Journal of
Marine Science and Engineering

Article

Identification of Suitable Mangrove Distribution Areas and Estimation of Carbon Stocks for Mangrove Protection and Restoration Action Plan in China

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Citation: Feng, B.; Tao, Y.; Xie, X.; Qin, Y.; Hu, B.; Jia, R.; Pan, L.; Liu, W.; Jiang, W. Identification of Suitable Mangrove Distribution Areas and Estimation of Carbon Stocks for Mangrove Protection and Restoration Action Plan in China. *J. Mar. Sci. Eng.* **2024**, *12*, 445. https://doi.org/10.3390/jmse12030445

Academic Editor: Gianluca Quarta

Received: 14 January 2024
Revised: 22 February 2024
Accepted: 27 February 2024
Published: 1 March 2024

Abstract: Mangrove forests are significant blue carbon pools on the Earth with strong carbon sequestration capacity and play an important role in combating climate change. To improve the capacity of regional carbon sinks, China has implemented a Special Action Plan for Mangrove Protection and Restoration (2020–2025). In this context, based on the MaxEnt model, this study analyzed the important environmental factors affecting the distribution of mangrove forests, combined with the planning objectives and carbon density parameters of different regions; assessed the habitat suitability areas of China's mangrove forests; and predicted their future carbon stock potential. The results showed the following: (1) Elevation was the most important factor affecting the overall distribution of mangrove forests in China, and the optimal elevation of mangrove distribution was 0.52 m. (2) The most suitable areas of mangrove forests in China were mainly distributed in Hainan, Guangxi, and Guangdong, which had great potential for carbon stock. Danzhou Bay and Hongpai Harbor in Hainan, Lianzhou Bay in Guangxi, and the Huangmao Sea in Guangdong are potential areas for habitat suitability but are not yet under high levels of protection. (3) Achieving the goals of this action plan was expected to increase carbon stocks by 4.13 Tg C. Other suitable areas not included in this plan could still increase carbon stocks by 7.99 Tg C in the long term. The study could provide a scientific basis for siting mangrove restoration areas and developing efficient management policies.

Keywords: carbon sink; mangrove; ecological restoration; MaxEnt model; potential assessment

1. Introduction

Globally, approximately 60% of marine ecosystems are degraded or used in an unsustainable manner [1]. Mangrove forests have declined by 35% over the past 20 years, leading to a significant increase in the ecological vulnerability of coastal areas and causing huge economic losses [2–4]. Although mangrove ecosystems cover a much smaller area than terrestrial forests, they play a crucial role in addressing the global climate crisis, nurturing terrestrial and marine biodiversity, and supporting human well-being [5]. As the most important blue carbon pools at the global scale, mangrove forests are increasingly emphasized for their strong carbon sequestration capacity, and the restoration and creation of mangrove forests contribute to the construction of blue carbon ecosystems [6,7]. In 2015, blue carbon protection was officially incorporated into China's national strategy, and in August 2020, China's Ministry of Natural Resources and the National Forestry and Grassland Administration jointly issued the Special Action Plan for Mangrove Protection and Restoration (2020–2025), which sets targets for the restoration and creation of mangrove forests in the relevant areas. In September 2020, China set goals for carbon peaking (2030) and carbon neutrality (2060). China is systematically creating and restoring mangrove forests on a large scale.

Mangrove forests grow in estuarine coastal areas, and their ecosystems are subject to the joint action of the marine and terrestrial environments. They also constitute one of the most active zones of land–sea interaction [8]. China's mangrove communities are part of the eastern group of the world's mangrove forests. They are rich in species resources and represent the northern boundary of the world's natural distribution of mangrove forests. Their unique geographic distribution and biodiversity make them a valuable ecological resource. Increasing the area of mangrove forests in the country's region and thereby increasing mangrove carbon stocks through large-scale artificial intervention activities to restore and create mangrove forests is a challenging ecological practice.

On the one hand, analyzing the main environmental factors of mangrove growth and evaluating the spatial suitability of mangrove distribution can guide site selection for mangrove creation and restoration. Some scholars have used ecological niche models, including the Genetic Algorithm for Rule-Set Production (GARP) model and the Maximum Entropy (MaxEnt) model, to predict the identification of species fitness zones [9,10]. The MaxEnt model is the most widely used and recognized to be the most accurate. It predicts the distribution of species by calculating the maximum entropy of their possible distribution areas and has proved to have good applicability in coastal zone areas [11,12].

On the other hand, many scholars have estimated the carbon stocks of different types and different regions of mangrove forests through field surveys, using empirical formulas or laboratory analysis methods [13]. The influencing factors of mangrove carbon stock are controlled by a variety of factors, such as latitude, tree species, and tree age, while showing spatial variability [14]. Therefore, mangrove carbon stock parameters should be optimized locally according to regional characteristics. Especially for the estimation of mangrove carbon stocks on a large scale, the accuracy can be improved by rationally dividing different small areas.

However, the above studies did not consider well the effect of spatial heterogeneity on carbon density parameters; nor did they assess the impacts of China's implementation of the action plan on mangrove forests. Finding appropriate locations for mangrove creation and restoration in China and calculating the changes in carbon stocks brought about by mangrove protection and restoration initiatives are important subjects that require more research.

In this study, the MaxEnt model was used to analyze the important environmental factors of mangrove distribution and assess the suitability of mangrove restoration and afforestation. Combined with differentiated regional mangrove carbon density data, the changes in forest carbon stocks before and after the Special Action Plan for Mangrove Protection and Restoration (2020–2025) and their future potential were estimated. This study answered the following questions: (1) What are the important environmental factors that should be considered in mangrove protection and restoration actions? (2) Where are the priority areas for conservation and restoration actions? (3) What are the expected effectiveness and future potential of mangrove protection and restoration actions? The results will provide basic data and decision support for the development of spatial planning and management policies for mangrove protection and restoration in various regions of China.

2. The Study Area

The distribution range of mangrove forests in China starts from Sanya in Hainan in the south and reaches up to Yueqing Bay in Wenzhou, Zhejiang in the north, with a coastline length of more than 14,000 km, which is widely distributed in the South China Sea and less in the East China Sea in terms of sea belonging [15]. The distribution area of mangrove forests in five provinces of China, including Hainan, Guangxi, Guangdong, Fujian, and Zhejiang, was used as the study area (Figure 1). These regions are characterized by a high degree of topographic relief, a diversity of coastal and tidal types, and significant spatial variation in substrates [16]. The climate types of the study area are tropical monsoon climate and subtropical monsoon climate, with simultaneous rain and heat, and the annual cumulative temperature greater than or equal to 10 °C ranges from 5200 °C to 9500 °C [17]. Latitude is the dominant factor in the variation in mangrove species and community complexity in the study area [18]. According to available surveys, 38 species of mangroves exist in China, including 26 true mangroves and 12 semi-mangroves [19]. The most dominant true mangrove species are *Avicennia marina*, *Aegiceras corniculatum* and *Kandelia obovate*.

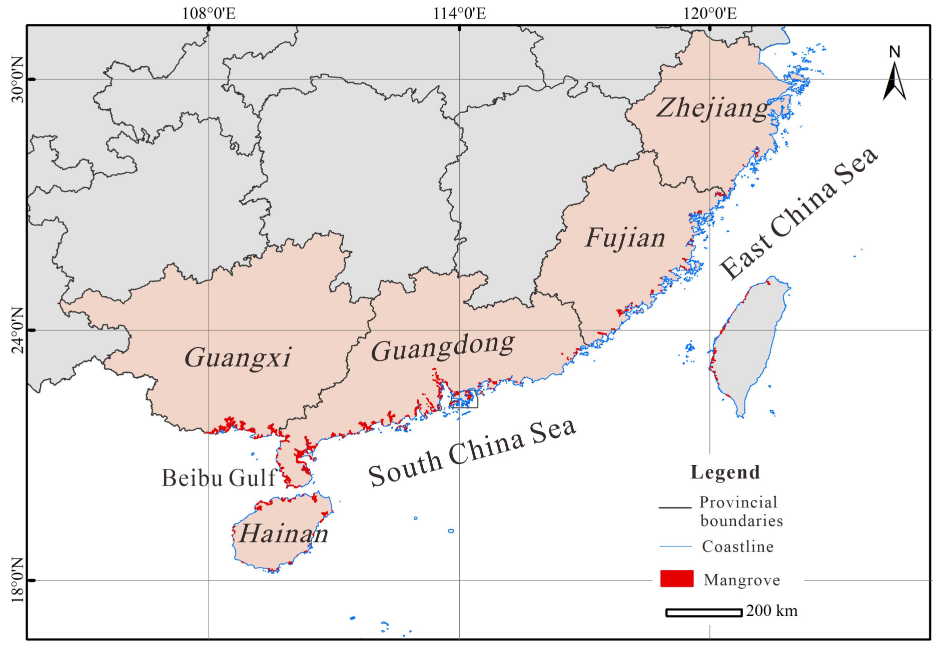

Figure 1. Distribution of mangroves in China.

3. Materials and Methods

3.1. Mangrove Area in China before the Action Plan (2019)

Mangrove distribution areas in China in 2019 were available from publicly available datasets [20]. The datasets not only improved the delineation of small mangrove patches along tidal creeks but also targeted the interpretation of small patches in marginal climatic zones. The overall accuracy of this dataset was 96.4 ± 0.3% as verified by the sample set, and the accuracy of this data was 96.2% as verified by the field sample plots. Statistically, the mangrove area in China in 2019 under the Albers projection is 25,585 ha.

3.2. Mangrove Restoration and Afforestation Targets

The aim of the action plan is to increase the coverage of mangrove forests and enhance the quality and functionality of mangrove ecosystems by establishing new mangrove forests in suitable areas and rehabilitating degraded ones. It is planned that by 2025, 18,800 ha of mangrove forests will be created and restored, of which 9050 ha will be created and 9750 ha will be restored (Table 1). At present, the scope of implementation of the action plan covers 52 established mangrove nature reserves in China.

Table 1. Restoration and new afforestation targets in various regions of China.

District	Restoration Area (ha)	Afforestation Area (ha)
Guangdong	2500	5500
Guangxi	3500	1000
Hainan	3200	2000
Fujian	550	350
Zhejiang	0	200
Total	9750	9050

3.3. Environment Variable

The main environmental factors affecting the distribution of mangroves include bioclimate, topography, substrate, and salinity [21,22]. Since mangrove forests grow at the land–sea interface, their suitability factors are influenced by both marine and terrestrial environmental factors. Therefore, in this study, we created a 10 km buffer zone near the coastline using ArcGIS 10.4 to enable the integration of marine and terrestrial environmental data.

Different types of publicly available environmental datasets were obtained from different websites. Bioclimatic data were obtained from the World Climate Database archive (https://www.worldclim.org/, accessed on 27 April 2023). We used WorldClim Version 2, which contains the standard 19 bioclimatic variables (30 s precision). Topographic data were from the GEBCO gridded bathymetry dataset (https://www.gebco.net/, accessed on 11 May 2023). Sea surface temperature and salinity data were from the ecological modeling ocean data layer produced by the Bio-ORACLE team (https://www.bio-oracle.org/, accessed on 17 May 2023). Substrate data were obtained from the National Marine Science Data Center of China (http://mds.nmdis.org.cn/, accessed on 2 June 2023). All the above environmental variables were used to standardize the spatial resolution of the datasets to 1 km using ArcGIS software, and the graphics were saved in ASCII format.

We calculated the topographic humidity index (TWI), which represents the spatial distribution of the runoff source and groundwater level in the basin, using the following equation:

$$\mathrm{TWI} = \ln\left(\frac{SCA}{tan\beta}\right) \quad (1)$$

Here, SCA is equal to (flow accumulation + 1) $\times$ pixel area (in m^2) and β represents the slope angle in radians.

To avoid the strong interactions between the influencing factors from affecting the model results, we performed correlation analysis on the data of all environmental variables, removed variables with absolute values of correlation greater than 0.8, and finally selected 15 environmental variables to enter the model (Table 2).

Table 2. Importing the MaxEnt model's environment variables.

Data Type	Variable	Interpretation	Unit	Data Source
Bioclimate	Bio 2	Mean Diurnal Range	°C	Global climate and weather data (https://www.worldclim.org/, accessed on 27 April 2023)
	Bio 3	Isothermality	°C	
	Bio 5	Max Temperature of Warmest Month	°C	
	Bio 7	Temperature Annual Range	°C	
	Bio 8	Mean Temperature of Wettest Quarter	°C	
	Bio 12	Annual Precipitation	mm	
	Bio 16	Precipitation of Wettest Quarter	mm	
	Bio 17	Precipitation of Driest Quarter	mm	
	Bio 19	Precipitation of Coldest Quarter	mm	

Table 2. *Cont.*

Data Type	Variable	Interpretation	Unit	Data Source
Terrain	TWI	Topographic Wetness Index	-	Gridded Bathymetry Data (https://www.gebco.net, accessed on 11 May 2023)
	Elevation	Sea floor elevation	m	
Substrate type	Substrate	Substrate type	-	National Maine Data Center (http://mds.nmdis.org.cn/, accessed on 2 June 2023)
Sea surface salinity	Max_SSS	Maximum sea surface salinity	-	Bio-ORACLE Marine data layers for ecological modelling (https://www.bio-oracle.org/, accessed on 17 May 2023)
	Min_SSS	Minimum sea surface salinity	-	
Sea surface temperature	Max_SST	Maximum sea surface temperature	°C	Bio-ORACLE Marine data layers for ecological modelling (https://www.bio-oracle.org/, accessed on 17 May 2023)

3.4. Geographical Zoning and Carbon Density Parameters Statistics

The study area was further divided into 12 subregions based on regional characteristics and similarities (Table 3). Based on the keywords (“mangrove forest”, “China”, “organic carbon”, “biomass”, “carbon content”, “carbon density”, and “carbon stock”), we searched the published journals and dissertations in Web of Science, Google Scholar, and CNKI and obtained a total of 31 articles that met the requirements. From these articles, carbon density values were obtained separately for each region. The organic carbon of litter was not considered in this study. This was because the proportion of organic carbon in litter was very small and most of it would move with the water flow, which has negligible effect on the spatial distribution pattern of mangrove organic carbon [23]. Finally, the carbon density parameters of mangrove forests in different regions of China are shown in Table 3.

Table 3. Carbon density parameters in mangrove areas in various regions of China.

District	Included Cities	AGBC (t/ha)	BGBC (t/ha)	SC (t/ha)	Reference
Southern Hainan (S_HN)	Ledong, Sanya, Lingshui	53.2	21.5	149.23	[24–28]
Western Hainan (W_HN)	Danzhou, Changjiang, Dongfang	47.91	15.94	216.84	[24–28]
Eastern Hainan (E_HN)	Qionghai, Wanning	41.4	18.63	127.84	[28]
Northern Hainan (N_HN)	Lingao, Chengmai, Haikou, Wenchang	47.91	22.06	167.01	[24–26,28–32]
Southern Guangxi (S_GX)	Fangchenggang, Qinzhou, Beihai	38.12	13.7	138.5	[33–38]
Western Guangdong (W_GD)	Zhanjiang, Maoming, Yangjiang	42.72	15.82	163.37	[25,26,39–43]
Central Guangdong (C_GD)	Jiangmen, Zhuhai, Zhongshan, Guangzhou, Dongguan, Shenzhen, Huizhou	47.72	15.35	155.67	[25,43–48]
Eastern Guangdong (E_GD)	Shanwei, Jieyang, Shantou, Chaozhou	55.14	15.49	185	[42,43]
Southern Fujian (S_FJ)	Zhangzhou, Xiamen, Quanzhou	36.26	18.17	105.27	[25,26,32,41,49]
Central Fujian (C_FJ)	Putian, Fuzhou	5.7	2.97	129.68	[25,30]
Eastern Fujian (E_FJ)	Ningde	11.91	7.43	135.05	[25,50–53]
Southern Zhejiang (S_ZJ)	Wenzhou, Taizhou	2.13	1.56	115.06	[25,54]

Note: AGBC indicates above-ground biomass carbon, BGBC indicates below-ground biomass carbon, and SC indicates soil carbon (0–100 cm).

3.5. Application of the MaxEnt Model

The MaxEnt model can be used to predict the species’ environmental requirements and potential distribution based on the principle of maximum entropy using data on species distribution points and environmental variables [55].

To ensure that each environmental variable image element corresponded to only one mangrove distribution point, we converted remotely sensed mangrove forests into point data and deleted redundant samples. This helps to improve the quality of the sample points and ensures that the results are not overfitted. We verified the applicability of the MaxEnt model to this study and subsequently used a cross-validation approach to confirm that the optimal regularization multiplier was 1, which controlled the complexity of the model well.

A total of 75% of the distribution data were used for model training, and the remaining 25% were used for model testing, and each model was repeated 10 times in "subsample" mode.

Referring to Phillips et al. [55], model outcome tests were analyzed using the Area Under the Curve (AUC). The AUC value ranges from 0.5 to 1. It is generally believed that the model prediction results are excellent when the AUC value is 0.9–1.0. The model prediction results are considered to have high confidence when the AUC value is 0.8–0.9. When the AUC value is 0.5, it indicates that the model prediction result is a random prediction.

3.6. Analysis of Mangrove Habitat Suitability

Referring to Baldwin [56], Jacknife was used to assess the impacts of different environmental factors on the model and calculate their contribution and importance. Contribution considered the interactions between environmental variables while importance did not. The response of environmental factors to mangrove habitat suitability was analyzed using the probability distribution logistic output value of 0.5 as a boundary. Meanwhile, referring to Chao et al. [57], mangrove habitat suitability was categorized into three grades, which were high suitability (>0.7), medium suitability (0.5–0.7), and low suitability (0.1–0.5).

On this basis, identified hotspots were used as priority areas for mangrove protection and restoration through kernel density analysis. We overlayed the priority areas with the mangrove nature reserves and wetland parks currently covered in the action plan to identify potential areas for the conservation and restoration of mangrove forests in China outside the plan.

3.7. Prediction of Carbon Stock Change

Before the action plan (2019), mangrove carbon stocks in different regions were multiplied by their corresponding carbon density parameters and area.

Currently, there are no unified site selection criteria for mangrove protection and restoration. Therefore, we used ArcGIS software to rank the pixel values of mangrove habitat suitability from high to low, selected a certain number of top-ranked pixels according to the targets set in the action plan, and used the geographic areas they represented as recommended sites for mangrove protection and restoration. We predicted the incremental carbon stocks resulting from this action plan by using the carbon intensity parameters and area corresponding to these recommended sites.

In the long term, we considered all areas with mangrove habitat suitability greater than 0.85 as potential areas for future increases in mangrove carbon stocks and predicted them according to the methodology described above.

The overall research framework is shown in Figure 2.

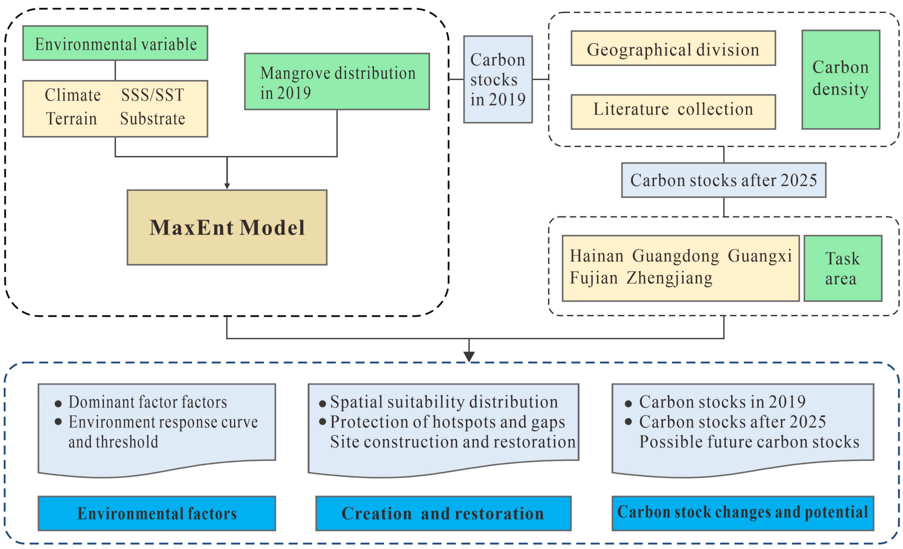

Figure 2. Research framework.

4. Results

4.1. The Model Accuracy

The AUC values for the training and test sets of the MaxEnt model were 0.845 and 0.838, respectively (Figure 3). Based on the AUC values of the test set, it could be concluded that the accuracy of the MaxEnt model for simulating mangrove forests was good. In addition, the data used were evaluated at the thresholds, and the results showed that the test omission rate and predicted omission were close to the same, which indicates that the model performs well and is accurate and reliable in predicting the potential distribution of mangroves.

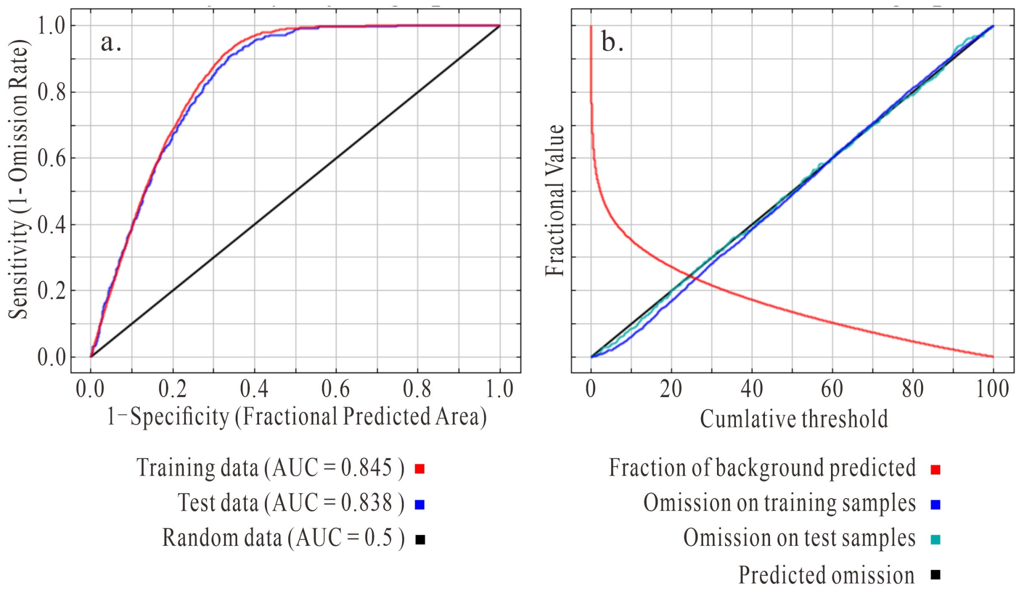

Figure 3. The performance results of the MaxEnt model. (**a**) AUC values for the model; (**b**) test sample omission rate versus predicted omission rate.

4.2. Performance of Environmental Factors

The contribution and importance of each environmental variable to mangrove distribution could be output in the MaxEnt model (Table 4). Among all the environmental variables, elevation had the greatest impact on the model results, with a contribution of 46.2% and an importance of 66.2%. Precipitation of the Coldest Quarter (Bio 19) and Max Temperature of the Warmest Month (Bio 5) also had significant effects on the distribution model, with importance values of 10.3% and 8.1%, respectively. The top six environmental variables ranked in order of importance had a cumulative importance of 93.2% on the model results, meaning they could be regarded as important environmental factors affecting the distribution of mangrove forests.

The contributions of environmental variables including Precipitation of Wettest Quarter (Bio 16), Substrate, Mean Temperature of Wettest Quarter (Bio 8), Isothermality (Bio 3), Mean Diurnal Range (Bio 2), Minimum sea surface salinity (Min_SSS), Maximum sea surface temperature (Max_SST), Maximum sea surface salinity (Max_SSS), Topographic Wetness Index (TWI), and Precipitation of Driest Quarter (Bio 17) were greater than their importance, indicating that the interaction between environmental factors had increased their importance in the model. Conversely, the contribution of environmental variables, including elevation, Precipitation of Coldest Quarter (Bio 19), Max Temperature of Warmest Month (Bio 5), Temperature Annual Range (Bio 7), and Annual Precipitation (Bio 12), performed worse than their importance, showing that interactions between environmental factors had then diminished their importance in the model.

Table 4. Contribution and importance of environmental variables.

Variable	Interpretation	Contribution (%)	Imporance (%)
Elevation	Sea floor elevation	46.2	66.2
Bio 19	Precipitation of Coldest Quarter	7.7	10.3
Bio 5	Max Temperature of Warmest Month	5.9	8.1
Bio 7	Temperature Annual Range	1.7	4.9
Bio 16	Precipitation of Wettest Quarter	14.6	1.9
Bio 12	Annual Precipitation	1	1.8
Substrate	Substrate type	8.3	1.8
Bio 8	Mean Temperature of Wettest Quarter	3.3	1.6
Bio 3	Isothermality	2.3	1.1
Bio 2	Mean Diurnal Range	0.1	0.7
Min_SSS	Minimum sea surface salinity	0.6	0.6
Max_SST	Maximum sea surface temperature	3.1	0.5
Max_SSS	Maximum sea surface salinity	0.5	0.3
TWI	Topographic Wetness Index	4.4	0.3
Bio 17	Precipitation of Driest Quarter	0.3	0

The Jacknife results of regularized training gains for mangroves are shown in Figure 4. The elevation had the greatest influence on the distribution of mangrove forests in China, and when it changed alone, it had a greater impact on the model results. In addition, Isothermality (Bio 3), Max Temperature of the Warmest Month (Bio 5), and Mean Temperature of the Wettest Quarter (Bio8) also had relatively significant gains. The other environmental variables had less of an effect on the model, with low gains when used in isolation.

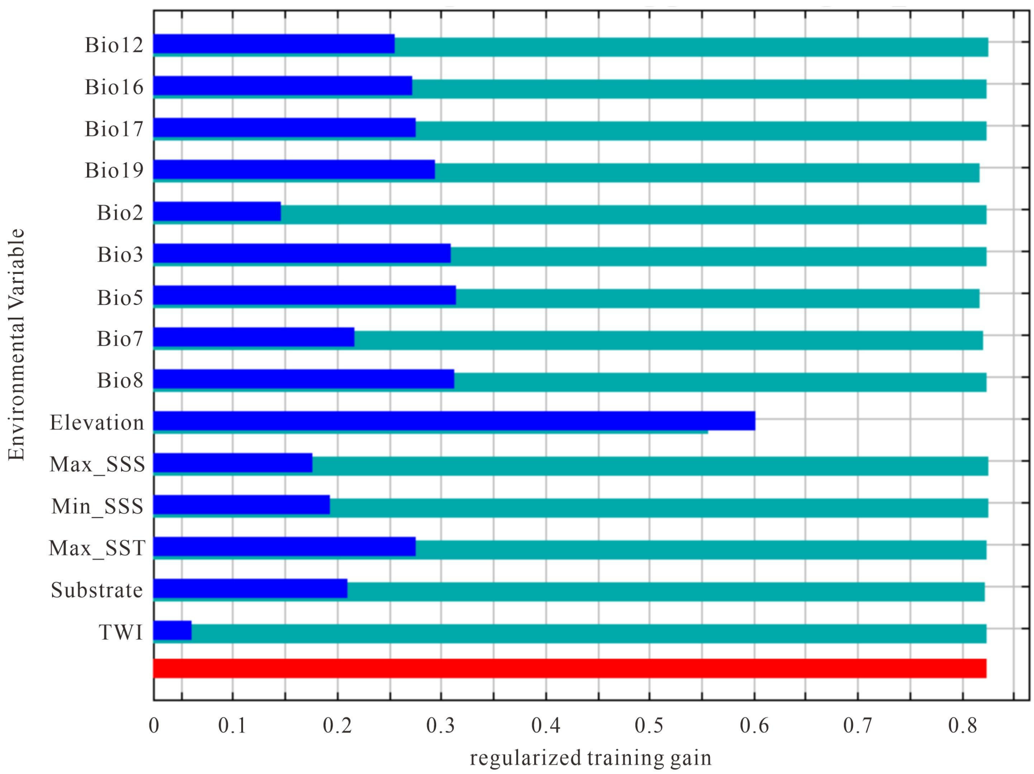

Figure 4. Jacknife results of regularized training gain for mangroves. Dark blue stripes indicate independent test results of each variable, light green stripes indicate test results excluding the variable, and red stripes indicate test results including all variables.

4.3. Response of Environmental Factors to the Suitability of Mangrove Habitats

The response curves of habitat suitability and major environmental variables for mangrove forests in China are shown in Figure 5, and the related threshold ranges are shown in Table 5. The mangrove distribution probability was very closely related to changes in topographic elevation, and the crest of the response relationship curve was very significant.

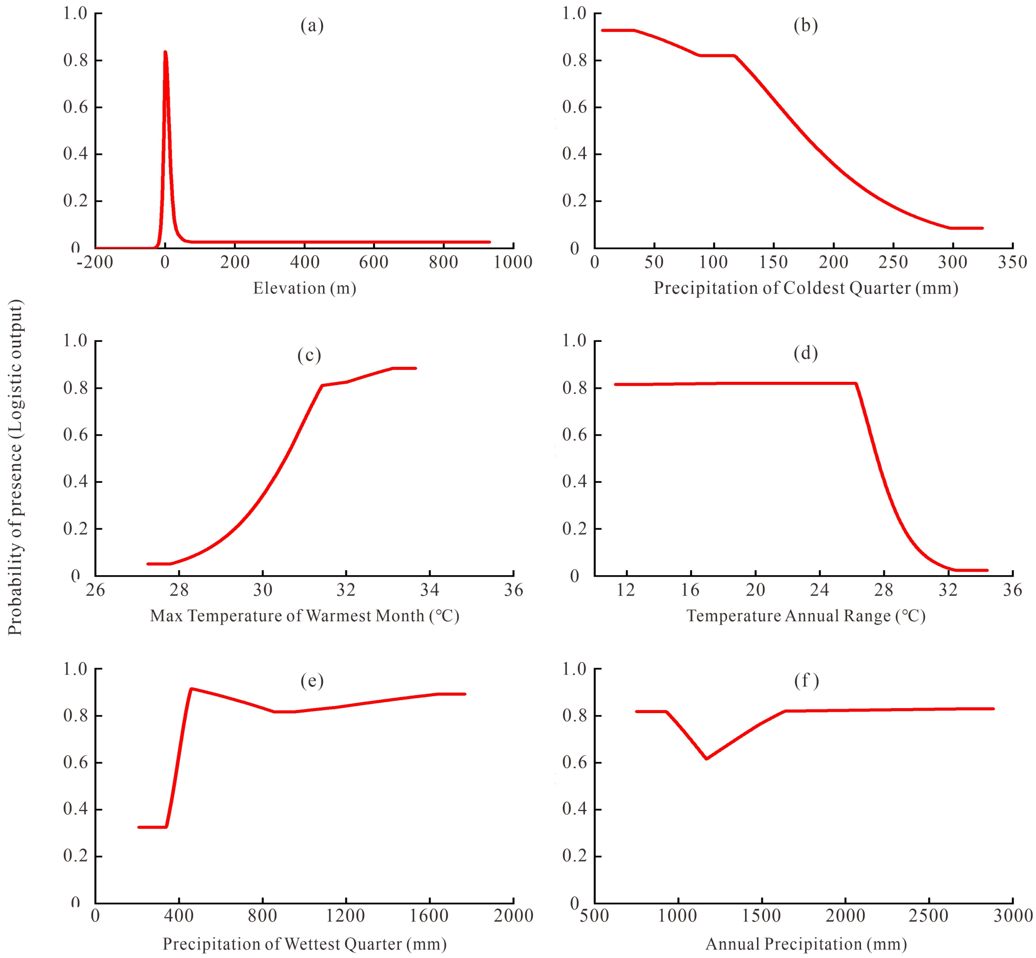

Figure 5. Response relationships between mangrove habitat suitability and major environmental factors. (**a**) Elevation. (**b**) Precipitation of Coldest Quarter. (**c**) Max Temperature of Warmest Month. (**d**) Temperature Annual Range. (**e**) Precipitation of Wettest Quarter. (**f**) Annual Precipitation.

Table 5. Suitable range and optimal value of environmental variables for mangrove habitats in China.

Variable	Interpretation	Unit	Threshold Range	Optimal Value
Elevation	Sea floor elevation	m	−1.73~4.30	0.52
Bio 19	Precipitation of Coldest Quarter	mm	6.44~172.34	6.44
Bio 5	Max Temperature of Warmest Month	°C	30.54~33.65	33.65
Bio 7	Temperature Annual Range	°C	11.29~27.55	18.77
Bio 16	Precipitation of Wettest Quarter	mm	376.63~1765.75	460.72
Bio 12	Annual Precipitation	mm	749.28~2882.55	2707.63

The range of elevations suitable for the distribution of mangroves was −1.73 m to 4.30 m, with an optimal threshold of 0.52 m (Figure 5a). The area with the warmest season maximum temperature of less than 33.65 °C and an annual temperature difference of more than 27.55 °C was not suitable for mangrove forests (Figure 5c,d). Mangrove forests tended to be in areas with low precipitation in the coldest season and high precipitation in the wettest season (Figure 5b,e).

4.4. Spatial Distribution of Mangrove Habitat Suitability in China

Figure 6 shows the spatial distribution of mangrove habitat suitability in China. Western and central Hainan, southern Guangxi, and western and central Guangdong were the main distribution areas of medium and high suitability for mangrove forests in China, concentrating below the 23° N latitude. While there were some areas in eastern Guangdong, southern Fujian, and central Fujian that were suitable for medium- to high-grade mangroves, they were limited in size. Zhejiang marks the northern boundary of China's mangrove distribution, which is primarily characterized by low-grade suitable areas.

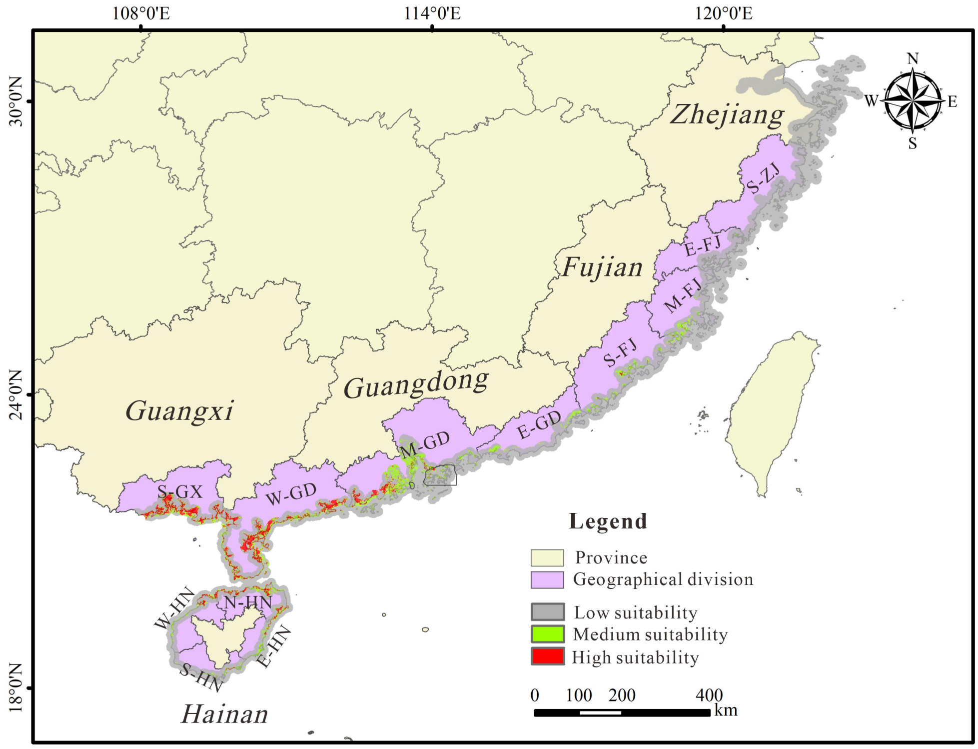

Figure 6. Distributions of suitable mangrove habitats in China.

The identification results showed that western and central Hainan, southern Guangxi, and western and central Guangdong were priority areas for mangrove protection and restoration in China. After comparison, Lianzhou Bay in Guangxi, Meilang Harbor in Hainan, and the Huangmao Sea in Guangdong were potential areas for mangrove protection and restoration outside the action plan (Figure 7).

4.5. Prediction of Carbon Stock Change in Mangrove Forests in China

As mangrove restoration and creation actions are being carried out in various regions while strongly protecting existing mangrove forests, the area of mangrove forests in China is expected to increase significantly in the coming period, which will directly enhance China's mangrove carbon stock.

Hainan, Guangxi, and Guangdong in the South China region were the key provinces to carry out mangrove afforestation and restoration (Figure 8a). In particular, northern and western Hainan, southern Guangxi, and western Guangdong had high carbon sink potential.

Fangchenggang, Qinzhou, and Beihai were the key areas for the protection and restoration of mangrove forests in Guangxi, and the specific recommended sites included Beilun

Estuary, Xiban Bay, Dongwan Bay, the Maowei Sea, areas along the Dafeng River, Lianzhou Bay, and Tieshan Harbor (Figure 8b–d).

Zhanjiang and Yangjiang were the key areas for the protection and restoration of mangrove forests in Guangdong, and the specific recommended sites included Anpu Harbor, Liusha Bay, Leizhou Bay, Zhanjiang Harbor, Hailing Bay, and the Moyang River estuary (Figure 8e–h).

Danzhou, Chengmai, Lingao, Haikou, and Wenchang were the key areas for the protection and restoration of mangrove forests in Hainan, and the specific recommended sites included Danzhou Bay, Touzui Harbor, Hongpai Harbor, Meilang Harbor, Dongzhai Harbor, and Qinglan Bay (Figure 8i–l).

The ideal areas for mangrove protection and restoration in both Fujian and Zhejiang were in their southern regions (Figure 9a). The recommended sites in Zhejiang were Yangpu Bay and the Aojiang River estuary (Figure 9b). The recommended sites in Fujian were the Jiulong River estuary and Weitou Bay (Figure 9c).

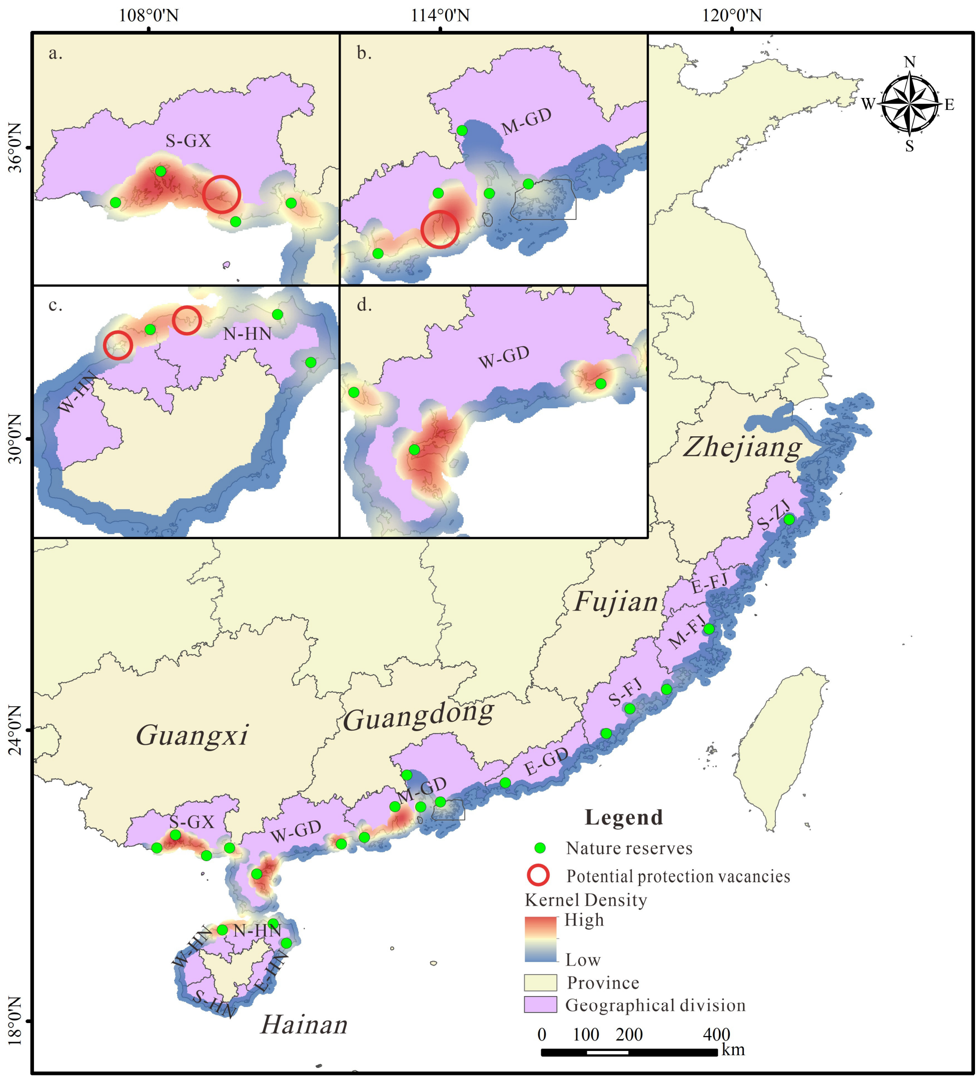

Figure 7. Priority areas for mangrove protection and restoration in China. (**a**) Southern Guangxi. (**b**) Central Guangdong. (**c**) Northern and western Hainan. (**d**) Western Guangdong.

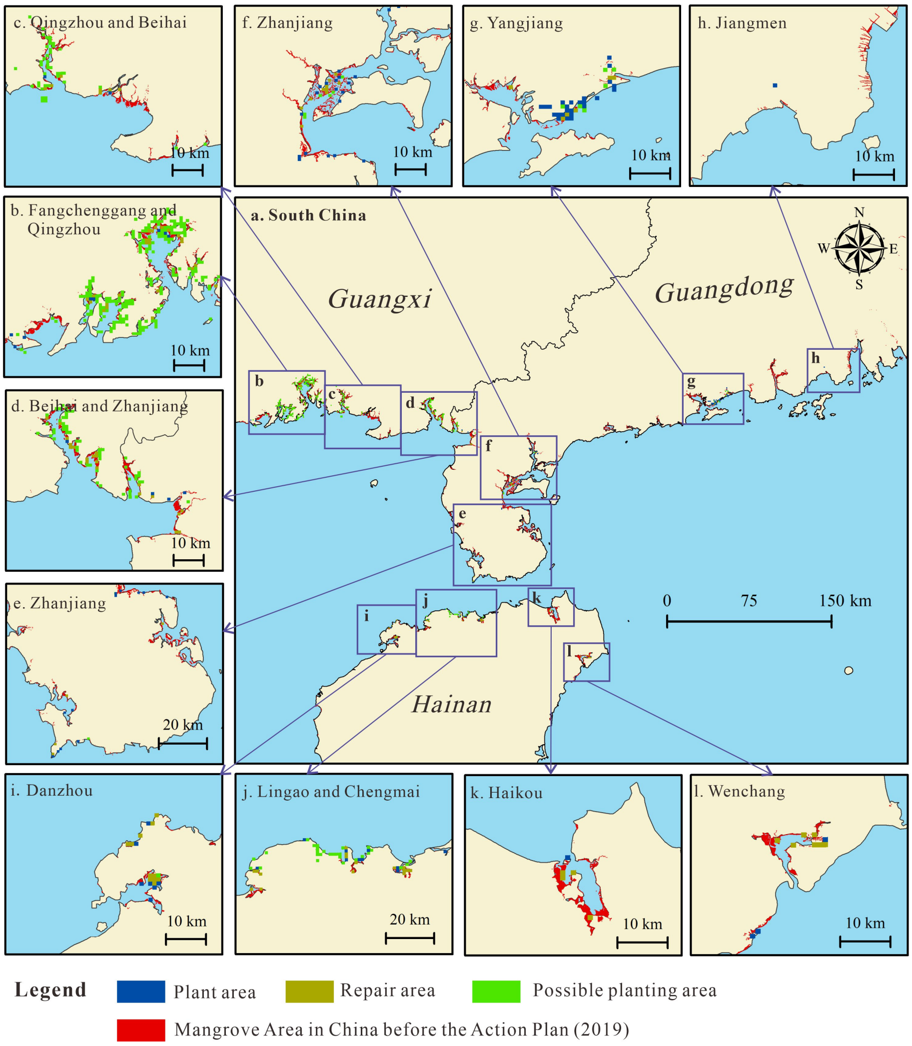

Figure 8. Recommended sites for mangrove creation and restoration actions in South China.

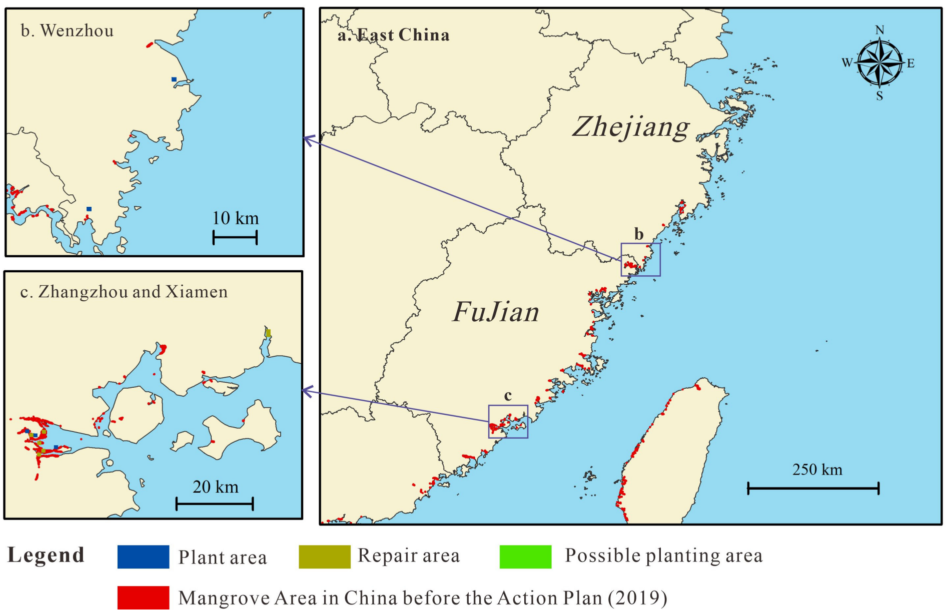

Figure 9. Recommended sites for mangrove creation and restoration actions in Eastern China.

The carbon stock of mangrove forests in five provinces in China was 5.17 Tg C before the action plan (2019), and it could increase by 4.13 Tg C after the completion of reforestation and restoration tasks. The order of provinces according to the increase in carbon stock was Guangdong > Hainan > Guangxi > Fujian > Zhejiang. Guangdong, Guangxi, and Hainan in South China accounted for about 96% of the total carbon stock increase while Fujian and Zhejiang in East China accounted for only about 4%. In the long term, China's mangrove carbon stock potential was expected to reach 17.29 Tg C. That is to say, after the completion of this action plan, there would still be an incremental carbon stock of 7.99 Tg C. The ranking of regional carbon stocks in South China changed to Guangxi > Guangdong > Hainan (Figure 10).

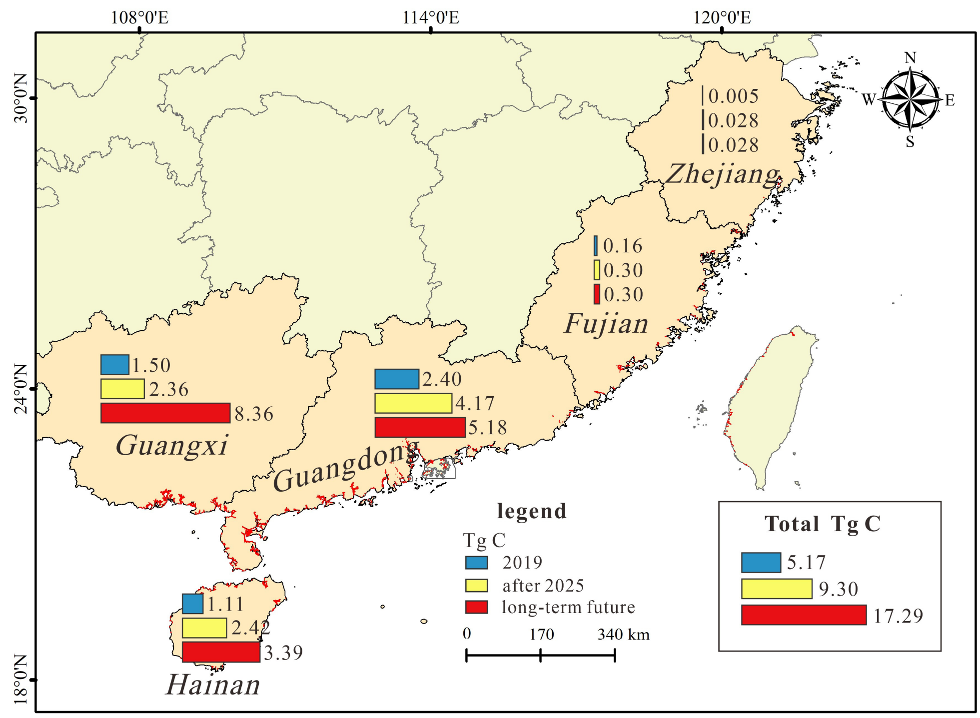

Figure 10. Spatial regional carbon stock changes induced by mangrove restoration and conservation actions in Chinese provinces.

5. Discussion

5.1. Accuracy of MaxEnt Model Predictions

The use of ecological niche modeling to predict potential habitat areas of species is meaningful for species conservation; however, the prediction of potential habitat areas of species varies among different models due to different algorithms, so it is crucial to improve the accuracy and reliability of model prediction. In some controlled experiments, MaxEnt has been shown to be more reliable than the GARP, BIOCLIM, and DOMAIN [58], and is therefore the most widely used, but it should be noted that the accuracy of the MaxEnt model depends on the selection of species distribution points and the diversity and quality of environmental variables.

Relevant studies have shown that it is reasonable to apply ecological niche modeling to predict the habitat of species under the premise of ecological niche conservatism [55]. In this study, we used 3300 mangrove distribution points to participate in the model construction after filtering the remotely interpreted mangrove forests into point data and eliminating some extreme distribution points. For the selection of environmental variables, we considered macro-geographical factors such as bioclimate, sea surface temperature, and salinity, and we also considered small-scale tidal flat environmental conditions such as topographic conditions and substrate types.

The AUC value of the MaxEnt model is affected by the problem of category imbalance, which leads to a decrease in precision when the number of samples from different categories of the target variable varies greatly. The geographic differences in mangrove distribution areas in China may have influenced the model's accuracy to not reach a very excellent degree (0.9). Based on the fact that the AUC value of the test set was greater than 0.8, which indicates that the model's sequencing ability is good and that the test omission rate is consistent with the theoretical omission rate, it can be concluded that the MaxEnt model simulates mangrove forests with good accuracy.

5.2. Estimation of the Difficulty and Effectiveness of the Action Plan

If the goals of the action plan can be realized, the quality and function of China's mangrove ecosystems will be greatly improved. However, different regions will face some challenges in the implementation process.

In this study, it was found that mangrove habitat suitability in Zhejiang and Fujian was mainly at low and medium levels. Their task was far smaller than that of other provinces, but there was no doubt that they had to invest more manpower, money, and technology, increasing the cost of protection and restoration.

Guangdong's afforestation target (5500 ha) was larger than that of the other provinces combined, and it would be very difficult to achieve in the short term. This was because its area of high-level suitable habitat was far from sufficient to support it.

This study showed that both Guangxi and Hainan were highly suitable areas for mangrove habitats. The restoration targets for Guangxi and Hainan were 3500 ha and 3200 ha, respectively, and the afforestation targets were 1000 ha and 2000 ha, respectively, which were relatively easy to achieve. They did not have to incur high restoration costs, and there were more restoration and reforestation sites to choose from.

5.3. Accuracy of Carbon Stock Estimation

The two basic data sources for mangrove carbon stock estimation are the area of regional mangrove forests and regional mangrove carbon density, which determine the accuracy of mangrove carbon stock estimates. In this study, the remotely sensed data used had been verified in the field with a high data accuracy of 96.2%. At the same time, we carried out zonal statistics of carbon density in China's mangrove regions and integrated the parameter values obtained by different scholars in different regions, which maximally overcame the defects of estimating with the average value. For example, according to a large number of surveys, the carbon density of mangrove forests in various regions of China ranged from 118.75 to 280.69 Mg C ha^{-1}, with an average value of 198.94 Mg C ha^{-1} [59]. If this average value is directly applied to the calculation without considering regional differences, it could lead to an overestimation of China's mangrove carbon stocks before and after the action plan by 2.94 Tg C and 6.03 Tg C, respectively.

It is important to note that effectiveness evaluations after an afforestation operation are often conducted after the afforestation work has been completed for a period of time, usually three years. Although the afforestation adds a certain area of mangrove forests, carbon stock will not increase simultaneously at the beginning of the afforestation.

It has been shown that in the early stages of forestation, biological carbon will rise rapidly while soil carbon accumulates slowly, and when the plant grows to a certain extent, vegetation carbon tends to increase slowly or stabilize while soil carbon continues to accumulate [59]. Thus, the total carbon will show a rapid increase in the initial stage, followed by a slow increase, and then finally tend to stabilize. Future studies should take this situation into account.

5.4. Outlook for Future Mangrove Protection and Restoration

In this study, we found that the distribution area of mangrove forests in China tended to be characterized by a rain–heat simultaneous climate, which was consistent with the results of some studies [60,61], reflecting that climatic factors can influence the geographical distribution and expansion of mangrove forests. The impact of climate change on mangrove forests requires continued attention in the future.

We also found that elevation was the most important factor affecting the overall distribution of mangrove forests in China, which is consistent with some studies that indicate elevation is an essential factor in determining the distribution area of each mangrove tree species. Therefore, elevation needs to be emphasized in the process of protecting and restoring mangrove forests [21,62]. Elevation represents the growth beach position of mangroves, which directly determines the frequency and duration of tidal inundation and has a significant relationship with wave intensity [63]. This has been verified in practice, for example, in Xiamen, Shenzhen, and Beihai, where low elevation mudflats are difficult to forestate successfully while mudflats above mean sea level are more suitable for mangrove growth [62,64,65]. In this study, the optimal elevation for mangrove distribution derived from the MaxEnt model was 0.52 m, which, it must be noted, was a rough average of the large-scale range model results, but this coincides with Liu's results showing that the dominant stands of the four natural communities of mangrove plants in Fangchenggang City, Guangxi were concentrated at a 0.2–0.8 m elevation (China's National Elevation Benchmark) as measured using RTK [66]. Although, in terms of the national scale, there will be variations in different places due to different tidal types, it is essential to consider elevation as an indicator of the critical line of desirable forests. Further study of the forested elevations of various tree species will be beneficial for the success of the project.

In future actions for mangrove protection and restoration, the protection of current mangrove forests should be the first priority, as the ecosystem services provided by native forests are generally superior to those provided by planted forests. Mangrove restoration and afforestation must maintain balance with the original ecosystem and protect its biodiversity. Habitat suitability should be given full consideration when selecting sites for mangrove protection and restoration. This study concluded that northern and western Hainan, southern Guangxi, and western Guangdong should be prioritized areas for mangrove protection and restoration in China, especially in the Beibu Gulf in Guangxi. It provided a reference for rational site selection.

In summary, in order to realize the goals of the action plan, it is recommended to select sites based on the results of the habitat suitability assessment, pay attention to the environmental factors of mangrove forests, and formulate corresponding management policies in a timely manner.

6. Conclusions

China has been improving the carbon sink potential of mangrove forests through the implementation of the Special Action Plan for Mangrove Protection and Restoration (2020–2025). In this context, based on the MaxEnt model, this study analyzed the major environmental factors affecting the distribution of mangrove forests, assessed the habitat suitability areas of China's mangrove forests, and predicted their future carbon stock potential. The main conclusions were as follows:

(1) Elevation was the most important factor affecting the overall distribution of mangrove forests in China, and the optimal elevation of mangrove distribution was 0.52 m, which should be considered in the protection and restoration of mangrove forests.

(2) Hainan, Guangxi, and Guangdong had large areas of suitable habitat for mangrove forests, which had a high potential for carbon sinks. Danzhou Bay and Hongpai Harbor in Hainan, Lianzhou Bay in Guangxi, and the Huangmao Sea in Guangdong were potential habitat suitability areas not yet strongly protected.

(3) Before the action plan, the carbon stock of China's mangrove forests was 5.17 Tg C. After the action plan, the carbon stock would be increased by 4.13 Tg C, and the total carbon stock would reach 9.30 Tg C. Other suitable areas not included in this plan could still increase carbon stocks by 7.99 Tg C in the long term.

Author Contributions: All authors contributed to the design of the analyses and the writing of the manuscript. Conceptualization, B.F., Y.T. and X.X.; methodology, B.F. and Y.T.; software, B.F.; resources, B.H. and W.L.; data curation, Y.Q., R.J. and L.P.; writing—original draft preparation, B.F., Y.T. and X.X.; writing—review and editing, B.F., Y.T. and X.X.; supervision, Y.T. and W.J.; funding acquisition, W.J., B.H. and W.L. All authors have read and agreed to the published version of the manuscript.

Funding: This study was supported by the National Natural Science Foundation of China (No. U21A2022 and No. 41930537), the Natural Science Foundation of Guangxi (No. AD22080027), the National Key Research and Development Program of China (No. 2021YFF0704005), the Guangxi Science and Technology Base and Talent Special Project (No. AD22035968), the Research Fund Program of the Guangxi Key Lab of Mangrove Conservation and Utilization (No. GKLMC-22A03), the Guangxi Mangrove Research Center Basic Research Fund (No. 2023GMRC-03), and the Guangxi Technology Innovation Guidance Project (No. AC19245001).

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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