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Change Detection of Mangrove Forests in Coastal Guangdong during the Past Three Decades Based on Remote Sensing Data

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Abstract: Mangrove forests are among the most productive ecosystems on Earth and mainly grow at tropical and subtropical latitudes. They provide many important ecological and societal functions. However, rapid spatiotemporal variations in mangroves have been observed worldwide, especially in the coastal zones of developing areas, and the integrity of mangroves has been significantly affected by anthropogenic activities in recent decades. The goal of this study was to determine the spatiotemporal characteristics of mangrove distribution over the past 30 years in Guangdong Province. This goal was achieved by classifying multi-temporal Landsat images using a decision tree method based on Classification and Regression Tree (CART) algorithm. The driving forces resulting in these spatiotemporal variations of mangroves were then discussed. Our analysis revealed that the classification method used in this study yielded good accuracy, with an overall accuracy and kappa coefficient of higher than 90% and 0.8, respectively. In Guangdong province, the mangrove forests covered areas of 9305, 9556, 6793, and 9700 ha in 1985, 1995, 2005, and 2015, respectively, with remarkable inter-annual changes. Mangrove forests are mainly located in Western Guangdong, and few are located in Eastern Guangdong. The distribution of mangrove patches became more fragmented from 1985 to 2005 and less fragmented from 2005 to 2015, and the distribution pattern in 2015 showed stronger connectivity than that in 1985. Natural factors, such as temperature, sea level rise, extreme weather events, and the length of the coastline, have macroscopic effects on the distribution of mangrove forests. Anthropogenic activities, such as deforestation, urbanization, and aquaculture development, have negative effects on the distribution of mangroves. On the other hand, the establishment of nature reserves has positive effects on the distribution of mangroves. The findings of this study provide a reference for the management and protection of mangroves, which is of great practical significance.

Keywords: mangrove; change detection; coastal zone in Guangdong Province; Landsat; CART

1. Introduction

Mangrove forests are among the most productive ecosystems on Earth and can be found at tropical and subtropical latitudes [1–3]. This ecosystem has received increasing attention from not only ocean and land managers but also academia and conservation communities [4,5] due to its important ecological and societal functions [6,7], such as providing food and breeding areas as well as nursing grounds for many fauna, reducing pollution, precipitating fine sediments, protecting coastlines, and storing carbon, among other functions [8–13]. However, mangroves have undergone rapid spatiotemporal variation worldwide, especially in developing areas [4], and the integrity of this ecosystem has changed at an alarming rate because of both natural and anthropogenic influences, especially extreme weather events; relative sea level rise; activities related to development, such as urbanization and highway construction, and the installation of shrimp and fish ponds [14]. Regular monitoring of the spatiotemporal characteristics of mangrove ecosystems could provide dynamic information to allow optimal coastal management policy to be formed in the future [15].

Remote sensing has numerous advantages for mangrove monitoring, such as providing synoptic and repeated coverage, low-cost or free data, and historical materials; therefore, remote sensing can largely complement field investigations in the vast swamps of mangrove forests [16]. Landsat images have been widely used to monitor mangrove forests because of their broad spatial coverage, long temporal coverage, and easy access [15,17–24], especially for large areas. A series of classification methods have been used to quantify the distribution and dynamic changes in mangroves around the world, including manual interpretation, supervised and unsupervised methods, hybrid classifiers, support vector machine (SVM), random forests classifier, classification and regression tree (CART), object-oriented classification, and so on. These methods have proven that the monitoring of mangrove forests by remote sensing is feasible [23–30]. In terms of classifying mangroves over large areas at different times, the decision tree classification method based on CART algorithm has shown the ability to obtain classification rules from training samples directly and has the advantage of being independent of the assumptions of value distribution. This method can assess variables independently from one another in contrast to other statistical analysis methods, such as maximum likelihood classification [31]. It is vital for incorporating multi-source ancillary datasets which usually exhibit different value distributions and are sometimes highly correlated [32]. Therefore, the decision tree classification method based on CART algorithm was adopted to retrieve the multi-temporal distribution information of mangroves in this study.

Mangroves in China, which are mainly distributed along the coastlines of Hainan, Guangdong, Fujian, and Taiwan provinces, have undergone dramatic changes in the past [33,34]. It was reported that Guangdong Province contains approximately half of the total mangrove area and it previously had the highest percentage among all provinces [34,35]. Guangdong province frequently suffers from the effects of rainstorms and tropical cyclones, and mangrove ecosystems provide superior protection of biodiversity and reduce storm damage. However, the total area of mangroves decreased from 62,000 ha in the 1950s to 15,000 ha in the late 1990s and 9289 ha in 2010 due to rapid urbanization and shrimp farming [36]. Although the total area of mangroves in Guangdong province has increased in recent years by means of artificial planting, plenty of natural mangrove areas, which are distributed along the coastal lines of silty sediment, have decreased over the past decades. The community structure and ecological function of mangroves have been significantly degraded. Therefore, monitoring the spatiotemporal characteristics and discovering the driving forces that may cause changes in the mangrove distribution in Guangdong province have become attractive to many researchers and are of great significance to ecological conservation. [35].

Previous studies mainly used descriptive and qualitative methods and focused on the protection and management of mangroves, thus leading to a lack of information on the mangrove distribution and corresponding variation. Furthermore, few investigations have considered the spatiotemporal variation in the mangrove distribution over a long period of time over the entire Guangdong Province [4,29]. Therefore, this study selected coastal Guangdong as a sample area to explore the distribution of mangroves over the past thirty years, from 1985 to 2015, and to discover the spatiotemporal variation pattern of mangrove distribution in this area. It attempts to provide referable information on the spatiotemporal pattern of mangrove distribution to aid in coastal management and mangrove protection.

2. Materials and Methods

2.1. Study Area and Data Source

Guangdong Province is located at 20°13′~25°31′N, 109°39′~117°19′E, as shown in Figure 1a. The province has 3368 km of mainland coastlines and 1805 km of island coastlines, with 1288 km of silt coastlines, 498 km of which are suitable for the growth of mangroves [37]. The mangroves in the region grow along the coastline between Raoping County (23°32′21″N, 116°57′22″E) and Lianjiang City (21°33′36″N, 109°45′03″E) [38]. Considering that mangrove ecosystems mainly distribute in the intertidal zone, the study area was limited within a buffer zone along coastal line with seaward and landward buffer distance of 10 km. Additionally, the spatial distribution of mangroves along the coastal lines in this province presents great differences, which are further discussed based on the three subregions—Eastern Guangdong, Pearl River Delta, and Western Guangdong—with the consideration of their geographical features. The province has an annual average temperature of 21.9 °C and an average annual rainfall of 1790 mm [39]. The region has both subtropical monsoon and tropical monsoon climates, and it is the most rainy region with the longest flood season among all the provinces in China; notably, the area is frequently affected by tropical cyclones, rainstorms, droughts, typhoons, strong winds, and other factors [39].

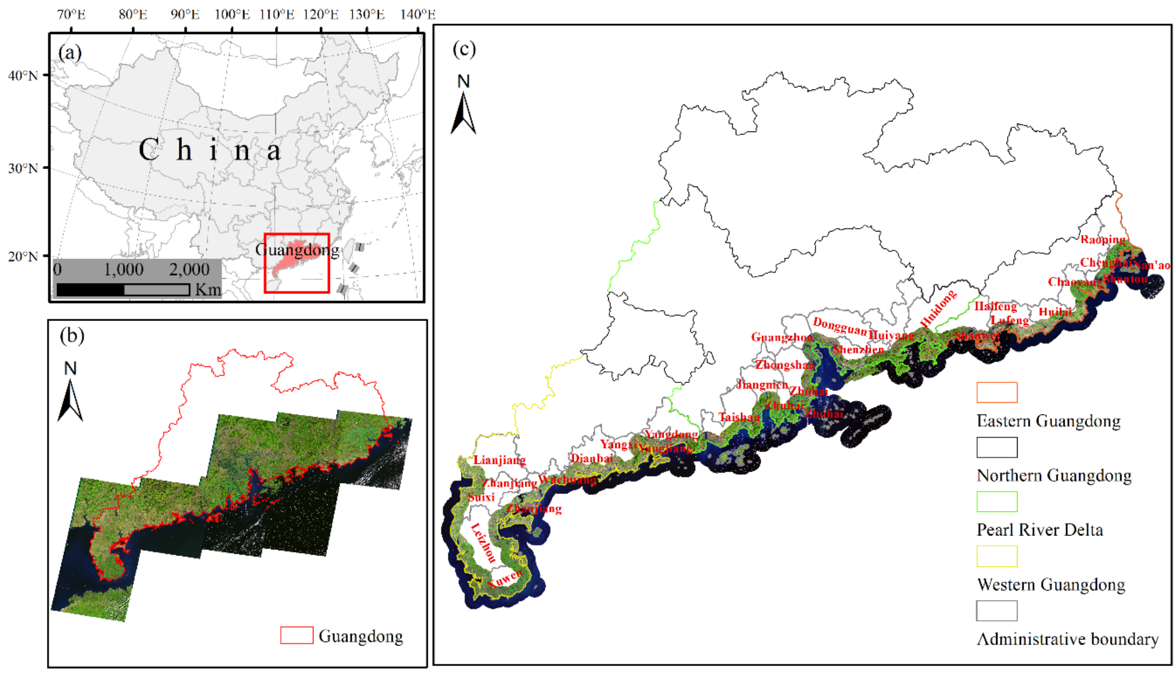


Figure 1. (**a**) Location of Guangdong province; (**b**) mosaic image (R, G, B = 5, 4, 3) covering coastal Guangdong collected in 1985; (**c**) subset image (R, G, B = 5, 4, 3) covering the study area in 1985, with the overlay of municipal administrative boundaries.

As it is often cloudy in the studied coastal area, which is vast and required eight mosaicked Landsat scenes, it was difficult to obtain cloud-free images of all scenes in the same year. As a result, images for study year 1985 were acquired in 1986 or 1987, and images for 1995, 2005, and 2015 were acquired in 1994 to 1996, 2004 to 2005, and 2013 to 2016, respectively. The Thematic Mapper (TM) scenes from 1985, 1995, and 2005 and the Operational Land Imager (OLI) scenes from 2015 had a spatial resolution of 30 m. The scenes were downloaded from websites of the United States Geological Survey (USGS) and the Geospatial Data Cloud. Their specific web addresses are https://www.usgs.gov/ and http://www.gscloud.cn/. Moreover, the high spatial resolution images, which were derived from Google Earth and collected in 2015, were used to validate the accuracy of the classification in 2015.

2.2. Image Preprocessing

First, radiometric calibration was performed for all images to eliminate the errors produced by variations in the sensor performance and characteristics over time as well as to generate the exoatmospheric reflectance images [40]. Second, atmospheric correction was implemented using the Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes (FLAASH) tool to eliminate atmospheric and light effects and to obtain the actual surface reflectance. Third, evenly distributed ground control points (GCPs) were selected to geometrically correct the images collected in 1985, 1995, and 2015 with the reference image collected in 2005. The fourth step was image mosaicking. For this process, the Seamless Mosaic tool was used to mosaic eight scenes for each study year, and the cubic convolution resampling method was selected because it provided a higher spatial accuracy than the nearest-neighbor resampling method [16]. The mosaic image from 1985 is shown in Figure 1b. Finally, we cropped the mosaic images to extract the subset images of coastal zone where mangrove forests grow. The result of cropped mosaic image covering the coastal zone of Guangdong province from 1985 is shown in Figure 1c.

This process improved the efficiency of the analysis by avoiding unnecessary calculations, and it improved the classification accuracy by reducing interference from inland areas. In addition, the final study region included Macao and Hong Kong. The mangroves in Macao and Hong Kong were counted with those in Zhuhai City and Shenzhen City, respectively.

2.3. Image Classification

To distinguish mangroves from other types of land use and to further discuss the factors influencing the mangrove distribution, six land cover types were defined: (1) mangroves, (2) water, (3) farmland, (4) built-up land, (5) other vegetation, and (6) other types (e.g., shadow areas, tidal flats, and bare land). These were mainly based on the consideration of the actual conditions, the characteristics identified through high spatial resolution images available on Google Earth, and other related studies [4,38]. Then, the decision tree method was used to retrieve the information about mangrove distribution. The decision tree method has been proven to be effective for mapping mangrove forests, as shown by [27]. The decision tree method based on CART algorithm is known as a machine learning or expert system and provides a non-parametric discriminating statistical relationship between multiple data layers to produce a binary decision tree. It splits the training data pixels into more and more homogeneous subsets through recursion and measures homogeneity according to classes defined by training data [24]. One advantage of this method is that it can incorporate multiple sources of data to define classification rules.

The main steps of the classification process, which are shown in Figure 2, include the following: (1) a multi-band image was composited to retrieve mangrove information; (2) the datasets used for classification were incorporated; (3) the training samples for each type of land use were selected with the Region of Interest (ROI) selection tool in ENVI (The Environment for Visualizing Images) 5.3. The false color composites combined with bands 3, 4, and 5 for TM and 4, 5, and 6 for OLI were used to assist the selection of training samples by referring to an established interpretation key (Table 1). The samples shown as polygons that were selected for training the classification rules are listed in Table 2. (4) The features of training samples were obtained and the CART algorithm was used to discover the relevant classification rules for each defined type of land use with the extension tool RuleGen of ENVI, which can analyze the ROI samples and generate the ENVI decision tree project file automatically; and (5) the rules were applied to stacked images to retrieve the classification results.

In this study, the original multi-spectral images; Normalized Difference Vegetation Index (NDVI) data, which is expressed as Formula (1); Inundated Mangrove Forest Index (IMFI) data, as proposed by Jia [41] and calculated using Formula (2); and the initial classification imagery obtained from ISODATA, were added as bands to improve the ROI separability. The NDVI, which ranges from −1 to 1, is an indicator of the health and density of vegetation, and a higher density of green leaves results in a value close to 1 [42]. The IMFI can help to distinguish between submerged mangroves and sea water.

Evenly distributed samples were selected to create decision trees, and the ROI separability values between different samples were greater than 1.8, which indicated that the samples were suitable.

$$\text{NDVI} = \frac{R_{nir} - R_{red}}{R_{nir} + R_{red}} \tag{1}$$

$$\text{IMFI} = \frac{R_{blue} + R_{green} - 2R_{nir}}{R_{blue} + R_{green} + 2R_{nir}} \tag{2}$$

where R_{red}, R_{blue}, R_{green} and R_{nir} represent the reflectance of the red band, blue band, green band, and near infrared band, respectively.

Table 1. Interpretation keys of all land cover types.

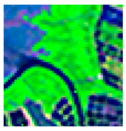
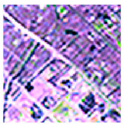
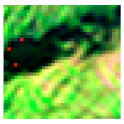
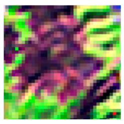
Land Cover Type	Landsat Image
mangrove	
water	
farmland	
built-up land	
other vegetation	
shadow	
tidal flat	
bare land	

Table 2. Number of polygon samples selected for training classification rules.

Year	Region	Mangrove	Water	Farmland	Built-Up Land	Other Vegetation	The Other Types
1985	Western Guangdong	39	208	272	148	269	140
	Pearl River Delta	67	160	250	170	155	142
	Eastern Guangdong	105	90	147	155	90	95
1995	Western Guangdong	576	300	817	658	406	225
	Pearl River Delta	60	120	370	430	600	115
	Eastern Guangdong	103	7	110	450	445	292
2005	Western Guangdong	600	295	900	761	488	390
	Pearl River Delta	75	580	830	555	687	101
	Eastern Guangdong	66	330	750	447	624	77
2015	Western Guangdong	150	80	262	231	135	87
	Pearl River Delta	38	210	130	175	123	36
	Eastern Guangdong	45	80	109	194	90	31

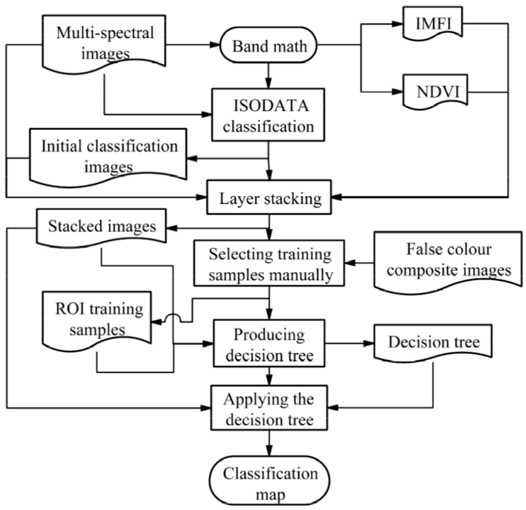


Figure 2. Flow chart of the classification process by using the Classification and Regression Tree (CART) algorithm.

2.4. Accuracy Validation

After classification, majority analysis was implemented, and further editing was performed to eliminate obvious errors. In addition, the accuracy of the classification results was further validated. To measure the quality of the classification, accuracy measures were used in this study. Generally, these measures were based on comparing a classification result with a reference classification obtained via a different method, e.g., on-site ground measurements, which are considered reliable and true. A confusion matrix that contains all the information about the relation between the classification and reference classification can be derived. Then, the overall accuracy (OA), producer's accuracy (PA), and user's accuracy (UA) can be calculated from the confusion matrix. The OA is defined as the proportion of all reference pixels that are classified correctly (in the sense that the class assignment of the classification and of the reference classification agree). As the OA, PA, and UA give no information about what classes are classified with high accuracy and cannot reflect the agreement between the two classification sets for each class, the kappa coefficient was further used to reflect this agreement.

Typically, high spatial resolution images from Google Earth can be regarded as ground truth data and have frequently been used to evaluate classification accuracy [43]. In this study, due to the difficulty in obtaining the ground truth data of mangrove distribution over such a large scope, high spatial resolution images derived from Google Earth were also regarded as the true references to calculate the OA, PA, UA, and kappa coefficient. The mangrove appearance on high spatial resolution images was confirmed by referring to the locations of mangrove reserves. In addition, accuracy validation was performed only for the classification result obtained in 2015 because of the difficulty in acquiring high-resolution images in previous study years. Evenly distributed samples were randomly selected from the Google Earth images collected in 2015 to calculate the indices. One hundred samples were selected for every land use type, except for the mangrove samples in Eastern Guangdong, where only 53 samples were selected, due to the small distribution of mangrove forest, and in Western Guangdong, Pearl River Delta, and Eastern Guangdong, where only 30 samples were selected for other types, due to the same reason. The distribution of these validation samples is shown in Figure 3.

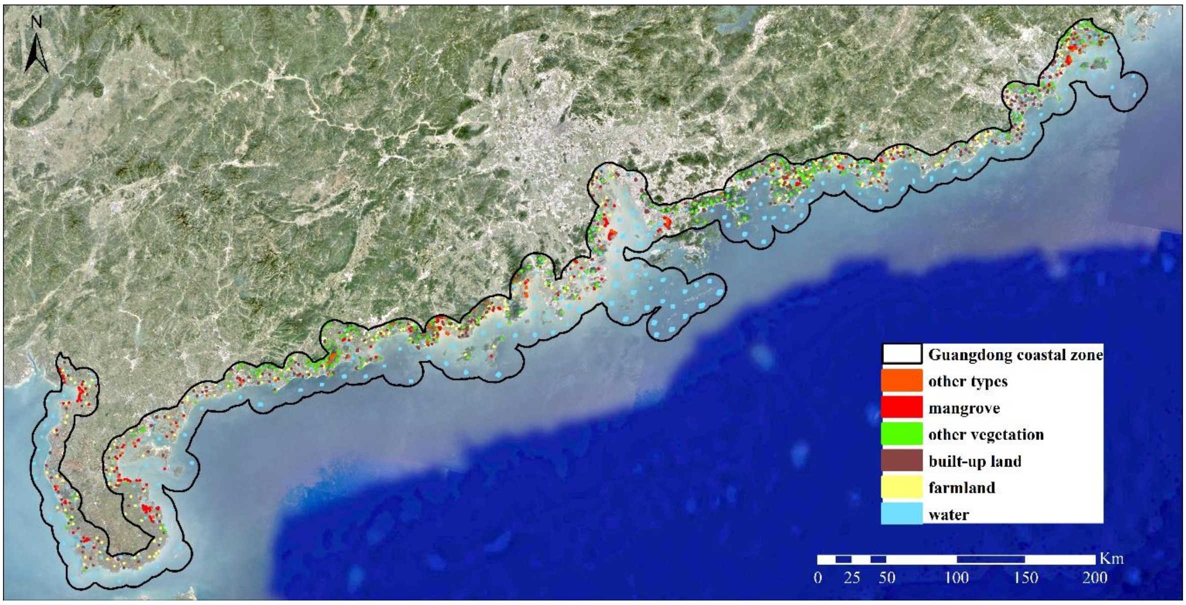


Figure 3. Spatial distribution of validation samples in 2015.

Image preprocessing and accuracy validation were performed in ENVI 5.3, and image classification was mainly implemented in ENVI 5.3, except for some editing that was done in ArcGIS 10.3.

2.5. Landscape Pattern of Mangrove Distribution

Furthermore, this study also focused on the spatiotemporal patterns of the mangrove distribution during the study period. Measures such as landscape metrics, which can reflect some ecological significance for land use change, have been adopted to discuss the spatiotemporal patterns of mangrove distribution based on the classification results. A total of six landscape metrics at the class level were selected in this study. These metrics are: (1) the mean patch area (AREA_MN); (2) the mean Perimeter-Area ratio (PARA_MN); (3) the mean shape index (SHAPE_MN); (4) the number of patches (NP); (5) the patch density (PD); and (6) the patch cohesion index (COHESION). Therein, AREA_MN and NP are size metrics, and the patch area is the basis for the calculation of many other metrics from the patch level to the class and landscape levels. PARA_MN and SHAPE_MN can measure the shape complexity of the patches. The higher the value of PARA_MN is, the more complex the patch shape is. The values of SHAPE_MN are usually larger than or equal to 1. When almost all the patch shapes are close to square-shaped, the value of SHAPE_MN is equal to 1, and when the patch shapes are more irregular, the value of SHAPE_MN will correspondingly increase. PD can reflect the spatial uniformity of mangrove distribution. Under the condition of keeping the total landscape area unchanged, the information reflected by NP and PD is consistent. For the COHESION, the values of it range from 0 to 100, and it can measure the connectivity between patches of the same landscape type, and larger values symbolize stronger connectivity between patches. All these metrics were calculated using Fragstats v4.2.1.

3. Results

The classifications of mangrove forests and other types of land use were derived from Landsat images based on the CART algorithm. Based on the selected training samples, classification rules were retrieved from the RuleGen.

3.1. Accuracy of the Classification Results

The classification results of the above defined land use types in 2015 are shown in Figure 4. The accuracy indices in 2015 are shown in Table 3. The producer's accuracy of the mangrove classification was around 93%, 83%, and 81% in Western Guangdong (WG), Pearl River Delta (PRD), and Eastern Guangdong (EG), respectively, and the user's accuracy was 88%, 97%, and 90%, respectively. Thus, the mangrove forests were extracted with acceptable accuracy. The OA was greater than 90% in the three regions, and the kappa coefficients of the classification results were between 0.81 and 1, indicating excellent to perfect agreement [44]. Users' accuracies and producers' accuracies of other types obtained almost acceptable values. According to the confusion matrices, the accuracies of classification were acceptable, suggesting that further analysis could be performed based on the classification results.

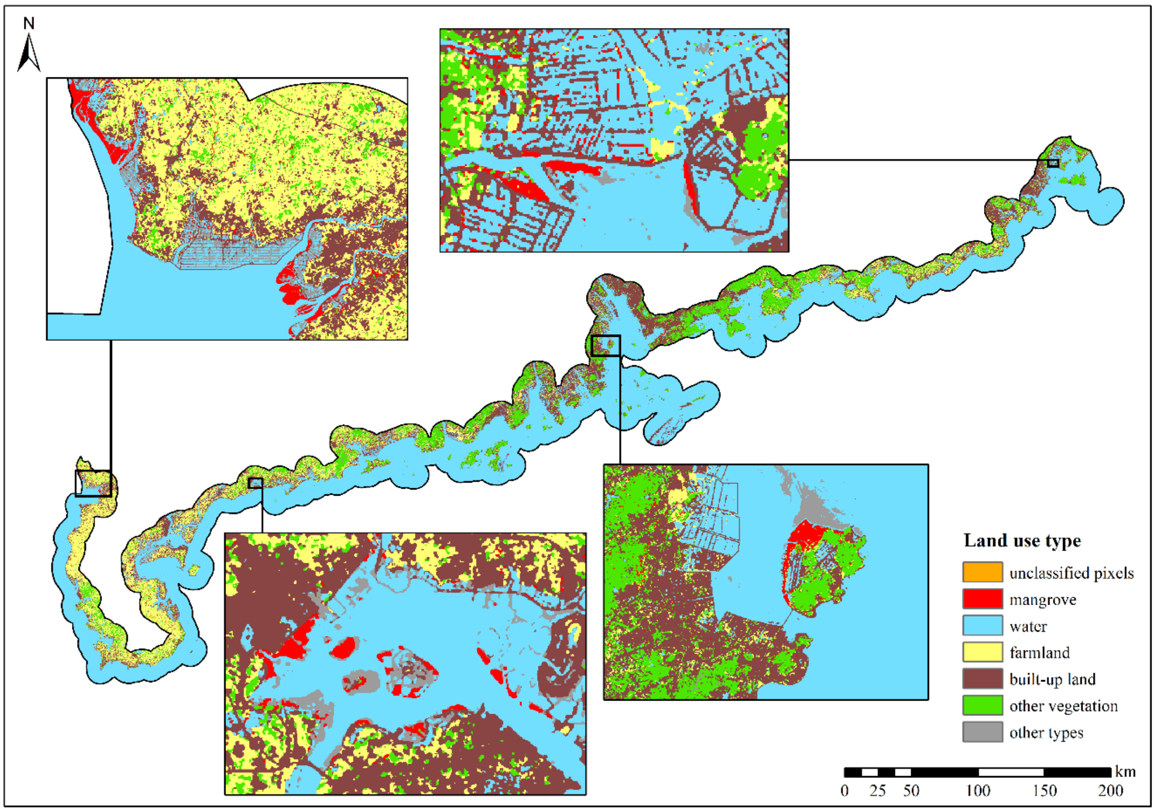


Figure 4. Classification results derived from Landsat image collected in 2015.

Table 3. Accuracy indices estimated from the classification image in 2015.

Indices		**Western Guangdong**	**Pearl River Delta**	**Eastern Guangdong**
Overall Accuracy (%)		96.08	97.26	93.27
Kappa Coefficient		0.94	0.91	0.89
Producer's Accuracy (%)	Mangrove	93.01	83.28	80.70
	Water	99.85	98.99	99.6
	Farmland	74.06	68.52	57.55
	Built-up Land	99.47	98.57	98.99
	Other Vegetation	92.4	96.39	91.34
	The other Types	80.3	83.53	12.58
User's Accuracy (%)	Mangrove	88.41	97.46	89.90
	Water	99.5	99.52	97.26
	Farmland	92.04	93.98	89.93
	Built-up Land	88.55	80.68	91.84
	Other Vegetation	99.01	87.21	76.1
	The other Types	78.2	99.69	82.61

3.2. Spatial Pattern of Mangrove Distribution

The distribution of mangroves over the past thirty years is shown in Figure 5 in detail. The classification results indicate that the distribution of mangrove forests has displayed similar patterns over the past thirty years. Mangrove forests are mainly distributed in Western Guangdong, especially in Zhanjiang City. Additionally, there are a few mangrove forests in Eastern Guangdong.

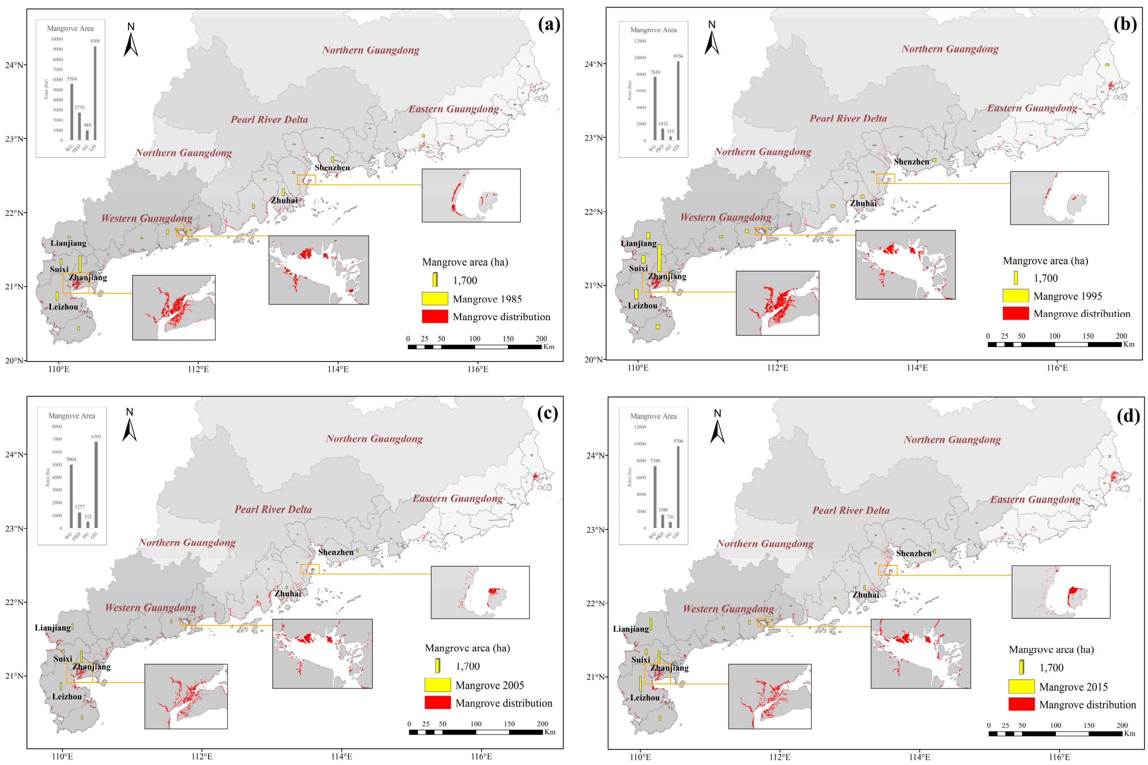


Figure 5. Spatial distribution of mangroves in coastal Guangdong during the period from 1985 to 2015: (**a**) spatial pattern of mangroves in 1985, (**b**) spatial pattern of mangroves in 1995, (**c**) spatial pattern of mangroves in 2005, and (**d**) spatial pattern of mangroves in 2015.

From Figure 5, it can be seen that in 1985, mangroves were mainly distributed in Zhanjiang city, Leizhou city, and Zhuhai city, which represented 45% of mangroves in Guangdong province. The areas of the mangroves in these three cities were 2199, 1054, and 895 ha, respectively, which represented about 24%, 11%, and 10% of the mangroves in Guangdong province, respectively. The mangrove forests in Zhanjiang city were mainly located in Leizhou bay, especially in the marine ecological nature reserve of Leizhou bay, where many silty coastlines and wide mudflats are distributed, and the land around this area is dominated by aquaculture. Mangroves in Zhuhai city were mainly distributed in the bay area and around islands, for example, Hengqin Island and Qi'ao Island. The main types of land use around mangrove growth areas were forest, aquaculture, and agricultural land.

In 1995, mangroves were mainly distributed in Zhanjiang city, Leizhou city, and Suixi County, which represented about 57% of the mangroves in Guangdong province. The mangrove areas in these three districts were about 3313, 1193, and 986 ha, representing about 35%, 12%, and 10% of the mangrove area in Guangdong province, respectively. Mangroves in Suixi County were mainly distributed in estuarine areas where the main types of land use were aquaculture and agricultural land. The situations in Zhanjiang city and Leizhou city were similar to those in 1985.

In 2005, mangroves were mainly distributed in Zhanjiang city, Leizhou city, and Lianjiang city, which represented about 44% of the mangroves in Guangdong province. The mangrove areas in these three districts were about 1407, 898, and 701 ha, representing about 21%, 13%, and 10% of the mangrove area in Guangdong province, respectively. Mangroves in Lianjiang city were mainly distributed in Zhanjiang mangrove national nature reserve, which was established in 1990; other estuarine areas also had large distributions. The main types of land use around mangrove growth areas were aquaculture and agricultural land. The situations in Zhanjiang city and Leizhou city were similar to those in 1985, except that more aquaculture existed around mangroves.

In 2015, mangroves were mainly distributed in Leizhou city, Zhanjiang city, and Lianjiang city, which represented about 50% of the mangroves in Guangdong province. The mangrove areas in these three districts were about 1840, 1502, and 1501 ha, representing about 19%, 15%, and 15% of the mangrove area in Guangdong province, respectively. The situations in Zhanjiang city, Leizhou city, and Lianjiang city were similar to those in 2005, except for the existence of wider mudflats around the mangroves.

3.3. Spatiotemporal Variations in the Mangrove Distribution

The variation in the total area of mangrove forest over the past thirty years is shown in Figure 6, and the spatial variation in mangroves from 1985 to 2015 is shown in Figure 7.

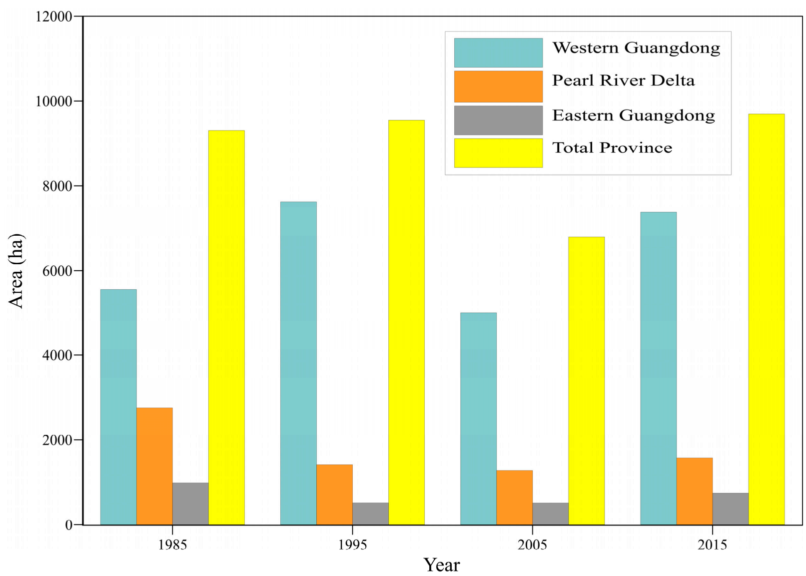


Figure 6. Total area of mangroves in coastal Guangdong during the period from 1985 to 2015.

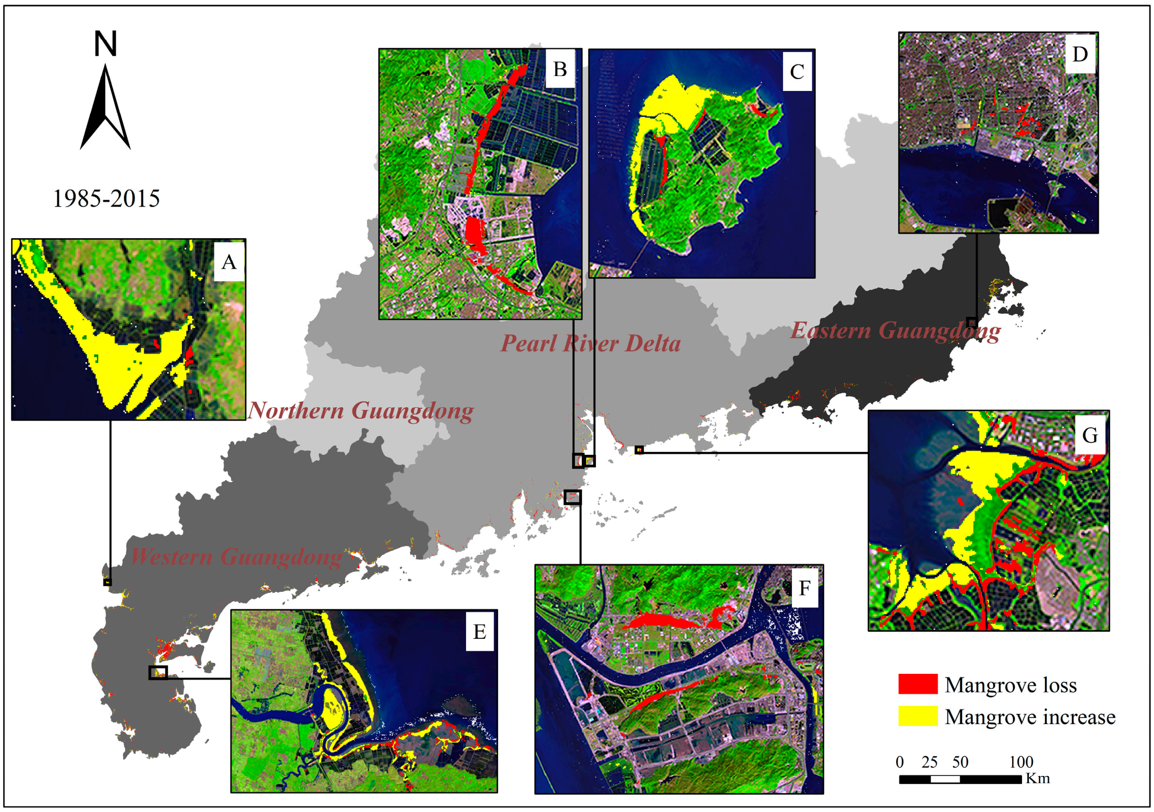


Figure 7. Spatial variation of mangrove forests in the coastal zone during the period from 1985 to 2015, with the overlay of the Landsat image collected in 2015.

The mangrove areas in the coastal zone of Guangdong Province were about 9305, 9556, 6793, and 9700 ha in 1985, 1995, 2005, and 2015, respectively. Notably, the area displayed an increase of about 251 ha from 1985 to 1995, a sharp decrease of about 2762 ha from 1995 to 2005, and a sharp increase of about 2907 ha from 2005 to 2015. From 1985 to 2015, a net increase of about 1816 ha mangrove was observed in Western Guangdong. For example, as subgraph A in Figure 7 shows, a substantial increase in mangroves occurred in the national nature reserve in Zhanjiang City, which was established in 1990. Different from Western Guangdong, the Pearl River Delta and Eastern Guangdong showed net decreases of about 1173 and 248 ha, respectively, from 1985 to 2015. Most areas exhibited mangrove loss because of sea reclamation (subgraphs D and F) and aquatic breeding (subgraph B). In PRD, the mangrove area also increased in many zones, for example, substantial mangrove increases occurred in the nature reserve on Qi'ao island (subgraph C) and at Mai Po Inner Deep Bay Ramsar Site (subgraph G). In EG, increases and decreases in mangroves were both rare due to the limited distribution of mangroves in the region. Mangrove loss always occurred landward, and increases often occurred seaward (Figure 7). In addition, the spatial pattern of mangrove distribution transformed from fragmented to aggregated.

In detail, the mangrove estimates in Western Guangdong in 1985, 1995, 2005, and 2015 were about 5564, 7630, 5004, and 7380 ha, respectively, accounting for about 60%, 80%, 74%, and 76% of the total provincial mangrove area in these years. The mangrove area was extremely small in Eastern Guangdong in the four study years, with values of about 989, 515, 512, and 741 ha in 1985, 1995, 2005, and 2015, respectively, accounting for only about 11%, 5%, 8%, and 8% of the total provincial mangrove area in those years. The mangrove estimates for the Pearl River Delta were between those for Western Guangdong and Eastern Guangdong, with values of about 30%, 15%, 19%, and 16% in 1985, 1995, 2005, and 2015, respectively.

Figure 8 shows the variations in the mangrove distribution at the county and city levels. Although there was a sharp decrease in the mangrove area from 1995 to 2005 in the province, remarkable increases of about 160, 86, and 59 ha were observed in Wuchuan City, Shenzhen City, and Yangxi County, respectively. From 2005 to 2015, a significant increase in mangroves occurred in the province, but notable decreases of about 83, 46, and 45 ha were found in Taishan City, Jiangmen City, and Wuchuan City, respectively. Thus, changes in the province did not represent regional trends. Similarly, long-term changes differed from short-term changes. For example, the mangrove area in Suixi County increased by about 24 ha from 1985 to 2015 but decreased by about 475 ha from 1995 to 2005. Additionally, the mangrove area decreased by approximately 697 ha in Zhanjiang City from 1985 to 2015 but increased by 1115 ha from 1985 to 1995. In addition, a decrease of 328 ha occurred in Zhuhai City from 1985 to 2015, but an increase of 222 ha was observed from 2005 to 2015. As a result, appropriate temporal and spatial scales should be selected according to the study objectives.

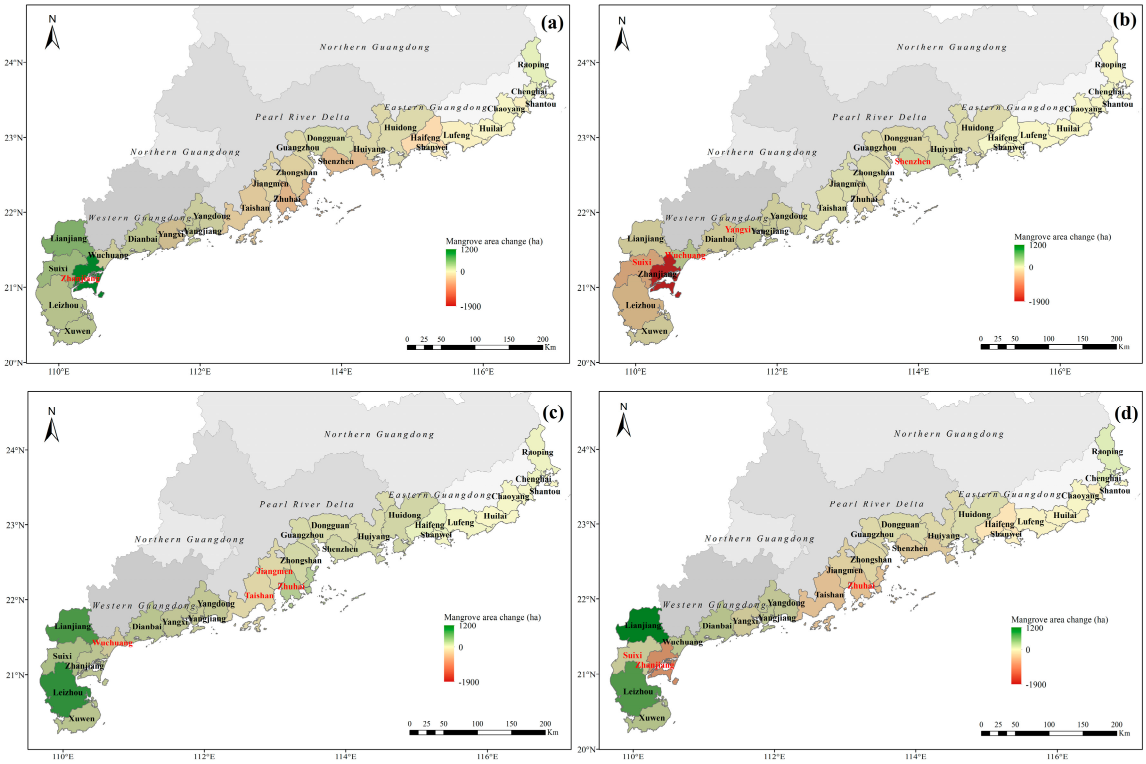


Figure 8. Temporal variation in the mangrove distribution at county and city level (Negative value means decrease, and positive value means increase): (**a**) from 1985 to 1995, (**b**) from 1995 to 2005, (**c**) from 2005 to 2015, (**d**) from 1985 to 2015.

4. Discussion

The total area and overall variation trend of mangrove distribution were close to those reported in other studies [38]. For example, the mangrove area in 2015 estimated in this study is similar to the estimation of 8136 ha provided in publication [35], and the mature mangrove area of Guangdong Province in 2001 was reported to be 9084 ha [45], which is between the areas of 9556 ha in 1995 and 6793 ha in 2005 derived in this study. As there are differences in the resolution of remote sensing imageries, classification methods, and the collection times of the images, there is a certain discrepancy in the classification results of mangrove forests. In the study area, the length of the coastline in Western Guangdong is the longest, followed by those in the Pearl River Delta and Eastern Guangdong. These differences may be why Western Guangdong is home to the majority of mangroves in Guangdong Province and why Eastern Guangdong had few mangrove forests compared to the other regions during the study period.

4.1. Distribution Characteristics of Mangrove Patches

Further analysis was carried out to discuss the distribution characteristics of mangrove patches; the results are shown in Figure 9. The Mean Patch Area showed a decreasing tendency from 1985 to 2005, while an increasing tendency was shown from 2005 to 2015. The change trend in the Mean Shape Index is consistent with that of Mean Patch Area. This means that the shapes of mangrove patches became more regular from 1985 to 2005, while they became more irregular from 2005 to 2015. The Mean Perimeter-Area Ratio showed an opposite trend to that of the Mean Patch Area, which further demonstrates that the shapes of mangrove patches became more complex. The Number of Patches and Patch Density also showed opposite trends to that of Mean Patch Area. The values of these two metrics increased from 1985 to 2005, while they decreased from 2005 to 2015, which demonstrates that mangrove patches became more fragmented from 1985 to 2005 and more compact from 2005 to 2015. However, in 2015, these five metrics still did not recover to their initial landscape levels presented in 1985, and the spatial pattern of mangrove distribution still presented more fragmented in 2015 than in 1985. The variation in the Patch Cohesion Index, which was more complicated than the other five metrics, showed an increasing tendency from 1985 to 1995 and from 2005 to 2015, whereas a decreasing tendency occurred from 1995 to 2005. The distribution pattern of mangrove patches presented stronger connectivity in 2015 than in 1985.

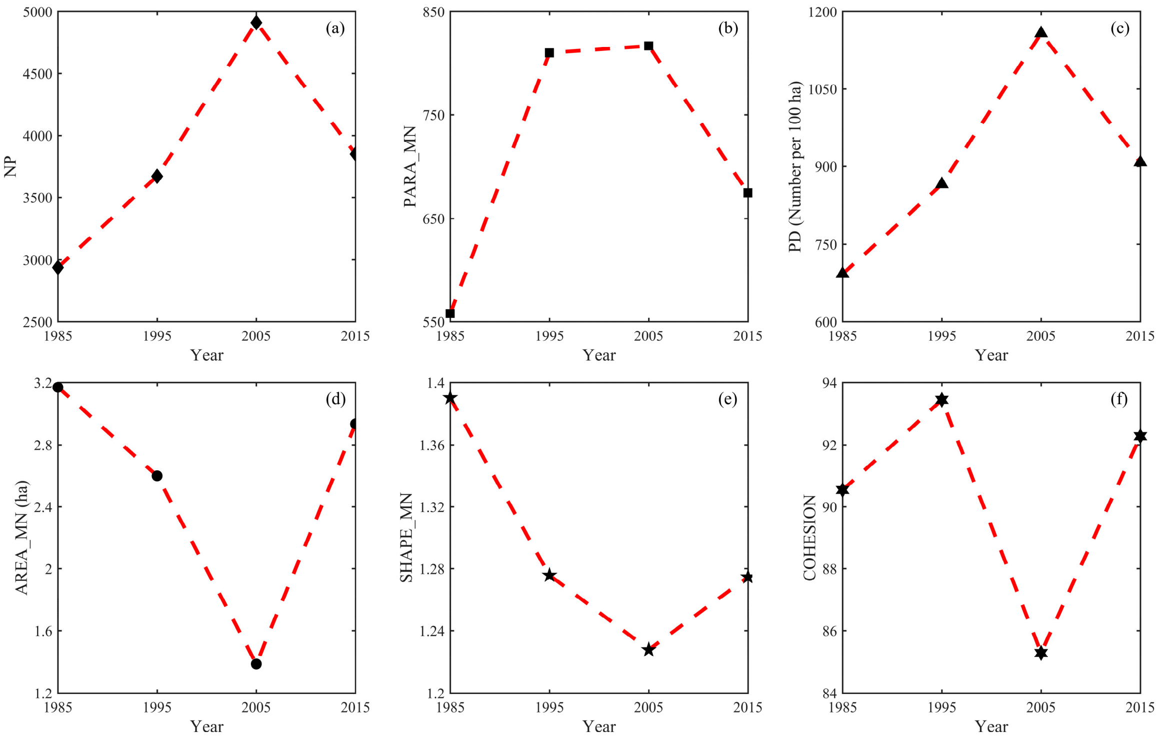


Figure 9. Class metrics of mangrove patches: (**a**) NP: Number of Patches, (**b**) PARA_MN: Mean Perimeter-Area Ratio, (**c**) PD: Patch Density, (**d**) AREA_MN: Mean Patch Area, (**e**) SHAPE_MN: Mean Shape Index and (**f**) COHESION: Patch Cohesion Index.

This spatial pattern of mangroves is actually dominated by characteristics of the distribution locations and coastal lines, and the increased area of mangroves was mainly due to artificial planting. It has been highlighted that biodiversity conservation is closely related to mangrove fragmentation [4]. This is of great significance for the formation of a compact pattern to expand the size of mangrove patches. This requires to further understand the difference between natural growing mangroves and artificial planting mangroves well, which can help improve the landscape pattern of mangrove patches to provide better ecological services. High spatial resolution images can help retrieve such information.

4.2. Factors Influencing Spatiotemporal Variations in Mangrove Forests

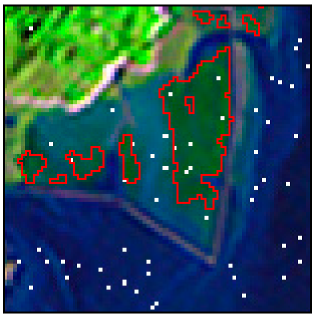
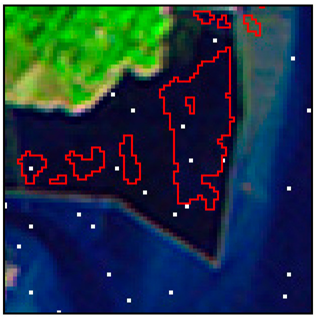
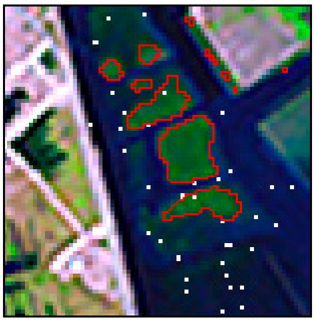
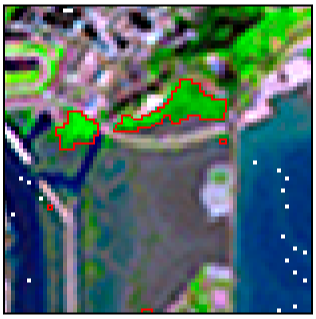
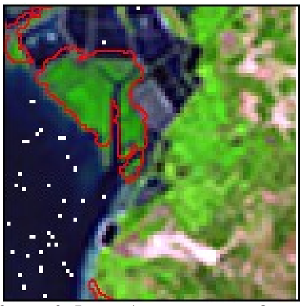
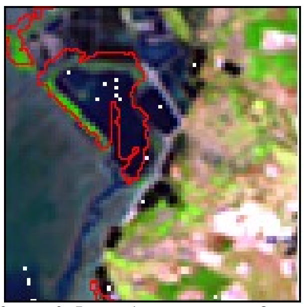
The variation in the area of mangrove forest is mainly influenced by natural factors and anthropogenic activities [28]. From the perspective of natural influence, temperature variation and sea level rise, which are also important indicators for measuring climate change, have been generally discussed. The related research has reported that the temperature has a macroscopic effect on the distribution of mangrove forests. In the northern hemisphere, the mangrove forest area, number of tree species, and tree height decrease with increasing latitude [46]. The results about the distribution pattern of mangroves among Eastern Guangdong, Pearl River Delta, and Western Guangdong also validated this evidence. Meanwhile, according to the results of the national wetland survey in 2001, 90% of the mangroves in Guangdong province are sensitive to sea level rise since they are in front of the seawalls [47]. It was reported that the relative sea level rise rate along the coast of Guangdong was 2–3 mm/a from 1986 to 2008, and the sea level will be 38–45 cm higher at the end of the 21st century than in 2000 [48]. The continuing variation trend will result in the serious disturbances to the mangrove ecosystem including a decrease in the total area and degeneration of the ecological quality over a very long period of time. Actually, the influence of the sea level rise requires further validation using the data materials collected over a very long period of time. On the other hand, Guangdong province, located along the South China Sea, suffers frequent typhoon attacks. Extreme weather events also play an important role in the distribution of mangroves; although mangroves can weaken wind and waves, they also experience severe disturbances [5]. In a study about Shenzhen city, it was reported that the total litter fall from mangroves increases after the passage of a typhoon. Typhoons can damage the mangrove ecosystem when the wind force is higher than the level of category 11, and the destruction depends on the origin, age, and density of the mangrove forests [49,50].

However, anthropogenic activities have had drastic influences on the spatiotemporal variations of the mangrove area in coastal Guangdong since the reform and opening-up, and this influence on the mangrove ecosystem may exceed that of natural factors. It was reported that, during the 1980s and 1990s, plenty of mangroves in Guangdong were degenerated into aquaculture area [51]. At the provincial level, a sharp decrease in the mangrove area was observed from 1995 to 2005, especially in Zhanjiang City, Suixi County, Leizhou City, Zhuhai City, and Dianbai County, with decreases of 1906, 475, 295, 102, and 69 ha, respectively. The majority of these decreases were due to urbanization and aquaculture development. Table 4 shows some examples of mangrove erosion in Zhuhai, Macao, and Zhanjiang from 1995 to 2005. Some causes of erosion are unclear, but we speculate that erosion may be caused by deforestation, urbanization or sea level rise in the study area. Further research on this topic is needed.

Anthropogenic activities may have a positive effect on the mangrove distribution, such as by establishing mangrove nature reserves. The first reserve of 815 ha was established in Shenzhen City in 1984, and the total area of mangrove nature reserves sharply increased to 27,489 ha in 1995 before steadily but continuously increasing from 1995 to 2015, as shown in Figure 10. Detailed information corresponding to the mangrove nature reserve in Guangdong is listed in Table 5.

Since the establishment of those nature reserves, some of them have achieved enormous success in protecting mangroves [29]. For example, the mangrove area increased by 1115 ha in Zhanjiang City from 1985 to 1995 because of the establishment of national nature reserves in 1990, and that in Shenzhen City increased by 86 ha from 2005 to 2015 because of the establishment of city nature reserves in 2010. The effect of some nature reserves may be neutralized by other factors, such as urbanization. For example, a decrease of 448 ha occurred in Zhuhai City from 1985 to 1995, even though a provincial nature reserve was established in 1989. However, some nature reserves had no obvious effect on the regional mangrove area; potentially, these reserves were lower-level types so that they did not have sufficient budget to support the conservation [38]. Further studies are necessary to confirm these evidences. For example, two county nature reserves were established in Xuwen County in 1997, but a decrease in the mangrove area of 62 ha was observed from 1995 to 2005. A similar phenomenon was found in Yangjiang City, where two county nature reserves were established in 2005, and the mangrove area increased by only 24 ha from 2005 to 2015. In addition, some nature reserves may have lag effects on the mangrove area; for example, a nature reserve was established in Leizhou City in 2003, but the mangrove area decreased by 295 ha from 1995 to 2005 before rapidly increasing by 941 ha from 2005 to 2015. Further studies are required to confirm these results.

Table 4. Examples of reasons for erosion during the period from 1995 to 2005.

Region	1995	2005	Erosion Reason
Zhuhai City			aquaculture
			unclear
Macao			urbanization
Zhanjiang City	 0 0.5 1 2 Km	 0 0.5 1 2 Km	aquaculture

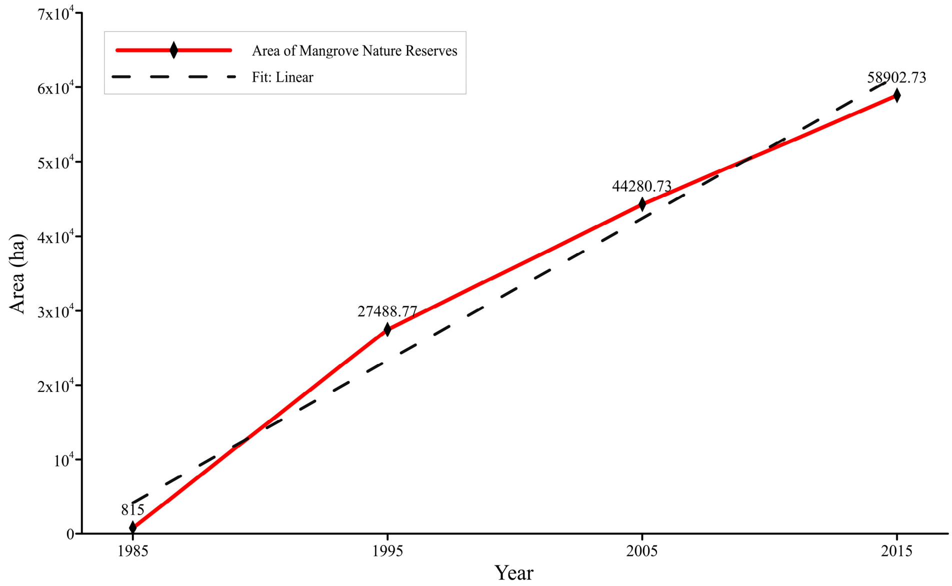


Figure 10. Total area of Mangrove Nature Reserves in Guangdong province from 1985 to 2015.

Table 5. Details of Mangrove Nature Reserves in Guangdong province.

Serial Number	Administrative Region	Area (ha)	Level	Established Time
1	Shenzhen City	815	national	1984.04.29
2	Zhuhai City	7373.77	provincial	1989.11.24
3	Zhanjiang City	19,300	national	1990.01.11
4	Xuwen County	7	county	1997.05.01
5	Xuwen County	309	county	1997.05.01
6	Dianbai County	1950	city	1999.12.20
7	Huidong County	533.3	city	1999.12.29
8	Yangxi County	1000	county	2000.06.01
9	Taishan City	119.33	county	2000.11.01
10	Shantou City	10,333.33	city	2001.08.22
11	Maoming City	800	county	2001.12.11
12	Leizhou City	200	county	2003.10.23
13	Enping City	700	county	2005.02.03
14	Yangjiang City	40	county	2005.07.19
15	Yangjiang City	800	county	2005.07.19
16	Shenzhen City	14,622	city	2010.11.16

Data in this table was cited from the National Nature Reserve directory in 2015 announced by China Environmental Protection Department.

Actually, there are a variety of factors that affect mangrove distribution. Future studies will explore the dominant factors to provide referable information for mangrove preservation.

5. Conclusions

In this study, the spatiotemporal patterns of mangrove distribution as well as its variation were detected from multi-temporal remote sensing images. The classification results indicated that the incorporation of NDVI, IMFI, and ISODATA data can improve the discrimination between mangrove forests and other land use types. The accuracy validation with high spatial resolution images indicated that the classification method used in this study yielded good accuracy, with overall accuracy and kappa coefficient higher than 90% and 0.8, respectively.

It can be concluded that mangrove distribution in the coastal zone of Guangdong province was shown to have a significant spatial difference and periodical evolution pattern, the total area of mangrove forests has had a net increase over the last 30 years. Additionally, the majority of mangroves in Guangdong province are distributed in Western Guangdong, while Eastern Guangdong has the smallest area of mangroves. Mangrove patches had stronger connectivity in 2015 than in 1985, the distribution pattern of mangrove patches still presented a fragmented trend from 1985 to 2015. It is necessary to recover the spatial distribution of mangroves with appropriate patterns during the recoverable period. The dynamic changes detected in this study are of great significance to mangrove conservation.

Furthermore, natural and anthropogenic factors influencing the spatial distribution of mangroves were discussed in this study. Natural factors have macroscopic effects on the distribution of mangrove forests, whereas anthropogenic activity may have a negative effect on the distribution of mangroves due to processes such as deforestation, urbanization, and aquaculture development. Some anthropogenic activities, such as the establishment of nature reserves, can promote an increase in the mangrove area. This study showed that enormous success in protecting mangroves has been achieved since the establishment of nature reserves. The findings of this study can provide referable information for coastal management particularly ecological protection.

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