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Using Medium-Resolution Remote Sensing Satellite Images to Evaluate Recent Changes and Future Development Trends of Mangrove Forests on Hainan Island, China

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Abstract: Mangroves are endemic forest communities in tropical and subtropical coastal zones. China's Hainan Island is very rich in mangrove plant species. In recent years, due to climate change and human disturbance, the living environment of many mangrove distribution areas has been seriously threatened. This study used land satellite series remote sensing images from 1990 to 2020 to monitor the coverage and area changes of mangroves on Hainan Island. The spatial distribution pattern and change trend of mangroves were explored using the standard deviation ellipse method, and the CA–Markov model was used to predict the possible changes of mangroves in the study area in 2025 and 2030. The development trend of mangroves in the future and the driving factors affecting the evolution of mangroves were also analyzed. Over the past 30 years, the area of mangroves has witnessed fluctuations. It decreased from 4578 hectares in 1990 to its lowest at 3870 hectares in 2005 and then rebounded to 4474 hectares by 2020, indicating an initial decline followed by a gradual increase. Although conservation and restoration efforts have yielded success, specific areas have witnessed a decline in mangrove coverage. From 1990 to 2020, mangrove areas in Huiwen decreased from 1055 hectares to 904 hectares, areas in Guannan decreased from 227 hectares to 167 hectares, areas in Xinyinggang decreased from 328 hectares to 298 hectares, areas in Yangpugang decreased from 747 hectares to 682 hectares, areas in Huachangwan decreased from 355 hectares to 327 hectares, and areas in Puqian decreased from 170 hectares to 141 hectares. In particular, the growth in the Eastern and Mayao port areas is especially significant. Additionally, data analysis has revealed the spatial distribution characteristics of mangroves in different regions, such as the mangrove area in Dongzhaigang, which remained relatively stable from 1990 to 2020, while in other areas like Huiwen and Guannan, the mangrove area decreased during these 20 years. By calculating the standard deviation ellipse, we observed that the overall change of mangroves on Hainan Island from 1990 to 2020 was relatively slow, mainly distributed along the northern coastal area of Hainan Island. Furthermore, the standard deviation ellipse and SDE center point of each mangrove growth area have visualized the growth trends of the mangroves. The Markov chain simulation results show that future changes in mangroves will mainly be concentrated in the marginal areas of the mangroves. These areas may be affected by rising sea levels, climate change, soil salinity, and human activities. In the future, mangrove areas are expected to display a dynamic equilibrium, experiencing periods of expansion and reduction, ultimately moving towards a more consistent state. To protect and restore mangroves, it is necessary to strengthen the monitoring and management of their ecological environment and socio-economic factors and improve their stability and diversity.

Keywords: mangrove; spatial distribution; driving factors; Landsat; CA–Markov model

1. Introduction

Mangroves are a woody plant community that grow in tropical and subtropical intertidal zones [1]. Mangroves are known for their high productivity and rich ecological, economic, and cultural values [2]. The dense vegetation of mangrove forests can dissipate the impact of the waves, protect the coastline from erosion, and provide a nursery habitat for many fish species [3]. At the same time, mangroves are a food source for many mammals [4]. In addition to providing many ecological and economic service values to human communities, including shoreline protection and ecotourism [5], mangroves can reduce blue carbon [6] and emit and sequester blue carbon to mitigate climate change [7].

However, mangroves have suffered significant damage due to population growth and economic development [8]. According to statistics, 52% of mangrove forests have been deforested globally since 1970, and 28% have been converted to commercial aquaculture ponds [9]. In China, mangrove forests were reduced from 48,801 to 18,702 hectares between 1973 and 2000 [10]. If no action is taken, 30%–40% of mangrove forests will lose their function in the next 100 years [11]. To combat climate change and protect the stability of the ecosystem, we must take measures to prevent the loss of mangroves. This will ensure that mangroves continue to provide ecological, economic, and cultural values in the future and provide essential services to the ecosystem [12].

Monitoring mangrove cover can help assess mangroves' growth range and dynamics and provide data support for mangrove protection and restoration. Currently, two main methods to monitor mangrove cover are traditional survey and imagery processing. Although the conventional methods are more accurate, they are costly, time consuming, and challenging to apply on a large scale. In contrast, remote sensing monitoring methods are less time consuming. Remote sensing monitoring methods can acquire data in some hard-to-reach areas and measure the mangrove coverage area over a large area [13]. Remote sensing has apparent advantages, especially for monitoring the same period in an ample space [14].

Currently, the methods to identify the coverage of mangroves from remote sensing data are mainly from remote sensing images combined with the spectral characteristics of mangroves. The identification accuracy of remote sensing monitoring methods depends on satellite datasets, of which Landsat is the most widely used dataset [15]. Landsat has been in operation since 1972 and has a large amount of historical data and images, which helps in comparative image analysis over a long period. In addition, Landsat 8/9 has a spatial resolution of 30 m, while Sentinel 2's usable time frame is too short despite its higher resolution [16]. Therefore, Landsat 8/9 can provide more accurate surface image detection and analysis [17]. Landsat is feasible and advantageous for analyzing mangroves' seasonal changes and growth trends [18]. Thus, some scholars have conducted time-series monitoring of mangroves based on the Landsat dataset and proved the feasibility of its dataset application [19].

For the classification techniques of satellite images, the two main categories include object-based image analysis (OBIA) and machine learning [20]. Researchers can apply object-based image analysis (OBIA) and support vector machine (SVM) methods to accurately strip mangrove growth areas from coastal vegetation. However, the spectral characteristics of some sparse vegetation are similar to those of mangroves, leading to errors in the identification results. Subsequently, researchers began to investigate using newer machine learning algorithms, including artificial neural networks [21,22], maximum likelihood classifier [23], Random Forest [24], and XGBoost [25]. Compared with traditional algorithms, machine learning classification techniques are more economical and efficient in detecting mangrove cover areas over large areas. Some scholars use Light Detection and Ranging (LIDAR) and the digital surface model of Unmanned Aerial Vehicles (UAV) to improve recognition accuracy. Some scholars have also proposed the temperature moisture index, mangrove vegetation index, and multi-index analysis to improve the accuracy of mangrove identification [26].

Based on monitoring the mangrove growth area, many scholars have started to study the factors influencing its area change, which mainly include both natural and anthropogenic factors. Mangroves are affected by natural factors, including tropical cyclones, precipitation anomalies, and seawater temperatures. In its 2013 report, the Intergovernmental Panel on Climate Change (IPCC) discussed in detail the impact of these natural factors on global ecosystems, which also involved the ecological environment of mangroves [27]. However, human activities, mainly logging and agricultural, are the main reason for the gradual decline of mangroves. The IPCC's 2014 report clearly stated that human activities have exerted tremendous pressure on mangroves and other wetland ecosystems, leading to their degradation and loss [28]. Various agricultural production activities, especially the development of farming, can destroy the growing environment of mangroves [29]. The prevalence of shrimp farming greatly accelerates the decay of mangroves [30]. These human activities have destroyed the mangrove ecosystem, significantly reducing biodiversity and economic value [31].

There are a lack of studies on the comprehensive and systematic assessment of mangrove-growing areas and the economic and social factors affecting mangrove area decline receive little attention. Previous studies suffer from certain deficiencies in terms of period and economic and social factors. For example, Li, M. et al. used the Normalized Difference Vegetation Index (NDVI) to detect changes in mangrove areas. Still, it did not analyze the economic and social factors driving mangrove land use changes in Madang, and the study only covered 18 years, making it challenging to capture long-term changes in mangrove areas; at the same time, this study also assessed mangrove cover changes in five mangrove areas of Pakistan from 1990 to 2020 but did not discuss the potential impacts of climate change on mangrove ecosystems in Pakistan [32]. Therefore, a comprehensive and systematic assessment of mangroves' growth extent and an in-depth study of economic and social factors are necessary [33]. This study analyzes mangroves' long-term morphological evolution trends from 1990 to 2020 based on high-density time-series medium-resolution satellite images in nine mangrove reserves on Hainan Island. Our specific goals are as follows: (1) to study the long-term evolution of mangrove areas; (2) to study the changing trend of the spatial distribution pattern of mangroves; (3) to predict the possible changing trends of mangroves in 2025 and 2030; (4) to discuss the impact of global change and human activities on mangrove changes. This study will help assess changes in modern mangroves in Hainan Province, China, support research on growth in the transition zone between the tropics and subtropics, and provide scientific reference for the protection of mangroves and sustainable development of coastal zones.

2. Materials and Methods

This study utilized Landsat remote sensing imagery from 1990 to 2020 to monitor the changes in mangrove forest cover on Hainan Island. Visual interpretation techniques were employed to identify the extent and area of mangrove forests. A combination of the stochastic and CA–Markov model was also used to forecast future trends in mangrove forest development and analyze the driving factors influencing changes in mangrove forests. The specific process of this study is shown in Figure 1.

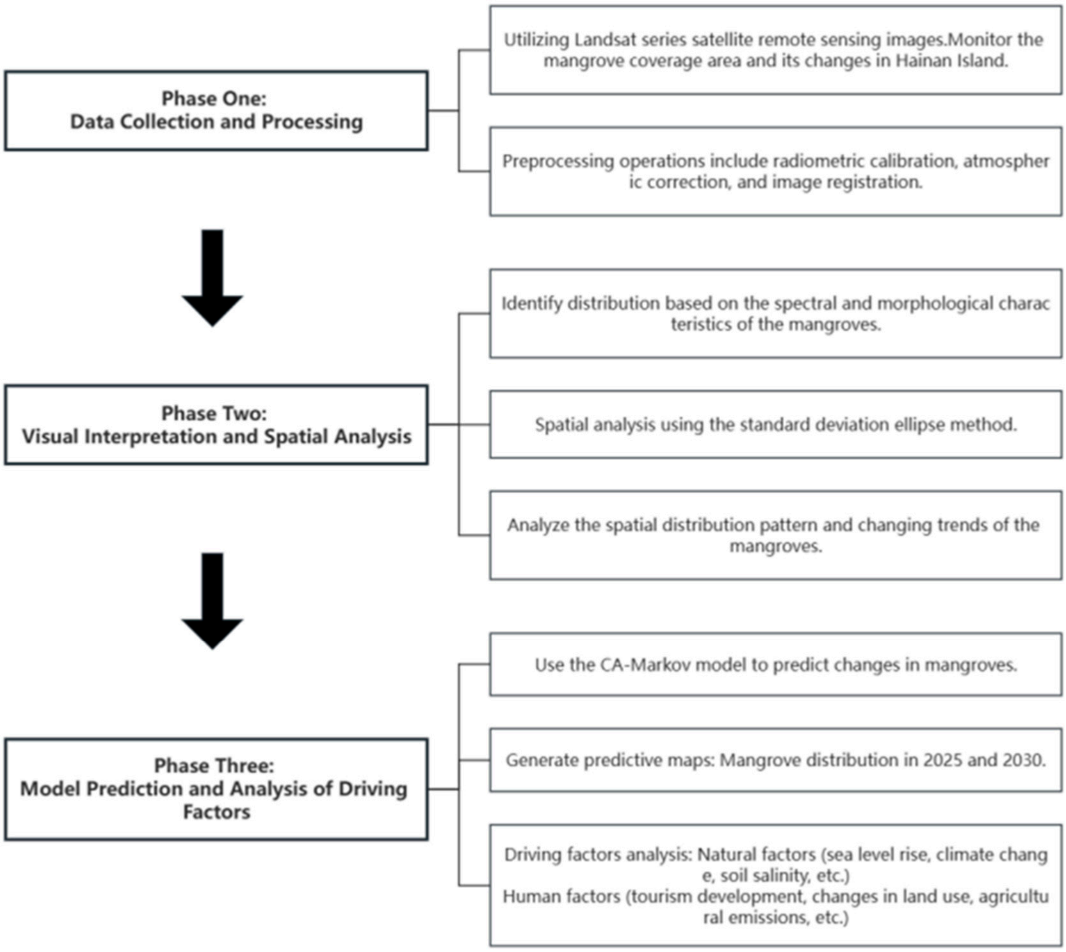


Figure 1. The specific process of this study.

2.1. The Study Area

The mangrove resources in China are mainly distributed in Guangdong, Guangxi, and Hainan. This study selected nine continuous, well-preserved mangrove nature reserves that the Chinese government declared national or provincial mangrove nature reserves as study areas. Hainan Island mainly consists of the Central Mountain Range and its branches, of which the highest peak is the Wuzhi Mountain at 1868 m above sea level. Hainan Province has a tropical humid monsoon climate [34], with an annual average temperature between 23–26 °C. There is no frost or snow throughout the year, and the daily temperature consistently exceeds 10 °C [35]. This combination of weather conditions and abundant sunshine and rainfall provides an optimal environment for mangrove growth and reproduction.

The total area of mangroves in Hainan Province is 5724 hectares, mainly distributed in Wenchang County, Qiongshan City, Chengmai County, Lingao County, Danzhou City, and Dongfang Li Autonomous County (Figure 2). Mangroves on Hainan Island are primarily located in the intertidal zones of the island's coastal regions. After years of extensive studies, it has been documented that the mangrove flora of Hainan encompasses 151 species from 118 genera and 46 families. This includes 32 true mangrove species, 31 mangrove associates, and 8 accompanying species [36]. These plants exhibit well-developed root systems that adapt to high salinity and low oxygen conditions. Mangroves growing below the high tide line typically possess thicker leaves, while those rising above the high tide line have comparatively thinner leaves. These mangrove ecosystems play a pivotal role in the region's ecology, offering habitats for various fish, mollusks, and avian species. Furthermore, they act as a buffer against coastal erosion and stabilize sediments. Given that a significant portion of Hainan Island's population resides within a 10-km range of the coast, these mangroves also offer invaluable services in water purification, microclimate regulation, and serving as recreational and tourism resources.

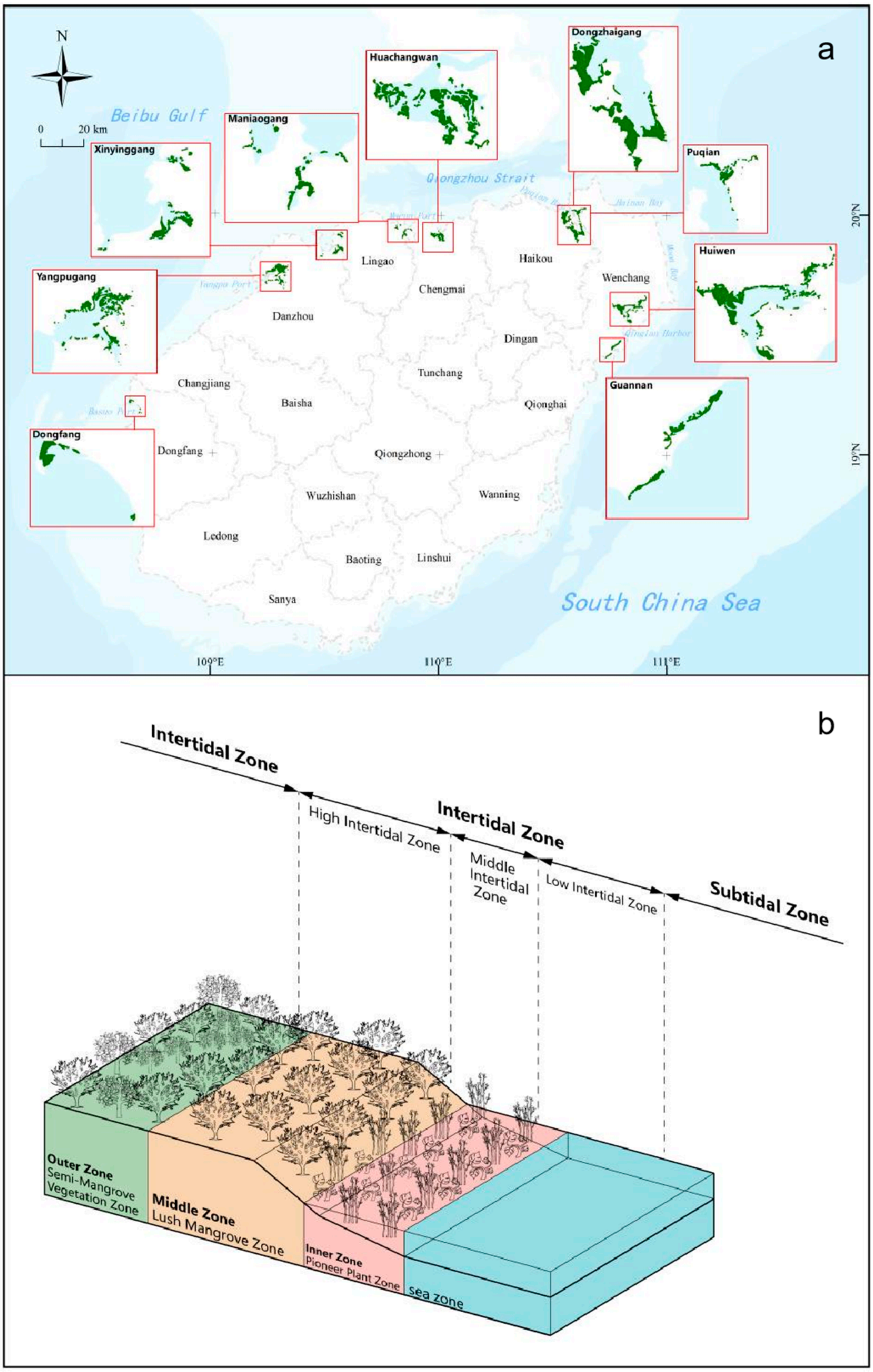


Figure 2. Location of the study area (**a**) and typical distribution patterns of mangroves (**b**).

2.2. Data Source

Given the slow dynamics of mangrove ecosystems, utilizing satellite imagery over extended temporal intervals can more effectively capture the changes in mangrove cover. Considering factors like data availability and the robustness of the scientific assessment, we determined that a 5-year interval would be most appropriate. After rigorous filtering, this study incorporated Landsat imagery from 1990, 1995, 2000, 2005, 2010, 2015, and 2020. We selected Landsat 5–8 satellite images with path and row numbers 123/46, 123/47, 124/46, 124/47, and 125/47, respectively. We screened 5 images every year and obtained a total of 35 satellite images. The specific parameters are shown in Figure 3 and Table 1.

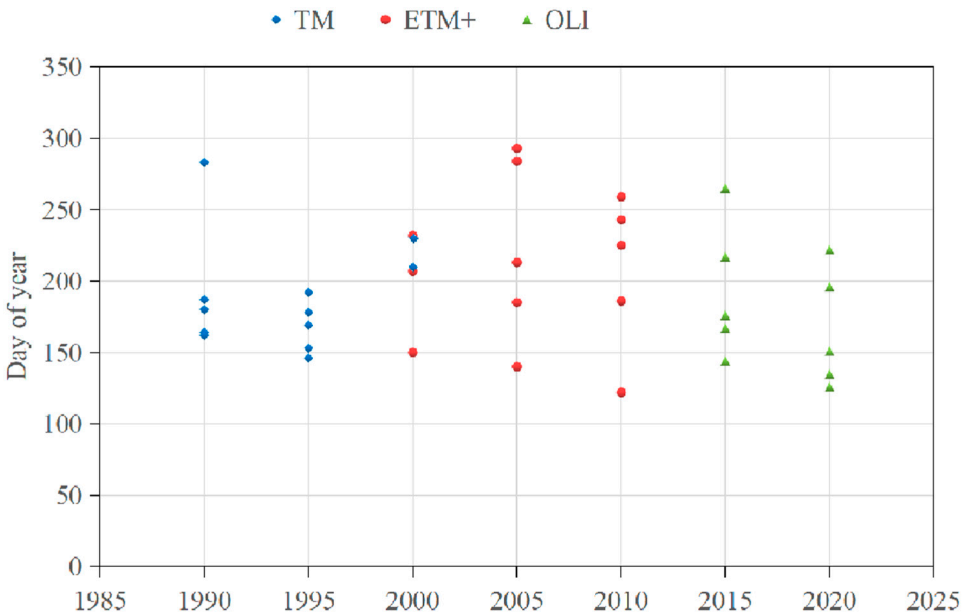


Figure 3. Introduction of the satellite images used in this study. Landsat 4–5 Thematic Mapper (TM); Landsat 7 Enhanced Thematic Mapper (ETM+) and Landsat 8 Operational Land Imager (OLI)).

Table 1. Date of acquisition of satellite imagery used in this study.

Year	Date	Year	Date	Year	Date	Year	Date
1990	6 July	2000	18 August	2010	2 May	2020	9 August
1990	13 June	2000	26 July	2010	16 September	2020	30 May
1990	10 October	2000	19 August	2010	5 July	2020	5 May
1990	11 June	2000	25 July	2010	13 August	2020	14 July
1990	29 June	2000	29 May	2010	31 August	2020	14 May
1995	18 June	2005	11 October	2015	24 May		
1995	27 June	2005	20 October	2015	22 September		
1995	2 June	2005	20 May	2015	25 June		
1995	11 July	2005	4 July	2015	16 June		
1995	26 May	2005	1 August	2015	5 August		

These Landsat images were downloaded from the United States Geological Survey (USGS) Earth Resources Observation and Science Center website (https://earthexplorer.usgs.gov/ (accessed on 10 September 2023)). The Landsat series of satellites has provided necessary data support for global remote sensing monitoring since the first satellite was launched in 1972. Landsat-5 TM, Landsat-7 ETM+, and Landsat-8 OLI satellites provide high-quality Earth observation data by collecting visible and infrared spectral data for monitoring surface changes, environmental changes, and natural resource management. With global coverage, long-term continuous observations, and multispectral information, these data can be used to analyze and study surface features and trends over different periods. Using these Landsat images, this study can obtain accurate surface information for in-depth analysis and research on the spatial characteristics and changes of the mangrove growth range within Hainan Island [37].

2.3. Data Processing

(1) Radiation calibration: Radiation calibration converts digital counts into radiation brightness or reflectance to reflect surface characteristics accurately. The calibrated data can provide more accurate quantitative analysis and comparison of images from different times or areas.

(2) Atmospheric correction: After the atmospheric correction process, the Landsat dataset was screened. In this correction process, the B7, B5, and B3 bands were selected as a combination to more accurately convey information on vegetation growth, soil moisture, and other relevant factors. The bands of the OLI sensor are different from those of the TM and ETM+ sensors. The B7 band corresponds to the SW IR (2.08–2.35 μm) of TM and ETM+ and the SWIR 2 (2.10–2.30 μm) of OLI. The B5 band corresponds to the TM and ETM+. The SW IR (1.55–1.75 μm) and OLI's NIR (0.85–0.89 μm), the B3 band corresponds to the red (0.63–0.69 μm) of TM and ETM+ and the green (0.53–0.60 μm) of OLI. Such processing improves the reliability and accuracy of the data and allows us to better study and understand the effects of these factors [38].

(3) Image alignment: It is crucial to ensure that Landsat images obtained at different times are spatially aligned before visually interpreting mangrove forests. Image alignment is achieved using the image registration tool in ArcGIS, where common points in both images are selected as Ground Control Points (GCPs). An automatic alignment algorithm is then applied. Finally, the accuracy of the corrected image is evaluated and verified. A correction was made based on the 1:250,000 land use type map and the 1:250,000 DEM data of Hainan Province, China.

2.4. Visual Interpretation

Visual interpretation is a method of classification and identification by direct observation and interpretation of the visible features of an image [39]. Currently, traditional remote sensing impact classification methods can adequately distinguish forests and other features in medium-resolution satellite images, but it is challenging to accurately differentiate mangroves from other forests. Manual interpretation corrections are often needed, which are time consuming and inefficient. Using the 2020 Dongzhaigang's Landsat8 image as a reference, random samples of mangroves, grasslands, and other forests were selected. The average atmospheric apparent reflectance of each feature was statistically recorded, and the spectral characteristics of the target features were plotted. As shown in Figure 4, it can be observed that mangroves and the other two vegetation types almost overlap in the visible light band, but there are some differences in the NIR (band 5) and SWIR bands (band 6,7). Therefore, this study mainly uses NIR (band 5) or SWIR (band 6,7) bands to distinguish mangroves from other vegetation.

This study used visual interpretation to identify mangroves on terrestrial satellite remote sensing images. First, terrestrial satellite remote sensing images were obtained. Then, by observing the spectral features of the images, the mangroves were characterized. Next, using ENVI5.3 and ARCGIS10.5, the pre-processed terrestrial satellite images were visualized into true color or pseudo-color images. The false color images map the red, green, and blue bands directly to the B7, B5, and B3 bands and appropriately increase the contrast. The image features and interpretation symbols of mangroves and other forests in the images are shown in Table 2. Visual observations of the visualized images were carried out to find areas with mangrove features. Finally, spectral information and other geographic information data were used to verify whether the observed area indeed contains mangroves.

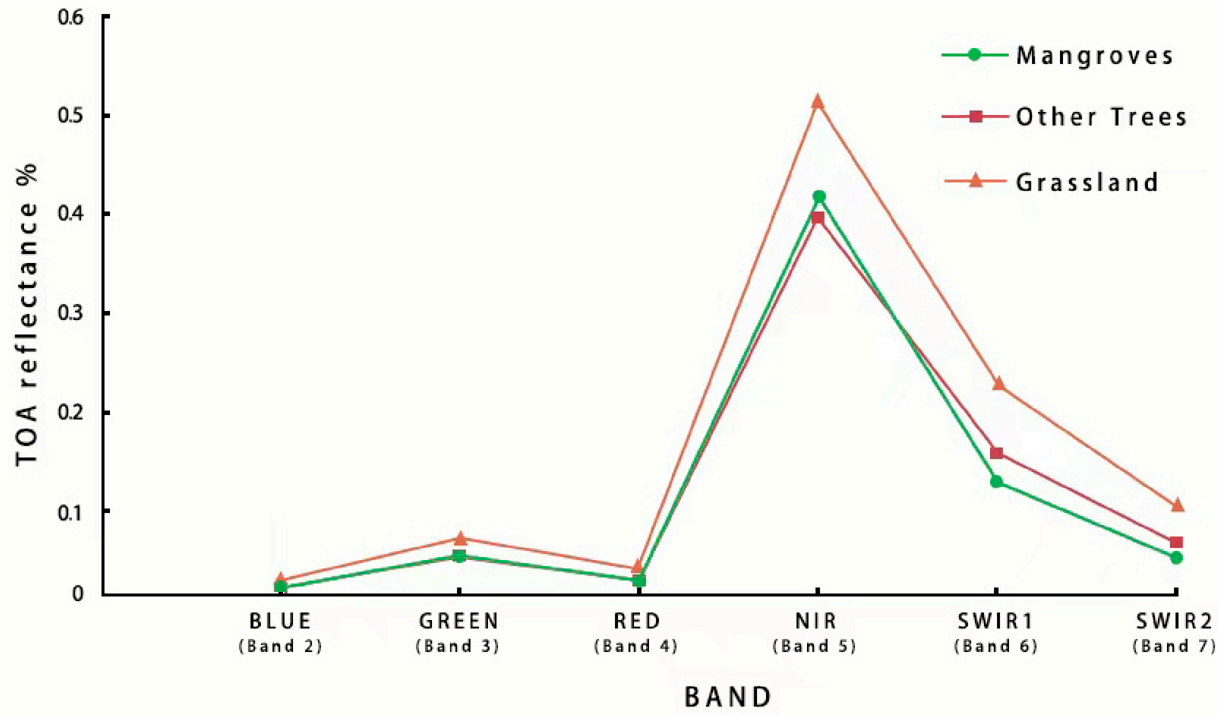
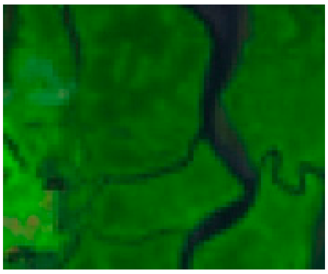
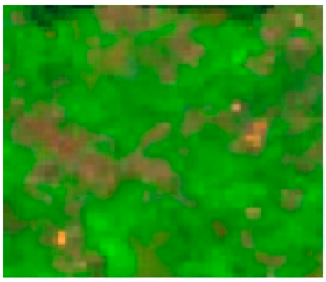


Figure 4. Spectral characteristics of ground objects in different bands of remote sensing images.

Table 2. Image characteristics and interpretation signs of target objects in the study area (false color image).

Feature Type	Interpretation Signs	Image Features
Mangrove		It mainly grows in the intertidal zone of estuaries. The image appears dark green, and densely distributed, and the patches have no stripes.
Other forests		The image is bright green or light green, relatively sparsely distributed, and has yellow patches in the middle.

2.5. Standard Deviation Ellipse Analysis

Standard deviational ellipse (SDE) analysis was applied to address the distribution direction of mangroves on Hainan Island. The core of SDE means the barycentric coordinate of mangrove distribution. The azimuth angle means the horizontal angle of mangrove distribution.

(1) Core:

$$\overline{X} = \frac{\sum_j^n w_i y_i}{\sum_i^n w_i}, \ \overline{Y} = \frac{\sum_j^n w_i y_i}{\sum_i^n w_i} \quad (1)$$

(2) Azimuth angle:

$$\tan\theta = \frac{\left(\sum_i^n w_i^2 x_i^{\sim 2} - \sum_i^n w_i^2 y_i^{\sim 2}\right) + \sqrt{\left(\sum_i^n w_i^2 x_i^{\sim 2} - \sum_i^n w_i^2 y_i^{\sim 2}\right)^2 + 4\sum_{i=1}^n w_i^2 {}^{\sim} y_i^{\sim}}}{\sum_{i=1}^n 2w_i^2 x_i^{\sim} y_i^{\sim}} \tag{2}$$

In Equations (1) and (2), n is the number of sample units; x_i and y_i are the longitude and latitude of the core in the ith sample unit; w_i is the number of expressions of mangroves; $\overline{X}$ and $\overline{Y}$ are the weighted average core coordination; θ is the azimuth angle of SDE, indicating the distribution direction of mangroves.

2.6. Markov Chains Analysis

To study the future area change trend of mangrove forests on Hainan Island, the future growth trend of mangrove forests on Hainan Island was studied. In this study, we used IDRISI17.0 software to select the spatial area data of Hainan Island in 2010 and 2015 and applied the Markov procedure and CA–Markov model algorithm to simulate the development of mangrove forest 2020 on Hainan Island.

2.6.1. Stochastic Matrix

The study on the evolution of mangroves on Hainan Island can be studied by using a stochastic matrix. A stochastic matrix is used to model the transition between mangrove-growing land and non-mangrove-growing land over a given time period. By examining the matrix, we can determine the rate at which one type of land transitions to the other. The method to calculate this matrix is detailed in Formula (3), as described in [40]:

$$S_{ij} = \begin{Bmatrix} S_{11} & S_{12} & S_{13} & \cdots & S_{1n} \\ S_{21} & S_{22} & S_{23} & \cdots & S_{2n} \\ S_{31} & S_{32} & S_{33} & \cdots & S_{3n} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ S_{n1} & S_{n2} & S_{n3} & \cdots & S_{nn} \end{Bmatrix} \qquad (i, j = 1, 2, 3, \ldots, n) \tag{3}$$

where S_{ij} refers to the area of land class, i converted to land class j; S_i refers to the land class before conversion; S_j refers to the land class after conversion; n refers to the total number of land classes in the study area.

2.6.2. CA–Markov Model

The cellular automaton (CA) is essentially a lattice dynamics model, which is characterized by discrete time, space, and state, and simulates the spatio-temporal evolution of complex systems based on spatial interactions and temporal causality.

The Equation (2) used is shown below:

$$S_t + 1 = f\,(S_t,\ N) \tag{4}$$

where S refers to the finite, discrete set of states of the tuple; N is the neighborhood of the tuple; t and t + 1 are different moments; and f is the transition rule of the tuple.

Markov models are discrete-time stochastic models. This model is widely used in land use forecasting. It mainly uses previous and current land use to calculate the number and probability of area shifted between different types of land in that period for future land use prediction [41].

When a piece of land is growing mangroves or not, it can also be seen as a difference in land use. If the area of mangroves decreases, it means that more and more land is converted to non-mangrove-growing land. This is like nature's selection for changing land use types. So, this study innovated the use of the Markov model to predict the area change of mangroves.

Equation (5):

$$S_t + 1 = P_{ij} S_t \tag{5}$$

where S_t, S_t + 1 refers to the state of the land use system at the moment t, t + 1; P_{ij} refers to the stochastic matrix.

In this study, the CA–Markov model was utilized under IDRISI17.0 software based on the following processes: (1) data conversion and reclassification; (2) using the Markov function to determine the mangrove transfer area matrix and transfer probability matrix of Hainan Island from 2000–2020 in the study area and function to establish the suitability atlas; (3) constructing CA filter, where this study used a Standard 5 $\times$ 5 contiguity filter for the neighborhood definition; (4) simulate the 2020 mangrove area based on 2010–2015 mangrove area data and compare the Kappa coefficient (greater than 0.75) with the actual 2020 mangrove area; (5) set the starting 2015 with 2020 to simulate the 2025 mangrove area; (6) set the starting point for 2020 and 2025 to simulate the 2030 mangrove area.

3. Results

3.1. Attitudinal Changes in Mangrove Forests of Hainan Island

We summarized the time-series images of the main mangrove growth areas in Hainan Island interpreted by remote sensing to obtain Figure 4 and created a table (Table 3) showing the data on the area of mangroves. Each row represents the name of a mangrove nature reserve, and each column represents the area data in different years. The dimensions of this table include time and space. The time dimension reflects data for different years, while the spatial dimension showcases data from various mangrove forest reserves. In data analysis, dimensions refer to different ways of categorizing data, such as time, geographical locations, and product types. Time and space are the two fundamental dimensions of this table, allowing for a comprehensive analysis and comparison of the mangrove forest areas. For instance, by comparing data from different years, we can understand the growth trends of the mangrove forests. Simultaneously, comparing data from different reserves enables us to grasp the differences and characteristics among them. The selection and definition of dimensions are crucial for accurately interpreting and analyzing data. This requires a rational choice and definition based on specific questions and research objectives to ensure the derivation of accurate and meaningful conclusions.

Table 3. Status of the mangrove area (he) on selected protected areas of Hainan Island from 1990 to 2020.

Label	Site	1990	1995	2000	2005	2010	2015	2020	Trend
A	Dongzhaigang	1615	1540	1664	1723	1787	1740	1751	
B	Dongfang	26	38	30	60	67	77	80	
C	Huiwen	1055	989	817	826	869	878	904	
D	Guannan	227	191	193	174	173	156	167	
E	Xinyinggang	328	301	289	230	273	290	298	
F	Yangpugang	747	730	498	492	609	627	682	
G	Huachangwan	355	300	234	220	367	334	327	
H	Puqian	170	167	147	145	160	138	141	
I	Maniaogang	55	30	46	50	192	112	124	

The data analysis shows that the mangrove area has experienced fluctuations over the past 30 years. The area declined from 4578 hectares in 1990 to its lowest point of 3870 hectares in 2005. However, it subsequently increased to 4474 hectares by 2020, showcasing an overall trend of initial decrease followed by a rebound. However, there have been areas where the mangrove area has declined. Among them, the Eastern and Mayao ports have demonstrated particularly significant growth. Despite the relatively small size of the Mayao port area before 2005, it experienced rapid expansion after that year, possibly due to artificial planting or effective conservation measures implemented in the region. On the other hand, the mangrove area in Yangpu Port drastically decreased after 1995, likely due to environmental changes or human activities impacting the mangroves [42].

Additionally, the Huiwen region had a larger mangrove area before 1995, but it gradually decreased afterward, while other areas experienced relatively minor changes in their mangrove areas. Overall, the conservation and restoration efforts for mangroves have achieved some level of success. However, further strengthening is still required to ensure the effective protection of this critical ecosystem.

Based on the provided data, we can conduct a frequency distribution and measure the central tendency of the mangrove area changes. Firstly, we calculate the average area of each mangrove in different years to understand the overall trend. Secondly, we compute the distribution of mangrove areas for each year to assess the magnitude and speed of changes. Finally, we visually represent the distribution of the data and the central tendency of the trend by creating a histogram, shown in the lower right corner of Figure 5.

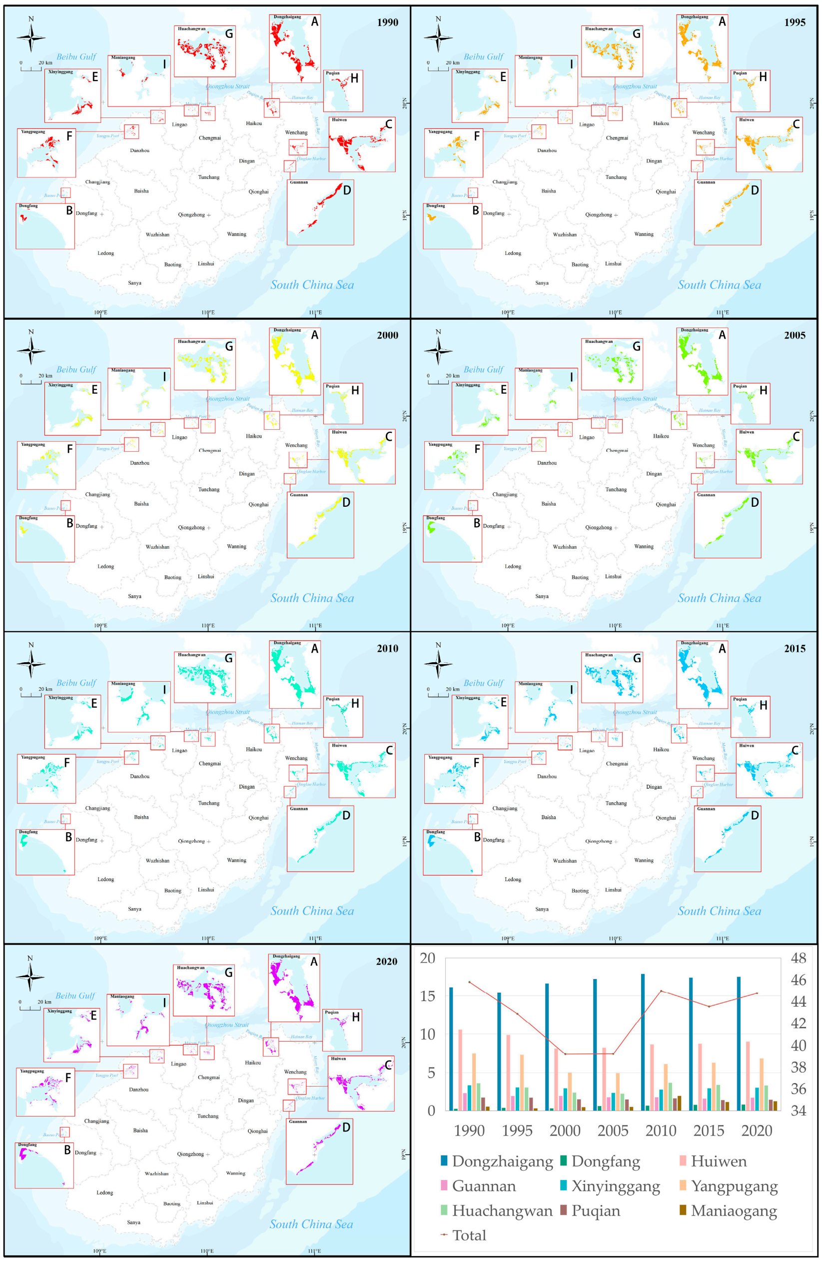


Figure 5. Time-series changes and area change trends of main mangrove growth areas in Hainan Island (A: Dongzhaigang; B: Dongfang; C: Huiwen; D: Guannan; E: Xinyinggang; F: Yangpugang; G: Huachangwan; H: Puqian; I: Maniaogang).

Based on the data, we can observe that the mangrove area in Dongzhaigang remained relatively stable from 1990 to 2020, with significant increases in 2000 and 2010. Conversely, the mangrove areas in Huiwen, Guannan, Xinyinggang, Yangpugang, Huachangwan, and Puzhong decreased over these 20 years, with Huiwen and Guannan experiencing the most significant reductions. These changes are likely associated with the local natural environment, human activities, and climate change factors. Therefore, to ensure the sustainable development of mangroves, we need to conduct in-depth research into the impacts of these factors on the mangrove ecosystem. Such research will facilitate the formulation of better conservation and management measures to address potential challenges and promote the healthy development of the mangrove ecosystem.

Meanwhile, we observed outliers in Yangpugang between 1995 and 2000, with the area decreasing from 7.30 to 4.98 and rebounding to 6.09 in 2010. Since the large ports around Yangpugang have experienced massive construction in recent years, the above changes may be attributed to human activity factors. Huachangwan also exhibited an outlier between 1995 and 2000, with the area decreasing from 3.00 to 2.34 and then rising to 3.67 in 2010. These fluctuations might have resulted from data collection or recording errors. When conducting data analysis, special attention should be given to these outliers to ensure data accuracy and reliability. Identifying and addressing outliers are crucial for properly interpreting and utilizing data.

The main mangrove forests on Hainan Island can be further divided into nine regions based on their spatial distribution. These regions are Dongzhaigang, Dongfang, Huiwen, Guannan, Xinyinggang, Yangpugang, Huachangwan, Puzhong, and Mayao. The specific spatial characteristics of mangrove area changes from 1990 to 2020 are depicted in the figure (Figure 6). The red areas represent regions where mangroves have grown, the green areas indicate regions where mangroves have decreased, and the gray parts represent areas where there are no changes in the mangrove range. This figure displays the spatial distribution of mangrove growth and decline within the same region.

From 1990 to 2020, the mangrove landscape on Hainan Island showed a trend of fragmented growth and reduced connectivity. The fragmentation level refers to the spatial division and dispersion of mangrove areas. From 1990 to 2020, it appears that the mangrove area expanded, though this observation suggests it occurred in a fragmented manner, with intervals and breaks between mangrove growth areas. This fragmented growth could be attributed to human activities such as urbanization, land use changes, and agricultural expansion, which led to disruptions in the continuity of mangroves. However, the connectivity of mangroves exhibited a decreasing trend. Connectivity refers to the degree of linkage and communication between mangrove fragments. Due to the influence of human activities and natural factors, the connections between mangrove areas gradually decreased. Overall, the conservation efforts for mangroves have achieved significant results, but some regions still require further strengthening.

We calculated the overall standard deviation ellipse from 1990 to 2020 for the main mangrove-growing areas in Hainan Island. Also, we calculated the standard deviation ellipses for each mangrove-growing area from 1990 to 2020. According to Figure 7, from the change of the overall standard deviation ellipse of mangroves in Hainan Island, the overall change of mangroves in Hainan Island is relatively slow from 1990 to 2020. The standard deviation ellipse is located in the northern part of Hainan Island, covering Haikou, Chengmai, Wenchang, Danzhou, Lingao, Ding'an, and Tunchang. The long axis of SDE is distributed almost along the east–west direction, the long axis increased from 89.54 km in 1990 to 97.64 km in 2020, and the short axis decreased from 26.74 km in 1990 to 26.01 km in 2020. There is a certain change in the circle's center, and the center coordinates generally move westward. This shows that the mangrove forests in Hainan Island are generally in a stable state, mainly distributed along the coast of the northern part of Hainan Island centered on Chengmai, and the mangrove forests in Hainan Island are mainly located in the mangrove area distributed along the east–west direction of Hainan Island.

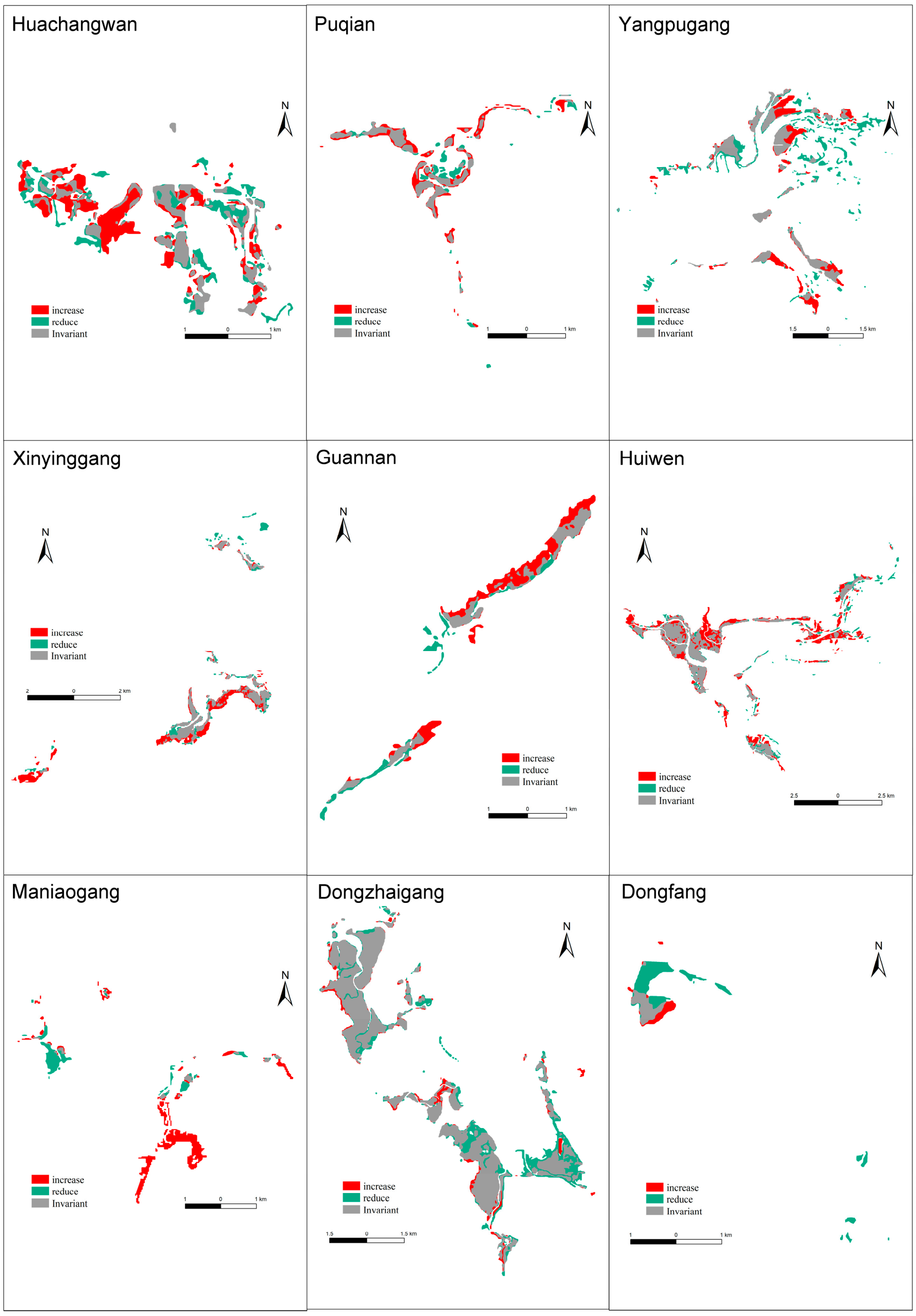


Figure 6. Comparison of the area of main mangrove-growing areas in Hainan Island in 1990 and 2000.

The change of standard deviation ellipse and SDE center point of each mangrove growth area in Hainan Island is shown in Figure 8. The SDE center point of Dongzhaigang generally presents a northwest–southeast distribution. The center point moved southward first and then moved northwestward after 1995. The long axis did not change significantly, and the short axis decreased from 6.6 km in 1990 to 5.8 km in 2020. The orientation angle changes from 148.38° to 151.75°. In examining the spatial patterns, we observe that the mangroves in Dongzhaigang have undergone contraction, particularly in the northwest–southeast direction. Furthermore, this contraction appears to be more pronounced and at a faster rate towards the southeast. The SDE center point position, long axis, short axis, and direction angle of Dongfang all have significant changes, and the distribution range of mangroves has increased to a certain extent. In the southeast of this area, a small amount of new mangroves are in the early stage of formation, and it remains to be seen through long-term observation whether they can continue to develop in the future. The

SDE center point of Huiwen first moved to the northwest and then to the northeast, the long axis increased from 52.15 km to 59.85 km, the short axis remained unchanged, and the direction angle gradually changed from 76.64° to 66.83°, indicating that the overall mangrove forest in this area It is in a state of growth, and the growth is mainly concentrated in the northeast direction. The SDE center point of Guanan moves to the northeast, the long axis decreases from 0.62 km to 0.45 km, and the long axis increases from 32.18 km to 35.45 km. It can be seen that the distribution of mangroves in Guannan presents a northeast-southwest direction, and the increased mangroves are mainly concentrated in the Northeast and northwest mangroves have decreased. The SDE center point of Xinyinggang moved to the northeast, the long axis was basically stable, the short axis decreased from 6.11 km to 5.56 km, and the distance and direction angle gradually changed from 42.48° to 26.79°. It can be seen that the mangroves in this area are distributed from northeast to southwest, and the distribution range is reduced. Moving northeast from the SD ellipses, the disappearing mangroves are mainly concentrated in the southwest. The SDE center point of Yangpugang is roughly moving to the northeast, the long and short axes are stable, and the direction angle is unchanged. It can be seen that in the northeast side of the region, mangroves have increased. On the southwestern side of the area, however, mangroves have declined. The SDE center point of Huachangwan generally moves to the southwest, the long axis increases from 2.44 km to 2.71 km, and the short axis and direction angle are stable. It can be seen that the distribution of mangroves in this area generally presents a northwest–southeast trend, and the mangroves move to both sides. expanded. The SDE center point of Puqian generally moved northeastward, the major axis decreased from 1.76 km to 1.46 km, the minor axis decreased from 2.93 km to 2.43 km, and the direction angle changed from 12.48° to 21.11°. It can be seen that the distribution of mangroves in this region shows a northeast–southwest trend, while the area of mangroves has shrunk, and the disappearance of mangroves in the southwest is relatively faster. The SDE center point of Maniaogang moved westward in general, the long axis increased from 2.72 km to 3.04 km, the short axis increased from 1.31 km to 1.67 km, and the direction angle changed from 102.47° to 123.71°. It can be seen that the distribution of mangroves in this area presents a northwest–southeast trend and the area of mangroves in the northwest of this area has increased.

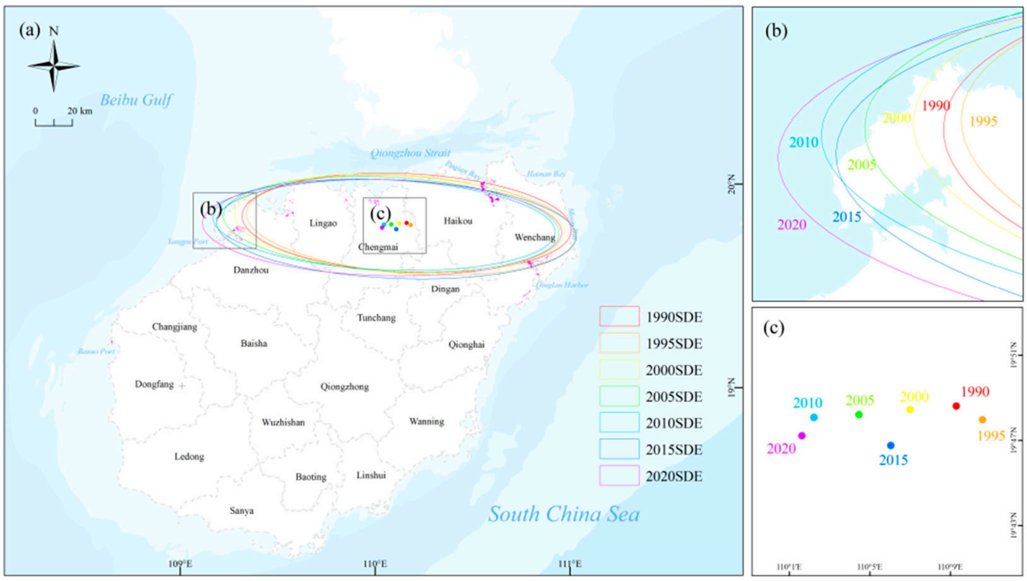


Figure 7. Population standard deviation ellipses (**a**,**b**) and SDE center point (**c**) of main mangrove distribution areas in Hainan Island from 1990 to 2020.

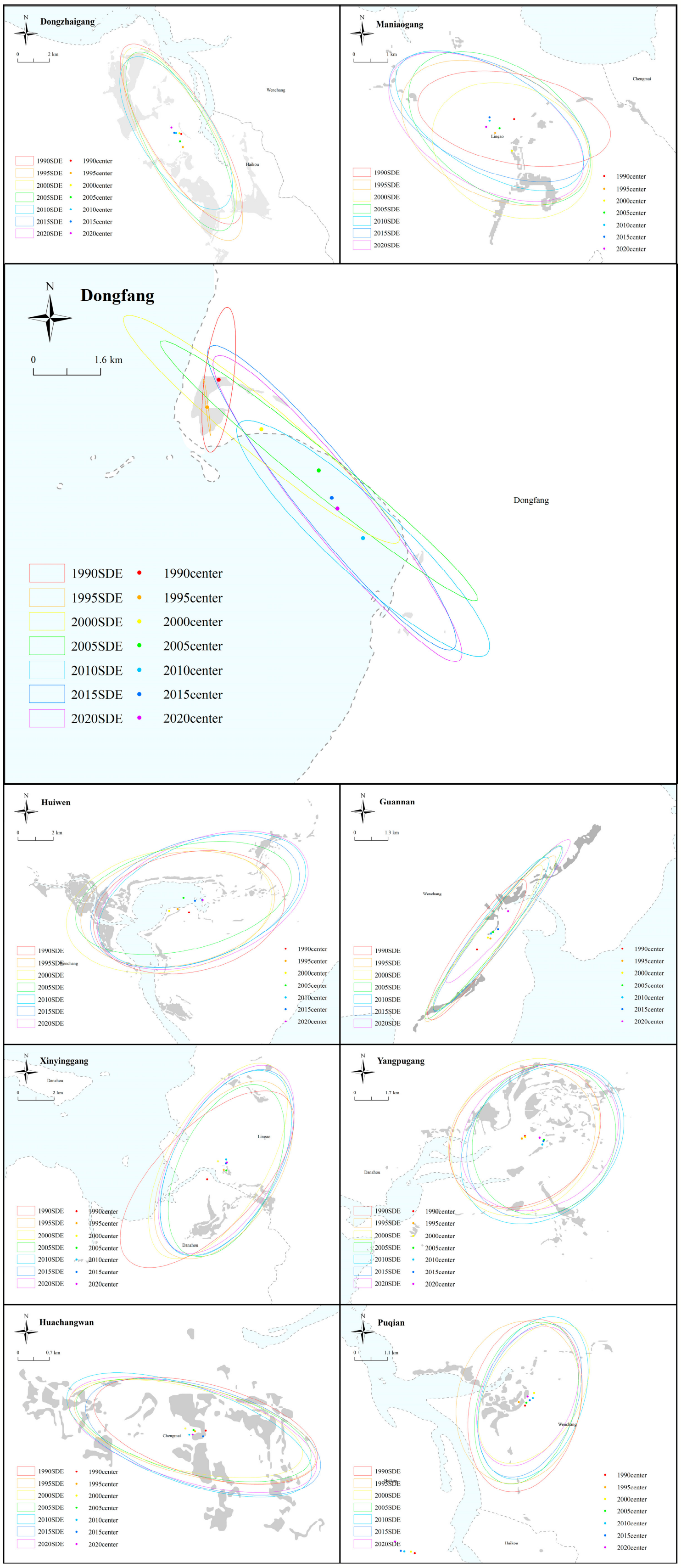


Figure 8. Standard deviation ellipse and SDE center point of main mangrove distribution areas in Hainan Island from 1990 to 2020.

3.2. Mangrove Growth Prediction

The transition matrix (Table 4) for the 2020–2030 decade was derived using the Markov procedure. Subsequently, the probability transition matrix for the2025–2030 period was also computed following the procedure.

Table 4. Stochastic matrix.

		Non-Mangrove	**Mangrove**
2020–2025	Non-mangrove	0.8498	0.1502
	Mangrove	0.1804	0.8196
2025–2030	Non-mangrove	0.7391	
	Mangrove		

Then, the stochastic probability matrix from 2020 to 2025 and from 2025 to 2030 (Table 4) was calculated according to the Markov procedure. The final simulation results in the change of mangrove area in Hainan Island in 2030 as shown in Figure 9.

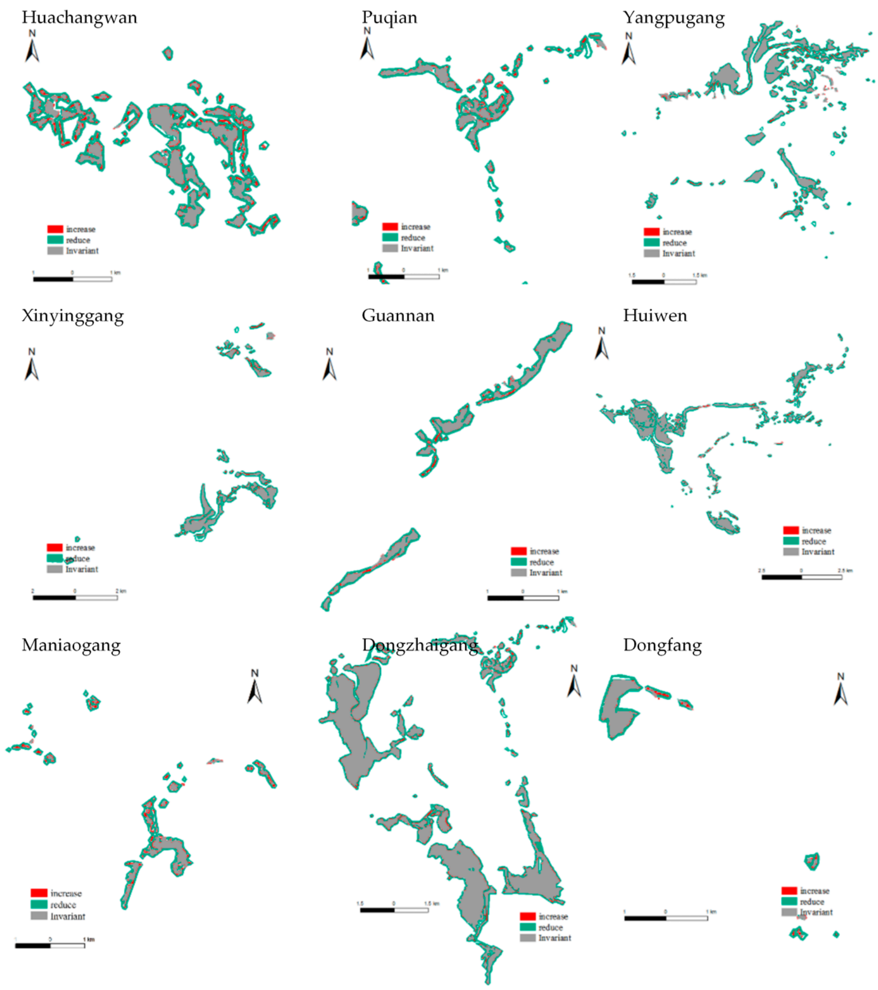


Figure 9. Mangrove changes on Hainan Island: 2020 vs. 2030.

3.3. Analysis of Driving Factors

Based on the detailed analysis of our simulation results from past data, we can understand more specifically that the future changes in mangrove forests on Hainan Island will mainly be concentrated in the marginal areas of mangrove forests. These marginal areas usually refer to the transition areas between mangroves and their surroundings, such as estuaries, wetlands, and shorelines.

In these marginal areas, we observe a series of dynamic changes in the area of mangroves, while remaining relatively stable overall. Specifically, the area of mangroves will experience some growth and contraction in the future, but the overall area tends to stabilize. This dynamic balance is due to a combination of factors, such as sea level rise, climate change, soil salinity, and human activities.

With the trend of global warming and sea level rise, the marginal areas of mangroves may be subject to more inundation and erosion. This may result in the retreat of some mangrove vegetation and a reduction in area. It is also likely that some new mangrove areas will begin to form to accommodate this change. These new mangroves may occur at higher elevations or away from the shoreline.

In addition, changes in soil salinity will also affect the marginal areas of mangroves. Mangrove plants are more adaptable to saline soils. Therefore, mangroves are usually able to survive in higher salinity environments. However, when salinity is too high, the marginal areas of mangroves may be suppressed to some extent, reducing area. Some human activities, such as agricultural discharges and industrial wastewater discharges, may increase the salinity content of the soil and thus have a greater impact on the marginal areas of mangroves.

Human activities can also significantly impact the marginal areas of mangrove forests [43]. In recent years, tourism and urbanization have been growing on Hainan Island, which has led to the development and alteration of the land surrounding the mangroves. These development activities may reduce mangrove areas as some areas originally belonging to mangroves are used for the construction of tourism facilities or urban infrastructure.

In conclusion, the drivers of mangrove change are changing in response to shifts in the patterns of human exploitation of the coast.

4. Discussion

4.1. Impact of Climate Change on Mangroves

As the concentration of greenhouse gases in the atmosphere rises, it results in a more pronounced greenhouse effect. This increases near-surface air temperatures, further contributing to climate warming and a continuous rise in sea levels [44]. Although the rate of sea level rise is relatively slow, it still adversely affects the growth of mangroves. Mangroves are usually found above the mean sea level in the intertidal zone of the coast. Therefore, their physiological characteristics do not allow them to be immersed in seawater for long periods. Sea level rise will cause the mangroves near the ocean side to be inundated by seawater, seriously threatening their survival. In particular, mangroves on Hainan Island have a small tidal range, making them more sensitive to sea level rise. On the other hand, Hainan Island is often subject to monsoonal flooding. As the root system of mangroves is not stable enough, they are susceptible to root displacement due to flooding [45]. Root displacement may further weaken the mangrove's ability to adapt to sea level rise. Because the roots are not firmly anchored in the soil, it increases the risk of mangrove collapse. Strong currents from floods may scour mangrove roots, further destabilizing them and making mangroves more vulnerable to seawater erosion and inundation [46]. In addition, climate warming directly affects the growth and reproduction of mangroves. High temperatures and drought conditions challenge mangroves with inadequate water and nutrient supplies. Mangrove plants are adapted to a specific intertidal environment and their physiological characteristics make them very sensitive to salinity and temperature fluctuations. High temperatures and droughts triggered by climate change may stress mangrove plants and reduce their growth rate and reproductive capacity [47]. This hurts maintaining the stability and diversity of mangrove ecosystems (Figure 10).

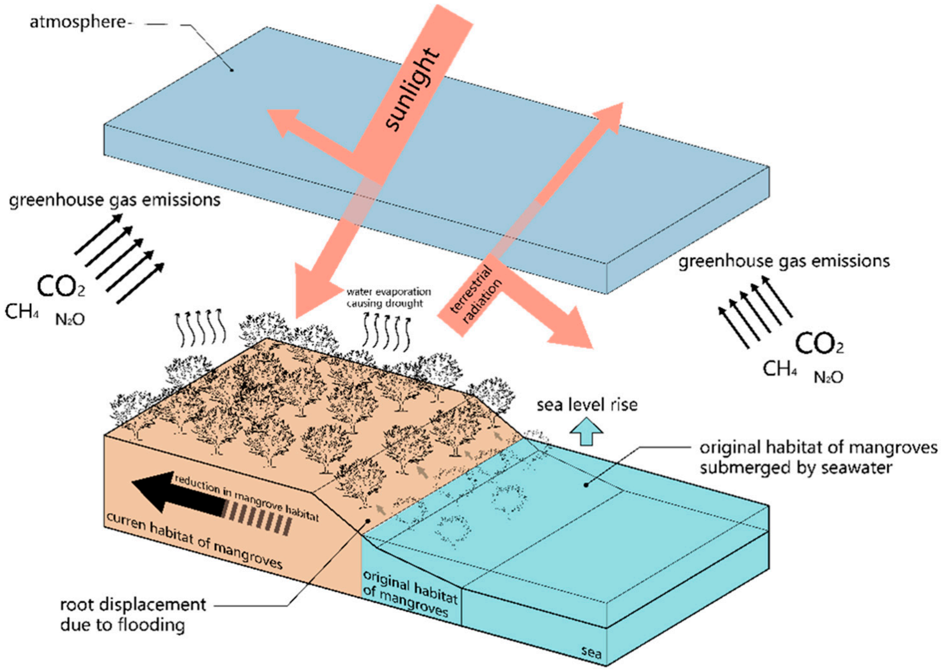


Figure 10. The impact mechanism of climate change on the stability and diversity of mangroves.

The IPCC, an acronym for the Intergovernmental Panel on Climate Change, is a cross-governmental organization established in 1988 by the World Meteorological Organization and the United Nations Environment Programme. Its primary mandate is to assess the scientific knowledge, potential impacts, and mitigation options of human activities on climate change. The IPCC formulates various CO_2 emission scenarios and global surface temperature scenarios to predict potential consequences and risks of future climate change.

Under different IPCC contexts, the impacts of CO_2 emission scenarios and global surface temperature scenarios on mangrove growth are outlined below (Figure 11) [48].

CO_2 emission scenarios are categorized into five levels: very low, low, moderate, high, and very high, corresponding to different levels of CO_2 emissions and growth rates. Generally, higher CO_2 emissions lead to faster sea-level rise (SLR), posing greater threats to mangroves. According to the paper's analysis, if the sea-level rise rate exceeds 6 mm per year, mangroves could be at risk of submergence and survival would be compromised. Hence, the highest risks for mangroves are observed under very high and high CO_2 emission scenarios, whereas better adaptability is anticipated under very low and low CO_2 emission scenarios.

Global surface temperature scenarios are divided into five categories: 1.5 °C, 2.0 °C, 3.0 °C, 4.0 °C, and 5.0 °C, representing different levels of the global average temperature increase. Generally, temperature rise affects mangrove species composition, physiological processes, primary productivity, and ecosystem respiration. Temperature elevation may promote mangrove growth and carbon fixation within a certain range (average daily temperature below 35 °C). However, surpassing a critical threshold can lead to adverse effects and even large-scale mortality. Furthermore, temperature rise might drive mangroves to expand towards higher latitudes, replacing low-productivity or marginalized ecosystems like salt marshes, thereby enhancing carbon storage. Consequently, favorable development prospects for mangroves are anticipated under the 1.5 °C and 2.0 °C global surface temperature scenarios, while severe losses may occur under scenarios exceeding 3.0 °C.

In conclusion, the impacts of CO_2 emission scenarios and global surface temperature scenarios on mangrove growth vary in complexity under different IPCC contexts, necessitating a comprehensive consideration of diverse factors and feedback mechanisms.

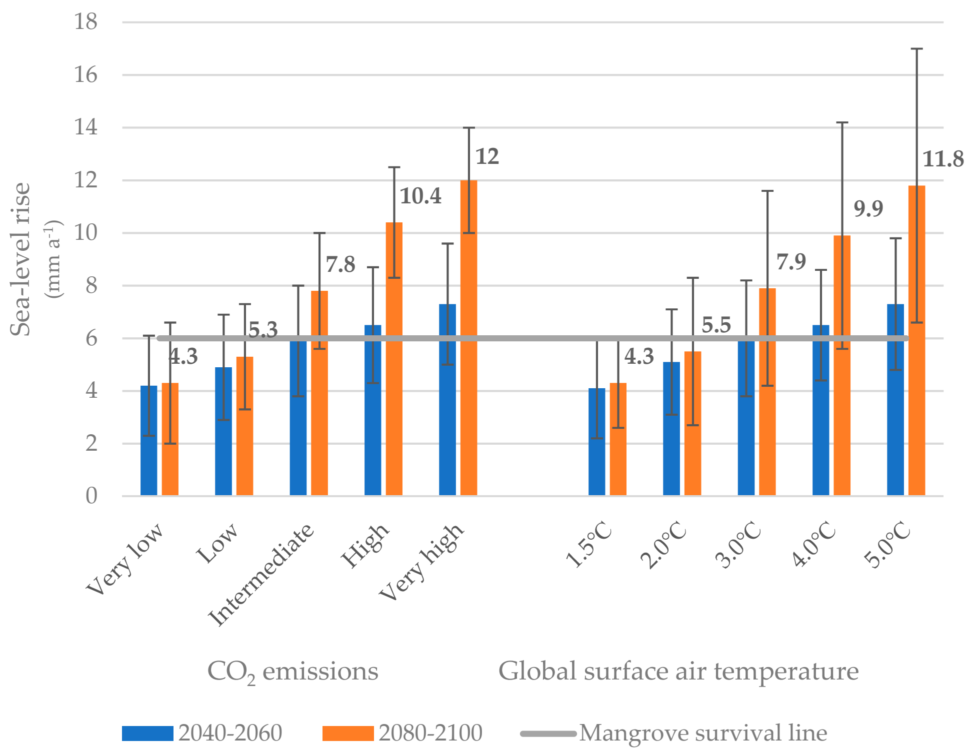


Figure 11. The impacts of CO_2 emissions scenarios and global surface air temperature scenarios on mangrove growth under different IPCC contexts.

4.2. Impact of Human Activities on Mangroves

In addition, human activities have led to rapid urbanization and significant greenhouse gas emissions from industrial production, further exacerbating the greenhouse effect and causing issues such as drought and water scarcity in mangrove forests. Table 5 summarizes the specific impacts of some typical human activities on mangroves. Over the nearly 20 years since 1998, the Chinese government has issued a series of policies and regulations aimed at curtailing illegal logging of mangroves for construction and other purposes, such as the "Mangrove Protection Regulations of Hainan Province" [25]. These actions not only cause damage to the mangrove forests themselves but also result in soil erosion in the surrounding areas, causing immeasurable impacts on the growth environment of the mangroves. Furthermore, the development of fishing resources also affects the survival of mangroves. Overfishing can lead to a reduction in the populations of certain species in the food chain. This depletion can then impact the food sources of mangroves, disrupt their ecological balance, and potentially reduce the area in which they can thrive.

Through data analysis of some mangrove growth areas on Hainan Island, we found that the growth of mangroves fluctuates, which is closely related to human activities. After Hainan Island became a province of China in 1988 and established the Hainan Special Economic Zone, the coastal area experienced rapid economic development and population growth. From the time Hainan became an economic special zone to 2013 when the Hainan provincial government began to strictly restrict coastal development intensity, Hainan Island's tourism, real estate, and other coastal development activities also experienced significant growth. During this period, the overall area of Hainan Island's mangroves decreased, and the fragmentation of mangrove distribution areas increased, largely due to road construction and other infrastructure developments, resulting in decreased connectivity. Despite the implementation of strict protection measures by the local government, more proactive steps are still needed to mitigate the negative impact of human activities on the mangrove ecosystem. To protect the ecological environment of mangroves, we recommend strengthening control over greenhouse gas emissions and promoting sustainable urbanization and industrial development. Additionally, increased monitoring and law enforcement are necessary to ensure the legal protection of mangroves. Furthermore, sustainable development of fishing resources should be actively promoted to avoid overfishing [49].

Table 5. Summary of the impact of human activities on mangroves.

Human Activity	Influence Type	Influence Description
Coastal cities and their development	Negative effect	Increased land development and urban sprawl may lead to loss of mangrove habitat, water pollution, industrial wastewater discharge may affect water quality, and litter and pollution may harm mangrove health.
Fishery industry	Positive and negative effects	May provide food and economic resources, but overfishing may lead to species decline, and fishing nets and gear may damage mangrove vegetation and habitat.
Tourism	Positive and negative effects	There can be economic gains and increased awareness, but the influx of tourists can lead to human disturbance, litter generation, and habitat destruction.
River and water pollution	Negative effect	Industrial and agricultural pollutants may flow into mangrove water bodies, affecting water quality and biodiversity.
River water level regulation	Negative effect	Water level regulation of rivers and reservoir construction may lead to changes in hydrological conditions in mangrove areas, affecting tree growth and reproduction.
Coastal Development Project	Negative effect	Dikes, piers, and waterfront structures can alter water flow and sediment movement, affecting mangrove habitat and ecosystem function.
Emission of greenhouse gases	Negative effect	Causing climate change, rising sea levels and higher temperatures could lead to loss of mangrove habitat, species migration, and changes in ecological balance.

By collaborating across sectors, including government agencies, local communities, and environmental organizations, and by implementing comprehensive conservation initiatives, research programs, and community engagement activities, we can ensure the sustainable growth and prosperity of mangroves and foster a harmonious coexistence between humans and nature.

4.3. How to Protect or Conserve Existing Mangrove

Preserving and maintaining existing mangroves is paramount for ensuring the health and sustainability of their ecosystems. Notable successes in mangrove conservation have been achieved in areas such as Dongzhaigang Mangrove Nature Reserve, Shankou Mangrove Nature Reserve, and Fujian Zhangjiangkou National Mangrove Nature Reserve [50]. To achieve such an objective, several measures can be employed. Establishing standardized mangrove protection zones is a foundational strategy for mangrove conservation. By creating such reserves and restricting human activities and development within them, the integrity of the mangroves and the continuity of their ecosystems can be safeguarded. Under these conditions, mangroves can flourish and evolve naturally. Dynamic monitoring remains crucial for mangrove protection. Close monitoring of changes in mangrove coverage, population dynamics, and ecosystem functions is essential [51]. Regular assessments of water quality [52], soil health [53], and plant vitality within these environments can detect and address adverse environmental impacts on mangrove growth. Advanced monitoring tools allow for a comprehensive understanding of mangroves' status, formulating appropriate conservation and management strategies.

Besides monitoring, strict regulation of human activities is essential to mitigate negative impacts on the mangroves. Curtailing pollution, destructive fishing, and illegal logging can alleviate pressures on mangroves, thus preserving their ecosystem integrity and species diversity [54]. Promoting sustainable fisheries and ecotourism is vital for the sustainable utilization of mangrove resources [55,56]. Harnessing these resources through sustainable fishing practices and tourism activities can provide economic incentives for local community development while safeguarding the mangrove ecosystem [57].

A collaborative effort among governments, communities, and stakeholders is warranted to implement Integrated Coastal Zone Management (ICZM) [4]. The institution of management bodies and accountability mechanisms can standardize mangrove development. Moreover, initiating coastal restoration projects to proactively rejuvenate degraded mangrove areas is crucial. Enforcing strict coastal development regulations, encompassing the regulation of tourism, infrastructure, and industrial activities in proximity to mangrove areas, along with pollution control, is indispensable to prevent mangrove degradation.

4.4. How to Restore the Disappearing Mangroves

Restoring lost mangroves is a challenging task. This task requires a combination of ecological, geographical, and socio-economic factors. To achieve the restoration of mangroves, the first step should be to restore their suitable growing environment. This includes improving water quality, providing a suitable water environment by purifying water sources, and controlling the discharge of pollutants [58]. At the same time, soil quality and restoration measures should be improved [59]. Such as planting trees, adding organic substances, and improving soil structure. These measures can increase soil fertility and water retention capacity. In addition, vegetation cover is enhanced to form a suitable habitat for mangrove growth by planting plants adapted to the local environment. Selecting suitable mangrove species is the key to mangrove restoration. New mangrove communities are gradually established through seed introduction and cultivation. Mangrove species adapted to local environmental and climatic conditions are selected to ensure their adaptability and viability. Scientific species selection and adaptation tests are needed during the introduction process. Ensure the introduced species adapt to the local ecosystem and play an ecological restoration role [60]. When determining the coverage of mangrove planting, the need for a stable shoreline needs to be taken into account. Mature mangroves are less sensitive to the effects of seawater. Therefore, new mangrove plantings should be closer to inland areas to reduce the risk of being affected by the marine environment [61]. When delineating the extent of mangrove planting, the establishment and management of ecological protection zones should also be considered to ensure the integrity and sustainability of the mangrove ecosystem [62]. The Chinese government has recognized the significance of mangroves and has consequently established several mangrove nature reserves, particularly in provinces like Guangdong, Hainan, and Fujian. Exemplary efforts include the Beilun River Estuary National Nature Reserve in Guangxi and the Shangkou Mangrove Nature Reserve in Guangdong. Additionally, the Chinese government has actively engaged in mangrove restoration projects, aiming to counteract the degradation caused by aquaculture and other human activities.

4.5. Significance and Limitations of the Research Method

Mangroves, unique forest communities endemic to the tropical and subtropical coastal zones, hold significant value for both ecosystems and human societies. Despite their importance, they face considerable threats due to climate change and anthropogenic disturbances. To address these threats and understand their implications, researchers utilized a range of methodologies to investigate the long-term changes in the mangroves of Hainan Island. Remote sensing images from the Landsat satellite series, spanning from 1990 to 2020, were analyzed to monitor the coverage and area fluctuations of the mangroves. The adoption of remote sensing technology facilitated continuous and systematic observations over large areas and extended time frames, providing invaluable data on mangrove dynamics. This method significantly surpasses traditional ground-based surveys in both accuracy and efficiency. Subsequent analyses employed the standard deviational ellipse method to interpret the mangroves' spatial distribution patterns and evolutionary trends. This technique is instrumental in deciphering the spatial characteristics of mangrove distribution and their temporal shifts, laying the groundwork for predicting future trends and designing effective conservation strategies. Furthermore, the CA–Markov model was utilized to project potential changes in the mangrove cover within the study area for 2025 and 2030.

Markov prediction offers a simplified approach to understanding complex systems by focusing on a finite set of states and their transition probabilities, enhancing predictive efficiency and reducing computational demands. Specifically, our study concentrated on two states: mangrove growth area and non-growth area, and their inter-transitions. While this method effectively infer future states based on the current state, facilitating decision-making processes such as predicting mangrove growth trends influenced by climate changes and human activities, it is not without its limitations. For instance, real-world data complexities can challenge the foundational assumption of the Markov property, which presumes that future states depend solely on the present state.

Markov predictions operate under the assumption that sequential data adhere to the Markov property, where future states rely solely on the present state, remaining independent of past states. However, in real-world scenarios, this assumption can sometimes prove to be insufficient, as various factors beyond the current state might influence sequential data. In this study, the growth of mangroves may be influenced by multiple determinants such as climate, soil composition, and sea levels, potentially leading to deviations from the observed growth trends.

Markov prediction fails to elucidate the underlying causes and mechanisms driving sequential data changes; it can merely offer probabilistic outcomes [41]. It does not provide insights into the reasons behind mangrove increases or decreases, solely indicating the magnitude of the associated probabilities. Consequently, it proves challenging to undertake a comprehensive analysis and understanding of sequential data changes solely through Markov prediction.

The accuracy of Markov predictions typically positively correlates with the volume of data. While the dataset utilized in this study is sufficient for the modeling performed, acquiring a more precise forecast of future mangrove states and transition probabilities might necessitate an even larger data volume. Markov prediction relies on statistical learning methods to estimate parameters. Insufficient or low-quality data could introduce bias or variance in parameter estimation, thereby affecting the reliability of prediction outcomes. To minimize incorrect predictions from such models, subsequent research could consider using Markov chain methods in combination with other prediction methods, such as statistical methods, machine learning methods, or deep learning methods, to improve accuracy. At the same time, the parameters of the Markov chain model can also be adjusted to suit the needs of a specific problem, such as increasing the size of the state space or changing the state transition probability [63].

5. Conclusions

Mangrove forests, vital coastal ecosystems, play a pivotal role in providing a range of ecological services. This study employed Landsat remote sensing imagery from 1990 to 2020 to meticulously assess mangrove forest dynamics on Hainan Island through visual interpretation techniques. Additionally, the future development of these forests was predicted using Markov chain analysis and the CA–Markov model.

Research shows that in the past 30 years, the area of mangroves has fluctuated, with an overall slow growth trend. The mangrove area in Dongzhaigang remained relatively stable during the period from 1990 to 2020, with significant increases in 2000 and 2010. Over the span of 20 years, several sites on Hainan Island witnessed a decrease in mangrove areas. Huiwen's mangrove coverage declined from 1055 hectares in 1990 to 904 hectares in 2020. Similarly, Guannan experienced a substantial reduction, starting at 227 hectares in 1990 and decreasing to 167 hectares by 2020. Xinyinggang's area shrank from 328 hectares in 1990 to 298 hectares in 2020, while Yangpugang's coverage diminished from 747 hectares to 682 hectares over the same period. Additionally, Huachangwan and Puzhong saw reductions in their mangrove areas, with the former dropping from 355 hectares to 327 hectares and the latter from 170 hectares to 141 hectares between 1990 and 2020. Although nowadays, the area covered by mangroves has increased, this growth has not been uniform. The mangroves have expanded in a fragmented manner, leading to patches of growth with noticeable gaps and interruptions between them, potentially due to human activities or environmental factors. According to the standard deviation ellipse analysis results, it can be seen that the mangroves in Hainan Island are generally in a stable state and are mainly distributed in the northern coastal area of Hainan Island centered on Chengmai. The mangroves in Hainan Island are mainly located in the mangrove areas distributed east–west on Hainan Island. Through Markov chain simulation, the total area of mangroves in Hainan Island will remain roughly unchanged between 2025 and 2030, with changes mainly concentrated in the transition areas between mangroves and their surrounding environments, including edge areas such as estuaries, wetlands, and coastlines.

Mangroves, unique forest communities native to tropical and subtropical coastal regions, play an indispensable role within ecosystems. They offer habitats for many marine species and aid in reducing coastal erosion, sequestering substantial amounts of carbon, and providing natural protective barriers for coastal communities. However, due to climate change and anthropogenic disturbances, the survival conditions for mangroves are under significant threat. This study has meticulously monitored the coverage and area changes of mangroves on Hainan Island, forecasting potential shifts for 2025 and 2030. Nonetheless, several questions remain and warrant further exploration:

1. Delving into mangrove ecological functions: Future studies could further elucidate specific functions of mangroves within ecosystems, such as their role in carbon cycling and support for marine life.
2. Mangrove restoration and conservation: Given the importance of mangroves, devising effective restoration and conservation measures emerges as a pressing issue. Subsequent research could evaluate diverse restoration and conservation strategies and their respective efficacies.
3. Interactions between mangroves and communities: Mangroves are important for coastal community residents. Upcoming studies might examine the symbiotic relationship between mangroves and communities, promoting greater awareness and involvement of local inhabitants in mangrove conservation.
4. Economic value of mangroves: Beyond their ecological significance, mangroves possess substantial economic value. Future research could dissect the economic potential of mangroves and explore avenues to translate this value into tangible economic benefits, thereby financially bolstering mangrove conservation efforts.
5. Mangroves in the face of climate change: The ramifications of climate change on mangroves represent a multifaceted issue. Advanced studies could delve deeper into this relationship and strategize for challenges induced by climate alterations.

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