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*Article*

# Predicting Mangrove Distributions in the Beibu Gulf, Guangxi, China, Using the MaxEnt Model: Determining Tree Species Selection

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**Abstract:** Mangrove restoration is challenging within protected coastal habitats. Predicting the dominant species distributions in mangrove communities is essential for appropriate species selection and spatial planning for restoration. We explored the spatial distributions of six mangrove species, including their related environmental factors, thereby identifying potentially suitable habitats for mangrove protection and restoration. Based on six dominant mangrove species present in the Beibu Gulf, Guangxi, China, we used a linear correlation analysis to screen environmental factors. In addition, we used the maximum entropy model to analyze the spatial distributions of potential mangrove afforestation areas. Based on the spatial superposition analysis, we identified mangrove conservation and restoration hot spots. The findings indicate that topographic and bioclimatic factors affect the distribution of suitable mangrove habitats in the Beibu Gulf, followed by land use type, salinity, and substrate type. We identified 13,816 hm$^2$ of prime mangrove habitat in the Beibu Gulf that is primarily distributed in protected areas. The protection rate for existing mangroves was 42.62%. According to the predicted spatial distributions of the mangrove plants, the findings suggest that mangrove restoration should be based on suitable species and site selection.

**Keywords:** maximum entropy model; Beibu Gulf; mangrove; suitable growth



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## 1. Introduction

Mangroves are woody plant communities located in tropical and subtropical bays and estuaries, and have important socioeconomic and environmental ecological functions [1]. Mangroves have become a focus for wetland ecology and biodiversity protection worldwide. From 1980 to 2000, over 35% of the global mangrove area was lost, exceeding the habitat loss rates of other ecosystems, including rainforests [2]. These losses have continued, with mangrove areas disappearing at a rate of 1% per year [3]. Therefore, mangrove restoration has recently received considerable research attention worldwide with respect to ecological protection [4,5].

Predicting the spatial distributions of potentially suitable mangrove habitats in the Beibu Gulf is essential for establishing a foundation for mangrove wetland restoration. The coastal area of the Beibu Gulf in the Guangxi Zhuang Autonomous Region is the most important mangrove swamp region in China. At the end of 2013, the mangrove wetland area in Guangxi covered 7243.15 hm$^2$ [6], which is approximately one-third of the total mangrove area in China that plays an important role in the ecological balance of the coastal environment. The development of the Beibu Gulf Economic Zone threatens the mangrove ecosystems in Guangxi. Seawall construction, shrimp pond enclosures, and mangrove cutting degrade mangrove habitats, leading to mangrove damage and death [7]. Identifying suitable mangrove restoration sites and determining suitable habitat conditions are key factors that affect the success of mangrove restoration [8,9]. However, few studies have focused on predicting the potential mangrove distributions in the Beibu Gulf.

Predicting the spatial distributions of potentially suitable habitats for species is the basis of ecological restoration [10]. Classical niche models include the genetic algorithm for rule set production (GARP), the maximum entropy model (MaxEnt), and species distribution models (SDMS) [11,12]. Of these, MaxEnt is the most widely used and is highly accurate [13–16]. Based on the MaxEnt model, species records can be obtained and combined with corresponding environmental variables to predict potential distributions. The MaxEnt model has been applied in studies of animal and plant protection, as well as in ecological research, and has been widely used to predict endangered animal and plant distributions [17,18], suitable habitats for invasive organisms [19], and determine the effects of global climate change on species distributions [20]. The MaxEnt model has recently been applied to studies of potential restoration areas for coastal and intertidal organisms, such as seagrass beds, *Tachypleus tridentatus*, *Carcinoscorpius rotundicauda*, and coral reefs [21–23].

Predicting potential mangrove distributions has also garnered considerable research attention [24–26]. Mangroves lie at the ocean–land interface; therefore, the contrasting ecological and environmental characteristics of the ocean and land must be considered when identifying suitability factors. Consequently, predicting mangrove distributions is more complex than predicting the distributions of terrestrial or marine organisms. Previous studies have incorporated mangrove communities while analyzing suitable mangrove restoration areas in China [27–30]. However, existing studies of mangrove distribution prediction have not differentiated between mangrove species during sampling. Owing to the diversity of mangrove species, previous studies have been unable to achieve the goal of selecting suitable trees that will adapt to the site. Factors that influence existing mangrove distribution predictions primarily include sea surface temperature (SST), terrain factors, bioclimatic factors, sea surface salinity, and substrate type. Mangrove patches are primarily distributed in wetlands, woodlands, and water bodies [31]; therefore, we included land use type in this study to appropriately limit the mangrove distributions, thereby increasing the accuracy of the predicted distributions.

In this study, we analyzed six dominant mangrove species to obtain their habitat condition thresholds, which are of practical significance for selecting appropriate species and building a community structure in mangrove restoration. We used the MaxEnt model to determine the potential distributions, areas, and response intervals of six mangrove species: *Avicennia marina*, *Aegiceras corniculatum*, *Kandelia obovata*, *Bruguiera gymnorrhiza*, *Rhizophora stylosa*, and *Acanthus ilicifolius.* In addition, all mangrove species were grouped to estimate the kernel density, which was used to analyze mangrove restoration hot spots and unprotected mangrove areas. This study provides a scientific basis for mangrove restoration and protection in the Beibu Gulf.

## 2. Methodology

### *2.1. The Study Area*

The Beibu Gulf is located in southern China (20°54′–21°24′ N, 107°56′–109°47′ E; Figure 1). The coastline extends westward from the Ximi Estuary (at Yingluo Port) at the junction of the Hepu and Lianjiang counties (Guangdong Province), to the Beilun Estuary at the junction of Dongxing City and Vietnam. The total length of the coastline is 1628.59 km. The coastline is tortuous and has many natural bays, including the Tieshan, Lianzhou, Qinzhou, and Fangcheng bays, as well as Pearl Harbor [1]. This region is characterized by a marginal tropical marine climate, with an annual rainfall of 1500–2000 mm and an average annual temperature of 22.0–23.4 °C. The Beibu Gulf has a relatively extensive mangrove distribution, with rich mangrove wetland resources, and contains the Shankou, Beilun Estuary, and Maoweihai mangrove nature reserves. The Beibu Gulf also contains a National Wetland Park. The dominant mangrove species include *A. marina*, *Aegiceras corniculatum*, *K. obovata*, *B. gymnorrhiza*, *R. stylosa*, and *A. ilicifolius*, with the top five mangrove communities (based on area) comprising *A. marina*, *A. corniculatum*, *A. marina* + *A. corniculatum*, *B. gymnorrhiza* + *A. marina*, and *R. stylosa*. The *A. marina* and *A. corniculatum* communities account for 41.74% and 32.91% of the total mangrove area, respectively [6].

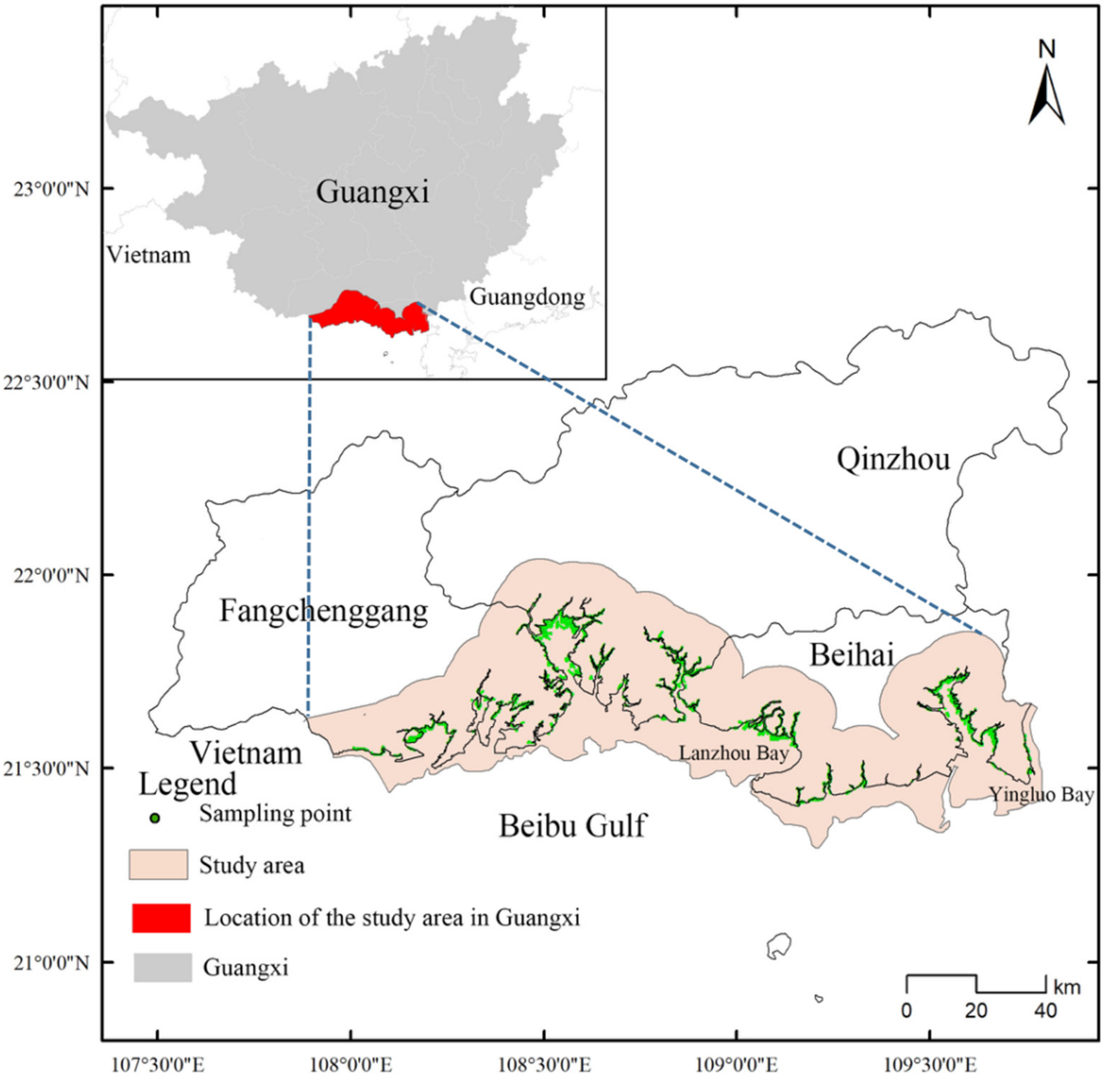


**Figure 1.** The study area and sampling locations in Guangxi.

### *2.2. Mangrove Distributions*

To predict suitable mangrove species distributions using the MaxEnt model, species distributions and environmental data are required. Mangrove distribution data for the Beibu Gulf were visually interpreted according to the 2020 Google Earth images (0.61–2.4 m resolution). The appearances of the various mangrove plants in the 2020 Google Earth images differed (Table 1). The crowns of *R. stylosa* were nearly round or round, the leaves were dark green, and the heights of the trees were greater than those of *A. marina* and *K. obovata*, resulting in dark shadows around the trees. *R. stylosa* was observed as independent patches on the map [32]. *B. gymnorrhiza* was distributed as a single plant with a nearly round or round blue-green crown. When an uncertain mangrove species was observed, we performed field surveys to verify the species. Additional data were obtained from previous studies, and 908 data points from a mangrove forest survey were provided by the Guangxi Mangrove Research Center. In the study area, re-adoption work was conducted using the fishing net tool in the ArcGIS 10.4 software package (Environmental Systems Research Institute, Redlands, CA, USA), supplemented by manual marking, from which a 300 m × 300 m grid was established. A total of 2270 sampling and coordinate data points were obtained in the study area. Among them, the 1076, 999, 98, 34, 28, and 35 sampling points were for *A. corniculatum*, *A. marina*, *K. obovata*, *B. gymnorrhiza*, *R. stylosa*, and *A. ilicifolius*, respectively. The sampling sizes had no obvious influence on MaxEnt [33]. Longitude and latitude data for the species distributions were extracted using the "Calculate Geometry" tool in ArcGIS 10.4 and data were stored as comma-separated value files to form a mangrove sample dataset. We used an analytical framework to predict the potential mangrove species distributions (Figure 2).

**Table 1.** Feature descriptions of mangrove plants in Google Earth images.

| Mangrove Species | Image Diagram | RGB | Characteristic Description |
| --- | --- | --- | --- |
| *A. marina* |  | R: 43<br>G: 67<br>B: 68 | Distributed in sheets with a blue-green crown |
| *A. corniculatum* |  | R: 60<br>G: 68<br>B: 60 | Distributed in sheets with a yellow-green crown |
| *K. obovata* |  | R: 24<br>G: 47<br>B: 34 | Distributed in sheets with a dark green crown |
| *B. gymnorrhiza* |  | R: 45<br>G: 76<br>B: 70 | Distributed as a single plant with a nearly round or round blue-green crown |
| *R. stylosa* |  | R: 31<br>G: 61<br>B: 33 | Distributed as a single plant with a nearly round or round dark green crown |
| *A. ilicifolius* |  | R: 26<br>G: 57<br>B: 35 | Distributed in sheets with a green tree crown |

### *2.3. Environmental Data*

Environmental data can be used to determine differences in growth factors between mangrove species. Environmental factors, including temperature, salinity, and distance from the coastline, are important indicators of potential mangrove growth and distribution [34]. We determined the influences of individual environmental characteristics on the individual tree species populations according to their natural regeneration abilities. Since mangroves grow in the ocean–land ecotone, their fitness factors are affected by both continental and marine environmental factors. Thus, in this study, we combined marine and terrestrial environmental data. To estimate the mangrove distributions in the Beibu Gulf, the boundary of the study area was fixed with the coastline as the reference. The estimated study area enclosed a 10-km buffer zone inland along the coastline, and outward to the 6-m isobath in the ocean. The Weizhou and Xieyang islands were not included in this study. ArcGIS resampling was used to extract environmental data for the existing mangrove sampling points, and Kriging interpolation was performed to expand the data seaward or landward and to integrate the marine and terrestrial data.

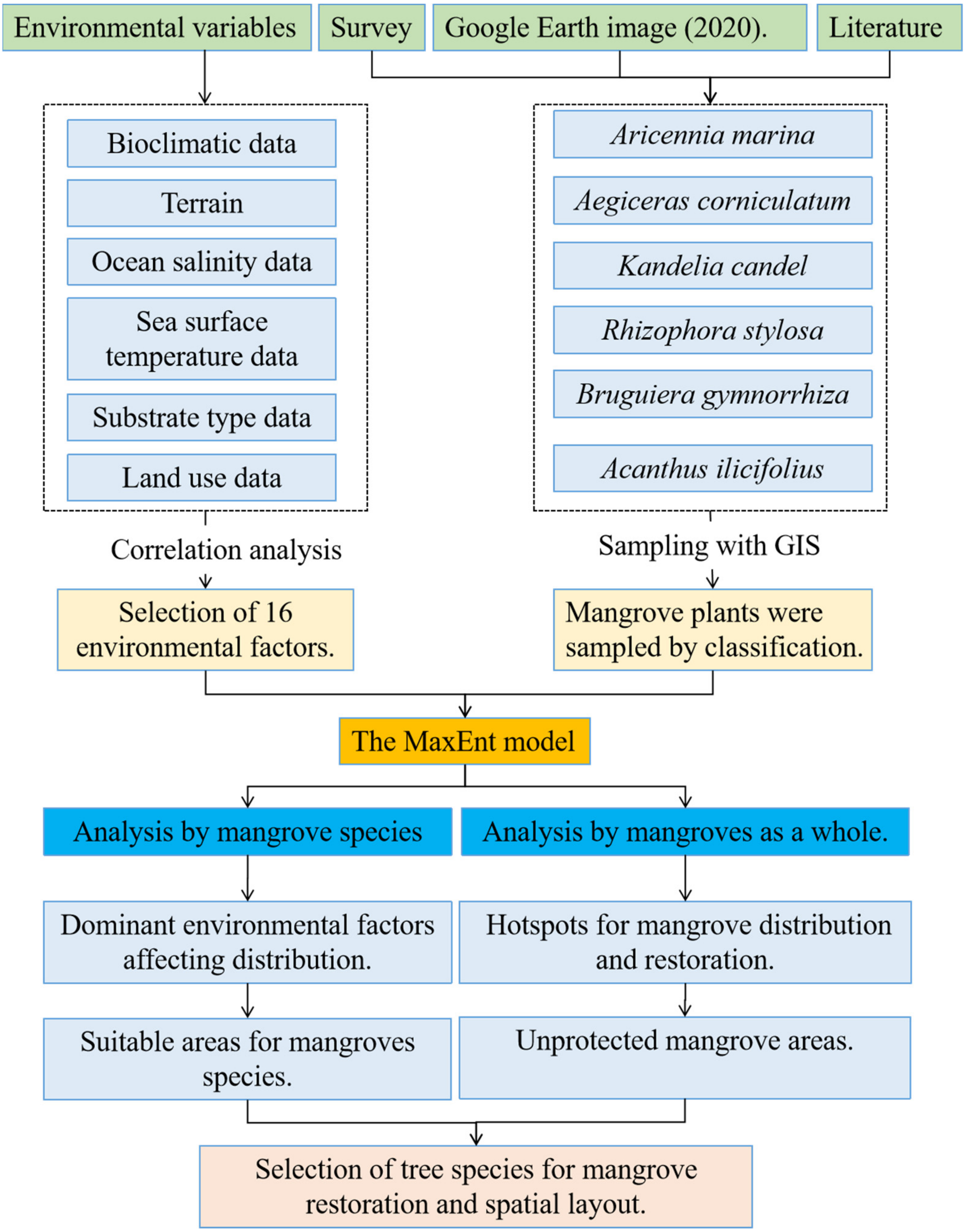


**Figure 2.** The analytical framework used to predict potential mangrove species distributions for restoration purposes.

The bioclimatic factors were obtained from the World Climate Database archive (https://www.worldclim.org/data/worldclim21.html, accessed on 25 June 2022). We used WorldClim Version 2, which contains standard (19) WorldClim bioclimatic variables (30 s precision). The data are the 1970–2000 averages.

The terrain data were extracted from the ETOP01 terrain elevation and ocean seafloor terrain data released by the United States Geophysical Center archive (https://www.ngdc.noaa.gov/mgg/global/global.html, accessed on 14 July 2022). The data were obtained from the National Oceanic and Atmospheric Administration's (NOAA) National Environmental Information Center archive (1981–2020 SST data; ftp://ftp.emc.ncep.noaa.gov/cmb/sst/oisst_v2/, accessed on 2 February 2022). The salinity data were obtained from the marine salinity products of the Institute of Atmospheric Physics, Chinese Academy of Sciences archive (http://159.226.119.60/cheng/, accessed on 2 February 2022). Auxiliary data, including seawater salinity [35,36] for the references in the study area were also obtained. The substrate data were obtained from the National Marine Science Data Center (nmdis.org.cn, accessed on 5 June 2022), as well as auxiliary data regarding substrate classification in the study area [37]. The land use data were obtained from the ESRI 10 m Cover (2020) dataset in the Google Earth Engine (GEE) archive (https://livingatlas.arcgis.com/landcover/, accessed on 24 June 2022). The resolutions of the datasets were normalized to 30" using a geographic information system (GIS), and the graph was saved in ASCII format.

Correlation analyses can screen environmental variables to analyze their closeness. The mangrove distributions and environmental data were sampled using GIS. The environmental data included nineteen environmental parameters, two terrain parameters, three SST data points, three salinity data points, one substrate type data point, and one land-use data point. Pearson's correlation analysis was used to identify the environmental variables and was performed for all 29 variables to calculate the correlation coefficient matrix. A correlation coefficient > 0.8 indicates a strong correlation. We eliminated the environmental variables that had less impact on species [38], with a total of 16 environmental variables used to establish the model (Table 2, Figures 3 and 4). We calculated the wetland index (WTI), which represents the spatial distribution of the runoff source area and groundwater level in the basin, using the following equation:

$$WTI = ln\left(\frac{\alpha}{\tan\beta}\right) \quad (1)$$

where $\alpha$ is equal to (flow accumulation + 1) $\times$ pixel area (in $m^2$) and $\beta$ represents the slope angle in radians.

**Table 2.** Environmental variables used to predict the mangrove distributions in the Beibu Gulf, Guangxi, China.

| Data Type | Variable | Description | Unit |
|---|---|---|---|
| Bioclimatic | Bio2 | Mean diurnal range [mean of monthly (max. temp–min. temp)] | °C × 10 |
| | Bio3 | Isothermality (BIO2/BIO7) (×100) | % |
| | Bio5 | Maximum temperature of warmest month | °C × 10 |
| | Bio6 | Minimum temperature of the coldest month | °C × 10 |
| | Bio10 | Mean temperature of the warmest quarter | °C × 10 |
| | Bio15 | Precipitation seasonality (coefficient of variation) | % |
| | Bio18 | Precipitation in the warmest quarter | mm |
| | Bio19 | Precipitation in the coldest quarter | mm |
| Terrain | Elevation | Topographic elevation | m |
| | WTI | Wetland index | – |
| Ocean salinity | C_sss | Mean sea surface salinity in the coldest season | ‰ |
| | W_sss | Mean sea surface salinity in the warmest season | ‰ |
| Sea surface temperature | C_sst | Mean sea surface temperature in the coldest season | °C |
| | W_sst | Mean SST in the warmest season | °C |
| Substrate type | Substrate | Substrate type | – |
| Land-use data | Land-use | Land use type | – |

*2.4. Model Parameters*

In this study, we used the MaxEnt version 3.4.1 (Steven J. Phillips, Columbia University) for the predictive analyses. To establish the model, 75% of the mangrove distribution data from the Beibu Gulf was used as training data, while the remaining 25% was used as test data [28]. To construct the MaxEnt model, the default feature combination was selected and sample data were randomly selected. To improve the accuracy, the number of repeated model calculations was set to 10. Default values were used for other settings. The grid output results obtained after the operation were visually converted and analyzed using ArcGIS 10.4. The pixel value of each grid represented the distribution probability of mangroves in the grid, with a value ranging from 0 to 1. Larger pixel values indicated higher potential mangrove distributions and higher habitat suitability. In this study, we used the natural breakpoint method to grade the fitness results as follows: 0–0.2, no fitness; 0.2–0.5, low fitness; 0.5–0.7, medium fitness; and >0.7, optimal fitness [27].

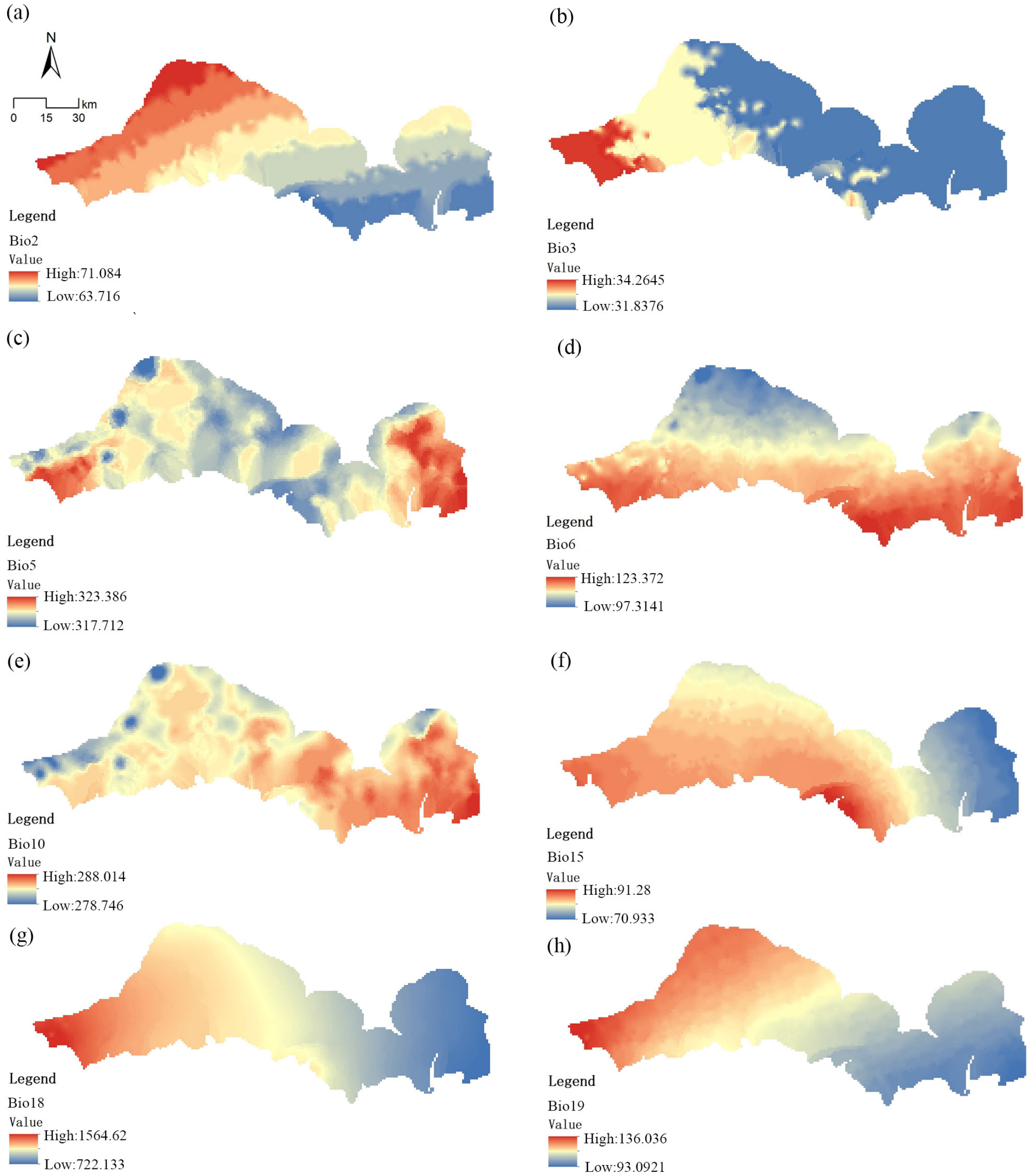


**Figure 3.** Environment variable. (**a**) Bio2, (**b**) Bio3, (**c**) Bio5, (**d**) Bio6, (**e**) Bio10, (**f**) Bio15, (**g**) Bio18, (**h**) Bio19.

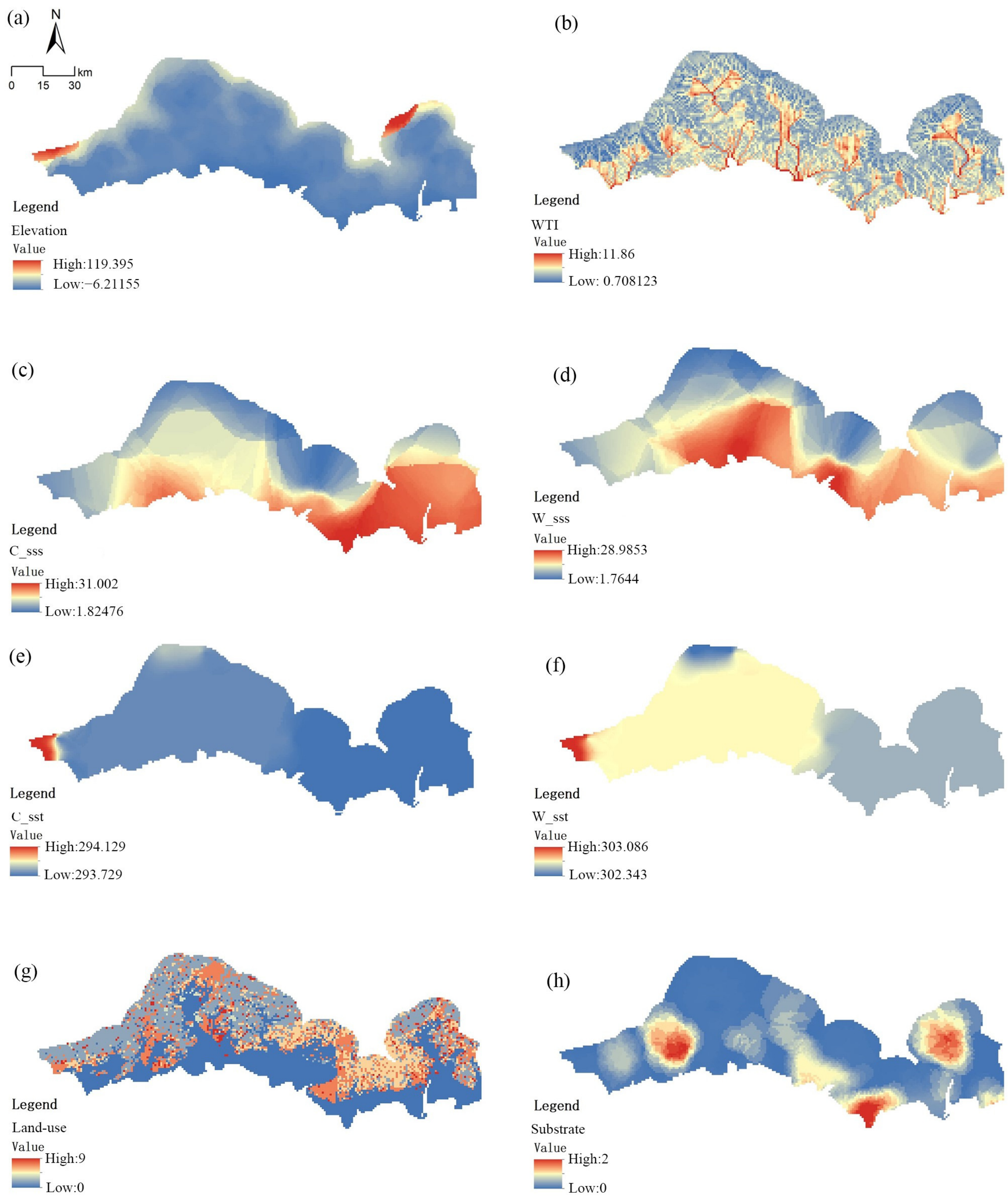


**Figure 4.** Environment variables. (**a**) Elevation, (**b**) WTI, (**c**) C_sss, (**d**) W_sss, (**e**) C_sst, (**f**) W_sst. (**g**) Land-use, (**h**) Substrate.

### 2.5. Model Testing

The MaxEnt model was applied to calculate the receiver operating characteristic (ROC) curve. The value of the diagnostic test was represented by the area under the curve (AUC) of the ROC curve, with AUC values ranging from 0 to 1. Values closer to 1 indicate a more accurate prediction [38]. The range of AUC values was interpreted as follows: 1–0.9, excellent prediction; 0.8–0.9, good prediction; 0.7–0.8, average prediction; 0.6–0.7, poor prediction; and 0.5–0.6, prediction failure [28].

### 2.6. Vacancy Analysis of Mangrove Protection and Restoration

Based on the mangrove habitat suitability results, priority areas for mangrove protection and restoration (potential mangrove hot spots) were calculated using the kernel density estimation (KDE), which is a hot spot spatial analysis method [39]. The distribution of discrete values in continuous space can be obtained by calculating the densities of the elements in their surrounding neighborhood. In this study, after the KDE analysis was performed in the ArcGIS software, we used a spatial superposition analysis of the mangrove distribution status, priority area spatial distributions, and nature reserve distributions to further analyze the protection status of the mangrove ecosystem in the Beibu Gulf. The protected area information, including the protection rate and the protection and repair of vacant areas, was also obtained from the spatial superposition analysis.

## 3. Results

### 3.1. The AUC Values

The AUC values of the training and test sets of the predictive model for the six mangrove species in the Beibu Gulf ranged from 0.912 to 1 (Figure 5), whereas those for all mangrove species combined were 0.882 and 0.869 for the training and test sets, respectively (Figure 6). Based on the AUC values of the test set, the MaxEnt model simulation of the mangroves was deemed accurate. Thus, the model was highly reliable and could predict the distribution of the dominant mangrove species in the Beibu Gulf.

### 3.2. Analysis of Dominant Environmental Factors

Factors affecting the mangrove habitats included bioclimate, topography, salinity, SST, substrate type, and land use type. The contributions of the variables were based on the interactions between the different environmental variables [15]. We investigated the test results of different factors affecting mangrove distributions to determine the dominant factors that affected the distributions of specific species. In the Beibu Gulf, elevation, WTI, mean temperature of the warmest quarter, and substrate type were the dominant factors that affected the overall mangrove distribution (Figure 7).

We investigated the importance of the environmental factors on the distribution probability of each of the six selected mangrove species. The three environmental factors crucial to the geographic distribution of *A. marina* were elevation, mean sea surface salinity in the coldest season, and maximum temperature of the warmest month (Figure 8a), with a cumulative contribution rate that accounted for 50.7% of its distribution, while the other 13 environmental factors accounted for 49.3% (Figure 9). Among the remaining factors, the contributions of bioclimatic factors, topography, sea surface salinity, SST, substrate type, and land use type accounted for 39.1%, 34.0%, 16.6%, 1.2%, 6.1%, and 2.9% of the total, respectively. Based on the contributions and importance of the various environmental factors for predicting *A. marina* distribution, elevation limited the optimal planting areas, while the mean sea surface salinity in the coldest season reflected the salt preference of this species. The contributions of land use type and SST to the distribution of *A. marina* were relatively low.

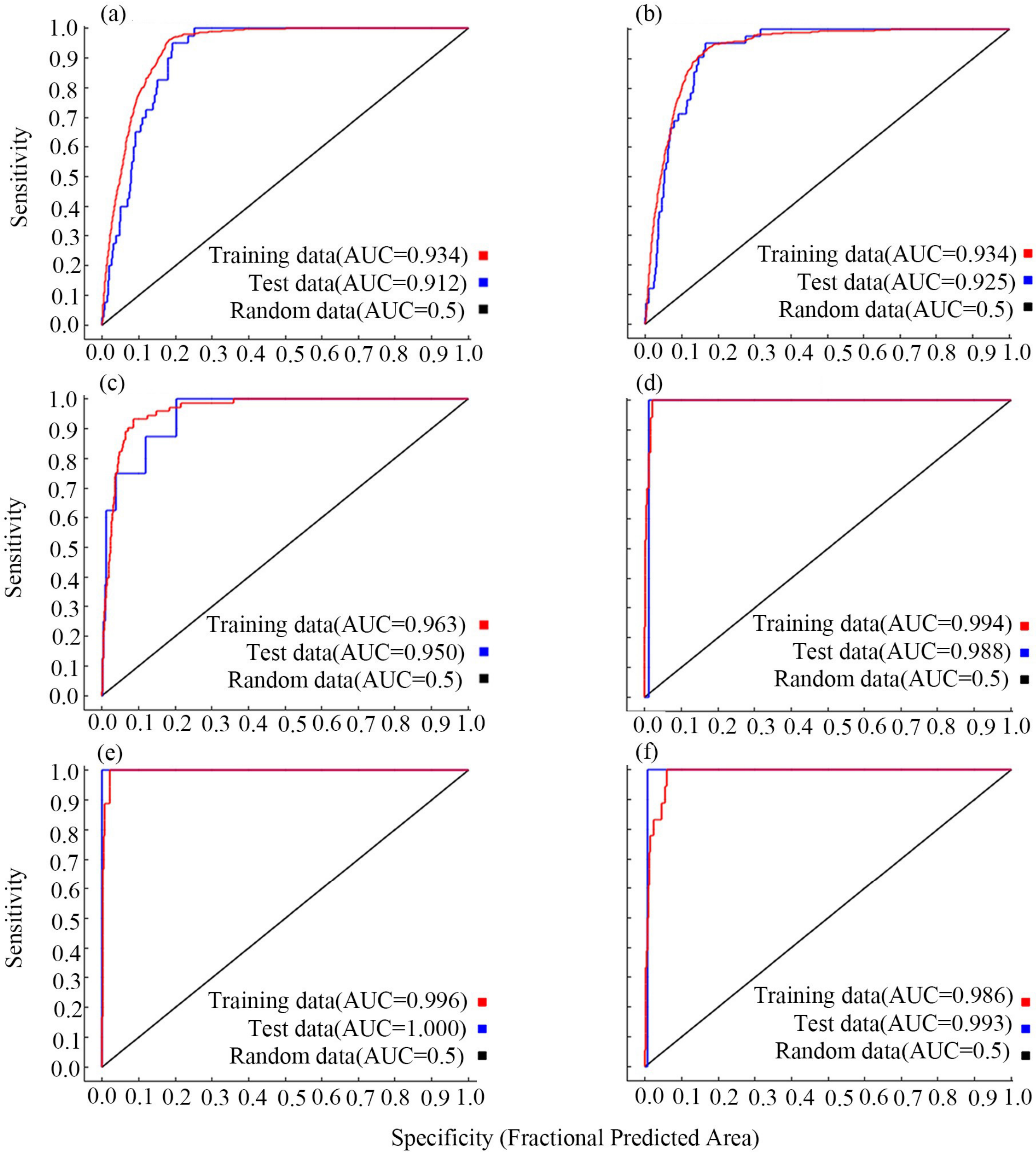


**Figure 5.** The receiver operating characteristic (ROC) curves of the mangrove species used to verify the MaxEnt model. (**a**) *A. marina* (**b**) *A. corniculatum* (**c**) *K. obovata* (**d**) *B. gymnorrhiza* (**e**) *R. stylosa* (**f**) *A. ilicifolius*.

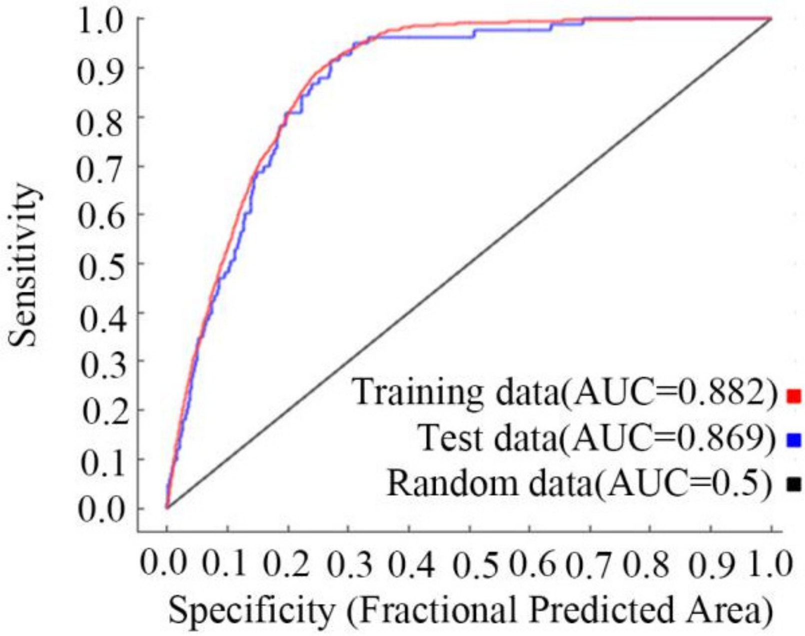


**Figure 6.** The ROC curve of combined mangrove species used to verify the MaxEnt model.

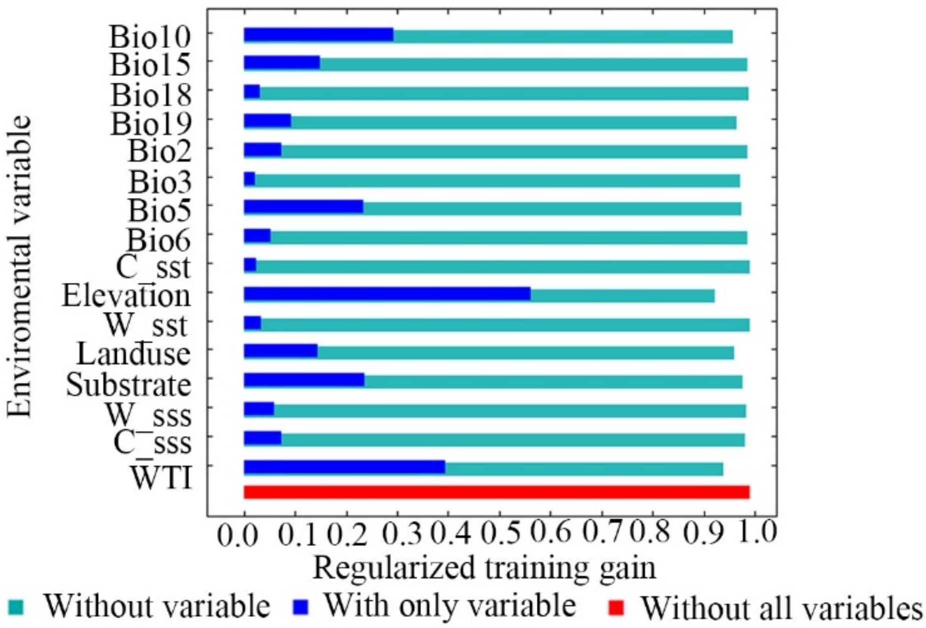


**Figure 7.** The regularized training gains of the combined mangrove distribution. Dark blue entries represent independent test results of each variable, light green entries represent test results excluding the variable, and red entries represent test results including all variables [40]. The length of each entry represents the size of its score (i.e., longer entries indicate more important variables).

For *A. corniculatum*, the three environmental factors that were critical to its geographic distribution were elevation, WTI, and substrate type (Figure 8b), with a cumulative contribution that accounted for 41.7% of its distribution, while the remaining 13 environmental factors accounted for 58.3%. Among the remaining factors, the contributions of topography, sea surface salinity, bioclimate, SST, substrate type, and land use type accounted for 36.3%, 39.6%, 18.9%, 0.1%, 2.1%, and 3.1% of the total, respectively (Figure 9). The contribution of marine salinity for predicting the *A. corniculatum* distribution was greater than that for *A. marina*, indicating that *A. corniculatum* is more sensitive to salinity than *A. marina*. The contributions of SST, substrate type, and land use type to the distribution of *A. corniculatum* were relatively low.

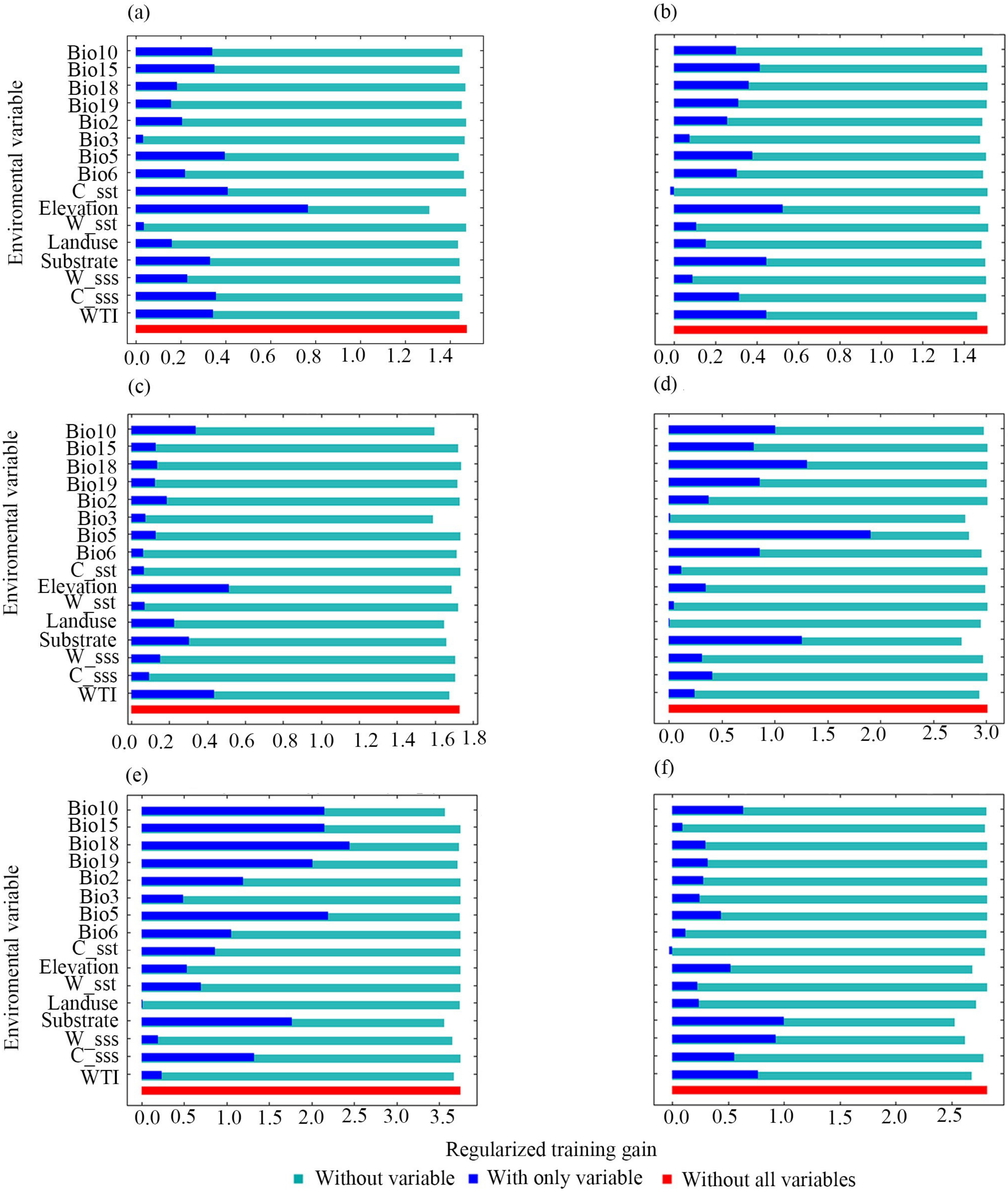


**Figure 8.** The regularized training gains for the six mangrove species: (**a**) *A. marina*, (**b**) *A. corniculatum*, (**c**) *K. obovata*, (**d**) *B. gymnorrhiza*, (**e**) *R. stylosa*, and (**f**) *A. ilicifolius* (entry definitions are the same as in Figure 5).

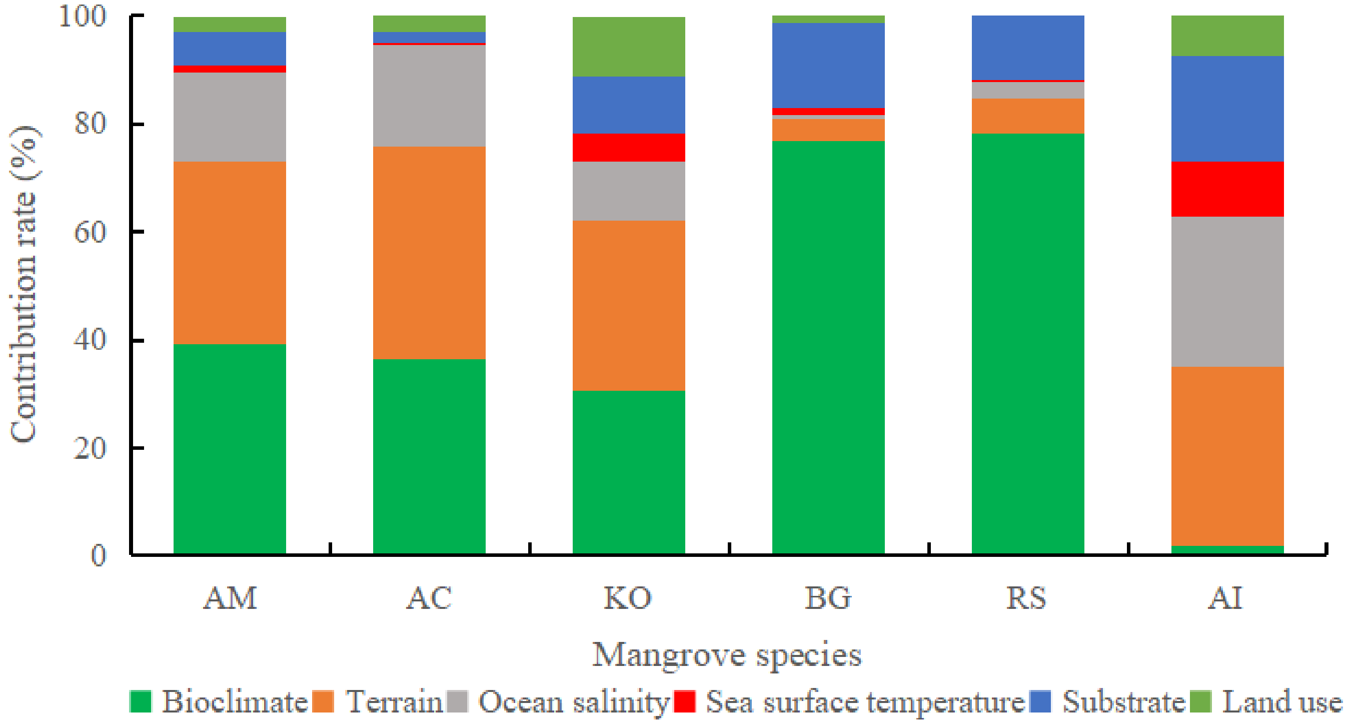


**Figure 9.** The contributions of the six environmental variables to predicting the mangrove species distributions (*A. marina*: AM, *A. corniculatum*: AC, *K. obovata*: KO, *B. gymnorrhiza*: BG, *R. stylosa*: RS, and *A. ilicifolius*: AI).

For *K. obovata*, elevation, substrate type, and WTI were the most important to its geographic distribution (Figure 8c), with a cumulative contribution of 42.3%. Among these influencing factors, elevation reflected the restrictions on *K. obovata* planting locations. In addition, it is possible that this species is relatively sensitive to the substrate type.

For *B. gymnorrhiza*, the maximum temperature of the warmest month, precipitation in the warmest quarter, and substrate type had the largest effects on its geographic distribution (Figure 8d), accounting for a cumulative contribution of 79.1%. Among the other factors, the contribution rates of bioclimate, topography, sea surface salinity, SST, substrate type, and land use type accounted for 76.9%, 4.1%, 0.7%, 0.4%, 15.8%, and 1.2%, respectively. These results indicate that *B. gymnorrhiza* is sensitive to bioclimatic factors and the substrate type.

For *R. stylosa*, precipitation in the warmest quarter, substrate type, and mean temperature of the warmest quarter most affected its geographic distribution (Figure 8c), accounting for a cumulative contribution of 82.9%. Among the factors influencing the distribution of this species, the contribution rates of bioclimate, topography, sea surface salinity, SST, substrate type, and land use type accounted for 78.3%, 6.6%, 2.9%, 0.4%, 11.9%, and 0%, respectively. These results indicate that the distribution of *R. stylosa* is sensitive to bioclimatic factors.

For *A. ilicifolius*, the substrate type, mean sea surface salinity in the warmest season, and WTI had the greatest importance for its geographic distribution (Figure 8f), with a cumulative contribution of 72.5%. The significance of the substrate type reflects the substrate preferences of *A. ilicifolius*, while the significance of the WTI reflects the limitations of topography on *A. ilicifolius*. Furthermore, the importance of mean sea surface salinity in the warmest season reflects the sensitivity of *A. ilicifolius* to salinity, as high salinity levels may affect its growth.

### 3.3. Ranges of Environmental Factors That Affect Mangrove Habitat Suitability

The variables representing the mangrove suitability factors in the Beibu Gulf were selected based on the logistic mode of the MaxEnt model. Correlations between habitat suitability and the environmental variables were analyzed using a probability distribution logic output value of 0.5 as the boundary. Using the main environmental variables (i.e., elevation, maximum temperature of the warmest month, precision in the warmest quarter, and substrate) and their corresponding species probabilities, the response curves of the most important environmental variables affecting mangrove distributions in the study area were obtained (Figure 10). This allowed us to investigate the optimal thresholds for the main environmental variables affecting the six mangrove species (Table 3).

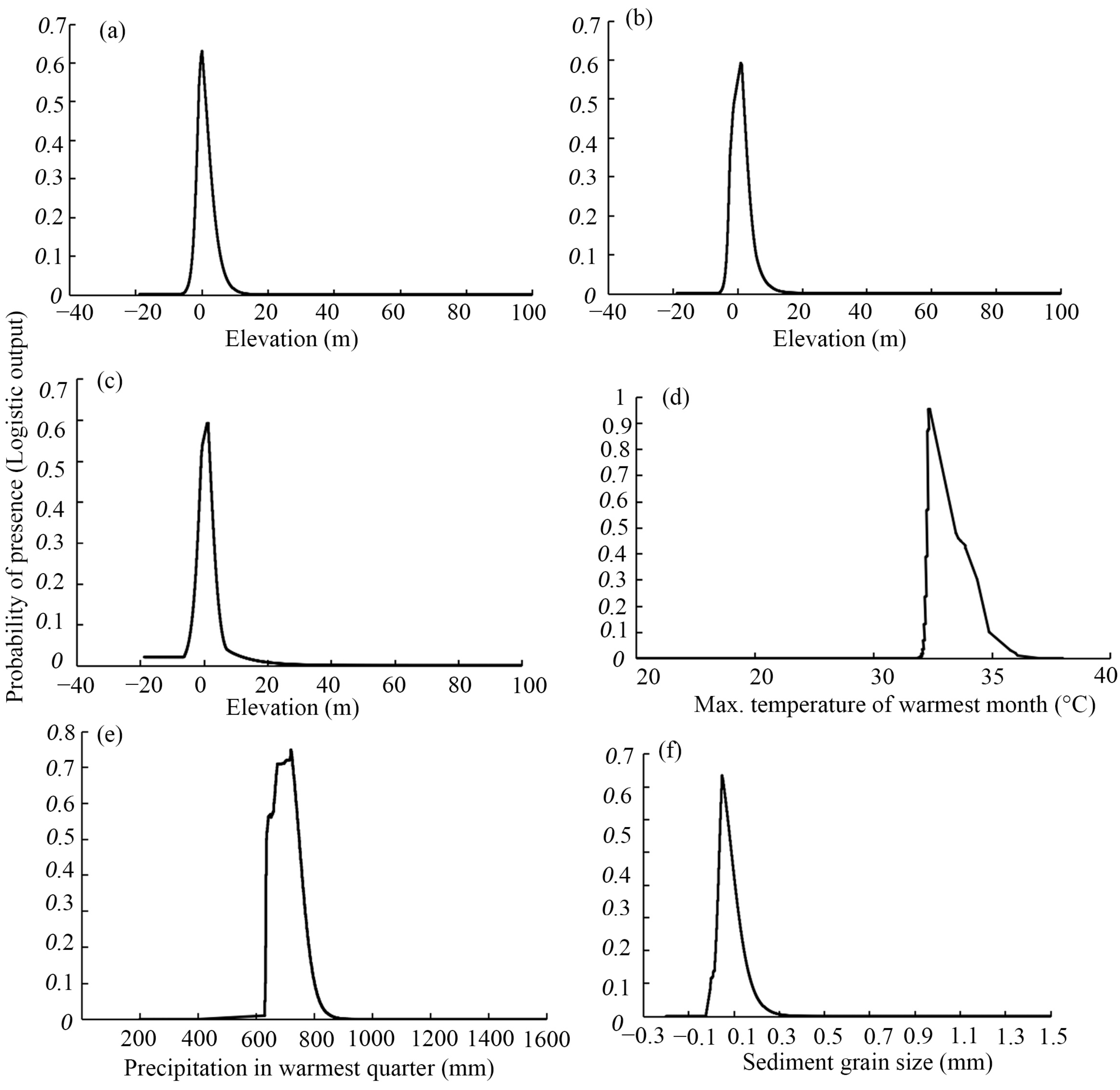


**Figure 10.** The response curves of environmental variables for (**a**) *A. marina*, (**b**) *A. corniculatum*, (**c**) *K. obovata*, (**d**) *B. gymnorrhiza*, (**e**) *R. stylosa*, and (**f**) *A. ilicifolius* (entry definitions are the same as in Figure 5).

**Table 3.** Thresholds of the dominant environmental factors that affected the six mangrove species distributions.

| Order | Mangrove Species | Dominant Environmental Factors | Limitation |
|---|---|---|---|
| 1 | *A. marina* | Elevation | −0.84–1.27 m |
| | | Mean sea surface salinity in the coldest season | 16.41–25.31‰ |
| | | Maximum temperature of the warmest month | 32.1–32.3 °C |
| 2 | *A. corniculatum* | Elevation | −0.68–2.02 m |
| | | Wetland index | 4.11–9.81 |
| | | Substrate type | Mixed mud flat |
| 3 | *K. obovata* | Elevation | −0.50–1.88 m |
| | | Substrate type | Mixed mud flat |
| | | Wetland index | 4.49–8.33 |
| 4 | *B. gymnorrhiza* | Maximum temperature of the warmest month | 32.3–32.4 °C |
| | | Precipitation in the warmest quarter | 638–753 mm |
| | | Substrate type | Mixed mudflat |
| 5 | *R. stylosa* | Precipitation in the warmest quarter | 637–746 mm |
| | | Substrate type | Mixed mudflat |
| | | Mean temperature of the warmest quarter | 28.7–28.9 °C |
| 6 | *A. ilicifolius* | Substrate type | Mixed mudflat |
| | | Mean sea surface salinity in the warmest season | 3.39–7.37‰ |
| | | Wetland index | >5.28 |

The minimum suitable elevations of the mangrove species were (from lowest to highest): *A. marina* < *A. corniculatum* < *R. stylosa* < *K. obovata* < *B. gymnorrhiza* < *A. ilicifolius.* The lowest elevation suitable for *A. marina* growth was −0.84 m, whereas that for *A. ilicifolius* was relatively high (Figure 11).

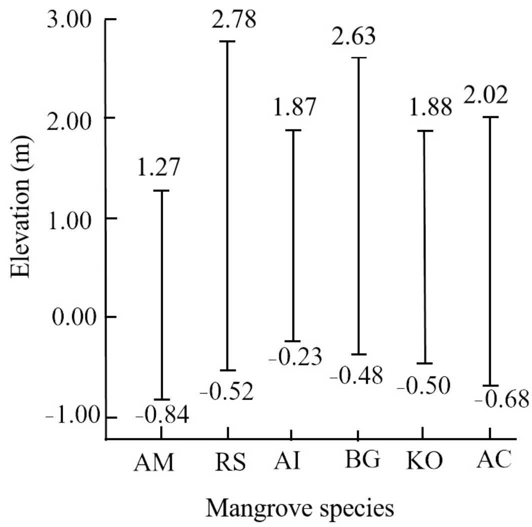


**Figure 11.** Mangrove elevation thresholds for *A. marina* (AM), *A. corniculatum* (AC), *K. obovata* (KO), *B. gymnorrhiza* (BG), *R. stylosa* (RS), and *A. ilicifolius* (AI).

For the average sea surface salinity in the coldest season, *K. obovata* had a relatively wide range (5.91‰–17.92‰; Figure 12). According to the highest suitable mean sea surface salinity value in the coldest season, the six species were in order (from highest to lowest) as follows: *R. stylosa* > *B. gymnorrhiza* > *A. marina* > *A. corniculatum* > *K. obovata* > *A. ilicifolius.* For the most suitable mean sea surface salinity in the warmest season, the species were in order (from highest to lowest) as follows: *A. marina* > *R. stylosa* > *K. obovata* > *B. gymnorrhiza* > *A. corniculatum* > *A. ilicifolius*. The most suitable mean sea surface salinity range in the coldest season for *A. marina* was 16.41‰–25.31‰, while the most suitable value was 24.27‰. The suitable average sea surface salinity range for *A. ilicifolius* in the warmest season was 3.39‰–7.37‰, and the most suitable value was 4.07‰.

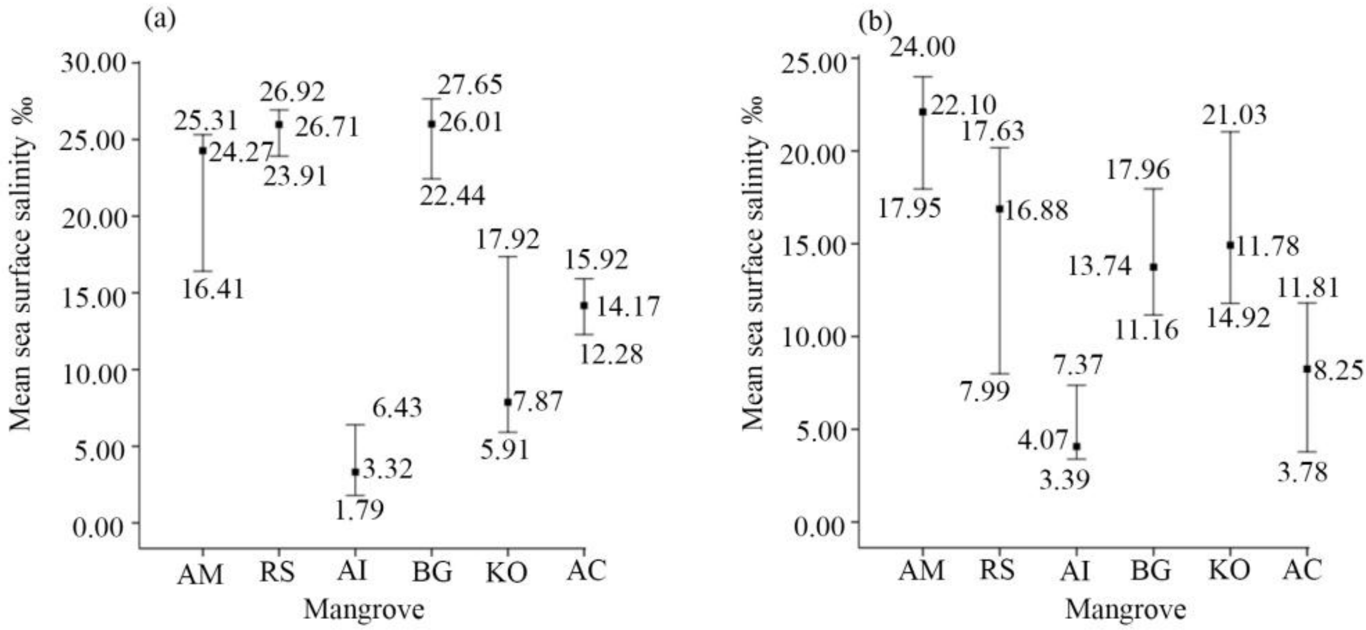


**Figure 12.** Salinity preferences of the different mangrove species in the coldest and warmest seasons. Mean sea surface salinity in the (**a**) coldest and (**b**) warmest seasons.

### *3.4. Suitable Mangrove Areas in the Beibu Gulf*

According to the findings of Hu et al. [28], we divided the potential mangrove areas based on their suitability as follows: best (>0.7), medium (0.7–0.5), low (0.2–0.5), and unsuitable (0–0.2). Using the six mangrove species as the overall inputs for the model (Figure 12g), we obtained an optimal suitable area of 13,816 hm$^2$. The best fitness areas were located primarily in the Dandou Sea on the western side of the Shatian Peninsula in southeastern Hepu County, Guangxi; Tieshan Harbor in Qinzhou Bay and the Dafeng River in the center of the Guangxi coastline; Fangcheng Bay on the western Guangxi coastline; and the Shankou Mangrove National Nature Reserve (Figure 13g).

The size of the best suitable area for *A. marina* was 10,341 hm$^2$ (Figure 13a, Table 4), with high fitness areas primarily located in Tie Shan Gang, Beihai Golden Bay mangrove reserve, and along the open coastline in the southern Beihai National Wetland Park and Beilun Estuary Mangrove National Nature Reserve. The size of the best suitable area for *A. corniculatum* was 13,154 hm$^2$ (Figure 13b), with highly suitable areas distributed primarily in estuaries, including Lianzhou Bay, the Maoweihai Mangrove Autonomous Region Nature Reserve, and the Dafeng River. The best suitable area for *K. obovata* was 10,672 hm$^2$ (Figure 13c), with highly suitable areas distributed along Qinzhou Bay, the Dafeng River, and the Beilun Estuary Mangrove National Nature Reserve. The size of the best area for *B. gymnorrhiza* was 2565 hm$^2$ (Figure 13d), with the highest fitness areas located primarily in the Dandou Sea region of the Shankou Mangrove Reserve, Yingluo Port, and the Beilun Estuary Mangrove National Nature Reserve. The size of the best suitable area for *R. stylosa* was 1158 hm$^2$ (Figure 13e), with optimal areas distributed primarily in the Dandou Sea region and Yingluo Port of the Shankou Mangrove Reserve; however, very few suitable areas were located in other parts of the study area. The size of the best suitable area for *A. ilicifolius* was 4054 hm$^2$ (Figure 13f), with highest fitness areas located primarily in regions with low estuarine salinities in Lianzhou Bay and the Shankou Mangrove Reserve.

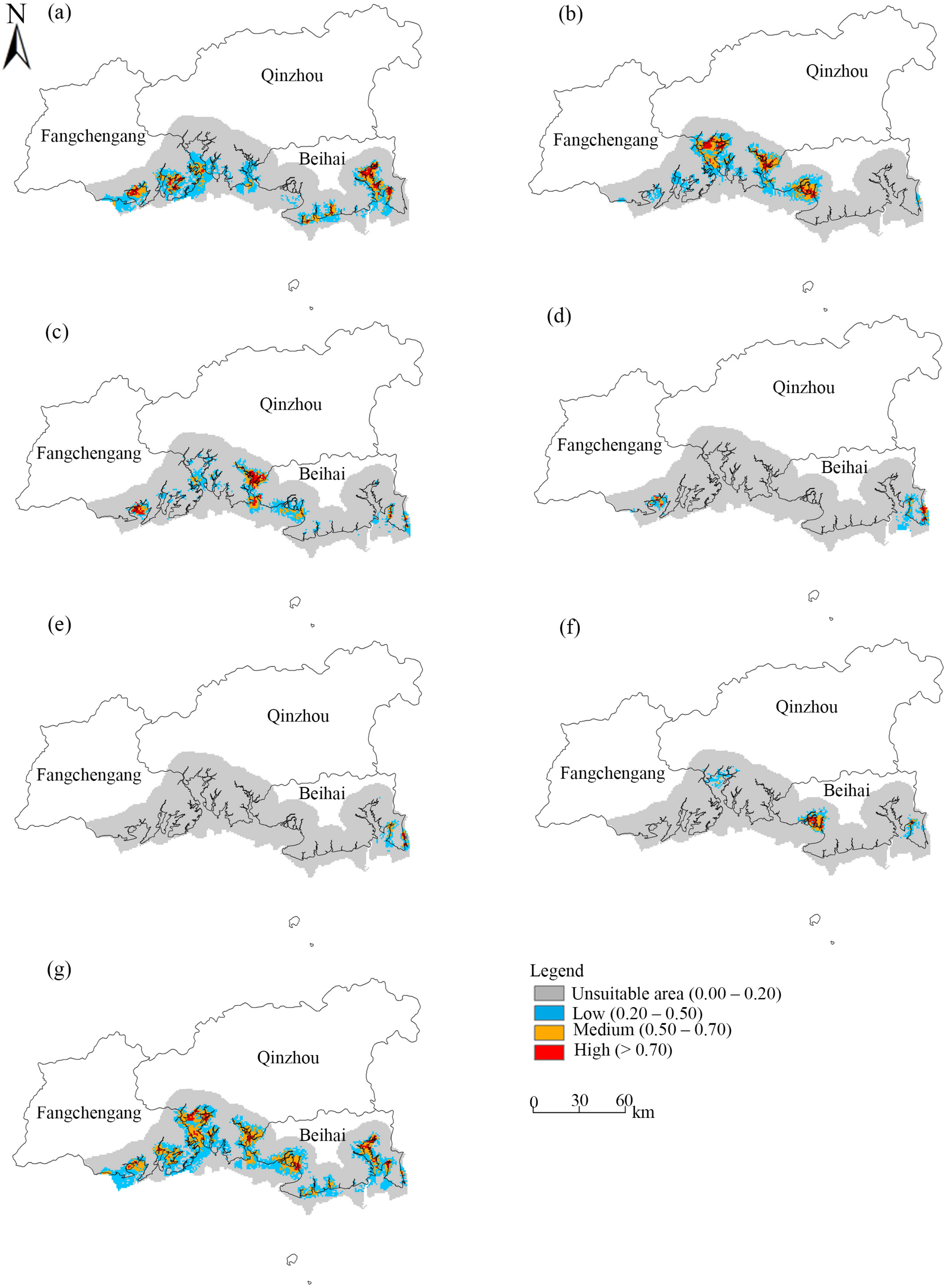


**Figure 13.** Distributions of suitable mangrove habitats in the Beibu Gulf. (**a**) *A. marina*, (**b**) *A. corniculatum*, (**c**) *K. obovata*, (**d**) *B. gymnorrhiza*, (**e**) *R. stylosa*, and (**f**) *A. ilicifolius* (**g**) Overall mangrove community.

**Table 4.** Suitable mangrove areas for species of interest.

| Mangrove Species | Best Suitable Area (hm$^2$) | Medium Suitable Area (hm$^2$) |
|---|---|---|
| *A. marina* | 10,341 | 39,875 |
| *A. corniculatum* | 13,154 | 37,063 |
| *K. obovata* | 10,672 | 20,682 |
| *B. gymnorrhiza* | 2565 | 4385 |
| *R. stylosa* | 1158 | 3226 |
| *A. ilicifolius* | 4054 | 6949 |

The Beibu Gulf contains three mangrove nature reserves and a national wetland park, with a total area of 15,794 hm$^2$ and mangrove coverage of 3977 hm$^2$. The mangrove protection rate in this region is 42.62%. Based on the analysis of the superposition of the distributions of protected areas and potentially suitable mangrove areas, 49.10% of the best suitable areas were located within protected areas (Figure 14). Eight areas were identified as priority areas for mangrove protection and restoration. The unprotected mangrove areas in the Beibu Gulf are primarily located in Lianzhou Bay, along the Dafeng River, East Fangchenggang Bay, and Tieshan Harbor.

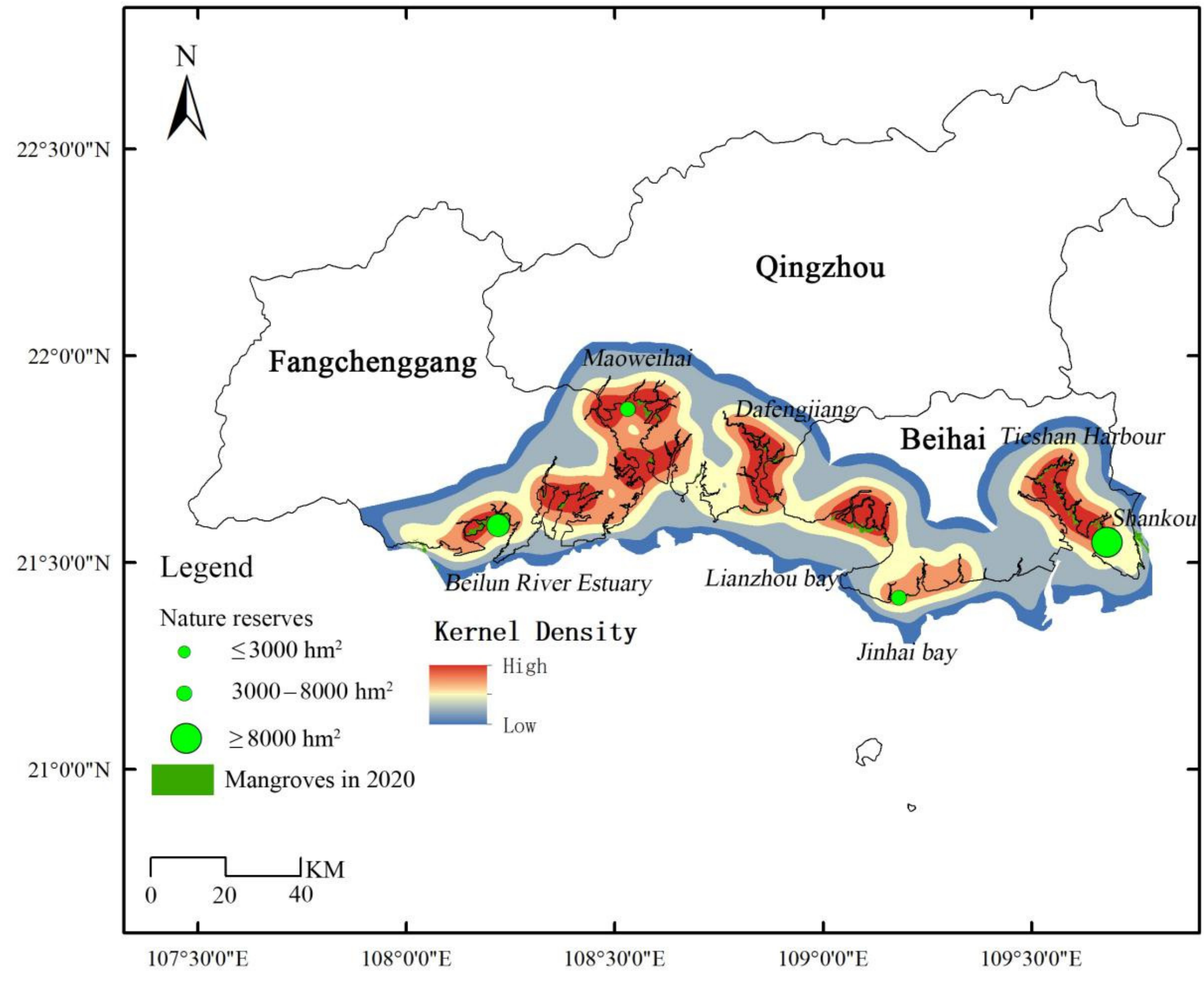


**Figure 14.** The map of the mangrove distribution and restoration hotspots in the Beibu Gulf.

## 4. Discussion

The species distribution studies based on the MaxEnt model presented herein can be used for mangrove restoration. Based on 908 mangrove survey data points and the visual interpretations of the remote sensing images, the AUC values of the training and test datasets of the mangrove species suitability distribution model ranged from 0.912 to 1. The values of all six species were "extremely accurate," indicating good model performance based on the survey data and remote sensing images.

### *4.1. Dominant Environmental Factors Affecting Mangrove Suitability*

Overall, the dominant factors that affected suitable mangrove habitat distribution in the Beibu Gulf were topography, bioclimate, land use type, sea surface salinity, and substrate type. The effect of SST on the distribution of suitable habitats was relatively weak.

In terms of topography, elevation was the dominant factor that affected the distributions of *A. marina*, *A. corniculatum*, and *K. obovata*. These findings are similar to those of Hu et al. [28], who showed that mangrove distribution was limited by topography at a small regional scale, while elevation exerted a considerable influence on species distribution and affected the habitat preferences of mangrove species [41]. In the present study, the minimum critical elevation for mangrove growth was negative or zero, indicating that mangrove plants could grow on the beach below the average sea level, which is comparable to the findings of Liu et al. [42], who reported that large communities of *A. corniculatum* and *K. obovata* can survive on beaches below the average sea level.

*Avicennia marina* had the lowest suitable elevation, indicating that this species is a pioneer tree species for mangrove afforestation. This is consistent with the results from a previous study [43], primarily because *A. marina* has respiratory roots, is resistant to flooding and hypoxia stress, and has a relatively high salt tolerance [44].

Bioclimatic factors were also critical for potential mangrove habitat distributions. These factors were also important for mangroves located in Guangdong and Fujian, China [27,28]. The *R. stylosa* and *B. gymnorrhiza* distributions were more sensitive to bioclimatic factors. Previous studies have shown that *R. stylosa* and *B. gymnorrhiza* are widespread thermophilic species [45], which is consistent with the temperature preferences of these two species observed in this study.

Sea surface salinity also affects mangrove distributions [46–48]. Although mangroves grow in an environment with a salinity of ~30‰ [49], they can adapt to a wide salinity range. Under different salinity gradients, the physiological parameters of mangrove plants can change [50]. In this study, the maximum sea surface salinity favored by all six mangrove species was <30‰, which is in accordance with the findings of previous research [48]. The model used in this study indicates that sea surface salinity was a dominant factor that affected the predicted distributions of *A. marina and A. ilicifolius*. The salinity tolerance intervals of different mangrove species can differ [51]. Based on the most appropriate average sea surface salinities in the coldest and warmest seasons, the three mangrove species investigated by Ye et al. [52], had salt tolerances as follows (from highest to lowest): *A. marina* > *A. corniculatum* > *A. ilicifolius*, which is consistent with the findings of this research.

For *A. ilicifolius*, the average sea surface salinity threshold in the warmest season ranged from 3.39‰–7.37‰. The suitable values for *A. corniculatum* ranged from 3.78‰–11.81‰, while those of *A. marina* ranged from 17.95‰–24.00‰. Therefore, within the threshold range, low-salinity beaches are more suitable for *A. ilicifolius*, whereas medium-salinity beaches are more suitable for *A. corniculatum* [52]. *A. marina* can be planted on beaches with relatively high salinity levels. However, during the dry cold season, the salinities of Dandou, Yingluo, and Tieshan Harbors in the Shankou Mangrove Reserve, which host high mangroves and *B. gymnorrhiza*, range from 26.8‰–28.0‰ [35]. Therefore, the average sea surface salinity in the coldest season and the optimal salinity values for *R. stylosa* and *B. gymnorrhiza* were higher than those for *A. marina*.

The substrate type was a main factor that affected the growth of *A. corniculatum*, *K. obovata*, *B. gymnorrhiza*, *R. stylosa*, and *A. ilicifolius*. Previous research has shown that a mixed beach substrate is more suitable for mangrove growth than single-component beach or mudflat substrates [53]. Therefore, mixed beaches can be an index used for beach selection in the afforestation of these mangrove species.

### *4.2. Mangrove Restoration Recommendations*

As of 2013, the mangrove area in the Beibu Gulf was 7243.15 $hm^2$ [6]. In 2020, this area had increased to 9331.53 $hm^2$ and continues to increase, indicating that there is still space for ecological restoration and confirming that the Guangxi coast has the potential for mangrove restoration. Areas suitable for forests (located in Lianzhou Bay and the Dafeng River in Qinzhou) and vacant areas in the Beibu Gulf can be used for mangrove restoration and protection. The most suitable habitats in this region should be included in ecological mangrove restoration projects that are based on establishing protected areas and wetland parks.

This study focused specifically on predicting the distributions of dominant mangrove species and their suitable growth thresholds. Focusing on individual mangrove species provides more targeted results that are conducive to selecting appropriate species for mangrove restoration.

Bioclimatic and topographic factors, as well as the sea surface salinity, substrate type, SST, and land use type were selected as environmental variables that affected mangrove distributions in this study. In addition to the factors used in previous mangrove distribution prediction studies, we added land use type here. Although land use type was not the most dominant factor affecting the distributions, it also had a certain impact on the mangrove distributions. The contributions of land use type to the predicted distributions of *K. obovata* and *A. ilicifolius* were 10.9% and 7.5%, respectively. We suggest that future studies should add biological invasion factors, substrate and seawater chemistries, and human interference factors (e.g., ports, waterways, and aquaculture) to expand the screening range of environmental variables in the model.

## 5. Conclusions

Predicting the distributions of important mangrove plants is crucial for the selection of tree species for mangrove restoration and their locations. We used remote sensing images combined with field survey data, SST data, land use data, and other environmental data to predict and analyze the potential distributions of six mangrove species in the Beibu Gulf based on the MaxEnt model. Specifically, we analyzed the dominant environmental factors that affected the predicted distributions of six mangrove species and the ranges of the main environmental factors that affected mangrove growth. In addition, we explored the potential locations for restoring the six selected mangrove species, as well as mangrove growth and protection hotspots.

The most important factor that affected the overall distribution of mangroves in the Beibu Gulf was topography, followed by bioclimatic factors, land use type, sea surface salinity, and substrate type. The SST had relatively weak effects on the overall distribution. Among the mangrove species, *R. stylosa* and *B. gymnorrhiza* were more sensitive to bioclimatic factors than the other four species.

The regions with potential for mangrove growth in the Beibu Gulf are located primarily in the Dandou Sea, Tieshan Harbor, Qinzhou Bay, Dafeng River, and Fangcheng Harbor, offering a combined optimal mangrove habitat of 13,816 $hm^2$. Vacant mangrove protection areas in the Beibu Gulf are primarily located in Lianzhou Bay and along the Dafeng River in Quinzou. Areas with low estuarine salinity in Lianzhou Bay and the Maoweihai Mangrove Autonomous Region Nature Reserve are suitable for the *A. corniculatum* and *A. ilicifolius* habitats. In addition, the Dandou and Yingluo ports in the Shankou Mangrove Reserve offer suitable *R. stylosa* and *B. gymnorrhiza* habitats. The Beilun Estuary National Nature Reserve is suitable for *A. marina*, *K. obovata*, and *B. gymnorrhiza*. In addition, Tieshan

Harbor offers suitable *A. marina*, *R. stylosa*, and *B. gymnorrhiza* habitats. In estuarine areas, *A. corniculatum* and *A. ilicifolius* are suitable species for mangrove restoration and afforestation. The mangrove species distribution map produced in this study can be used as a basis for mangrove afforestation and restoration in the Beibu Gulf. For mangrove restoration, optimal growth areas should be selected, and land and trees should be adapted according to the suitable environmental threshold ranges for the specific mangrove species. Thus, this study provides an important reference for predicting the distributions of six dominant mangrove species, as well as for the selection of appropriate species and their locations for successful mangrove restoration.

**Author Contributions:** All authors contributed to the design of the analyses and the writing of the manuscript. Conceptualization, L.L., S.C. and J.D.; methodology, W.L. and J.A.; software, L.L.; validation, J.A. and S.C.; investigation, L.L., W.L., S.C. and J.D.; data curation, J.A.; writing—original draft preparation, L.L.; supervision, J.D.; funding acquisition, W.L. All authors have read and agreed to the published version of the manuscript.

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

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**Conflicts of Interest:** The authors declare no conflict of interest.

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