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Mangrove wetlands distribution status identification, changing trend analyzation and carbon storage assessment of China

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A B S T R A C T

This research investigates the ecological importance, changes, and status of mangrove wetlands along China's coastline. Visual interpretation, geological surveys, and ISO clustering unsupervised classification methods are employed to interpret mangrove distribution from remote sensing images from 2021, utilizing ArcGIS software platform. Furthermore, the carbon storage capacity of mangrove wetlands is quantified using the carbon storage module of InVEST model. Results show that the mangrove wetlands in China covered an area of 278.85 km^2 in 2021, predominantly distributed in Hainan, Guangxi, Guangdong, Fujian, Zhejiang, Taiwan, Hong Kong, and Macao. The total carbon storage is assessed at 2.11×10^6 t, with specific regional data provided. Trends since the 1950s reveal periods of increase, decrease, sharp decrease, and slight-steady increases in mangrove areas in China. An important finding is the predominant replacement of natural coastlines adjacent to mangrove wetlands by artificial ones, highlighting the need for creating suitable spaces for mangrove restoration. This study is poised to guide future mangrove-related investigations and conservation strategies.

1. Introduction

Mangrove, characterized as evergreen woody plant communities, thrive in the intertidal zones of tropical and subtropical coasts. Distributed across shallow lagoons, estuaries, rivers, and deltas in 124 countries and regions (IUCN, 1983), mangroves currently span approximately 147000 km^2 globally (Global Mangrove Alliance, 2022).

Mangroves a pivotal role in ecological improvement, offering benefits such as protection against wind and waves, shoreline preservation, siltation promotion, and environmental purification. They provide vital habitats for waterfowl and serve as breeding grounds for aquatic species like fish, shrimp, crabs, and shellfish. Being one of the three coastal blue carbon ecosystems, mangrove forests significantly contribute to marine carbon sinks (Wang FM et al., 2022; Wang Y et al., 2021). Their carbon storage capacity (Duarte CM et al., 1996, 2005), mainly due to complex aboveground structures conducive to particulate organic carbon sedimentation, surpasses that of terrestrial ecosystems (Alongi DM, 2014; Ezcurra P et al., 2016). However, as coastal zones continue to develop and house an increasing proportion of the population, economy, and wealth, the natural habitats of mangroves face serious threats. In China, coastal zones hold 46.3% of the population and 59.1% of GDP, according to the 2021 data (seventh national population census and province GDP data). This concentration has led to vast areas of mangroves being replaced by aquaculture areas, cities, roads, and ports, and the rising sea levels further shrink the mangrove ecosystems' living space (Fan HQ, 1995; Fan HQ et al., 1997; Chen GQ et al., 2007; Fu HF et al., 2014; Fu HF, 2019). Previous studies on Chinese mangroves primarily focused on protection, restoration effectiveness monitoring (Xu CL et al., 2012; Feng XP et al., 2017), ecological

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environment monitoring (Li PS et al., 2010; Zhan N et al., 2019), and remote sensing monitoring of mangroves in a certain region (Ma YM et al., 2021; Jia K et al., 2022; Li C et al., 2022), with limited research on a national scale. Gaining a comprehensive understanding of the status, health, and development trends of mangrove ecosystems, evaluating their carbon storage capacities, and improving the carbon sequestration potential are crucial for coastal sustainable development and mangrove conservation and restoration efforts.

This study focuses on mangroves in China, employing remote sensing interpretation, geological surveys, ArcGIS spatial analysis, and InVEST model to investigate the distribution and carbon storage of these ecosystems. By examining changes over the past 70 years, the core problems for the ecological protection and restoration are proposed, aiming to serve as a valuable reference for future mangrove conservation and restoration efforts in China.

2. Method

Data source: For this study, the base year is 2021, and the data collected consists of Landsat 8 OLI remote sensing images and 91 Satellite images (download from 91 Satellite Map Assistant: http://www.91weitu.com) covering the coast of China. The resolution for Landsat 8 OLI remote sensing images is 15 m, while that of 91 satellite remote sensing images ranges from 2–4 m (Fig. 1). All selected satellite image data are either free of clouds or contain minimal cloud coverage, providing clear visibility of the coastline and mangrove distribution, thus ensuring data quality during the process of human-computer interaction interpretation.

Interpretation method: Given that mangrove forests primarily thrive in tropical and subtropical intertidal zones, visual interpretation signs for mangrove wetlands were established, and extraction principles were formulated. Images were pre-processed using ArcGIS 10.2 software. Subsequently, according to the characteristics of each band of Landsat 8 OLI, the 6 (SWIR1) 5 (NIR) 2 (Blue) bands and 5 (NIR) 4 (Red) 3 (Green) bands were selected for band synthesis (Fig. 1). The unsupervised classification of ISO clustering was used for automatic extraction of mangrove wetlands information, followed by discriminated and boundary modification of the automatically extracted data based on the high-precision 91 satellite images. Field verification was also conducted in some areas (Fig. 2).

Landsat 8 OLI Synthetic remote sensing image: a–Dongzhai Harbor, Hainan Province; b–Maoweihai, Guangxi Province; c–Yangjiang, Guangdong Province; d–Ningde, Fujian Province. Remote sensing image from 91 Satellite Map Assistant: e–Dongzhai Harbor, Hainan Province; f–Maoweihai, Guangxi Province; g–Yangjiang, Guangdong Province; h–Ningde, Fujian Province.

Carbon storage assessment: The carbon storage assessment method leverages the total carbon storage calculation formula in InVEST model, which subdivides the carbon storage of each land type into four basic carbon pools: aboveground biomass (C_{above}), belowground biomass (C_{below}), soil carbon (C_{soil}), and dead organic carbon (C_{dead}). The corresponding calculation formula is as follows:

$$C_{totali} = (C_{abovei} + C_{belowi} + C_{soili} + C_{deadi}) \times A_i \quad (1)$$

where i is the type of land use, A_i is the area of i type land use, and C_{totali} is the total carbon storage of i type land use.

InVEST model, a simulation-based approach to estimating carbon storage, offers advantages such as minimal data requirements and rapid processing speeds. It facilitates the representation of spatial distribution and dynamic changes in carbon storage, and it depicts the relationship between changes in carbon storage and the impacts of natural and human activities across flexible scales (Sharp R et al., 2020; Liu YZ et al., 2021).

Historical data collection: A systematically collection of previously published papers, books, and internal geological survey reports pertaining to mangrove was undertaken. These resources cover various aspects including the status, changes in distribution and area, vegetation types, habitats, and span timeframes as early as the 1950s. This wealth of data allows for an in-depth analysis of the changes in mangroves and their underlying mechanisms over the past 70 years.

3. Results and discussions

3.1. Status of mangrove distribution

The total area of mangrove forests in China is 278.85 km^2 (Fig. 3; Table 1). The breakdown of this area by region is as follows: Hainan accounts for 54.11 km^2, Guangxi Zhuang Autonomous Region covers 90.80 km^2, Guangdong spans 105.72 km^2, Fujian includes 12.24 km^2, Zhejiang incorporates 4.62 km^2, Taiwan comprises 4.77 km^2, while Hong Kong and Macao contribute 6.23 and 0.36 km^2, respectively (Fig. 4, Fig. 5).

The geographical spread of mangrove forests in China exhibits a decreasing trend from south to north, both in terms of total area and density per unit area. The spatial distribution of mangrove forests mainly occurs in patchy, striped, and point formats. The distribution pattern transitions from a concentrated, large-area patchwork in the south to a more scattered, point-like distribution from south to north (Fig. 3).

3.2. Carbon stock assessment

Variations in mangrove tree species and carbon density across provinces and regions have been documented in previous studies. This investigation collected and consolidated the relevant results concerning mangrove forests in China. The species proportion in Hainan mangrove forests was derived from the research of Fang FZ et al. (2022), while the carbon density data for the mangrove wetlands came from the studies of Yan K (2015), Li CH et al. (2020), Hu YK et al. (2019), Zhang HD et al. (1998), and Tan SY (2017). The species proportion in Guangxi mangrove forests was derived from the work of Ma YM et al. (2021), and the carbon density data was from the studies of He QF et al. (2017) and Gao TL et al. (2018). The species proportion in Guangdong mangrove forests was derived from Li ZQ et al. (2002), while the carbon density data was from the aforementioned studies. The species

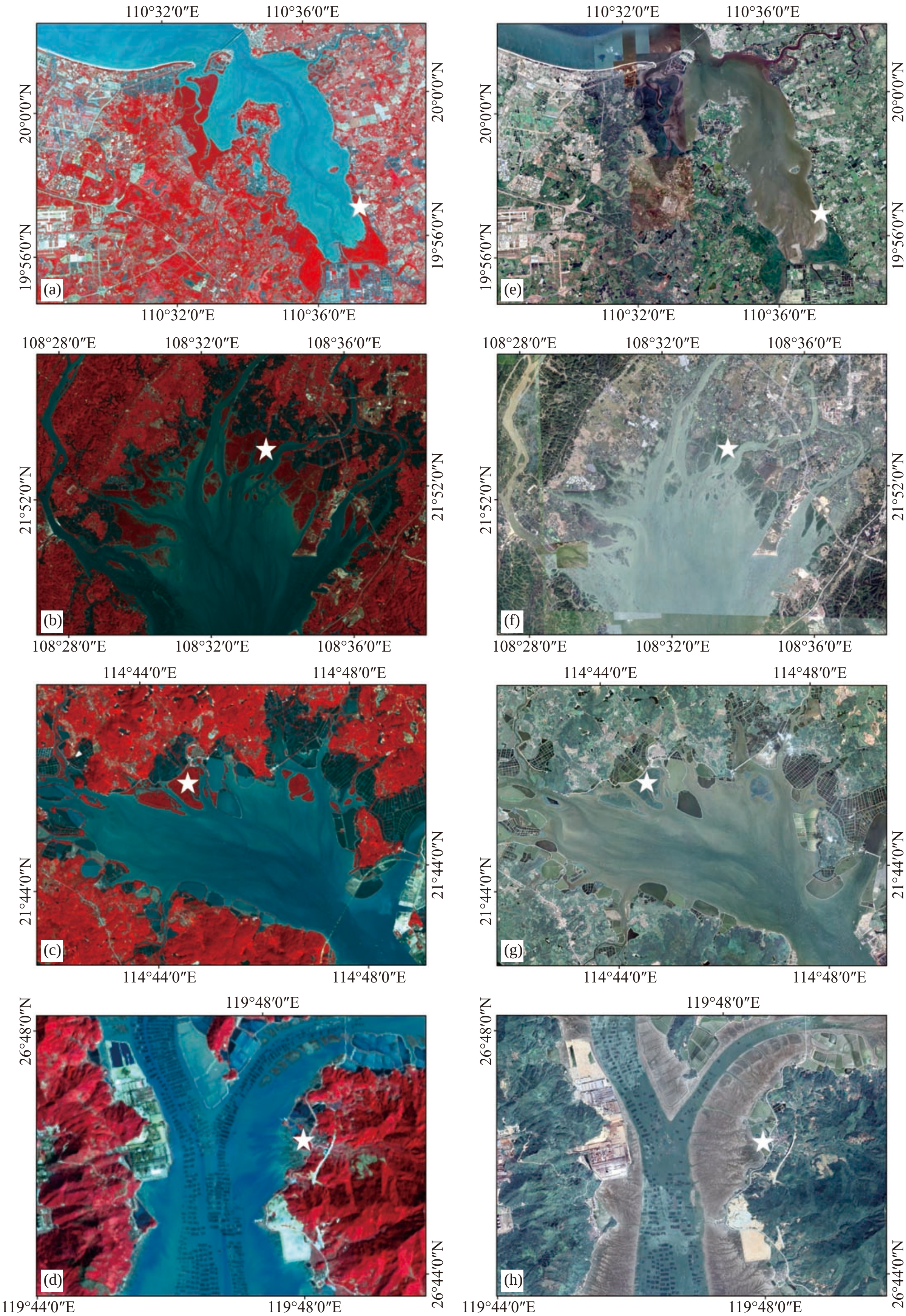

Fig. 1. Landsat 8 OLI composite image and 91 satellite image.

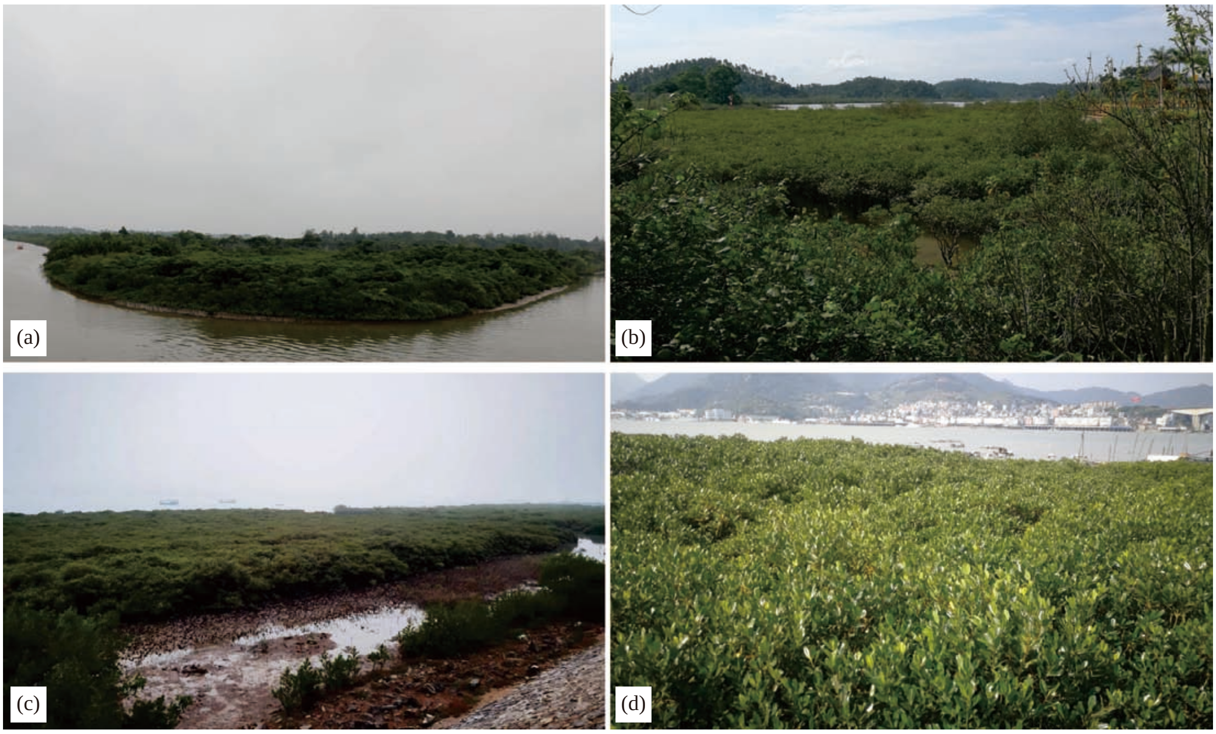

Fig. 2. Main mangrove circumstances of China (picture a, b and c cited from Hu YZ et al., 2022). a–Dongzhai Harbor, Hainan Province; b–Maoweihai, Guangxi Province; c–Yangjiang, Guangdong Province; d–Ningde, Fujian Province.

proportion in Fujian mangrove forests was taken from Wang WQ (2000), and the carbon density data was from the studies of Hu YK et al. (2019), Zhang HD et al. (1998), Tan SY (2017), He QF et al. (2017), and Gao TL et al. (2018). The carbon storage data from Fujian was used to estimate the mangrove forests in Zhejiang and Taiwan, while the data from Guangdong was used to estimate the mangrove forests in Hong Kong and Macau. Parameters including species proportion, aboveground biomass, belowground biomass, soil carbon, and dead organic carbon density are shown in Table 2.

Utilizing the total carbon calculation formula (1) from the total carbon module of InVEST model, the total carbon storage in China's mangrove wetlands was determined to be 2.11×10^6 t. This includes: Hainan with 5.09×10^5 t, Guangxi with 6.47×10^5 t, Guangdong with 7.35×10^5 t, Fujian with 9.61×10^4 t, Zhejiang with 3.62×10^4 t, Taiwan with 3.75×10^4 t, Hong Kong with 4.34×10^4 t, and Macao with 2.50×10^3 t. In general, carbon storage in mangrove wetlands declines from south to north, as shown in Figure 6.

3.3. Historical changes in mangrove wetlands area

The Tropical and Subtropical Resources Survey in 1956 estimated the area of China's mangrove forests at approximately 400 km^2, corroborated by the same year's forest resource survey that reported an area of 420 km^2. Jia MM et al. (2021) showed the mangrove forest area to be 488.01 km^2 in 1973, which reduced to 282.46 km^2 in 1980, 204.5 km^2 in 1990, 186.02 km^2 in 2000, and then increased to 207.76 km^2 in 2010 and 280.1 km^2 in 2020. The National Forestry Survey in 2001, excluding Hong Kong, Macao and Taiwan, put the total mangrove forest area at 220.249 km^2. Wu PQ et al. (2013) estimated the mangrove area to be 135.196, 160.536, and 245.782 km^2 for the periods before and after 1990, 2000, and 2010, respectively. Wang H et al. (2020) indicated that the mangrove forest area was 155.052 km^2 in 1990, which expanded to 216.129 km^2 by 2019, marking an increase of 61.077 km^2 from 1990.

Despite the differing estimates of mangrove wetland areas by various institutions and researchers, a pattern can be discerned when examining these figures collectively: about 400–420 km^2 (average 410 km^2) in the 1950s, about 488.01 km^2 in the 1970s, about 282.46 km^2 in the 1980s, about 135.2–204.5 km^2 (average 169.85 km^2) in the 1990s, about 220.25 km^2 in the 2000s, about 207.76–245.78 km^2 (average 226.77 km^2) in the 2010s, and about 274.2–280.1 km^2 (average 277.15 km^2) in the 2020s (Fig. 7). This data reveals a slight increase in mangrove area from the 1950s to the 1970s, a significant decline from the 1970s to the 1990s, and a consistent increase since the 1990s.

The overall trend of mangrove forests in China since the 1950s can be delineated as follows: From the 1950s to the 1970s, despite detrimental human activities such as deforestation and land reclamation from the sea, the overall area of mangrove forests exhibited a minor increment. However, from the 1970s to the 1980s, the proliferation of human activities led to a rapid decrease in mangrove forest areas. Despite the escalating intensity of human activities, governmental efforts aimed at protecting mangrove forests began to mitigate the rates of decline from the 1980s to the 1990s. The period from the 1990s to the 2000s marked a critical turning point, where the trend of decreasing mangrove forest areas gradually transitioned into a slight increase. In the period since the 2000s, the successful implementation of a

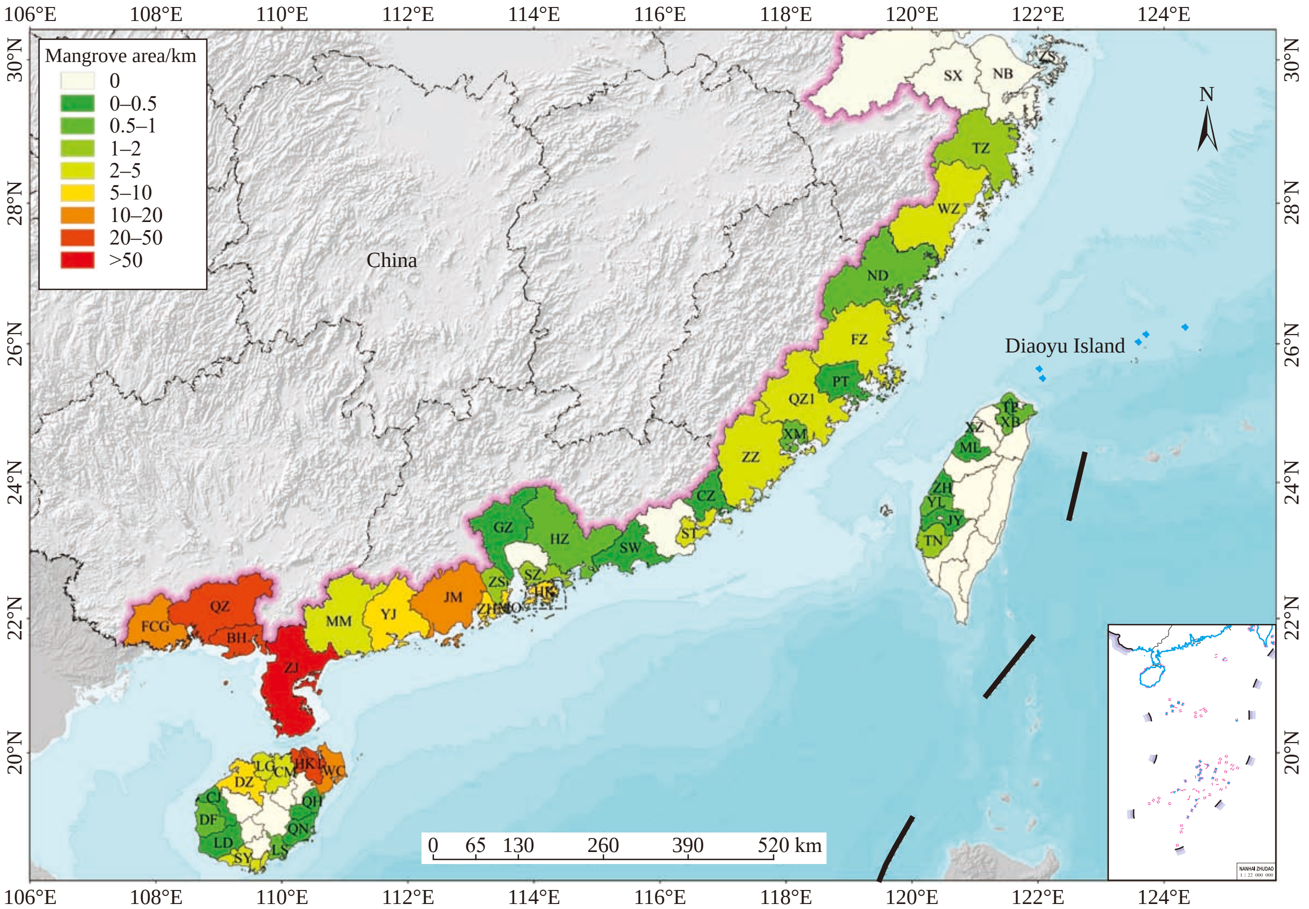

Fig. 3. Distribution of mangroves in China. Zhejiang Province: ZS–Zhoushan, SX–Shaoxing, NB–Ningbo, TZ–Taizhou, WZ–Wenzhou; Fujian Province: ND–Ningde, FZ–Fuzhou, PT–Putian, QZ1–Quanzhou, XM–Xiamen, ZZ–Zhangzhou; Taiwan: TP–Taipei, XB–Xinbei–XZ–Xinzhu, ML–Miaoli, ZH–Zhanghua, YL–Yunlin, JY–Jiayi, TN–Tainan; Guangdong Province: CZ–Chaozhou, ST–Shantou, SW–Shanwei, HZ–Huizhou, GZ–Guangzhou, ZS–Zhongshan, ZH–Zhuhai, JM–Jiangmen, YJ–Yangjiang, MM–Maoming, ZJ–Zhanjiang; MO–Macao; HK–Hong Kong; Guangxi Zhuang Autonomous Region: BH–Beihai, QZ–Qinzhou, FCG–Fangchenggang; Hainan Province: HK1–Haikou, DZ–Danzhou, SY–Sanya, CM–Chengmai, LG–Lingao, DF–Dongfang, LS–Lingshui, WC–Wenchang.

Table 1. Distribution of mangroves in various provinces and regions (counties and cities).

Province/Region	Main distribution area
Hainan	Wenchang, Haikou, Chengmai, Lingao, Danzhou, Changjiang Li Autonomous County, Dongfang, Ledong Li Autonomous County, Sanya, Lingshui, Wanning, Qionghai
Guangxi	Fangchenggang, Qinzhou, Beihai
Guangdong	Zhanjiang, Maoming, Yangjiang, Jiangmen, Zhongshan, Zhuhai, Guangzhou, Shenzhen, Huizhou, Shanwei, Shantou, Chaozhou
Fujian	Zhangzhou, Xiamen, Quanzhou, Putian, Fuzhou, Ningde
Zhejiang	Wenzhou, Taizhou
Taiwan	Jiayi, Miaoli, Taipei, Tainan, Xinbei, Xinzhu, Yunlin, Zhanghua
Hong Kong	North District, Yuen Long District, Tuen Mun District
Macao	Cotai Ecological Reserve, Coloane Shipai Bay Reclamation Area

series of ecological protection and restoration projects, coupled with the establishment of dedicated mangrove forest protection areas, managed to halt the declining trend in mangrove forest area. Consequently, the area of mangrove forests has been progressively expanding.

3.4. Examining the drivers and existing challenges in mangrove wetlands dynamics

In the early 21st century, China made considerable strides in curbing the decreasing trend of mangrove forest areas through stringent protection measures and large-scale artificial restoration. However, the preservation and restoration of mangrove forests are still confronted with numerous challenges due to the combined effects of global climate change and human activities (Chai MW et al., 2019; Yu BM et al., 2021), the influence of alien species (Ren H et al., 2009), the aggravation of pests and diseases (Huang JS et al., 2012), coastal city construction (Fan HQ, 1995; Fan HQ et al., 1997; Chen GQ et al., 2007) and the negative effects of sea-level rise (Fu HF, 2019; Fu HF et al., 2014; Wang F et al., 2019).

Fig. 4. Distribution of mangroves in coastal counties and cities of China.

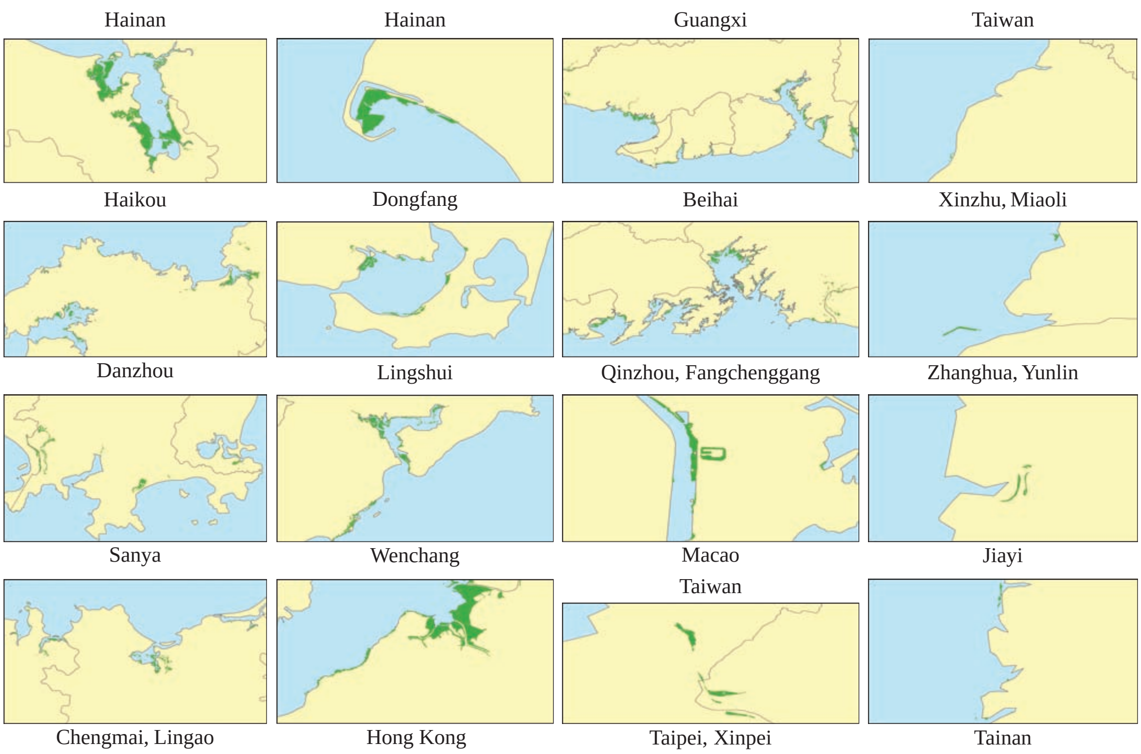

Fig. 5. Distribution of mangroves in coastal counties and cities of China.

Among these, the adverse consequences of coastal city development and sea-level rise on mangroves are particularly pronounced. Nearly five decades of sea-level monitoring in China's coastal areas show that the rate of sea-level rise has gradually increased from 2.5 mm/yr during 2000–2007 to 3.4 mm/yr in 2019–2021 (Ministry of Natural Resources,

Table 2. Carbon density of each part of Mangrove Wetlands (t/hm^2).

Region	Mangrove species	Proportion/%	C_{above} ($t\times10^2/km^2$)	C_{below} ($t\times10^2/km^2$)	0–30 cm C_{soil}($t\times10^2/km^2$)	C_{dead} ($t\times10^2/km^2$)	Data sources
Hainan	*Aegiceras corniculata*	3	22.73	11.15	65.25	5.63	Proportion data: Fang FZ et al., 2022; Carbon density data: Yan K, 2015; Li CH et al., 2020; Hu YK et al., 2019; Zhang HD et al., 1998; Tan SY, 2017
	Avicennia marina	14	6.95	3.41	65.25	5.63	
	Bruguiera gymnorrhiza	4	44.81	21.97	65.25	5.63	
	Rhizophora stylosa	40	8.25	4.05	65.25	5.63	
	Ceriops tagal	3	13.76	6.74	65.25	5.63	
	Bruguiera sexangula	11	37.24	18.26	65.25	5.63	
	Acanthus ilicifolius	3	0.76	0.37	65.25	5.63	
	Other	22	19.21	9.42	65.25	5.63	
	Calculated value		15.51	7.61	65.25	5.63	
Guangxi	*Aegiceras corniculata*	45.55	27.86	6.02	45.25	0.12	Proportion data: Ma YM et al., 2021; Carbon density data: He QF et al., 2017; Gao TL, 2018
	Avicennia marina	46.54	7.27	3.09	51.73	1.3	
	Other	7.91	17.57	4.56	48.49	0.71	
	Calculated value		17.46	4.54	48.52	0.72	
Guangdong	*Aegiceras corniculata*	12	26.84	13.16	39.75	0.54	Proportion data: Li SQ et al., 2002; Carbon density data: Yan K, 2015; Li CH et al., 2020; Hu YK et al., 2019; Zhang HD et al., 1998; Tan SY, 2017; He QF et al., 2017; Gao TL, 2018
	Avicennia marina	18	6.95	3.41	39.75	1.3	
	Rhizophora stylosa + Kandelia candel - Aegiceras corniculata + Avicennia marina	6	21.16	10.38	39.75	2.01	
	Kandelia candel - Aegiceras corniculata +Avicennia marina	9	25.47	12.49	39.75	0.8	
	Aegiceras corniculate+ Avicennia marina	7	16.9	8.29	39.75	0.92	
	Rhizophora stylosa- Aegiceras corniculata	6	17.55	8.61	39.75	3.09	
	Kandelia candel - Aegiceras corniculata	10	34.73	17.03	39.75	0.55	
	Avicennia marina+ Rhizophora stylosa	12	7.6	3.73	39.75	3.4	
	Rhizophora stylosa+ Kandelia candel	4	25.43	12.47	39.75	3.1	
	Other	16	20.29	9.95	39.75	1.73	
	Calculated value		18.92	9.28	39.75	1.61	
Fujian	*Aegiceras corniculata*	33.3	26.84	13.16	39.75	0.54	Proportion data: Wang WQ, 2000; Carbon density data: Hu YK et al., 2019; Zhang HD et al., 1998; Tan SY, 2017; He QF et al., 2017; Gao TL, 2018
	Avicennia marina	33.3	6.95	3.41	39.75	1.3	
	Kandelia candel	33.3	42.61	20.89	39.75	0.56	
	Calculated value		25.47	12.49	39.75	0.8	
Zhejiang	Calculated value		25.47	12.49	39.75	0.8	the same with Fujian data
Taiwan	Calculated value		25.47	12.49	39.75	0.8	the same with Fujian data
Hong Kong	Calculated value		18.92	9.28	39.75	1.61	the same with Guangdong data
Macao	Calculated value		18.92	9.28	39.75	1.61	the same with Guangdong data

2001–2022), indicating an escalating trend, especially since 2010. The relative sea-level rise rate, when superimposed on land subsidence, is significantly higher (Wang F et al., 2023), reaching its highest rate since 10 ka BP (Wang F et al., 2015; Wang F et al., 2020; Xiong HX et al, 2018; Wang H, 2022).

The rising sea-level leads to increased duration and frequency of mangrove flooding, thereby affecting the growth and development of mangroves (Chen LZ et al., 2004; He BY et al., 2007). Under natural circumstances, to adapt to sea-level rise, mangroves retreat to newly generated beaches on the landward side (Lovelock CE et al., 2015; Thomas WD et al., 2010). However, large-scale coastal city development in China, particularly the construction of artificial shorelines, has solidified the coast (Fig. 8). This has weakened the resilience of mangrove plants to the adverse effects of sea-level rise, damaged the environment in which mangrove forests thrive, and impeded mangroves' ability to adjust landward when faced with sea-level rise. Therefore, coastal construction and sea-level rise compress the habitat of mangroves, presenting a fundamental issue for the protection and restoration of mangrove wetlands.

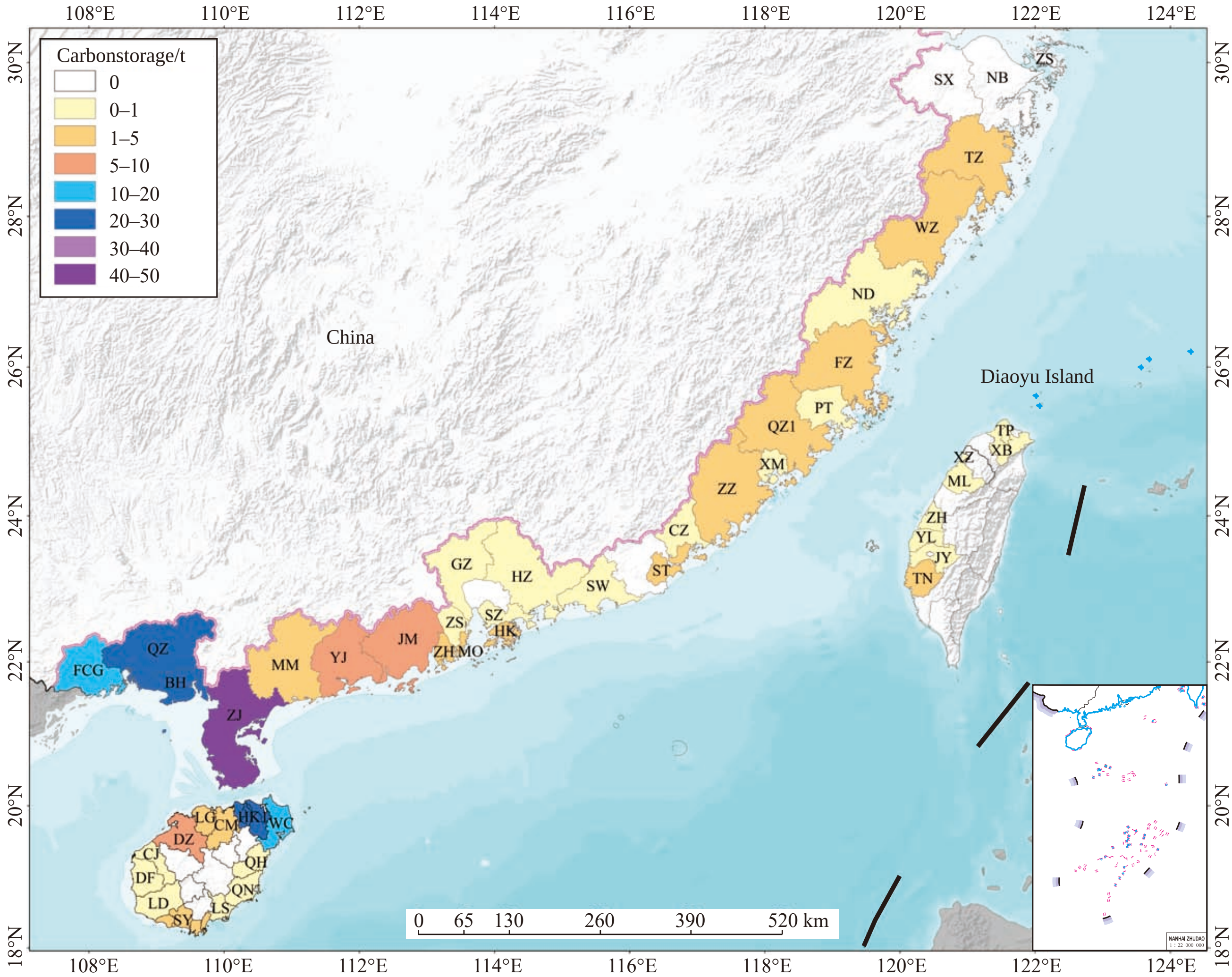

Fig. 6. Distribution of carbon reserves in mangrove wetlands in coastal counties and cities of China. Zhejiang Province: ZS–Zhoushan, SX–Shaoxing, NB–Ningbo, TZ–Taizhou, WZ–Wenzhou; Fujian Province: ND–Ningde, FZ–Fuzhou, PT–Putian, QZ1–Quanzhou, XM–Xiamen, ZZ–Zhangzhou; Taiwan: TP–Taipei, XB–Xinbei, XZ–Xinzhu, ML–Miaoli, ZH–Zhanghua, YL–Yunlin, JY–Jiayi, TN–Tainan; Guangdong Province: CZ–Chaozhou, ST–Shantou, SW–Shanwei, HZ–Huizhou, GZ–Guangzhou, ZS–Zhongshan, ZH–Zhuhai, JM–Jiangmen, YJ–Yangjiang, MM–Maoming, ZJ–Zhanjiang; MO–Macao; HK–Hong Kong; Guangxi Zhuang Autonomous Region: BH–Beihai, QZ–Qinzhou, FCG–Fangchenggang; Hainan Province: HK1–Haikou, DZ–Danzhou, SY–Sanya, CM–Chengmai, LG–Lingao, DF–Dongfang, LS–Lingshui, WC–Wenchang.

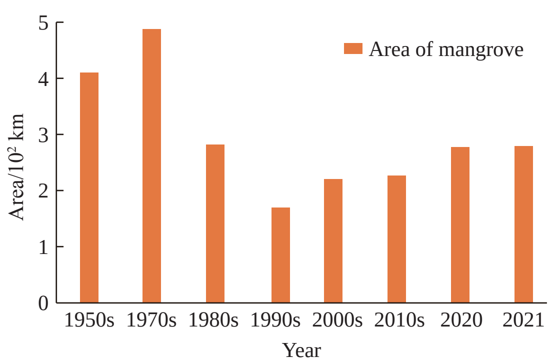

Fig. 7. Mangrove area change since 1950s of China.

Fig. 8. The solidified seawall on the landward side of mangroves in Ningde, Fujian.

3.5. Geologic recommendations for enhancing mangrove ecosystem conservation, restoration, and carbon sequestration

In response to the primary challenges facing mangroves in China, the following recommendations for their conservation and restoration are proposed.

3.5.1. Geologic recommendations for mangrove conservation and restoration

Increase the retention rate of natural shorelines and cultivate habitats for mangrove forests. It is necessary to ensure the relative stability of the selected mangrove restoration area and its resilience against the effects of sea level rise induced by human activities (e.g., seawalls). Additionally, the implementation of natural-based coastal ecological conservation and restoration strategies should be sustained. Efforts should be made to restore damaged shorelines and ecologically rehabilitate artificial shorelines, thereby increasing the retention rate of natural shorelines and generating additional habitats for mangrove forests.

Conduct research on the fundamental causes of typical mangrove degradation. For severely degraded mangrove forests, thorough analyses should be analyzed to identify the root causes of such degradation. This could involve assessing whether the degradation stems from human activities like reclamation, aquaculture, seawall construction, or from climate change caused sea-level rise, biological invasions such as *trifoliate jewelvine* and *spartina alterniflora*, or environmental pollution caused by human activities.

Formulate natural-based mangrove ecological restoration plans. A comprehensive geological assessment of the mangrove restoration area should be investigated. Factors that affect the growth space of mangrove forests, such as shoreline and beach elevation changes, modern sedimentation rates, hydrodynamic conditions, salinity, and sea-level fluctuations, need to be identified. Modelling and forecasting the process and trends of surface environmental changes in mangrove forest areas should be undertaken. On this basis, a nature-based mangrove ecological restoration plan should be developed that addresses the key factors leading to mangrove degradation.

Additionally, equal importance should be given to both man-made and natural restoration of mangrove forests. Suitable growing environments for mangrove wetlands should be chosen to improve the survival rate of artificial planted saplings. While ensuring suitable growth conditions, priority should be given to species of mangrove forests with rapid growth rates. Furthermore, a balance should be achieved between constructive and non-constructive species, trees and shrubs, and sun-loving and shade-tolerant species.

3.5.2. Recommendations for enhancing mangrove carbon sequestration and storage

Research shows that riverine areas promote the growth of mangrove plants (Castañeda-Moya et al., 2006). Among various mangrove wetland habitats, riverine areas are particularly conducive to boosting the carbon storage capacity of mangrove wetlands (Donato DC et al., 2011; Alongi DM, 2014; Sha C et al., 2018), and the carbon storage in these areas exceeds that in other habitats (Alongi DM, 2014). Additionally, salinity is a primary environmental factor affecting the distribution of mangrove vegetation, which in turn influences the biomass accumulation, and thereby, the carbon fixation and storage rates of mangrove wetlands. High salinity environments can reduce the decomposition and transformation of soil organic carbon, thereby reducing soil organic carbon loss (Biswas H et al., 2007; Poffenbarger HJ et al., 2011). As a result, whenever possible, artificial reforestation should be carried out in estuaries, rivers, deltas, bays, and lagoons to ensure that mangrove vegetation grows within optimal salinity ranges. This strategy not only promotes mangrove growth, thereby improving the survival rate of artificial planted saplings, but it also maximizes the carbon storage sequestration potential of mangrove wetlands and increases soil organic carbon content within these ecosystems.

4. Conclusions

This study provides a comprehensive analysis of the distribution and carbon storage status of mangrove ecosystems in China, identifies the core challenges facing the ecological protection and restoration of mangroves based on historical data, and arrives at the following principal conclusions:

(i) The total area of mangroves in China is 278.85 km^2, which includes 54.11 km^2 in Hainan, 90.8 km^2 in Guangxi, 105.72 km^2 in Guangdong, 12.24 km^2 in Fujian, 4.62 km^2 in Zhejiang, 4.77 km^2 in Taiwan, 6.23 km^2 in Hong Kong, and 0.36 km^2 in Macao.

(ii) The total carbon storage of mangrove wetlands in China is 2.11×10^6 t. This includes 5.09×10^5 t in Hainan, 6.47×10^5 t in Guangxi, 7.35×10^5 t in Guangdong, 9.61×10^4 t in Fujian, 3.62×10^4 t in Zhejiang, 3.75×10^4 t in Taiwan, 4.34×10^4 t in Hong Kong, and 2.50×10^3 t in Macao.

(iii) Since the 1950s, the mangroves in China have experienced distinct phases of change. During the 1950s–1970s, despite adverse human activities such as deforestation and sea reclamation, the overall mangrove area slightly increased. However, in the 1970s–1980s, due to intensified human activities, the mangrove area experienced a rapid decline. From the 1980s to the 1990s, increased national protection efforts managed to slow down this rate of decline. In the 1990s–2000s, there was a minor increase in the mangrove area. Since the 2000s, the implementation of a series of ecological protection and restoration projects, along with the establishment of mangrove conservation areas, have successfully stemmed the decline of mangrove wetland areas, leading to a steady increase.

(iv) Under the influence of sea-level rise caused by human activities and global climate change, the protection and restoration of mangrove wetlands are challenged by a seaward pressure increase and a blockage of landward adjustment. The core issue for mangrove ecological protection and restoration is the safeguarding and construction of spaces conducive to mangrove forest growth.

CRediT authorship contribution statement

Chang Li: Investigation, interpretation of remote sensing images, original draft, figures. Fu Wang: Scientific question choice, field work design, investigation, data collection, results and discussion, paper writing and revising. Peng Yang: Data collection, discussion. Fei-cui Wang: Remote sensing images collection and interpretation. Yun-zhuang Hu: Investigation and discussion. Yan-lin Zhao: Remote sensing images collection and interpretation, figures. Li-zhu Tian: Investigation and discussion. Rui-bin Zhao: discussion.

Declaration of competing interest

The authors declare no conflicts of interest.

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