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Spatiotemporal Evolution of Carbon Storage in Mangrove Forest along the Coast of Guangdong Province Based on Remote Sensing Monitoring Data

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Abstract

Mangroves is one of the three major blue carbon systems, possessing significant ecological functions of carbon sequestration and carbon storage, and is also an important symbol of China's marine ecological construction. This paper employs computer analysis of various remote sensing monitoring data and field discrimination, utilizing a long-time series satellite remote sensing monitoring dataset of mangrove forests from 1978 to 2018. Through an intelligent computing platform, it conducts carbon storage accounting, dynamic degree analysis, kernel density analysis, and visualization analysis. Taking Guangdong Province, which possesses superior mangrove resources in China, as a case study, the paper delineates the spatiotemporal distribution and evolution characteristics of the mangrove forests along the Guangdong coastal zone over a 40-year period. Furthermore, it uses a carbon storage estimation model to uncover the spatiotemporal evolution characteristics of the mangrove carbon storage along the Guangdong coastal zone. The results showed that: during the study period, (1) the distribution area of mangroves along the Guangdong coastal zone showed a trend of falling first and then rising in general, which can be divided into two stages. The spatial distribution was not uniform, and the medium or above value areas of kernel density were mainly distributed in the bay areas, and the overall pattern was “more in the west than in the east”. The distribution morphology evolved from strip to scattered patches, and after partial restoration, the patches area increased, but the consistency and agglomeration were not as good as before. (2) The carbon storage in mangroves along the Guangdong coastal zone has generally decreased. The Cartesian heat map value of mangrove carbon storage is centered around Zhanjiang City, showing a spatial pattern of "higher in the west and lower in the central and east". Before 2000, the mangrove carbon storage of most cities was reduced, after which there was an overall increase in mangrove carbon storage. The changes of mangrove carbon storage in various cities along the Guangdong coastal zone can be divided into five types, with differing reasons for the changes in their carbon storage.

Keywords: Mangroves along Guangdong coastal zone, long-time series satellite remote sensing monitoring dataset, carbon storage, spatiotemporal evolution.

1. Introduction

In response to climate change, enhancing carbon sink capacity has become one of the effective ways to achieve climate sustainability and carbon neutrality[1-3]. Mangrove is a unique plant community in the low-latitude coastal intertidal strip. Mangrove is one of the three blue carbon systems. It has important ecological functions of carbon storage and carbon storage, and is also an important symbol of marine ecological construction in China. Mangroves are one of the forests with the highest carbon content in the tropics[4], and the average carbon storage capacity of land forests is about $5g/m^2 \cdot a$. The average carbon storage capacity of mangroves is about $226g/m^2 \cdot a$, which is also of great practical significance for achieving the balance of the ecosystem carbon cycle[5]. Scholars at home and abroad have made useful studies on this. Some scholars have quantified the carbon storage of mangrove through the regional mangrove biomass, soil carbon density, etc. [6-9]. Some scholars used remote sensing monitoring and GIS spatial analysis technology to realize the estimation of large-area carbon storage and spatial expression of the results [10-12], and then to explore its spatiotemporal evolution law and influencing factors [13,14]. These studies showed that the mangroves carbon storage capacity varies across different geographic locations and time scales. The spatial distribution characteristics and the evolution of carbon storage of mangrove ecosystem can be analyzed by combining remote sensing monitoring data and GIS spatial analysis technology. However, most of the existing studies are of single-temporal phase, with few long-term series studies on regional carbon storage[15], and lack of simulation analysis on the spatiotemporal evolution of long-time series of regional mangroves and the reflection on the changing characteristics of carbon storage. In this paper, the Chinese mangrove long time series satellite remote sensing monitoring dataset is used. The dataset includes domestic satellite images with 2m resolution (including Ziyuan-3 01/02, Gaofen-1 and Gaofen-1 B/C/D) and Landsat series satellite images[16-18], which provides high resolution and high time frequency information of mangrove distribution and biomass for this study. Through computer simulation, the temporal and spatial change characteristics of mangroves along the coast of Guangdong Province in recent 40 years are reflected, and the evolution of mangrove carbon storage is analyzed through the carbon storage estimation model, so as to supplement the research on the long-term series of regional mangrove carbon storage through computer simulation.

Mangroves in China are distributed in low-latitude southeast coastal provinces. According to the monitoring data of Remote Sensing Satellite Center of the Ministry of Natural Resources, the mangrove reserve in Guangdong Province is the highest among the provinces in China, but the area has generally decreased in recent 40 years. In 1978, the area of mangroves along the Guangdong coastal zone was 17752.3ha, accounting for 59.98% of the whole country's, and decreased to 10330.67ha in 2018, accounting for 40.22% of the whole country's (Figure 1). As a big economic province and a province with large carbon emissions, Guangdong Province should not only maintain sustained economic growth, but also take the lead in achieving carbon peak growth and carbon neutrality, so as to create a model area for the construction of beautiful China[19,20]. In order to contain the degradation of mangroves, strengthen the protection, restoration and sustainable management of mangroves, in response to the requirements of the Global Wetland Convention and the establishment of the International Mangrove Center to promote carbon trading, Guangdong Province has taken mangrove ecological restoration and protection as an important key to the construction of ecological civilization in recent years. All cities along the Guangdong coastal zone have successively carried out mangrove carbon sequestration and afforestation projects along the coastal zone, actively and orderly promoting the construction and restoration of mangroves and the exploration of the path to realize the value of ecological products. In view of this, the coast of Guangdong is divided into 14 research units according to the administrative region. Among them, the cities of Zhanjiang, Maoming and Yangjiang belong to the western coast, the cities of Jiangmen, Zhongshan, Zhuhai, Guangzhou, Shenzhen, Dongguan and Huizhou belong to the central coast, and the cities of Shanwei, Shantou, Jieyang and Chaozhou belong to the eastern coast. With the mangroves along the coast as the study object, the spatiotemporal evolution of mangrove distribution and carbon storage along Guangdong coastal zone from 1978 to 2020 were analyzed, in aims to identify the key areas for carbon reduction and sink increase in Guangdong Province and provide experience for other coastal provinces and other similar regions in the world[21,22].

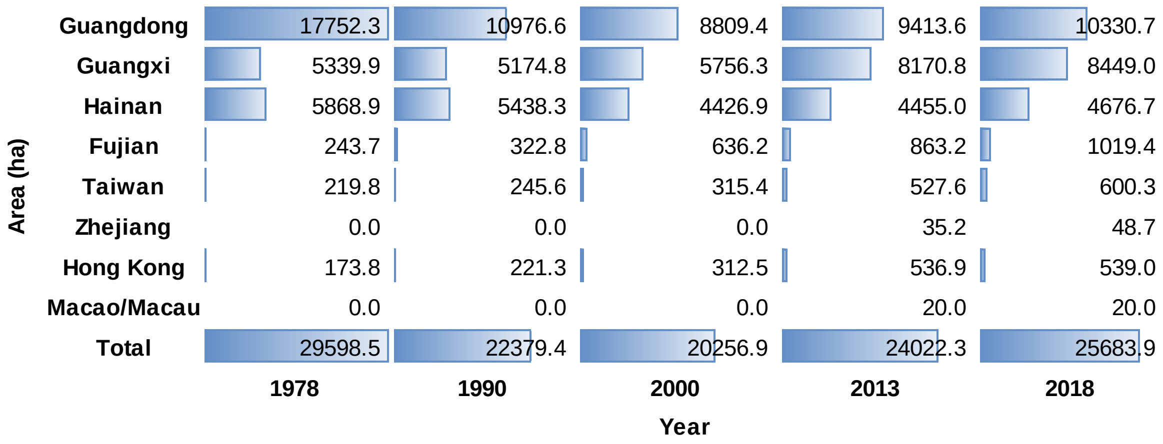


Figure 1 Distribution of mangroves in various provinces of China from 1978 to 2018

2. Data Sources and Research Methods

2.1 Data sources

The distribution number of mangrove resources used in this study is derived from the Chinese mangrove long-time series satellite remote sensing monitoring dataset of the Remote Sensing Satellite Center of the Ministry of Natural Resources. There are 5 issues (1978, 1990, 2000, 2013 and 2018). The data type is vector, and the resolution is 2m-90m.

2.2 Dynamic degree analysis

The dynamic degree index can quantify the change speed of mangrove forest, and can be used to analyze the change of mangrove forest in different years and predict the future.

$$\mathrm{P} = \frac{V_b - V_a}{V_a}\frac{1}{T} \times 100\% \tag{1}$$

Where, P represents the dynamic change of mangroves within a specified time period; V_a represents the initial mangrove area at the onset of monitoring, while V_b represents the final mangrove area at the conclusion of monitoring; T indicates the duration of the study.

2.3 Kernel density analysis

The kernel density analysis is to calculate the density value according to the distance between the mangrove element points and other element points within a certain range of time period, which can express the spatial density distribution and aggregation of mangrove in a certain area.

Assuming that the density function of a mangrove point c is $f_n(c)$, the probability density at point c can be expressed by equations (2) and equations (3):

$$f_n(c) = \frac{1}{nd_n}\sum_{i=1}^{n} K\left(\frac{c-c_i}{d_n}\right) \tag{2}$$

where n is the number of samples, $d_n$is the bandwidth, and $K\left(\frac{c-c_i}{d_n}\right)$is the kernel function.

$$K(c) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}c^2} \# \tag{3}$$

The d_n bandwidth used in this paper is shown in Equation (4).

$$d_n = 0.9 * \min\left(SD, \sqrt{\frac{1}{\ln(2)}} * D_m\right) * n^{-0.2} \tag{4}$$

where SD is the standard distance and D_m is the median distance.

2.4 Estimation of carbon storage

The mangrove is taken as an evaluation unit, and the total carbon storage of the mangrove is equal to the sum of the two parts of the carbon storage of the plant and the soil. It is equivalent to calculating the sum of the carbon density of the aboveground plants, underground plants and the litter and the soil carbon density, according to the distribution area and the corresponding carbon density value. The carbon storage is calculated as follows:

$$C_{total} = C_{above} + C_{below} + C_{soil} + C_{dead} \# \quad (5)$$

C_{total} is the total carbon storage (t/ha), C_{above} is the aboveground carbon storage with the mangrove study area as the statistical unit, C_{below} is the underground carbon storage with the mangrove study area as the statistical unit, C_{soil} is the soil carbon storage with the mangrove study area as the statistical unit, and C_{dead} is the litter carbon storage with the mangrove study area as the statistical unit.

Based on the carbon density data of mangroves, the calculation formula of carbon storage of mangroves in the study area is:

$$\mathrm{C_{totali}} = (\mathrm{C_{abovei}} + \mathrm{C_{belowi}} + \mathrm{C_{soili}} + \mathrm{C_{deadi}}) \times \mathrm{A_i} \# \quad (6)$$

where i is the study area, $\mathrm{C_{totali}}$ is the total carbon storage of the mangroves in the study area, and $\mathrm{A_i}$ is the area of the mangrove study area. The total carbon storage in the study area is the sum of the carbon storage of 14 mangrove units along the coast of Guangdong.

2.5 Carbon density of mangrove in coast of Guangdong

In this study, the carbon density of cities in Guangdong Province is determined by integrating existing studies. The indexes of mangrove litter carbon density, soil carbon density and vegetation carbon density in each city of Guangdong Province are respectively obtained from relevant literatures [8, 23-29], and the total carbon density of each coastal city of Guangdong is calculated through the carbon storage estimation model (Table 1).

Table 1 Carbon density of mangrove in cities of Guangdong coast (t·ha-1).

	Carbon density of mangrove litter	Carbon density of Mangrove soil	Carbon density of mangrove vegetation	Mangrove total carbon density
Zhanjiang	0.98±0.11	73.32±2.71	125.79±14.6	200.09±17.42
Maoming	1.34±0.12*	183.47±3.63	25.70±4.45	210.51±8.2
Yangjiang*	1.34±0.12*	151.45±3.15	60.26±9.04	213.05±12.31
Jiangmen	1.34±0.12*	197.55±3.12	29.28±8.06	228.17±11.3
Zhongshan	1.34±0.12*	246.83±3.30	80.18±11.98	328.35±15.4
Zhuhai	1.39±0.14	190.77±9.4	79.82±5.4	271.98±14.94
Guangzhou	1.34±0.12*	237.56±9.34	36.01±4.27	274.91±13.73
Shenzhen	2.81±0.01	339.925±2.99	155.17±11.115	497.9±14.115
Dongguan*	1.34±0.12*	317.95±6.66	77.09±7.64	396.38±14.42
Huizhou	1.34±0.12*	574.66±8.28	34.25±5.43	610.25±13.83
Shantou	1.34±0.12*	321.18±1.33	65.10±6.83	387.62±8.28
Chaozhou	1.34±0.12*	143.49±0.92	76.16±5.82	220.99±6.86
Shanwei*	1.34±0.12*	232.34±1.12	70.63±6.33	304.31±7.57

Note: The table is mean value ± standard deviation. The mean value is used for carbon storage statistics in this study; the carbon density of mangrove vegetation includes the sum of aboveground and underground biomass; * represents lack of data in this area. Cities lacking data on litter carbon density are replaced by the average value of Guangdong Province. Cities lacking data on soil and vegetation carbon density are replaced by the average value of eastern coast, central coast and western coast. For example, the data lacking in Yangjiang City is replaced by the average value of Zhanjiang City and Maoming City. There has no mangrove species distribution in Jieyang City for 40 years.

3. Spatiotemporal Evolution of Mangrove Distribution Along Guangdong Coastal Zone

3.1 The temporal evolution of mangroves along Guangdong coastal zone

The dynamic degree of mangrove is an important indicator to measure the temporal evolution of mangrove. From 1978 to 2018, the mangrove area along the coast of Guangdong generally showed a decreasing trend, of which the total area decreased by 7421.63ha, and the dynamic degree was-1.04% during the 40 years (Table 2).

Table 2 Distribution area of mangrove along coast of Guangdong in 40 years and changed quantity and dynamic degree of mangrove in each period.

Year	Area(ha)	Period (years)	Changed Quantity (ha)	Dynamic degree (%)
1978	17752.3	1978-1990	-6775.78	-3.18%
1990	10976.52	1990-2000	-2167.14	-1.97%
2000	8809.38	2000-2013	604.13	0.52%
2013	9413.51	2013-2018	917.16	1.95%
2018	10330.67	1978-2018	-7421.63	-1.04%

The temporal evolution may be divided into two stages. The first stage (1978-2000) is the rapid decrease stage, and the mangrove area decreased by 6775.78ha and 2167.14ha during 1978-1990 and 1990-2000, with dynamic degrees of-3.18% and-1.97% respectively. During this period, the primary reasons for the significant decrease of mangrove area were urban construction and reclamation from sea activities. The second stage (2000-2018) is the slow growth stage, with the area of mangrove increased by 604.13ha and 917.16ha during 2000-2010 and 2010-2013, respectively, with dynamic degrees of 0.52% and 1.95% respectively. On the one hand, the supervision department strengthened the protection and supervision of the ecological environment and the mangrove forest, and the state, province and cities issued special plans for the mangrove forest; on the other hand, the social ecological protection awareness was improved, and the mangrove forest protection work was consciously coordinated.

3.2 Spatial distribution evolution of mangrove along Guangdong coastal zone

Using ArcGIS spatial analysis technology, the mangrove surface elements of cities in Coast of Guangdong Province were extracted as point elements, which were classified into five grades: very low density, low density, medium density, high density, and very high density, and the spatial agglomeration characteristics of mangrove forests in past 40 years were analyzed.

The distribution pattern of mangrove in Coast of Guangdong Province is more in the west and less in the east. Mangrove in the study area starts from Gaoqiao Mangrove Nature Reserve in Zhanjiang City in the west and ends at Nan'ao Island in Shantou City in the east. Among them, the coasts of Zhanjiang City, Yangjiang City, Zhuhai City and Shanwei City are the main distribution areas, and the medium or above value area of kernel density is mainly distributed in the bay area, such as Leizhou Bay in Zhanjiang City, Bohe Bay in Maoming City, Hailing Island in Yangjiang City, Pearl River Estuary and Haimen Bay in Shantou City. During the study period, the mangrove very high density space of the whole coast was stably distributed in the area of Leizhou Bay of Zhanjiang City in the western coast, which showed a shrinking trend before 2000. After 2000, there was a large expansion from Leizhou Bay to Jinsha Bay of Chikan District in northeast and Houhaisha of Xuwen County in the south. The central coastal zone was a low density area before 2013, and the mangrove forest of Nansha Bay in Guangzhou City and Daya Bay in Huizhou City increased to a large extent after 2013. The form change of the mangrove forest in the eastern coast from concentration to dispersion was most obvious before 2013, and the kernel density value decreased year by year. From 2013 to 2018, the mangrove forest in Honghai Bay in Shanwei City slowly recovered (Figure 2). Therefore, the coast in the central and western part of Guangdong will become the pilot area for mangrove carbon trading in the future, while the eastern coast should accelerate the restoration and protection of the mangrove ecosystem.

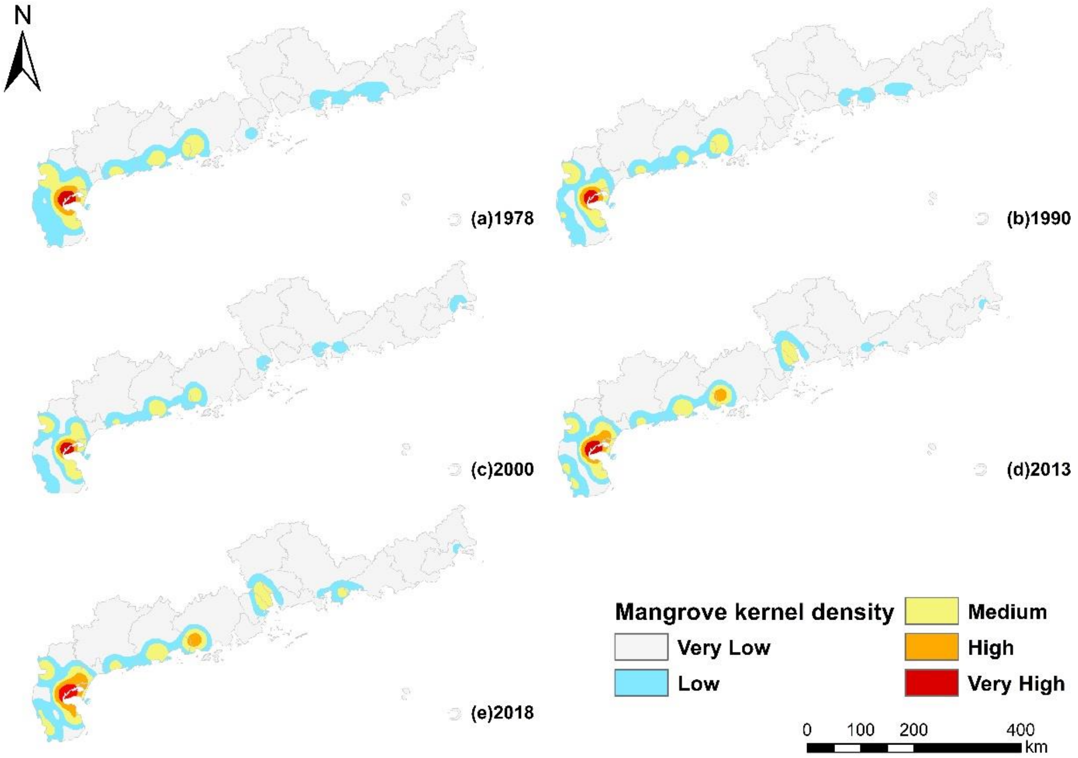


Figure 2 Spatiotemporal evolution of mangrove along Guangdong coastal zone from 1978 to 2018

3.3 Spatiotemporal evolution of mangrove distribution along Guangdong coastal zone

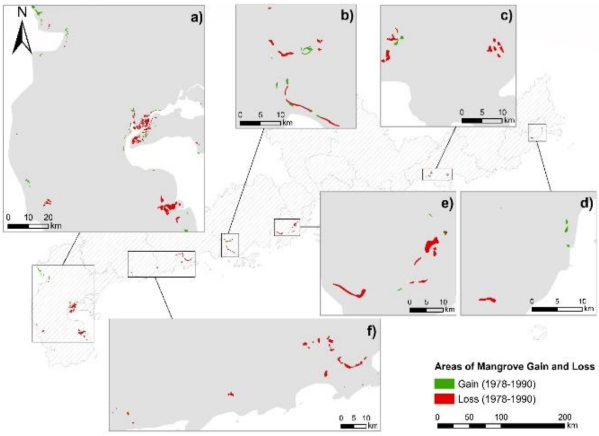
It is helpful to reveal the temporal and spatiotemporal evolution characteristics of mangrove distribution by analyzing the specific space of mangrove distribution expansion and degradation along the coast of Guangdong in recent 40 years (Figure 3).

From 1978 to 1990, the distribution of mangroves changed from strip-like distribution to scattered patchwork distribution. In 1978, the mangroves in Mazhang District of Zhanjiang City were distributed along the coastline of Leizhou Peninsula in a large scale, while the mangroves in Gaoqiao Town of Zhanjiang City, Shenqian Bay in Hailing Island of Yangjiang City and Zhenhai Bay in Jiangmen City were distributed discontinuously, and the rest of the mangroves were distributed in patches and scattered on the intertidal strip. In 1990, the distribution range of mangroves in each city was reduced significantly, among them, the mangrove area of Zhuhai City, Yangjiang City and Zhanjiang City all lost thousands of hectares, and the mangroves in Shenqian Bay of Hailing Island in Yangjiang City and Jiti Gates of the Pearl River and Pingsha Town in Zhuhai City changed from strip-like distribution to scattered patchwork distribution.

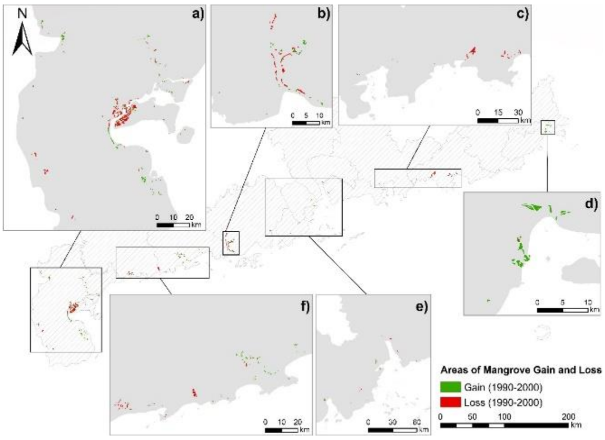
From 1990 to 2000, the increase and decrease of mangrove in the eastern coast was most obvious. During this period, the secondary restoration of the mangrove forest in Raoping County of Chaozhou was 74.54 ha, while the mangrove forest in Shanwei City was reduced by nearly 800ha due to improper development. In addition, a large amount of mangrove forests were lost in Dongguan City. Only remained 3ha of mangroves distributed along Shiziyang Channel of Humen Town. The distribution range of mangroves in the western coast is reduced in general as the characteristic. Except for the mangroves still distributed in strip shape in Huguang Town in Zhanjiang City, the remaining mangroves were distributed in scattered patches, and the strip width of mangroves was reduced.

From 2000 to 2013, the patch area of mangrove has increased after artificial or natural restoration. In the western coast, except for the continuous decrease of mangroves in Zhanjiang City, the mangroves in Maoming City and Yangjiang City gradually increased due to artificial or natural restoration. As a result of the active protection and restoration of mangroves in the Pearl River Delta coast region, the patches were obviously enlarged and the area has been increased, especially in Zhuhai City and Guangzhou City. The restored mangroves were mainly located in the estuaries and bay areas.

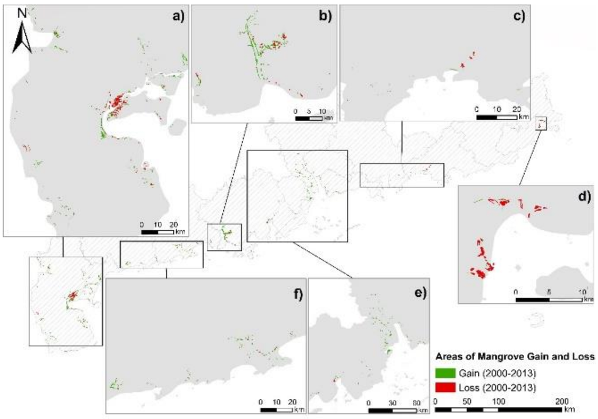
Mangrove protection measures in 2013-2018 showed results, but the consistency and concentration were less than in the past. In 2018, the mangrove forest in the study area increased by 717.16 ha compared with that in 2013, and the mangrove in each city showed different degrees of growth, which reflects that after the “12th Five-Year Plan”, the construction of ecological civilization in Guangdong Province has been well implemented and the protection measures of mangrove forest were effective. However, although the patches have strip restoration, most of the restored mangrove forests were artificial forests.



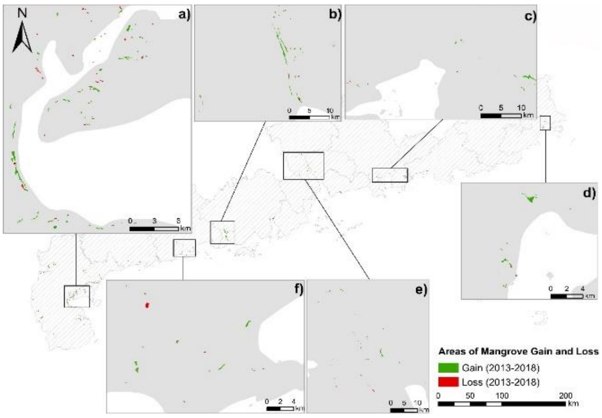
(a)Area of mangrove gain and loss from 1978 to 1990



(b) Area of mangrove gain and loss from 1990 to 2000



(c)Area of mangrove gain and loss from 2000 to 2013



(d) Area of mangrove gain and loss from 2013 to 2018

Figure 3 Temporal and spatiotemporal evolution of mangrove along Guangdong coastal zone from 1978 to 2018

4. Temporal and Spatiotemporal Evolution of Mangrove Carbon Storage Along Guangdong Coastal Zone

4.1 Temporal evolution of mangrove carbon storage along Guangdong coastal zone

The carbon storage of mangrove along the coast of Guangdong has decreased for 40 years. The weight of carbon storage in 1978,1990,2000,2013 and 2018 were 3,980,900 tons/ha, 2,431,000 tons/ha, 1,965,100 tons/ha, 2,141,000 tons/ha and 2,394,600 tons/ha respectively. In contrast to 1978, almost half of the total carbon storage was lost until 1990. Despite a reduce in the rate of decrease from 1990 to 2000, there was still a loss of 500,000 tons/ha. Since 2000, it recovered slowly, with an increase of 429,400 tons/ha between 2000 and 2018. But overall, there has been a cumulative decrease of 1,586,300 tons/ha over the past 40 years (Figure 4).

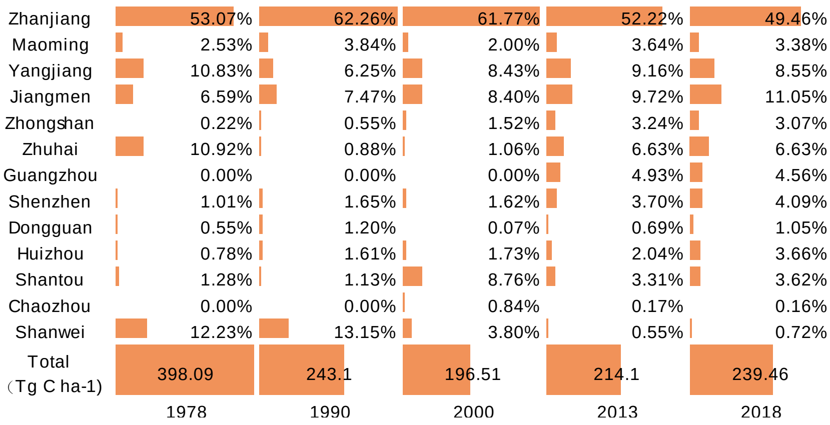


Figure 4 Percentage distribution of mangrove carbon storage of cities along Guangdong coastal zone from 1978 to 2018

4.2 Spatial change of mangrove carbon storage along Guangdong coastal zone

Using a Cartesian heat map, this paper categorizes mangrove carbon storage into three levels—red, yellow, and green—to visually demonstrate the spatiotemporal distribution of heat values and cold values. The higher the heat value, the darker the color (red), and the lower the heat, the lower the color (green) (Figure 5). From 1978 to 2018, the mangrove carbon storage of cities in coast of Guangdong Province was significantly different, which showed that the mangrove carbon storage in the western coast was higher than those in the central and eastern parts, especially in Zhanjiang City. The mangrove carbon storage showed a "single-core" distribution in space. The medium or above values of mangrove carbon reserves was concentrated in the western coast and the carbon storage were relatively stable. The low values was mainly in the central and eastern coasts, and the reserves changed significantly during the study period.

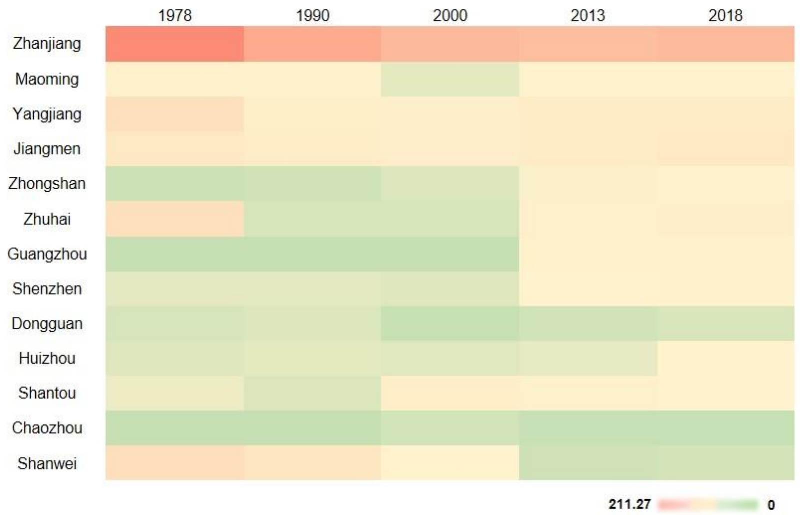


Figure 5 Heat map of mangrove carbon storage along Guangdong coastal zone

According to the natural breaks method, the carbon storage is divided into five grades: very low, low, medium, high, and very high, so as to discuss the spatiotemporal distribution characteristics of mangrove carbon storage along Guangdong coastal zone (Figure 6). In general, from 1978 to 2018, the mangrove carbon storage along Guangdong coastal zone showed a spatial pattern of “higher in the west and lower in the central and east”. Especially before 2000, this regional differentiation was most obvious. The carbon storage of mangrove in the central and east of Guangdong coastal zone was generally lower than 80,000 tons/ha, while that of the western coast was mostly between 80,000 and 180,000 tons/ha. After 2000, the carbon storage of mangroves along Guangdong coastal zone increased in general, and the difference between regions was reduced.

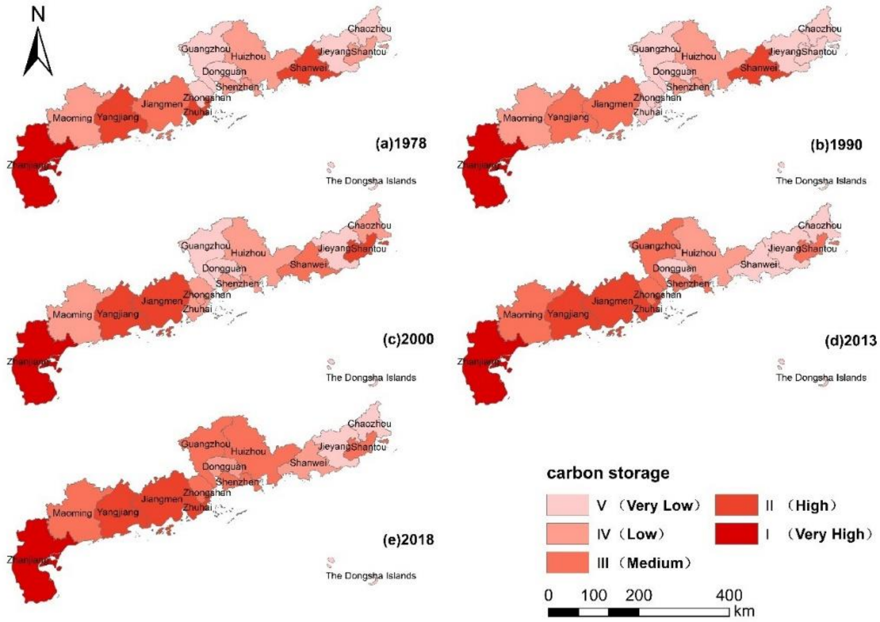


Figure 6 Spatial pattern evolution of carbon storage along Guangdong coastal zone from 1978 to 2018

4.3 Spatiotemporal evolution of mangrove carbon storage along Guangdong coastal zone

The changes in mangrove carbon storage along the coast of Guangdong Province in the past 40 years can be roughly divided into two stages. In the first stage (1978-2000), mangrove carbon storage decreased sharply. Especially in the years of 1990-2000, the carbon storage of each part of the coastal zone were reduced to varying degrees. In the second stage (2000-2018), the mangrove carbon storage showed a gradual increase. During this period, the overall mangrove carbon storage of Guangdong Province increased, and the difference between regions narrowed (Figure 7).

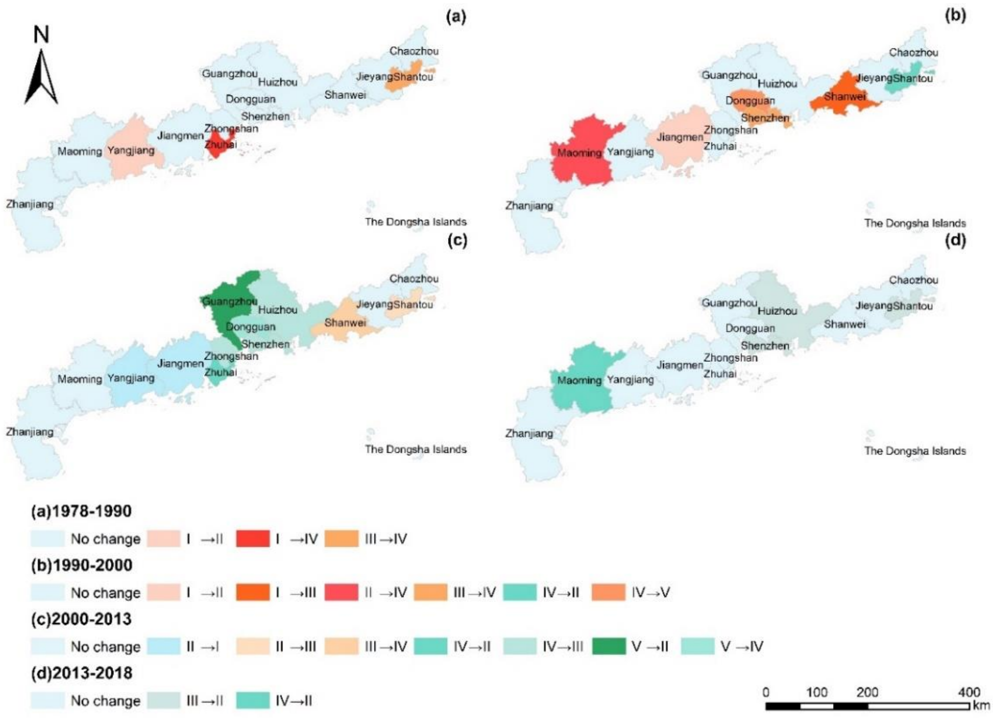


Figure 7 Temporal and spatiotemporal evolution of carbon storage along Guangdong coastal zone from 1978 to 2018

In the first stage, the decrease of mangrove carbon storage from 1978 to 1990 occurred in Yangjiang City in the western coast, Zhuhai City in the central coast, and Shantou City in the eastern coast, while the carbon storage in the other cities was relatively stable. Since 1990, the cities of Maoming, Jiangmen, Shanwei, Shenzhen and Dongguan have all experienced a decrease in carbon storage, mainly due to the land expansion caused by urbanization and encroachment of mangrove growth space. The carbon storage of Shantou City and Chaozhou City in the eastern coast increased slightly. The main reason was that from 1994 to 1998 in Shantou City, the artificial forests of Sonneratia apetala, Brugula officinalis and Kandelia candel were introduced in Chenghai District for ecological restoration, while the increase of mangrove forest in Raoping County of Chaozhou City was mainly natural restoration.

In the second stage, from 2000 to 2018, the mangrove carbon storage in the whole province increased, and the differences between regions were narrowed. The carbon storage of cities such as Guangzhou, Maoming, Huizhou and Shenzhen all increased to a large extent, which may be due to the implementation of ecological environment protection in the "12th Five-Year Plan". A series of mangrove forest protection plans, policies and regulations have been formulated by the whole province and each city, including the planning of the Pearl River Delta Mangrove Nature Reserve in 2014, the general plan for the construction of national forest cities of Maoming City and Jiangmen City in 2016, and the Management Measures for Mangroves in Zhanjiang City in 2017. These measures have partly strengthened the protection of mangroves and t increased the mangrove carbon storage along Guangdong Coastal Zone.

Table 3 Change types of mangrove carbon storage in coastal cities of Guangdong from 1978 to 2018.

Type	City	Reason
High and stable carbon storage type	Zhanjiang, Jiangmen and Yangjiang	Mangrove area base is large, and latitude is lower than other cities in the province
Low but stable carbon storage type	Maoming, Dongguan	The area of the original mangrove is small, while the damage is small.
Increasing carbon storage type	Shenzhen, Guangzhou, Zhongshan, Huizhou	Effective measures have been taken to protect mangroves through the combination of natural restoration and artificial restoration, and the mangrove carbon storage has increased.
Decreasing carbon storage type	Zhuhai and Shanwei	The original mangrove base is large, but due to urban expansion and land occupation for reclamation, the mangrove is rapidly lost.
Carbon storage initially increasing then decreasing type	Shantou and Chaozhou	The short duration of the ecological construction reform, the lack of supervision, and the problems of a large number of reclamation from sea and the construction of breeding farms make the medium-term ecological recovery only a flash in the pan, and the sustainability is low

Looking at the temporal evolution of mangrove carbon storage in coastal cities of whole province over the past 40 years, coastal cities can be divided into five types (Table 3). The first type is of high and stable carbon storage, including Zhanjiang City, Jiangmen City and Yangjiang City. The mangrove carbon storage in Zhanjiang has a high primacy ratio, accounting for 62.26%-49.46% of the carbon storage of the whole province in 40 years. The reason is that the distribution area of mangroves in Zhanjiang City is large and the latitude is lower than that of other cities in the province. The mangrove carbon storage in Jiangmen City and Yangjiang City both account for 5-11% of the whole province. The second type is the type with low but stable carbon storage, including Maoming City and Dongguan City, in which Dongguan City has a small proportion of original mangrove area, but the change is relatively stable. The third type is the increasing carbon storage type, including the cities of Shenzhen, Guangzhou, Zhongshan and Huizhou. All four cities have taken effective restoration measures through the protection of mangroves, and increased the mangrove carbon storage through the combination of original restoration and artificial restoration. The fourth type is the decreasing carbon storage type, including Zhuhai City and Shanwei City. During 1978-2000, Zhuhai City lost mangroves sharply due to urban expansion and land occupation for reclamation, and the proportion changed greatly. The fifth type is the carbon storage initially increasing then decreasing type, including Shantou City and Chaozhou City in the eastern coast of Guangdong Province. Due to the short duration of ecological construction reform and lack of supervision, as well as a large number of problems such as reclamation from sea and construction of coastal farms, the carbon storage increase is unsustainable.

5. Conclusions and Discussions

5.1 Conclusions

In this paper, the mangroves along the coast of Guangdong Province are taken as the research object, and Chinese long-time series satellite remote sensing monitoring dataset of mangroves are used to analyze the temporal and spatiotemporal evolution characteristics of mangroves along Guangdong coastal zone from 1978 to 2018 by means of dynamic degree and kernel density analysis. The following conclusions were drawn:

(1) In terms of distribution, from the perspective of quantity, the distribution area of mangroves has generally decreased during the past 40 years, with a trend of falling first and then rising in general, which can be divide into two stages: the first stage (1978-2000) is a rapid decrease period, and the second stage (2000-2018) is a slow growth period. From the perspective of spatial distribution, the mangrove in coast of Guangdong Province is generally in the pattern of "more in the west than in the east". The medium or above value area of mangrove kernel density in coast of Guangdong Province are mainly distributed in bay area, such as Leizhou Bay of Zhanjiang City, Bohe Bay of Maoming City, Hailing Bay of Yangjiang City, Pearl River Estuary and Haimen Bay of Shantou City. During the study period, the kernel density of mangrove in the coastal area of East Guangdong decreased year by year, while that in Hailing Bay of Yangjiang City and Pearl River Estuary increased. From the perspective of spatiotemporal evolution, the loss of mangrove forest along Guangdong coastal zone was serious from 1978 to 2000, and the distribution pattern developed from strip to strip discontinuous distribution, finally distributed in scattered patches on the intertidal strip. In that year 2000 onwards, the mangrove patches area increased after artificial or natural restoration, and the mangrove restoration and protection measures were effective. However, the consistency and aggregation of patches were not as good as before.

(2) In terms of mangrove carbon storage, from the perspective of quantity, the mangrove carbon storage along Guangdong coastal zone has generally decreased in the past 40 years. Before 2000, due to the human disturbance of urban construction and coastal reclamation, the growing range of mangroves was constantly reduced, and the mangrove carbon storage in 2000 was reduced to 49% in 1978. After 2000, the protection and restoration measures of mangroves have been implemented successively, and the mangrove carbon storage has increased slowly, but the mangrove carbon storage has still cumulative decreased by 1.5863 million tons/ha during 40 years. From the perspective of spatial distribution, it was a spatial pattern of "higher in the west and lower in the central and east". The carbon storage of mangrove showed the "single core" distribution of Zhanjiang city, accounting for half of the carbon storage of the whole province. From the perspective of spatiotemporal evolution, before 2000, the mangrove carbon storage was reduced due to the transitional development of tidal flats, building coastal farms and reclaiming land from the sea in the cities of Yangjiang, Zhuhai, Shantou, Maoming, Jiangmen, Shanwei, Shenzhen and Dongguan. After 2000, the mangrove carbon storage in the whole province was improved, mainly due to the implementation of mangrove protection plans and policy measures. The ecological restoration of mangroves has been basically realized, and the mangrove carbon storage has been improved.

5.2 Discussions

Through the analysis of the spatiotemporal evolution of mangrove carbon storage along the coast of Guangdong Province over the past 40 years, it is found that the distribution area of mangroves is the key factor of carbon storage. The study shows that areas with higher carbon intensity depend on the growth area of mangroves, which are mostly low latitude, good hydrothermal conditions, and mostly located in coastal bays. Studies have shown that the minimum total carbon density of mangrove in the coastal cities of Guangdong Province is in Zhanjiang City, but because of the wide distribution area of mangroves, the mangrove carbon storage in the coastal areas of

Zhanjiang still accounts for about half of the carbon storage of the whole province. The total carbon density of mangroves in Huizhou City, Shenzhen City, Dongguan City, and Shantou City is at the forefront of the province. However, due to the small distribution area of mangroves, the carbon reserves of mangroves in each city do not exceed 5% on average. Therefore, to exert the carbon sequestration capacity of mangroves more effectively, the expansion of the distribution range of coastal mangroves is particularly important. For Shanwei City, Chaozhou City and other areas with mangrove degradation due to urban expansion and construction of coastal farms, ecological restoration and supervision should be strengthened, and restore mangrove communities along appropriate shorelines. For the areas with good original growth foundation and conditions of mangroves in Zhanjiang City, Yangjiang City and Jiangmen City, it is necessary to restore the connectivity of mangroves to restore the scattered or strip-shaped mangroves to a concentrated lumps, so as to further improve the ecological function and carbon sink function of mangroves. For areas with a small number of mangrove but high total carbon density in the Pearl River Estuary, it is recommended to build mangrove forest parks in combination with the planning of the urban coastal area, taking into account the functions of ecology, recreation, and science popularization, so as to make mangroves become the new name card of the land of Southern Guangdong.

The results of mangrove carbon storage in this paper are primarily based on the quantity and overall spatial distribution of mangroves. However, the influence of factors such as the morphology, fragmentation, dominance, and connectivity of mangrove patches on carbon storage still requires further research. Therefore, the direction for further research involves integrating landscape ecology and computer science techniques to simulate and analyze the evolution of mangrove carbon storage based on ecological processes and landscape patterns, providing more specific recommendations for mangrove ecological restoration and conservation.

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