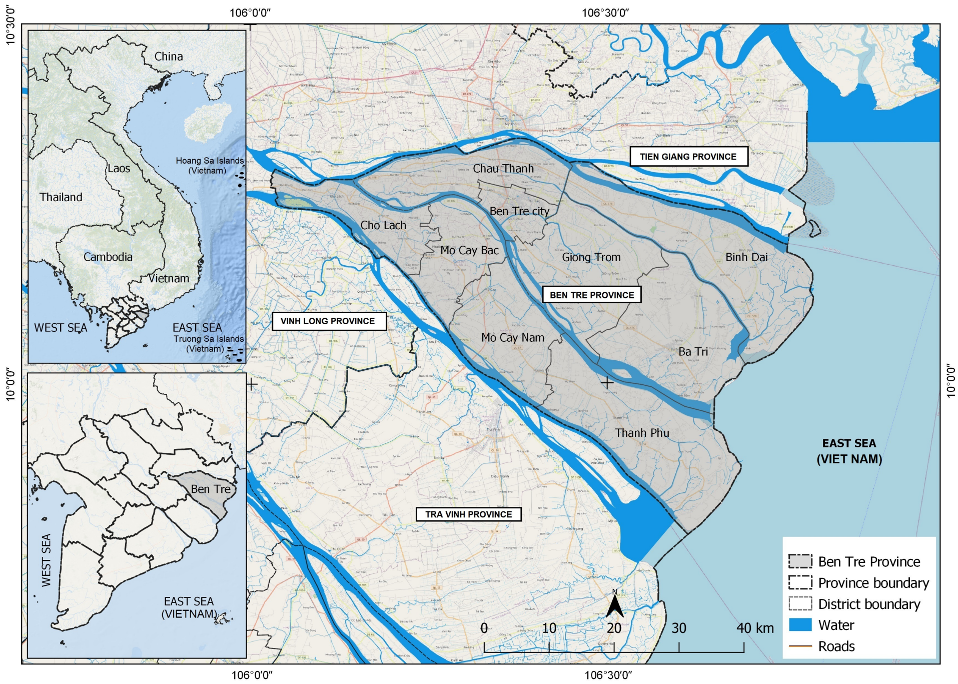


Fig. 1. Administrative map of Ben Tre province

Data sources

The study used Landsat image data for the years 1990, 2000, 2010 and 2020. The data was downloaded from the website of the United States Geological Survey [USGS] 30 m resolution for conventional channels and 15 m for panchromatic channels.

In the study, Landsat 5-TM and Landsat 8-OLI images are used because these are two generations of satellites with stable quality and provide data during the research period (1990–2020). Meanwhile, Landsat 7-ETM satellite has many limitations in data quality due to the error of the Scan Line Corrector (SLC) since 2003.

In order to minimize the influence of clouds, it is preferable to use photos taken in the dry season (November — April), the time when the photos were taken is suitable for the time to be evaluated, but due to the limited number of photos, using photos with not much difference in time is completely acceptable.

Image Processing and Classification: The first stage is pre-processing of the image which includes atmospheric and radiometric correction to remove noise from the image and improve its clarity. In the second stage, Maximum Likelihood classifier was used to classify the satellite image into different categories including forest, water bodies, and urban areas. The training samples were selected for each class using visual interpretation of the image. For the forest class, different forest types, such as mangroves, natural and plantation forests, were used for training. For urban areas and water bodies, characteristic features such as color, texture, and shape were used for training. Visual interpretation of the classified images was conducted to assess accuracy using field data collected from the study area.

Mapping and Analysis: Maps of forest status in 1990 and 2020 were established using the Maximum Likelihood Classifier (MCL) approximation method, which was applied to classify the Landsat images.The CMRI threshold calculation was based on the NDVI and NDWI indexes, combined with the MNDWI index to improve contrast between mangrove areas and other objects. The Kappa index (K) was used for accuracy assessment, and the reliability rating scale of Kappa index [McHugh, 2012] was used to evaluate the accuracy of the interpretation results relative to the field test results.

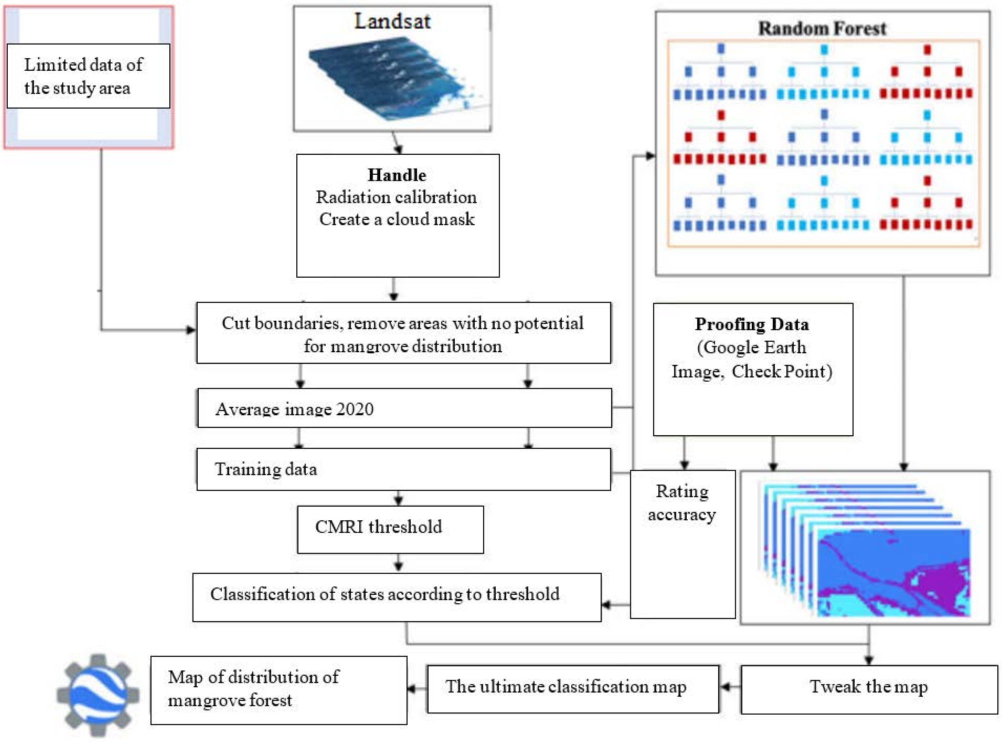
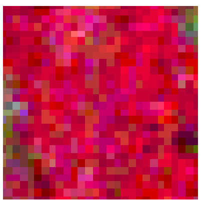
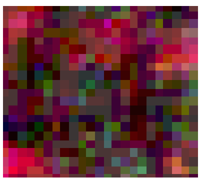
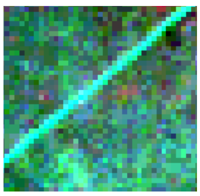
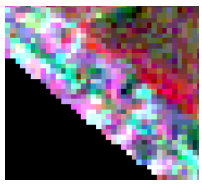


Fig. 2. Diagram of research implementation

In the study, the characteristics between forest and other subjects in the study area are distinguished based on the key to interpreting remote sensing images (Table 2) by the criteria of shape, size, color, structure, brightness.

Table 1

Keys to deciphering remote sensing images

The key to deciphering	**Forest (new plantation forest, thick forest)**		**Other subjects (Ex: water surface, construction site, agricultural land)**	
Object Pattern (N-R-G* Infrared Color Combination)				
Color, Brightness	Red, bright	Dark, Black	Green	Bright
Structure	Rough	Rough	Smooth	Rough
Distribution shape	Centralized distribution in clusters	Cluster distribution	Long and narrow (canal, river)	Plot format
Size/area	Large array	Large	Small	Small, adjacent

The training sample areas in Table 1 consist of pixel collections representing forest and non-forest objects. These sample areas are used for image analysis and interpretation on Google Earth Engine (GEE) to recognize and classify similar pixels and correct objects according to the trained sample area. The random split method is employed to reduce bias in the final classification results. The scores derived from this process are fed into GEE for automatic programming and calculation using both the vegetation indices method and the random forest method. During the referencing process, GEE carries out resampling based on the nearest neighbor algorithm (Nearest Neighbor — NN) by default to minimize errors.

At the same time, based on the different reflectance characteristics of the objects in the image through the vegetation difference index (NDVI), water difference (NDWI), mangrove identification index (MMRI) and combined forest identification index (CMRI). Indicators and typical values are shown in Table 2.

Table 2

Summary of indicators to determine the current status of forests in the study area

Index	Symbol	Formula	References
Normalized Difference Vegetation Index	NDVI	(NIR – RED) / (NIR + RED)	Tucker C. J. (1979)
Normalized Difference Water Index	NDWI	(GREEN – NIR) / (GREEN + NIR)	Gao B. C. (1996)
Modified. Normalized Difference Water Index	MNDWI	(GREEN – SWIR) / (GREEN + SWIR)	Xu H. Q. (2005)
Modular Mangrove Recognition Index	MMRI	(|MNDWI| – |NDVI|) / (|MNDWI| + |NDVI|)	Diniz C. et al. (2019)
(Combine Mangrove Recognition Index)	CMRI	NDVI – NDWI	Gupta K. et al. (2018)

The calculation of the CMRI threshold is based on the NDVI and NDWI indexes, but intermediate values are required to improve the contrast between mangrove areas and other objects, hence the need for the MNDWI index. The CMRI index is computed by subtracting NDWI from NDVI, but its range is not restricted to −1 to 1. Moreover, NDWI may not effectively eliminate signals from built-up land, causing extracted water features to be mixed with built-up land noise. Therefore, this study adopts MNDWI to extract the water features. The MMRI consists of a combination of two classic indices — vegetation and water indices — that enhance mangrove contrast.

The classification using the CMRI Index yields the Combined Mangrove Recognition Index, with NDVI referring to Normalized Difference Vegetation Index, IM to Mangrove Index, MMRI to Modular Mangrove Recognition Index, NIR to Near Infrared (Band 4 at L5 (Landsat 5) and L7, Band 5 at L8), SWIR to Shortwave Infrared (Band 5 at L5 and L7, Band 6 at L8), and Red to Red (Band 3 at L5 and L7, Band 4 at L8).

For statistical purposes and to assess the agreement between different data sources or when various algorithms are used, this study employs two indicators: the global accuracy (T) and the Kappa index (K). The Kappa index (K) is used to evaluate the accuracy of interpretation results compared to field test results. The reliability rating scale of Kappa index [McHugh, 2012] is used to evaluate the accuracy of the interpretation results relative to the field test results.

To calculate the K-factor, T represents the global precision (computed from the number of pixels in the diagonal cell in the matrix table divided by the total number of pixels in the sample area), while E is calculated similarly to T but the data are drawn from the product matrix of rows and columns of the classification error matrix.

With T and E, the K-coefficient can be calculated. With this coefficient, it is possible to publish the accuracy of the forest maps interpreted on the basis of the field-tested sample areas.

The way to determine the global precision (T) is shown in the following formula:

$$T = \frac{\sum_{\square j=1}^{K} Oii}{n} \cdot 100\ \%\ , \qquad (1)$$

in there $T = \sum_{\square j=1}^{K} Oii$ — total number of correctly classified pixels;

n — total number of pixels classified.

The way to determine the Kappa index is shown in the formula:

$$K = \frac{T - E}{1 - E}, \qquad (2)$$

in there K — Kappa index;

T — global precision given by error matrix;

E — a quantity that represents a predictable (expected) accurate classification, that is, E contributes to an estimate of the likelihood of an accurate classification in the actual classification process.

Table 3

Reliability rating scale of Kappa index [McHugh, 2012]

Value of Kappa	Level of Agreement
K < 0.2	None
0.2 < K < 0.4	Minimal
0.4 < K < 0.6	Weak
0.6 < K < 0.8	Moderate
0.8 < K < 1.0	Strong
K = 1	Almost Perfect

When the Kappa coefficient = 1, the classification accuracy is absolute. In addition to the Kappa coefficient, the classification accuracy is also evaluated based on the error matrix, or confusion matrix. This matrix compares on a one-to-one basis.

The error matrix obtained from comparing random points on Google Earth images with the classification results in 1990 and 2020 is used to perform reliability assessment. Google Earth is utilized to collect a representative sample area of objects that need to be interpreted in the past but cannot be accessed in the field. The study also employs data from the current status monitoring system of SERVIR-Mekong organization to verify and assess accuracy. The global accuracy and Kappa index aid in evaluating the results of the image classification and highlight confusion among objects during the classification process.

The results of object decoding yield discrete regions that are not connected to each other in the same object. Therefore, regions of the same object require connection or grouping to facilitate overlap and analysis of fluctuations in analytical algorithms. This makes the process of switching back and forth between the three main subjects that the study aims to track feasible. Before conducting statistics on the current status of mangroves, it is essential to group targets into three main categories to enable the statistics and analysis of changes. These categories are coastal mangroves, rivers/lakes/canals, and other subjects (including all remaining targets). The area of each group is then calculated at two levels (district and commune) for each year.

To analyze changes in coastal mangrove areas and determine the primary drivers of change in mangroves, overlapping maps of the mangrove state grouped by 10-year periods are created using the union method. This method aids in overlapping and comparing data to identify areas of change while keeping the general and individual regions intact for each year.

Determine changes in mangrove status by analyzing data attributes at two time points, for example: mangroves (1990) → mangroves (2000) unchanged mangroves; mangroves (1990) → other lands (2000) mangroves lost due to farming change; mangroves (1990) → water surface (2000) mangroves lost due to coastal erosion. Then proceed to calculate the area for each type of change for each 10-year period.

Research results

I. The state of coastal mangrove forest in Thanh Phu district, Ben Tre province in 1990.

Based on the results of image interpretation Landsat 4.5 TM, the authors have created a map of the current state of coastal mangroves in 1990 with a confidence level of 97.7 % and a Kappa coefficient of 0.96. The map of the current state of coastal mangrove forest in Thanh Phu district, Ben Tre province in 1990 is shown in Figure 3.

The results of Table 4 show that the total area of mangroves in Thanh Phu district, Ben Tre province in 1990 was 3061.112 ha, of which Thanh Hai commune was the highest with 1701.71 ha (55.6 %), followed by Thanh Phong commune with 944.12 ha (30.8 %), finally An Dien commune was the lowest distributed mainly on the narrow coastal strip with only 1.1 thousand ha (13 %).

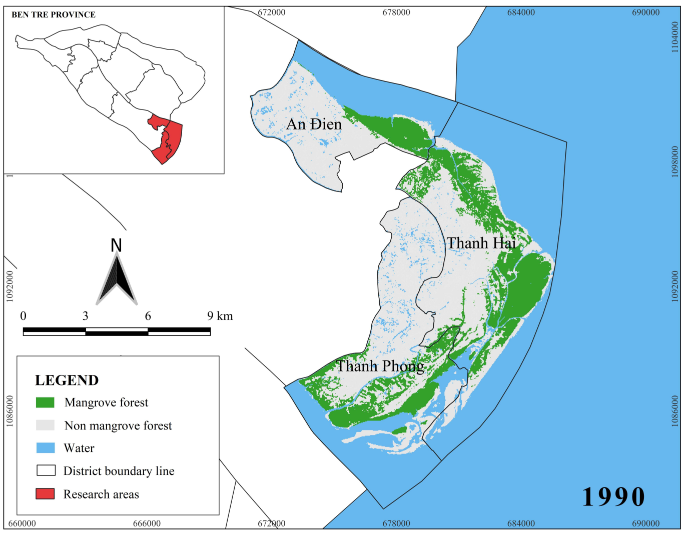


Fig. 3. Map of the current state of coastal mangrove forest in Thanh Phu district, Ben Tre province in 1990

Table 4

Mangrove area in Thanh Phu district, Ben Tre province in 1990

№	Distric	Commune	Acreage (ha)	Ratio (%)
1	Thanh Phu	An Dien	415.282	13.6
2		Thanh Hai	1701.710	55.6
3		Thanh Phong	944.120	30.8
		Total	**3061.112**	

II. The state of coastal mangrove forest in Thanh Phu district, Ben Tre province in 2000

Based on the results of image interpretation Landsat 7 TM, the authors have built a map of the current state of coastal mangroves in Thanh Phu district in 2000 with a confidence level of 96.7 % and a Kappa coefficient of 0.95. The map of the current state of coastal mangroves in Thanh Phu district, Ben Tre province in 2000 is shown in Figure 4.

The results of Table 5 and Figure 4 show that the total area of mangroves in Thanh Phu district, Ben Tre province in 2000 was 2162.969 ha, of which Thanh Hai commune was the highest with 1128.2 ha (52.2 %), followed by Thanh Phong commune with 661.899 ha (30.6 %), finally An Dien commune the lowest distributed mainly on the narrow coastal strip with only 372.87 ha (17.2 %).

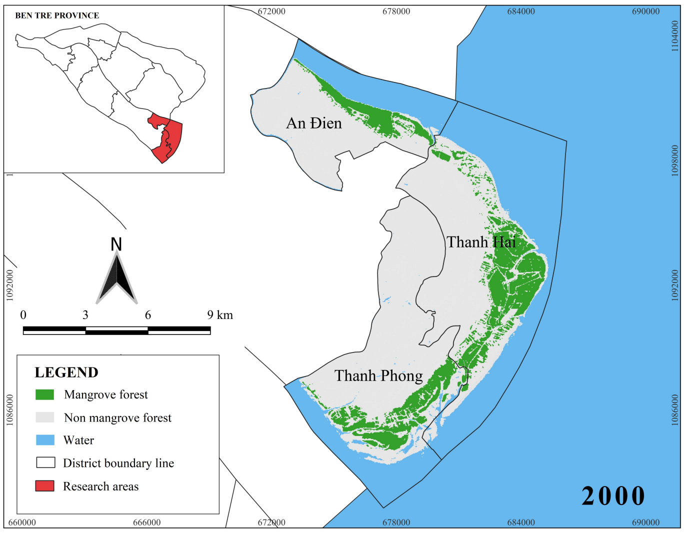


Fig. 4. Map of the current state of coastal mangroves in Thanh Phu district, Ben Tre province in 2000

Table 5

Mangrove area in Thanh Phu district, Ben Tre province in 2000

№	Distric	Commune	Acreage (ha)	Ratio (%)
1	Thanh Phu	An Dien	372.87	17.2
2		Thanh Hai	1128.2	52.2
3		Thanh Phong	661.899	30.6
		Total	**2162.969**	

III. The current state of coastal mangroves in Thanh Phu district, Ben Tre province in 2010

Based on the results of image interpretation Landsat 7 TM, the authors have established a map of the current status of coastal mangroves in 2010 with a confidence level of 96.7 % and a Kappa coefficient of 0.95. The map of the current state of coastal mangroves in Thanh Phu district, Ben Tre province in 2010 is shown in Figure 5.

The results of Table 6 show that the total area of mangroves in Thanh Phu district, Ben Tre province in 2010 was 2537.909 ha, of which Thanh Hai commune is the highest with 1087.5 ha (42.9 %), followed by Thanh Phong commune with 1033.42 ha (40.7 %), finally An Dien commune was the lowest distributed mainly on the narrow coastal strip with only 416.979 ha (16.4 %).

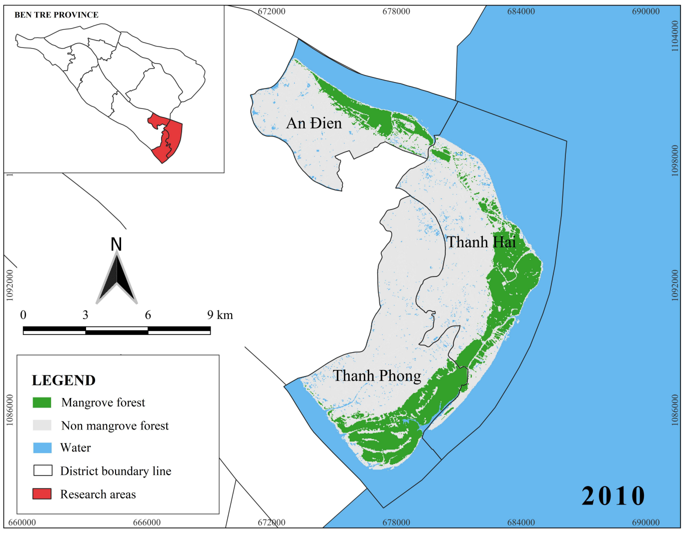


Fig. 5. Map of the current state of coastal mangroves in Thanh Phu district, Ben Tre province in 2010

Table 6

Mangrove forest area in Thanh Phu district, Ben Tre province in 2010

№	Distric	Commune	Acreage (ha)	Ratio (%)
1	Thanh Phu	An Dien	416.979	16.4
2		Thanh Hai	1087.51	42.9
3		Thanh Phong	1033.42	40.7
		Total	**2537.909**	

IV. The state of coastal mangroves in Thanh Phu district, Ben Tre province in 2020

Based on the results of image interpretation Landsat 8 TM, the authors have established a map of the current state of coastal mangroves in 2020 with a confidence level of 95.3 % and a Kappa coefficient of 0.93. The map of the current state of coastal mangroves in Thanh Phu district, Ben Tre province in 2020 is shown in Figure 6.

Results of Table 7 show that mangrove area in Thanh Phu district, Ben Tre province in 2020 was 2420 ha, of which Thanh Phong commune was the highest with 1050.4 ha (43.4 %), followed by Thanh Hai commune with 966.676 ha (39.95 %), and finally An Dien commune, the lowest distributed mainly on the narrow coastal strip of only 402.924 ha (16.65 %).

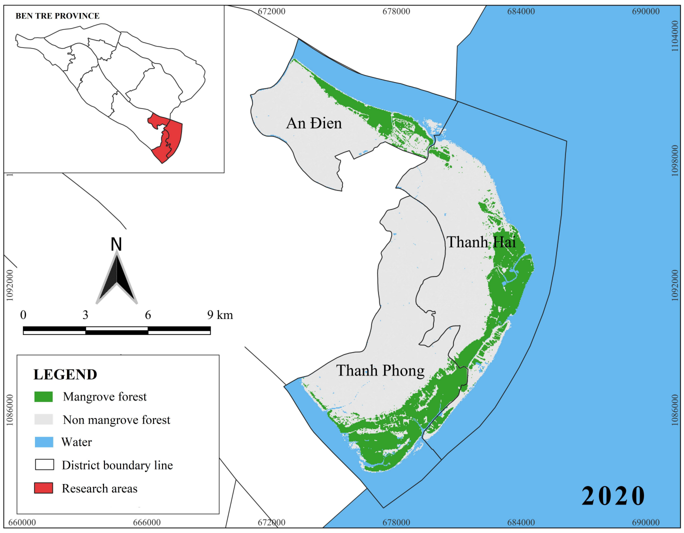


Fig. 6. Map of the current state of coastal mangroves in Thanh Phu district, Ben Tre province in 2020

Table 7

Mangrove area in Thanh Phu district, Ben Tre province in 2020

№	Distric	Commune	Acreage (ha)	Ratio (%)
1	Thanh Phu	An Dien	402.924	16.65
2		Thanh Hai	966.676	39.95
3		Thanh Phong	1050.4	43.40
		Total	**2420**	

V. Period 1990–2000

This is a period with many changes in the mangrove area of Thanh Phu district. There have been 898.143 ha of mangroves degraded, mainly in Thanh Hai commune (573.71 ha). Figure 7 shows the change in mangrove area in Thach Phu district in the period 1990–2000.

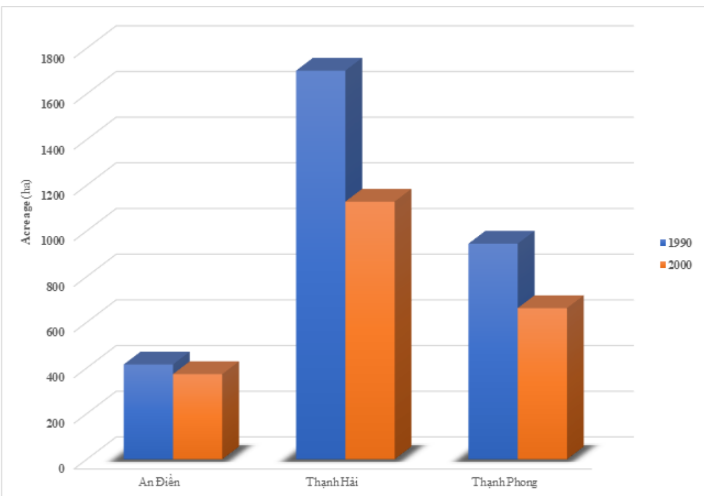


Fig. 7. Chart of changes in mangrove area in Thanh Phu district, Ben Tre province in the period 1990–2000

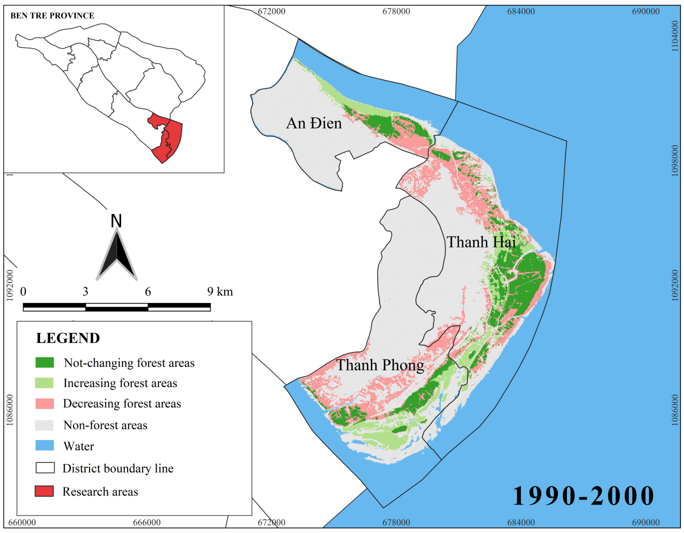


Fig. 8. Map of changes in mangrove area in Thanh Phu district, Ben Tre province in the period 1990–2000

Figure 8 shows that almost all mangrove areas are reduced in communes. The largest decrease in area is Thanh Hai commune, followed by Thanh Phong commune. While An Dien commune is almost unchanged. In Thach Hai commune, the forest area decreased by 573.51 ha, accounted to 33.7 % of the forest area. Meanwhile, in Thach Phong commune, the reduced forest area is 282.221 ha (29.9 %).

Based on the above research and analysis results, the authors have established a map of changes in mangrove area in Thanh Phu district, Ben Tre province in the period 1990–2000 (Figure 8).

Table 8

Mangrove area in Thanh Phu district, Ben Tre province in 2020

1990-2000	Other objects	Mangroves	Rivers, lakes, canals
Other objects	6844.7	455.4	193.6
Mangroves	1804.7	1214.1	42.8
Rivers, lakes, canals	960.0	493.5	5301.0

Figure 8 and Table 8 show that the area of mangroves in Thanh Phu district is mainly lost and concentrated in 02 communes — Thanh Phong and Thanh Hai. The forest area lost during this period is quite large: 1804.7 ha has been converted to other uses, 42.8 ha has been converted to rivers, lakes, canals. However, the forest area is increased due to accumulation is also quite large (948.9 ha), concentrated mainly in the coastal area of Thanh Phong commune and part of the periphery of An Dien commune. In general, during this period, Thach Phu district lost about 1000 ha of mangrove forest.

VI. Period 2000–2010

This is the period when the mangrove area in Thanh Phu district increased again. While the mangroves in Thanh Hai commune continued to be reduced slightly, the mangrove area in Thanh Phong commune significantly increased (371.5 ha).

Figure 9 shows that almost all areas tend to increase in communes of Thanh Phu district. The largest increase in area is Thanh Phong commune. While An Dien and Thanh Hai communes are almost unchanged. Compared with the period 1990–2000 we can see that the area of mangroves that was not affected in the period 2000–2010 has increased significantly, from 1214.1 ha to 1739.8 ha.

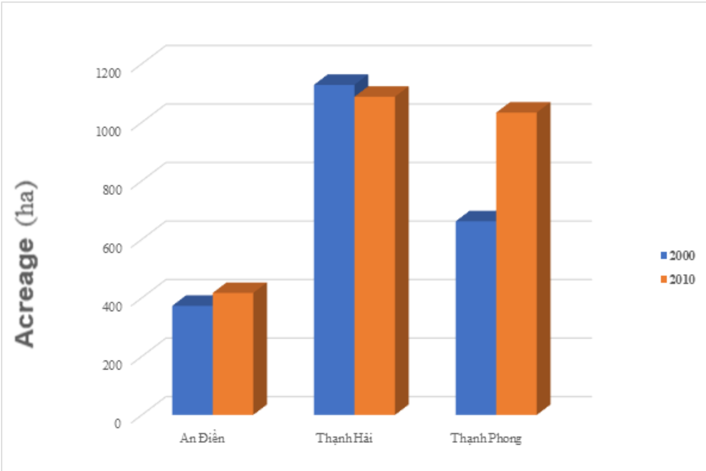


Fig. 9. Chart of changes in mangrove area in Thanh Phu district, Ben Tre province in the period 2000–2010

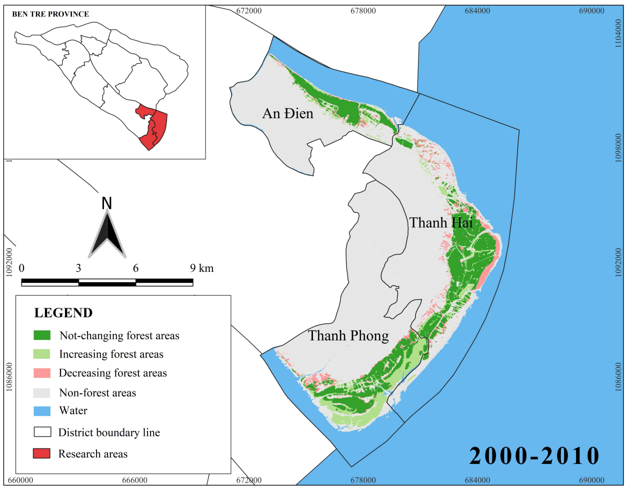


Fig. 10. Map of changes in mangrove area in Thanh Phu district, Ben Tre province in the period 2000–2010

Table 9

Table of rotation of mangrove areas in Thanh Phu district in the period 2000-2010

2000-2010	Other objects	Mangroves	Rivers, lakes, canals
Other objects	8339.3	716.0	554.0
Mangroves	351.4	1739.8	71.8
Rivers, lakes, canals	116.5	82.4	5338.5

Figure 10 and Table 9 show that the area of mangroves in Thanh Phu district was in the recovery stage. It can be clearly seen that the forest area unchanged during this period was quite large (1739.8 ha) and the additional forest area due to accretion was also quite large (798.4 ha), mainly concentrated in the coastal zones of Thanh Phong beach. The area of mangroves converted to other purposes has decreased significantly compared to the period 1990–2000. During this period, only 351.4 hectares were converted to other purposes (1804.7 ha in the 1990–2000 period). However, the forest area converted into rivers, lakes and canals tends to increase (71.8 ha). Based on the above research and analysis results, the authors have established a map of changes in mangrove area in Thanh Phu district, Ben Tre province in the period 2000–2010 (Figure 9).

VII. Period 2010–2020

This is a period with very little fluctuation and the trend of forest area has been saturated due to appropriate protection policies. Only Thanh Hai commune has the forest area continues to decrease with 120.8 ha while Thanh Phong commune has an increase of 16 ha.

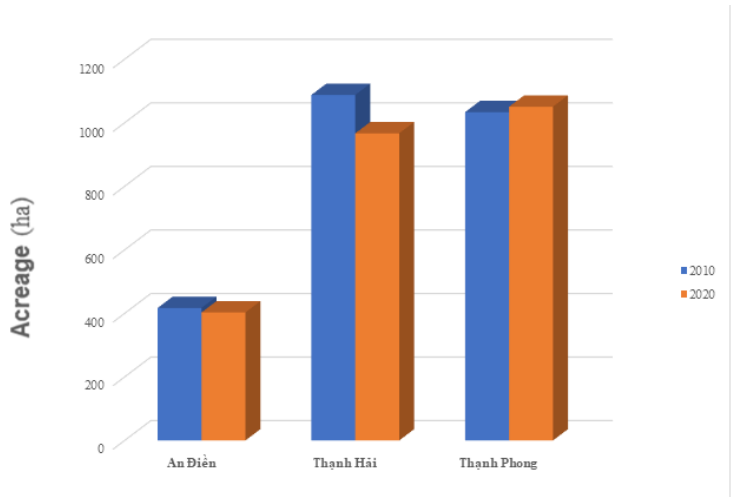


Fig. 11. Chart of changes in mangrove area in Thanh Phu district, Ben Tre province in the period 2010–2020

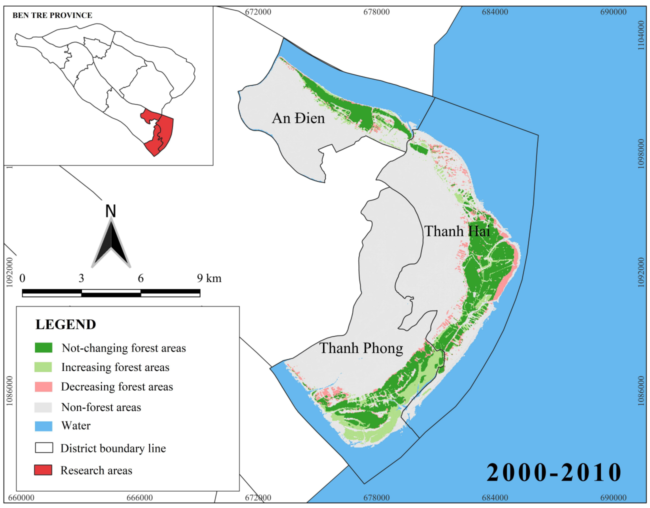


Fig. 12. Map of changes in mangrove area in Thanh Phu district, Ben Tre province in the period 2010–2020

Figure 12 and Table 10 show that the area of mangroves in Thanh Phu district is in a relatively stable stage. It can be clearly seen that the forest area unchanged during this period is quite large (2115.2 ha) in which the forest area increased by accretion is also quite large (305.7 ha), mainly concentrated in the coastal area of Thanh Phong commune. Forest area converted to other uses continued to decrease compared to previous periods (291.6 ha). During this period, the area of mangroves turned into rivers, lakes and canals continuously increased (131.5 ha).

Table 10

Table of rotation of mangrove areas in Thanh Phu district in the period 2010–2020

2010-2020	Other objects	Mangroves	Rivers, lakes, canals
Other objects	8312.3	261.4	233.5
Mangroves	291.6	2115.2	131.5
Rivers, lakes, canals	372.2	44.3	5547.9

Based on the above research and analysis results, the authors have established a map of changes in mangrove area in Thanh Phu district, Ben Tre province in the period 2000–2010 (Figure 12).

Figure 13 shows the variation of mangrove area in Thanh Phu district, Ben Tre province in the period 1990–2020. Through Figure 12, we see that the area of mangroves in Thanh Phu district in the period 1990–2020 has fluctuated, from 3061.6 ha, it decreased to 2163.0 ha in 1990, then increased to 2538.3 ha in 1990, and recently reduced to only 2420.8 ha. The reason for the decrease is due to the movement of encroaching on forests for shrimp farming in the 2000s and in recent times due to deforestation to build houses, especially in An Dien and Thanh Hai communes. Though, Thanh Phong commune has recently increased in terms of mangrove area due to alluvial accretion.

To see more clearly the variation of mangrove area in Thanh Phu district, the authors studied the change of forest area in each commune through each period during the research period from 1990 to the year (Figure 14). From Figure 14, we can see that in the period 1990–2020, the area of mangroves in An Dien commune was relatively unchanged, while Thanh Phong commune fluctuated a lot in the period 1990–2000, then increased and stabilized. Particularly in Thanh Hai commune, the area of mangroves has tended to decrease continuously over the years, from 1701.7 ha (1990) to 966.7 ha (2020). This is alarming and needs deep attention.

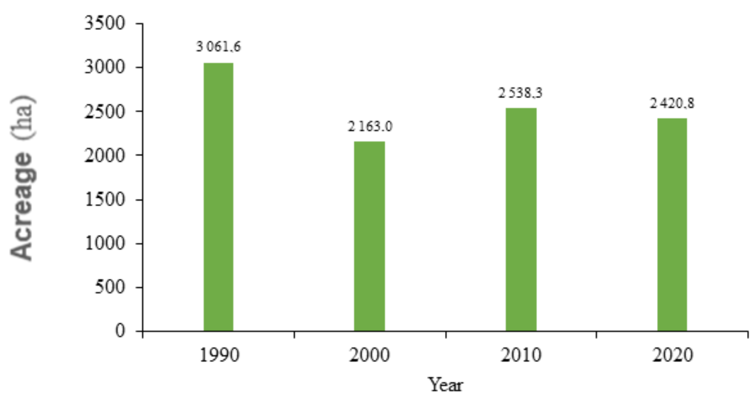


Fig. 13. Area of mangroves in Thanh Phu district in the period 1990–2020 (ha)

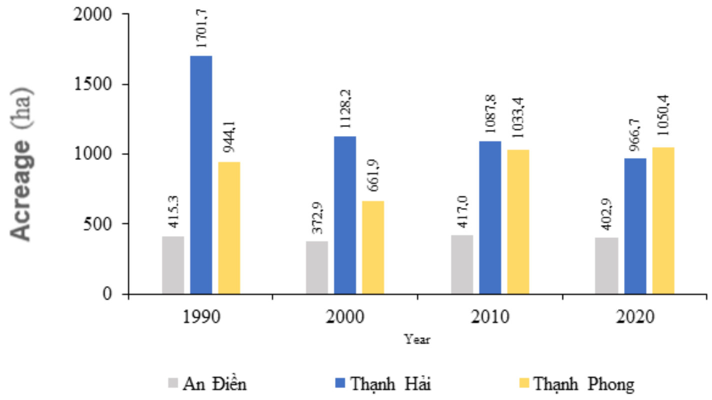


Fig. 14. Area of mangroves by commune over the years

Coastal erosion and the conversion of mangroves to aquaculture are the main factors contributing to the loss of mangrove habitat. Not much mangrove habitat has been converted to agricultural land or other uses. Mangrove erosion is occurring in Thanh Phu district, Ben Tre province, as it is in other districts and provinces across the Mekong Delta. Plate erosion impacts the top layer of the soil, which can lead to the exposure of tree roots, soil loosening, a decrease in mangrove soil level, and widening of the river mouth. Estuary erosion, on the other hand, is caused by tides and can result in the destruction of riverbanks and the depletion of forest cover. Mangrove soil erosion happens quickly and is widespread in many regions as a result of sea level rise. Mangrove erosion is caused by: Because of human-caused logging, the forest belt is too thin, there is no longer a regenerating tree belt, and as a result, the number of canopy layers, ability to absorb wave energy, and wave resistance of the forest all decrease. poor, effortlessly swept away by waves. Sand washed up on the shore by the high tide, covering the submerged tree stump and the mangrove trees' breathing roots, rendering them unable of breathing and ultimately killing them. Currently, mangroves are buried and several sites have been alluvialized, including Thanh Phu in the province of Ben Tre.

Discussion

In general, the area of mangrove forests in Thanh Phu district has decreased over 30 years. Despite the fact that after 2000y. there has been an increase in the area of mangrove forests in the study area. Deforestation and replacement with aquaculture ponds has been the main contributor to the reduction of mangroves [Son, Ye, Stive, 2017]. Changes in mangrove forests covers were affected by two activities: deforestation and replanting, but planting capacity was slower than deforestation. Recent mangrove changes are due mainly to shrimp farming expansion, which is developing in an unplanned way. Shrimp farm development and degradation also caused environmental and natural resource problems with socio-economic consequences such as land degradation, environmental pollution, the conflicts among natural resource users and the gap between the rich and poor.

For example, according to our data and according to the literature, these processes have had the largest scale in the provinces of Ca Mau and Tra Vinh [Binh et al., 2005; Van et al., 2015]. The decline in the popularity of aquaculture has been associated with a decrease in the economic efficiency of mariculture and changes in management measures [Vo, Kuenzer, Oppelt, 2015]. In recent decades, «clean» aquaculture in the form of open ponds has been gradually replaced by mixed mangrove-shrimp farms [Truong, Do, 2018]. In the total balance of the area covered by mangroves, these farms have a positive effect. Their ecological efficiency and the extent to which these artificial plantings correspond to natural mangrove forests require a separate discussion. The second direction of anthropogenic impact on the mangroves of the delta provinces is the artificial planting of mangroves. Traditionally, such landings are arranged to protect coasts from wave abrasion. These activities have been carried out in all provinces in recent decades and are gaining momentum. The natural process behind mangrove dynamics in the Mekong Delta is the redistribution of sediment along the coast. On the eastern coasts, abrasion processes predominate, on the western coasts — accumulation of bottom sediments. This process can be called completely natural with some stretch, since many researchers associate the observed changes in the dynamics of bottom sediments with an increase in the number of dams in the middle and upper reaches of the Mekong [Li et al., 2017], as well as with the development of a canal system in the southern part of the delta [Nguyen et al., 2016]. Both on the abrasion and on the accumulative, newly formed sections of the coast, intensive work is underway on the cultivation of mangroves. As a result, the current dynamics of mangrove vegetation is a reflection of oppositely directed natural and anthropogenic processes occurring at different rates. The turnover rates of artificial mangroves in the southern provinces of Vietnam is about 20 years. At this age, plantings of Rhizophora apiculata, the main mangrove species in shrimp-mangrove farms, go to felling [Alongi et al., 2000]. Thus, during the studied period of time in the areas occupied by mangrove-shrimp aquaculture, a complete cycle of vegetation transformation could have occurred, which remained unnoticed, since it fell between the survey periods. The average rate of loss of mangrove area in the study area is about 0.7 %/year, close to the average rate of loss of mangrove area in the Mekong Delta, which is about 1 % per year. Over a thirty-year period, the total area of mangroves has decreased by about 20 %. This estimate does not take into account the transformation of mangrove forests and their redistribution in space. The average mangrove extinction rate (0.7 % per year) obtained by us is close to the minimum estimates given for Vietnam, and less than the average values for Southeast Asia and the world — 1–2 % [Duke et al., 2007].

The reduction of mangrove resource causes the loss of coastal fisheries. Breeding areas of economically important fish and shrimp species have been lost. Habitat of biological species is degraded, leading to a decrease in biodiversity. The number of birds in the protected forest belt has decreased significantly and many mammal species have disappeared. The complete absence of a mature coastal protective mangrove belt is a major obstacle to sustainability and resource values in the coastal belt.

Conclusion

Using multi-temporal satellite images allows researchers to assess the fluctuations of large spatially distributed elements quickly and relatively accurately. In which, the change in vegetation cover, especially in mangrove forests.

Through analysis of satellite images, it was found that over a period of 30 years (1990–2020), the total area of mangroves in Thanh Phu district, Ben Tre province has decreased by more than 20 % (equivalent to 640.8 ha) compared to the original (from 3061.6 ha in 1990 reduced to 2420.8 ha in 2020). Thanh Hai commune has the most mangrove area but is also the experienced the largest reduction in mangrove area (from 1701.7 ha in 1990 to 996.7 ha). An Dien commune had the least mangrove area and its the area of mangroves decreased in a small amount (from 415.3 in 1990 to 402.9 ha in 2020). Thanh Phong commune's area of mangroves fluctuated between 1990 and 2000; it decreased from 944.1 ha to 661.9 but then increased to 1033.4 ha in 2010 and continued to increase to 1050,4 in 2020. The recovery rate of mangroves was low, the mangrove restoration took place mainly in Thanh Phong commune. Specifically, from 1990 to 2020, a mangrove area of 640.8 ha disappeared but then appeared on a new area of 3061.6 ha. The decrease in mangrove area in Thanh Phu district, Ben Tre province is closely related to the process of deforestation of mangroves to dig shrimp ponds and landslides in the eastern coastal areas. The process of mangrove restoration mainly takes place on newly accreted coastal areas, estuaries and reforestation in inefficient shrimp ponds.

The research results determine the spatial change of coastal mangroves in Thanh Phu district, Ben Tre province after 30 years, the causes leading to the decline in mangrove area, along with their recovery process through the different stages, thereby helping policymakers propose solutions to restore and develop mangrove ecosystems, contributing to the restoration and enrichment of diverse coastal ecosystems.

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ИЗМЕНЕНИЯ ПЛОЩАДИ МАНГРОВЫХ ЛЕСОВ В РАЙОНЕ ТХАНЬФУ ПРОВИНЦИИ БЕНЧЕ В ТЕЧЕНИЕ 1990–2020 гг.

Фунг Тхай Зыонг[1], Фам Кам Ньунг[2], Нго Тхи Нгок Ту[3], Хуинь Тхи Шань[4], Нгуен Куок Хау[5], Нгуен Ван Зунг[6]

[1] Университет Донгтхап, провинция Донгтхап, Вьетнам ,
[2] ФГБУН ФИЦ «Институт биологии южных морей имени А. О. Ковалевского РАН», Севастополь, Российская Федерация ,
[3] Неполная средняя школа Мй Хиеп, провинция Донгтхап, Вьетнам,
[4] Неполная средняя школа Тан Хой, провинция Донгтхап, Вьетнам,
[5] Строительный университет Миен Тай, провинция Виньлонг, Вьетнам,
[6] Университет народной полиции, Хошимин, Вьетнам,
e-mail: ptduong@dthu.edu.vn

Аннотация: Сложная экосистема мангровых лесов имеет большое экологическое и экономическое значение. К сожалению, за последние полвека обширные площади мангровых лесов были утрачены из-за стремительного роста населения, быстрой урбанизации, расширения аквакультурных хозяйств и других видов деятельности человека. В частности, в Азии произошло наиболее значительное сокращение мангровых лесов, включая Вьетнам. Однако недавние исследования показывают, что территория мангров во Вьетнаме либо расширяется, либо фрагментируется. Целью исследования является оценка изменения площади прибрежных мангровых лесов в районе Тханьфу провинции Бенче в период 1990–2020 гг. с применением технологии дистанционного зондирования. Планирование и повышение роли мангровых лесов может стать

важным фактором в обеспечении экосистемных услуг, ресурсом для местных бюджетов и глобальных выгод. По результатам исследования авторы составили карту изменения площади мангровых лесов в районе Тханьфу (провинция Бенче). В целом площадь мангров в округе Тханьфу за 30 лет сократилась, несмотря на то что после 2000 г. в районе исследований наблюдается увеличение их площади. В исследовании показана пространственная трансформация прибрежных мангровых зарослей в районе Тханьфу провинции Бенче за 30 лет и факторы, ответственные за их сокращение. Исследование также раскрывает процесс восстановления мангровых зарослей на различных этапах, предоставляя ценную информацию для формирования правительством решений по восстановлению и улучшению мангровых экосистем. В конечном итоге это может помочь в восстановлении и обогащении разнообразных прибрежных экосистем.
Ключевые слова: мангровые леса, площадь лесов, дистанционное зондирование, Landsat, Вьетнам.

Authors Details

Phung Thai Duong	PhD of Geography, Vice Dean of the Faculty of Social Sciences Pedagogy, Dong Than University, Dong Thap City, Dong Thap Province, Vietnam, e-mail: ptduong@dthu.edu.vn, (phungthaiduongdhdt@gmail.com).
Pham Cam Nhung	PhD of chemistry, junior researcher, A. O. Kovalevsky Institute of Biology of the Southern Seas of RAS, Sevastopol, Russia, e-mail: nhung5782@yahoo.com.
Ngo Thi Ngoc Tu	MS in Geography, My Hiep junior high school, province Dong Thap, Viet Nam, e-mail: minhtugd@gmail.com.
Huynh Thi Sanh	MS in Geography, Tan Hoi Trung junior high school, province Dong Thap, Viet Nam, e-mail: huynhthisanhtht@gmail.com.
Nguyen Quoc Hau	PhD of Geography, Mien Tay Construction University, province Vinh Long, Viet Nam, e-mail: nguyenquochau@mtu.edu.vn.
Nguyen Van Dung	Bachelor, People’s Police University, Ho Chi Minh city, e-mail: vandung.csmtr@gmail.com.

Сведения об авторах

Фунг Тхай Зыонг	PhD (география), заместитель декана факультета социальной педагогики, Университет Донгтхап, ptduong@dthu.edu.vn
Фам Кам Ньунг	PhD (химия), младший научный сотрудник, ФГБУН ФИЦ «Институт биологии южных морей имени А. О. Ковалевского РАН», nhung5782@yahoo.com
Нго Тхи Нгок Ту	MS (география), Неполная средняя школа Мй Хиеп, minhtugd@gmail.com
Хуинь Тхи Шань	MS (география), Неполная средняя школа Тан Хой, huynhthisanhtht@gmail.com
Нгуен Куок Хау	PhD (география), Строительный университет Миен Тай, nguyenquochau@mtu.edu.vn
Нгуен Ван Зунг	бакалавр, Университет народной полиции, vandung.csmtr@gmail.com

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