# Analysis of mangrove distribution and suitable habitat in Beihai, China, using optimized MaxEnt modeling: improving mangrove restoration efficiency

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**Introduction:** Mangroves are an important component of coastal ecosystems, and determining the spatial dispersion of prevalent mangrove species and the most suitable land-use source for mangrove growth is of great importance for judicious restoration and effective conservation approaches. Maximum entropy (MaxEnt) models are well suited for this task; however, the default parameterization such models for distribution prediction has limitations and may produce results with low accuracy, requiring elucidation of useful parameter settings. Further, a focus on predicting only the mangrove distribution is insufficient for mangrove restoration, and clarification of suitable habitats is required. Here, we examined the geographical distribution of six mangrove species in Beihai, China (*Aricennia marina*, *Aegiceras corniculatum*, *Kandelia obovata*, *Rhizophora stylosa*, *Bruguiera gymnorrhiza*, and *Acanthus ilicifolius*).

**Methods:** We used the ENMTools tool to select 16 variables from environmental factors, including bioclimate, terrain, sediment type, land-use classification, and sea-surface salinity and temperature. Using the selected variables and mangrove distribution data, a MaxEnt model optimized using the "kuenm" package in R was used to establish a mangrove prediction distribution model for Beihai City. Transition analyses of land-use types within suitable zones further clarified their current and potential functional roles.

**Results and discussion:** The spatial occurrences of *A. marina*, *A. corniculatum*, and *K. obovata* were strongly driven by topographical features, those of *R. stylosa* and *B. gymnorrhiza* mostly depended on bioclimatic variables, and that of *A. ilicifolius* was driven mostly by edaphic conditions, notably the substrate type. The predicted optimal suitable area for mangrove growth in Beihai City was 50.76km[2], of which 55.04% are currently officially protected. Unprotected areas suitable for mangrove growth were mainly located in Lianzhou Bay, Tieshangang Bay, Dafengjiang, and Xicun Port. The majority of these regions were derived from land-use transitions from wetlands and aquaculture ponds to forested ecosystems. We suggest that careful development of selected wetland ecosystems and transmutation of aquaculture ponds into forested landscapes are crucial for effective mangrove

restoration. Our results will assist in selecting suitable species for mangrove restoration sites and improving mangrove restoration efficiency.

# 1 Introduction

Mangroves are woody plant communities composed of evergreen trees and shrubs (Li and Dai, 2015). As an important marine wetland type (Jia et al., 2023), mangroves are mainly distributed in tropical and subtropical coastal intertidal zones (Valiela et al., 2001). Natural and human factors, such as coastal development (He et al., 2007) and climate change (Bertness et al., 2002), have resulted in mangrove wetland losses (Renzi et al., 2019). The global mangrove wetland area has declined by 35% since approximately 1980 and continues to decrease at a rate of 1–2% per year (Polidoro et al., 2010; Curnick et al., 2019). Global temperature increases affect mangrove growth, such as in areas where sea levels are rising rapidly, and mangroves have become extinct in some regions (Alongi, 2015). In China, the total mangrove forest area decreased by nearly 50% from 1950 to 2001 (Wang W. et al., 2020).

Therefore, mangrove restoration has become an important topic in ecological protection worldwide (Thomas et al., 2017; Hai et al., 2020); however, some reforestation actions lack scientific guidance in selecting locations and tree species, which is an important reason for the low survival rate of restored mangroves (Hu et al., 2020a). Mangrove growth is influenced by factors such as elevation, salinity, substrate, and temperature (Hu W. J. et al., 2020); however, the dominant factors influencing the growth of different mangrove types vary. In addition to considering local species, the main environmental factors driving mangrove growth need to be considered. An efficient approach to select suitable mangrove species and determine suitable land sources for mangrove restoration remains an unsolved issue (Balke and Friess, 2016; Fan and Mo, 2018). The majority of studies examining habitat suitability for mangrove restoration have not specified species using geographic information system methods (Jumawan and Macandog, 2021); direct planting remains the most commonly used mangrove restoration method (Gerona-Daga and Salmo, 2022). Therefore, the mangrove survival rate is often uncertain. Furthermore, restoration work cannot be effectively carried out if the land-use type of a potential mangrove area is not specified.

Employing a maximum entropy (MaxEnt) model and accounting for land-use transfer can solve these problems. At present, classic ecological niche models include MaxEnt, Rule Set Genetic Algorithm (GARP), support vector machine (SVM), and decision tree (DT) models, among other approaches (Peterson et al., 2007). Among these approaches, the MaxEnt model is more suitable for predicting the potential habitats of species in complex forests, featuring higher accuracy than SVM and DT models (Tu et al., 2012). The MaxEnt model outperformed the GARP model in predicting the potential mangrove distribution (Hu et al., 2020b). The MaxEnt model employs maximum entropy principles to simulate and predict suitable habitats for species based on species distribution records and environmental variables using machine-learning methods (Liu et al., 2017; Mukul et al., 2019; Wan et al., 2019; Bao et al., 2022). As the MaxEnt model is easy to implement (Wang et al., 2007), it
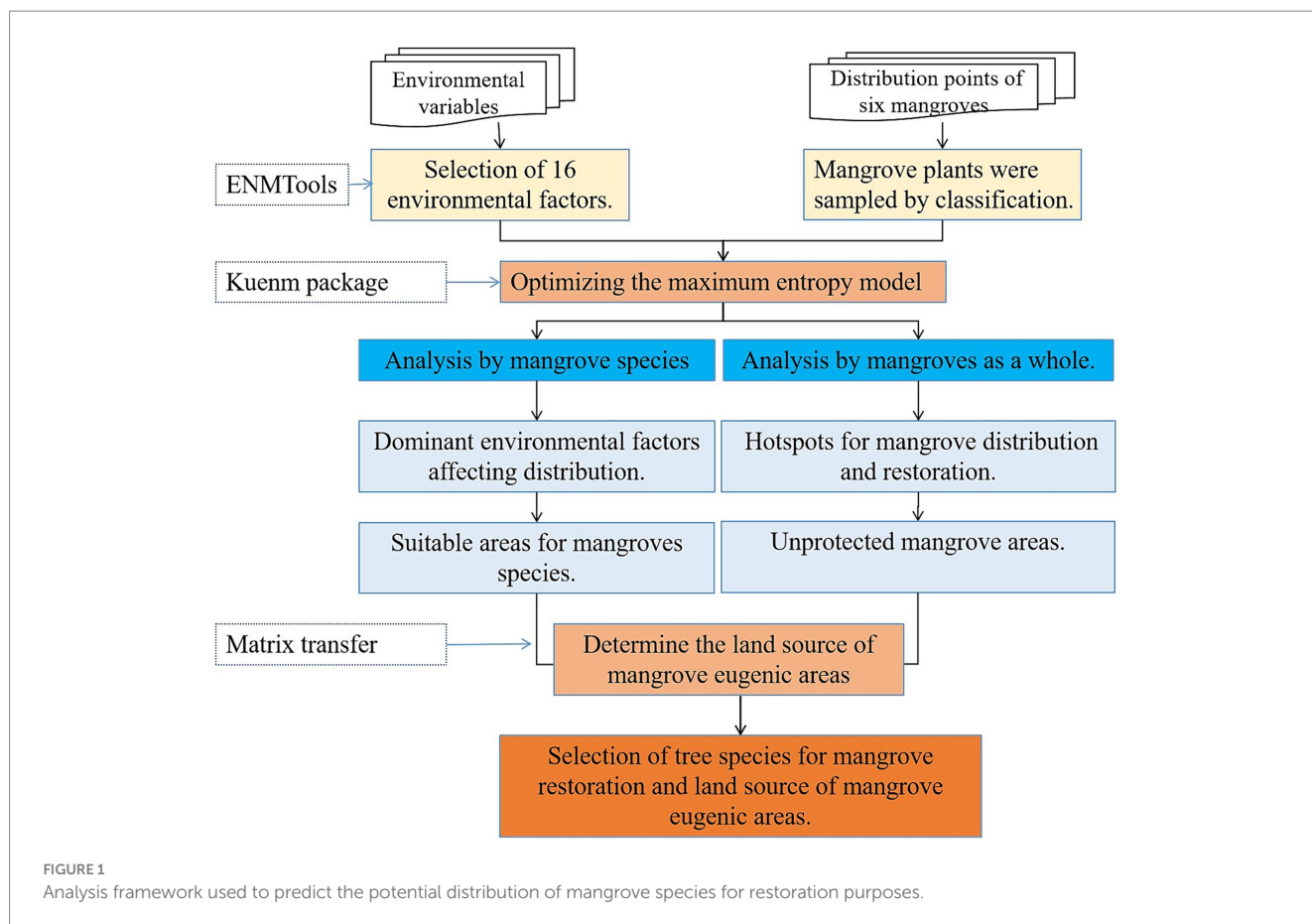
has been widely used in species distribution modeling (Cobben et al., 2015; West et al., 2016; Liu et al., 2019).

Global-scale studies have used species distribution models to predict the response of 30 mangrove species to future climate conditions (Record et al., 2013); however, analysis on the impact of factors such as land use and sea-surface salinity is lacking. At the regional scale, Charrua et al. (2020) used the MaxEnt model to predict the distribution of *Aricennia marina* and *Rhizophora mucronate*. The capacity of species distribution modeling to predict the geographic distribution of the mangrove community in Mexico was also evaluated (Rodríguez-Medina et al., 2020). Banerjee et al. (2022) analyzed the predicted distribution of 10 mangrove species in the Indian Western Pacific region at temporal and spatial scales. Research on predicting the mangrove distribution in China has been conducted at the national scale (Hu et al., 2020a) and for specific locations such as Guangdong (Chao et al., 2021), Fujian (Hu W. J. et al., 2020), and the Beibu Gulf (Li L. F. et al., 2023). All of these studies adopted default system parameters for modeling and did not perform any optimization (Wang W. et al., 2020). Furthermore, overfitting may occur under default settings (Radosavljevic and Anderson, 2014), which negatively affects the prediction accuracy. Therefore, this study differed from previous research that predicted the distribution of mangroves in the following two aspects. First, we used the "kuenm" package (Cobos et al., 2019) in R to balance the fitting and complexity of the MaxEnt model by optimizing the regularization multiplier (RM) and feature class (FC) parameters. We used the optimized MaxEnt model, which served as the computational framework for elucidating the spatial configuration, potential distribution, and critical environmental requirements for an ensemble of six important mangrove species: *A. marina, Aegiceras corniculatum, Kandelia obovata, Rhodophora stylosa, Bruguiera gymnorrhiza,* and *Acanthus ilicifolius* (Figure 1). Second, existing research has only determined suitable locations for mangroves; however, an in-depth analysis on the specific sources of areas suitable for the growth of mangroves has not been conducted. In this study, we used a land-use transfer model to identify the land types most suitable for the distribution of mangroves, providing a basis for the selection of mangrove restoration areas. The purpose of this study was to determine suitable species and planting sites for the restoration of different mangrove species, aiming to improve the efficiency of mangrove restoration.

# 2 Materials and methods

## 2.1 Study area

Beihai City is located in the southern Guangxi Zhuang Autonomous Region in south China (108°50′–109°47′E, 20°26′–21°55′N, Figure 2). It is characterized by a marine monsoon climate, with an annual average temperature of 22.9°C and an annual precipitation of 1,670 mm. The total length of the continental coastline is 553.08 km, accounting for approximately one third of the length of the coastline in Guangxi. The study

**FIGURE 1**
Analysis framework used to predict the potential distribution of mangrove species for restoration purposes.

area contains many natural bays, including Tieshangang Bay, Lianzhou Bay, and Yingluo Port, and features a mangrove nature reserve and a national wetland park. We mainly focused on the predicted mangrove distribution along the continental coastline. The dominant mangrove species were *A. marina*, *A. corniculatum*, *K. obovata*, *B. gymnorrhiza*, *R. stylosa*, and *A. ilicifolius*, and the top six mangrove communities in terms of area were *A. marina*, *A. corniculatum*, *K. obovata*, *A. marina* + *A. corniculatum*, *B. gymnorrhiza* + *A. marina*, and *R. stylosa* + *A. corniculatum*. The *A. marina*, *K. obovata*, and *A. corniculatum* communities accounted for 47.16, 28.18, and 11.65%, respectively, of the total area (Tao et al., 2017).

We selected Beihai City as the model area, mainly because the Beihai mangrove area accounts for 48.73% of the total mangrove area in the Beibu Gulf in Guangxi, China. Mangroves in the Beihai Sea play an important role in balancing the coastal environment, significantly affecting the local ecosystem. Urban development continues to impinge on the mangrove forests on the east coast of Beihai City. The cumulative survival rate of mangrove artificial afforestation in Guangxi from 2002 to 2015 was only 33.6% (Fan and Mo, 2018). This suggests that modeling and predicting the mangrove tree species distribution in Beihai City and determining suitable areas for different mangrove types is of great significance for improving the success rate of local mangrove restoration.
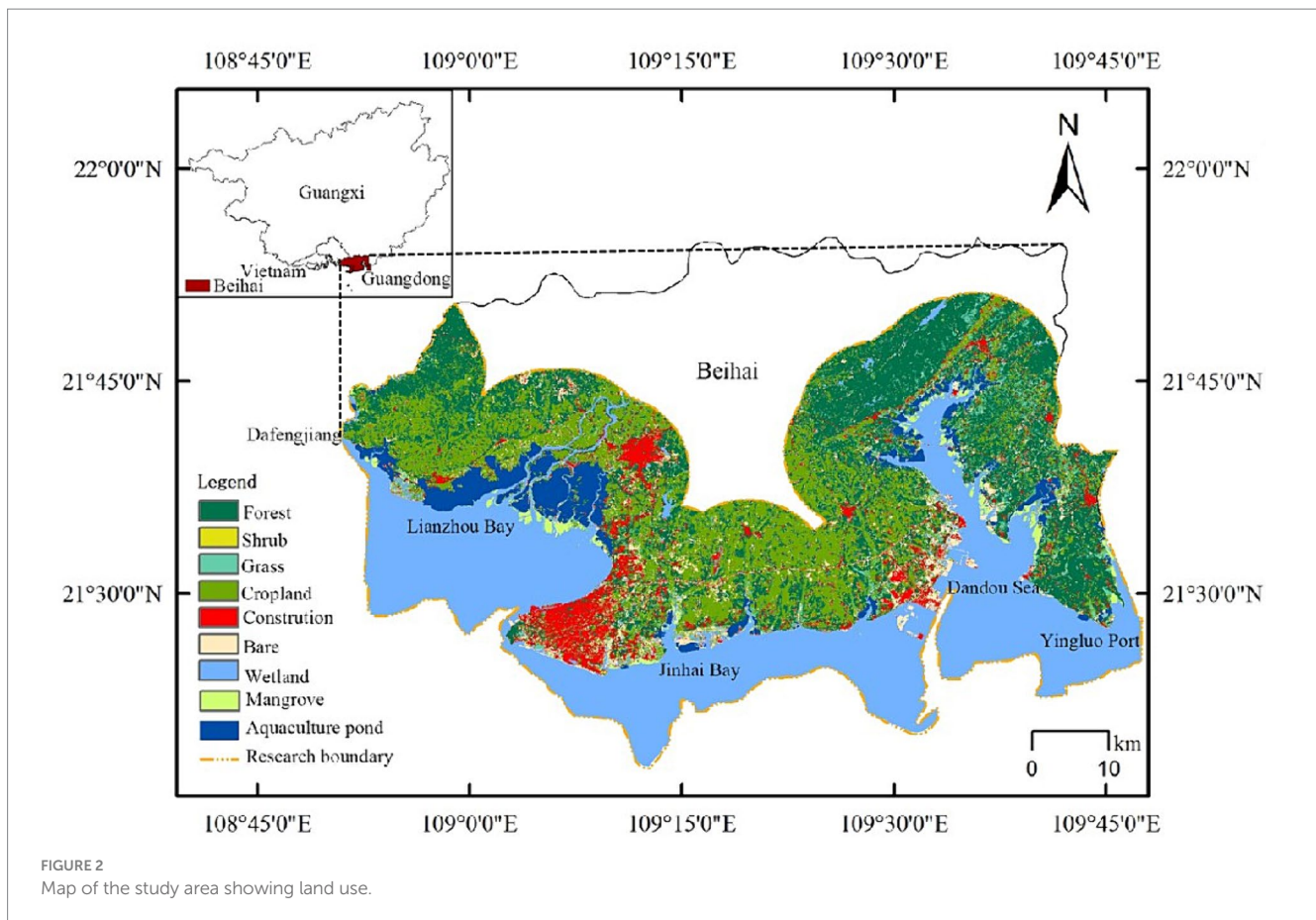
## 2.2 Mangrove distribution

We have been conducting research on mangroves for several years and are familiar with the distribution of mangroves in Beihai City. Photos were taken of each patch using drones, which allows confirmation of various mangrove species. Mangrove distribution data for Beihai were visually interpreted based on 2020 Google Earth images (0.61–2.4-m resolution). To avoid misclassification, we extracted various mangrove sample points using the following steps: (1) we visually interpreted and extracted 438 small mangrove patches in Beihai City; (2) the mangrove species were differentiated based on the appearance of patches and image color (Table 1; Liu et al., 2021; Li L. F. et al., 2023); the mangrove species were registered in the aforementioned mangrove patches. In doubtful instances, photos and targeted field surveys were used for confirmation; (3) the Fishnet tool in the ArcGIS 10.4 software package (Environmental Systems Research Institute, Redlands, CA, USA) was used to resample the interpreted mangroves (sampling accuracy of 300 m). The plant names and coordinates of mangrove sampling points were recorded, forming a distribution dataset of six mangrove plants. In total, 1,030 sampling and coordinate data points were obtained from the study area, consisting of 362, 537, 43, 36, 28, and 24 sampling points for *A. corniculatum*, *A. marina*, *K. obovata*, *B. gymnorrhiza*, *R. stylosa,* and *A. ilicifolius*, respectively.

## 2.3 Environmental data

Environmental data can be used to determine differences in growth factors among mangrove species. Environmental factors

FIGURE 2
Map of the study area showing land use.

such as sea-surface temperature (SST), sea-surface salinity temperature, salinity, and distance from the coastline are important indicators of potential mangrove growth and distribution (Peng et al., 2016). As mangroves grow in sea–land ecotones, their fitness is affected by both continental and marine environmental factors; thus, we combined terrestrial and marine environmental data. To estimate the mangrove distribution in Beibu Gulf, the study area boundary was fixed using the coastline as a reference. The study area was determined based on the distribution pattern of mangroves and referring to existing research on mangrove distribution prediction (Hu et al., 2020a; Hu W. J. et al., 2020). The estimated study area enclosed a 10-km inland buffer zone (Hu et al., 2020a) and a 5-m isobath in the sea. Resampling was carried out in ArcGIS v.10.4 to extract environmental data, and Kriging interpolation was conducted to expand the data to sea or land and to integrate marine and terrestrial data. The sources of environmental data are shown in Table 2. The data accuracy was normalized to 30″ using ArcGIS, and the dataset was saved in ASCII format.

We sourced 29 descriptive variables of environmental data (19 parameters), terrain (2 parameters), SST data (3 parameters), sea-surface salinity (3 parameters), substrate type (1 parameter), and land use (1 parameter). Pearson correlation analysis (Li L. F. et al., 2023) was used to screen environmental variables to detect collinearity. We conducted this analysis using ENMTools (Li D. X. et al., 2023; https://github.com/danlwarren/ENMTools) as this approach does not

rely on species distribution data and provides stable analysis results (Figure 3).

The final dataset included 16 bioclimatic variables: mean diurnal range (mean monthly [max. Temp–min. temp]; bio2), isothermality ([bio2/bio7]×100; bio3), temperature seasonality (standard deviation×100; bio4), temperature of the warmest month (bio5), mean temperature of the warmest quarter (bio10), precipitation seasonality (coefficient of variation; bio15), precipitation in the warmest quarter (bio18), precipitation in the coldest quarter (bio19), topographic elevation (alt18), wetland index (WTI), mean sea-surface salinity in the coldest season (c_sss), mean sea-surface salinity in the warmest season (w_sss), mean SST in the coldest season (c_sst), mean SST in the warmest season (w_sst), substrate type (substrate), and land-use type (land-use).

## 2.4 Model parameter settings

The "kuenm" package[1] was used to optimize the RM and FC parameters in R (version 3.6.3; https://www.rproject.org/; Warren and Seifert, 2011). These two parameters were essential for building a species distribution model using MaxEnt version 3.4.4.[2]

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1 https://github.com/marlonecobs/kuenm

2 http://biodiversityinformatics.amnh.org/open_source/maxent/

TABLE 1 Feature descriptions of mangrove plants in Google Earth images.

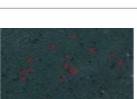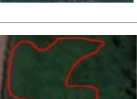| Mangrove species | Image diagram | RGB | Characteristic description |
|---|---|---|---|
| A. marina | | R: 43 G: 67 B: 68 | Distributed in sheets with a blue-green crown |
| A. corniculatum | | R: 60 G: 68 B: 60 | Distributed in sheets with a yellow-green crown |
| K. obovata | | R: 24 G: 47 B: 34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

TABLE 2 Sources of environmental data.

| Data | Year | Data source | Data download website or reference |
|---|---|---|---|
| Bioclimatic factors | 1970–2000 | World Climate Database | www.worldclim.org |
| Terrain data | 2022 | ETOP01 terrain elevation and ocean seabed terrain data released by the United States Geophysical Center | https://www.ngdc.noaa.gov/mgg/global/global.html |
| SST data | 2020 | National Environmental Information Center of the Oceanic and Atmospheric Administration of the United States (1981–2020 SST data) | https://ftp.emc.ncep.noaa.gov/cmb/sst/oisst_v2/ |
| Salinity data | 2020 | Marine salinity products of the Institute of Atmospheric Physics, Chinese Academy of Sciences. | http://159.226.119.60/cheng/ Auxiliary data including seawater salinity information (Wei et al., 2006; Lan et al., 2014) for study area references |
| Land-use data | 2020 | ESRI 10-m cover data (2020) in the Google Earth Engine | https://livingatlas.arcgis.com/landcover/ |

During modeling, 75% of the data were used as the training set. In total, 1,160 candidate models were evaluated with parameters reflecting 40 RM setting combinations (from 0.1 to 4, with an interval of 0.1) and 29 FC combinations. Model selection was based on statistical significance (partial receiver operating characteristic), predictive ability (low omission rates), and complexity (we used Akaike's information criterion with small sample size correction [AICc] to evaluate the model fit). First, the set of models was reduced using the omission rate criterion (<5% when possible). Second, the models with a delta AICc value <2 were selected from the resulting candidate set (Cobos et al., 2019; Figure 4). Model parameters for MaxEnt analysis were configured in alignment with FC and RM specifications (Table 3). Among the six mangrove plant species, *A. marina* and *R. stylosa* had a feature class of quadratic (Q), and the determined feature class settings for the other four mangrove plants differed. *Bruguiera gymnorrhiza* and *R. stylosa* had regulation multipliers of 0.5, and the other four species had different values.

## 2.5 Land-use transfer

The land source for the optimal mangrove growth area was obtained using the land-use transfer method. We used a transfer matrix of land types to analyze the structural characteristics of the change direction of different land-use types (Shi et al., 2000) and ArcGIS 10.4 to obtain the land-use type transfer matrix.

## 2.6 Division of suitable areas for mangrove growth

Stratification of habitat fitness was conducted utilizing the natural breakpoint algorithm, with 0–0.2 denoting unfit conditions, 0.2–0.5 denoting low fitness, 0.5–0.7 denoting medium fitness, and values >0.7 denoting optimal fitness as mangrove habitat (Chao et al., 2020). Based on these results, potential mangrove distribution hotspots were calculated using kernel density estimation (Cai et al., 2012).

## 3 Results

### 3.1 Suitable areas for mangroves in Beihai, Guangxi

Optimal fitness areas were located in the Guangxi Shankou Mangrove Reserve, Tieshangang Bay, Lianzhou Bay, and Beihai National Wetland Park. The optimal area for *A. marina* was 33.51 km² in size (Table 4), with the highest fitness areas mainly distributed in Jinhai Bay and Tieshangang Bay (Figure 5A); that for *A. corniculatum* was 22.07 km² and was mainly distributed in Lianzhou Bay and Dafengjiang (Figure 5B); that for *K. obovate* was 40.87 km² and was along Dafeng River and in Guangxi Shankou Mangrove Reserve (Figure 5C); that for

FIGURE 3
Heat map for the correlation analysis of environmental factors based on ENMTools.
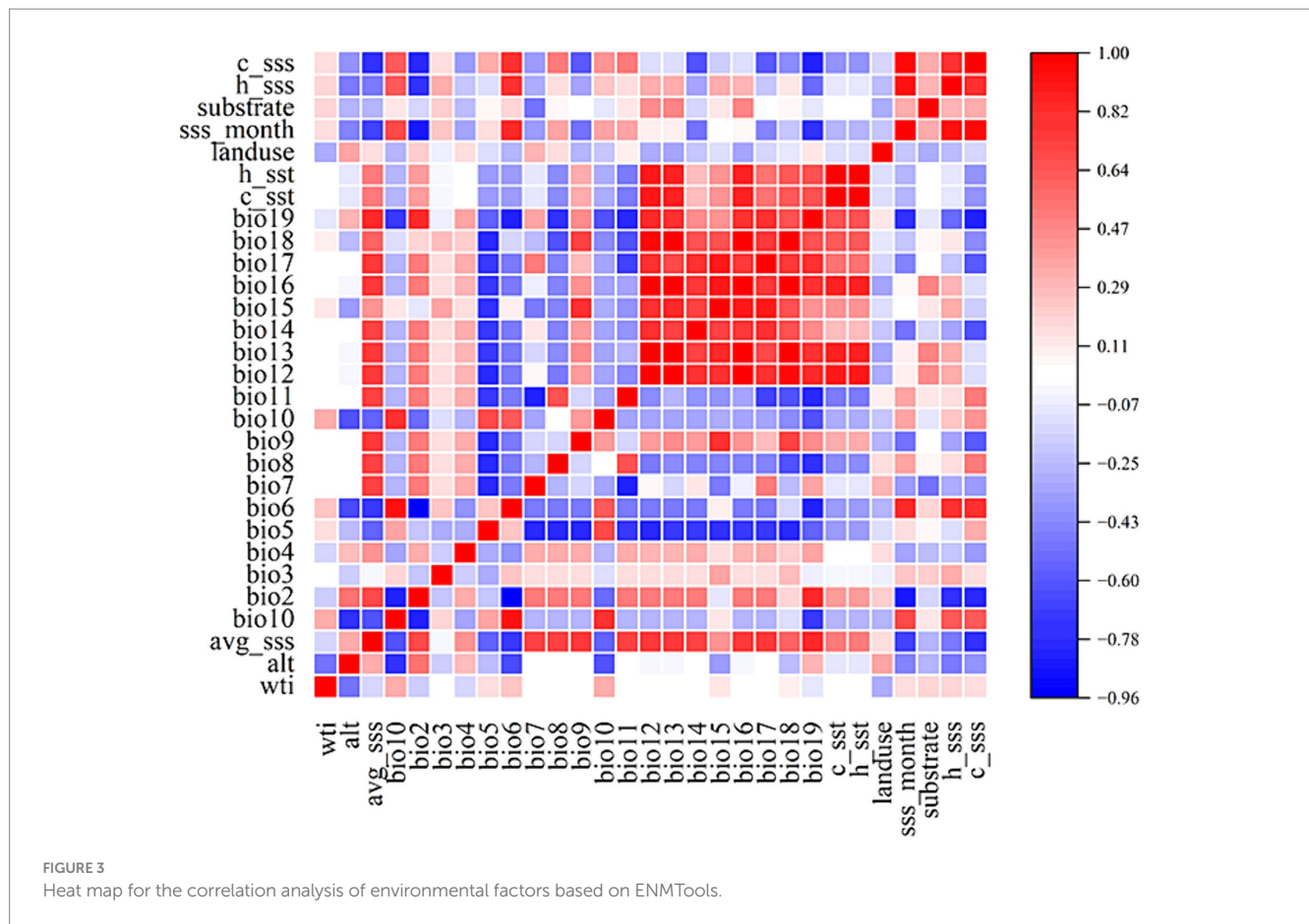
*B. gymnorrhiza* was 9.81 km² and was located in the Dandou Sea area (Figure 5D); that for *R. stylosa* was 21.25 km² and mainly distributed in the Dandou Sea area and Yingluo Port (Figure 5E); and that for *A. ilicifolius* was 6.54 km² and primarily located in regions with low estuarine salinity in Lianzhou Bay (Figure 5F).

## 3.2 Contribution of environmental factors affecting the mangrove distribution

Contributions of variables are based on interactions between different environmental variables (Liu et al., 2019; Hu et al., 2020a). The contributions of the six topographical factors were greater than those of the other factors (Figure 6). The influence of these factors on individual species decreased in the order *A. marina* > *K. obovate* > *A. corniculatum* > *A. ilicifolius* > *R. stylosa* > *B. gymnorrhiza*. Topographic factors contributed significantly to predicting the *A. marina* distribution, with a contribution value >50%.

The contribution of bioclimatic factors to the *R. stylosa* and *B. gymnorrhiza* distribution was 53.5 and 49.9%, respectively. Sea-surface salinity was among the top-three influencing factors for *A. ilicifolius*, *A. corniculatum,* and *A. marina*, with a relative contribution of 37.4 and 30.7%, respectively, for *A. ilicifolius* and *A. corniculatum*, indicating that these species are sensitive to salinity.

## 3.3 Land-use analysis of suitable areas for mangroves based on land-use transfer

The land-use map for 2020 and the potential distribution grade map of the six mangrove species were used as the area transfer matrix to analyze the land source of potentially suitable mangrove areas that could provide the basis for mangrove restoration sites. Only a very small proportion of the coastal land area in Beihai City was transformed into the optimal habitat for the six mangrove species (Figure 7). The optimal mangrove habitat in Beihai mainly originated from wetlands and aquaculture ponds (Figure 8). The area transferred from wetlands to the optimal habitat for *K. obovata* was the largest (15.71 km²), and that for *A. marina* was 11.78 km². The area transferred from aquaculture ponds to eugenic areas for mangroves was the largest for *A. corniculatum* (13.63 km²) and mainly distributed in Lianzhou Bay (Figure 9); this area was 11.33 km² for *K. obovata*. This indicated that suitable wetlands can be developed in the region for mangrove restoration, particularly for *K. obovata* and *A. marina*. Furthermore, restoring aquaculture ponds to forest could constitute the main measure for mangrove restoration, with *A. corniculatum* and *K. obovate* as well-suited restoration species.

## 3.4 Protection status and priorities

Based on the superposition of the distribution of protected and potentially suitable mangrove areas, 55.04% of the most

**FIGURE 4**
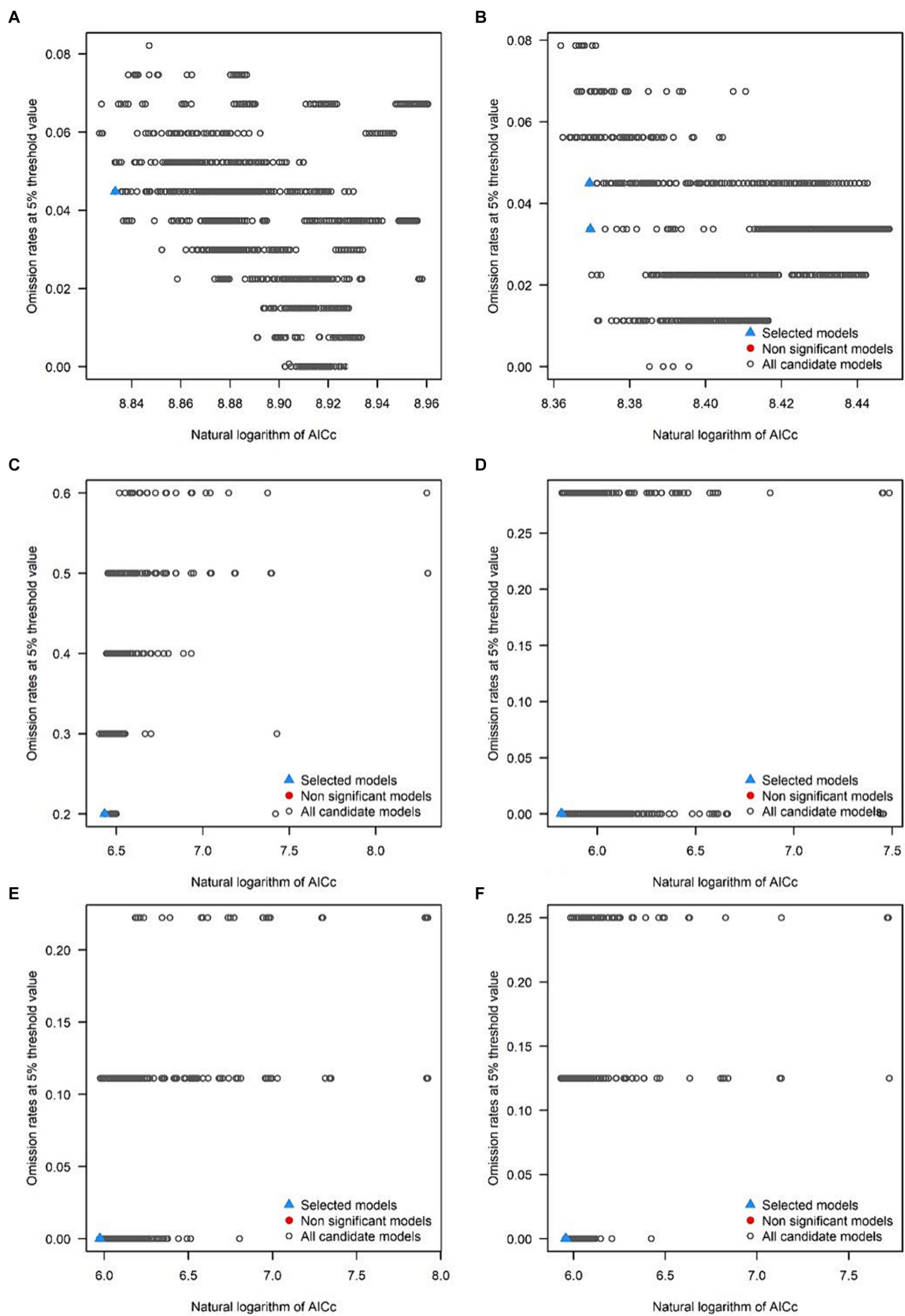Omission rates and AICc values for all, non-significant, and selected "best" candidate models for: **(A)** *A. marina*, **(B)** *A. corniculatum*, **(C)** *K. obovate*, **(D)** *R. stylosa*, **(E)** *B. gymnorrhiza*, and **(F)** *A. ilicifolius*.

TABLE 3  MaxEnt parameter settings for mangroves based on optimization using the "kuenm" package in R for each species.

| Mangrove species | Feature class (FC) | Regularization multiplier (RM) |
|---|---|---|
| *Aricennia marina* | Quadratic features (Q) | 0.1 |
| *Aegiceras corniculatum* | Threshold hinge features (TH) | 0.4 |
| *Kandelia obovata* | Linear quadratic features (LQ) | 0.3 |
| *Bruguiera gymnorrhiza* | Linear features (L) | 0.5 |
| *Rhizophora stylosa* | Quadratic features (Q) | 0.5 |
| *Acanthus ilicifolius* | Quadratic product features (QP) | 0.9 |
| Overall mangroves | Hinge features (H) | 0.2 |

TABLE 4  Suitable mangrove areas in the study area as determined by MaxEnt analysis for each species.

| Mangrove species | Optimal suitable area (km$^2$) | Medium suitable area (km$^2$) |
|---|---|---|
| *Aricennia marina* | 33.51 | 197.79 |
| *Aegiceras corniculatum* | 22.07 | 107.07 |
| *Kandelia obovata* | 40.87 | 170.82 |
| *Bruguiera gymnorrhiza* | 9.81 | 35.15 |
| *Rhizophora stylosa* | 21.25 | 39.23 |
| *Acanthus ilicifolius* | 6.54 | 58.85 |

suitable localities were included within protected areas (Figure 10). Six areas were identified as priority areas for mangrove protection and restoration: Dafeng, Lianzhou, Jinhai, Xicun, Tieshangang Bay, and Shankou mangrove reserves. The unprotected mangrove areas in Beihai were primarily distributed in Lianzhou Bay, Dafeng River, Xicun Port, and Tieshangang Bay.

# 4 Discussion

Previous studies have focused on predicting the mangrove distribution and paid minimal attention to the potentially available land sources for mangrove eugenic areas (Wang et al., 2021). On the basis of predicting the mangrove distribution, this study explored suitable land sources for mangrove growth to effectively guide mangrove protection, restoration, and management.

## 4.1 Dominant environmental factors affecting suitability for mangroves

Analysis of the combined mangrove forests distributed along the coast of Beihai City indicated that the influence of bioclimatic factors was likely to be less significant than that of topographic factors. In contrast, a previous study on factors predicting the mangrove distribution in Fujian found that bioclimate and SST were the most relevant (Hu et al., 2020a), which may have been due to differences in geographical latitude between the two regions. The limited regional geographic latitude span of the present study (20°26′–21°55′34″N)

resulted in a small SST range; consequently, its influence on the mangrove distribution was relatively weak.

The distribution of *Rhizophora stylosa* and *B. gymnorrhiza* was more sensitive to bioclimatic factors than that of other mangroves, which constituted 49.9 and 53.3% of the factor influence, respectively. The sensitivity of these two species to bioclimatic factors has previously been empirically demonstrated (Li et al., 2023), which is consistent with our prediction of their distribution in Beibu Gulf.

Elevation greatly affects the mangrove distribution (Leong et al., 2018). The contribution of terrain factors to the predicted habitat suitability for *A. marina* and *K. obovata* was greater than that of other factors, indicating that these species were more sensitive to this type of habitat characteristics. The effect of topographical factors on the mangrove distribution decreased in the order *A. marina* > *K. obovate* > *A. corniculatum* > *A. ilicifolius* > *R. stylosa* > *B. gymnorrhiza*. Related studies have shown that *A. marina* is more tolerant of low intertidal altitude than *K. obovata* (Chen and Ye, 2013), which is consistent with the conclusions of the present study.

Sea-surface salinity is an important factor affecting the mangrove distribution (Barik et al., 2018; Sinsin et al., 2021). In this study, the predicted distribution areas of *A. corniculatum* and *A. ilicifolius* were mainly in Lianzhou Bay, which has low salinity. *Aricennia marina* was distributed in Tieshan gang Bay, Beihai Jinhai Bay Mangrove Reserve, and the southern coast of Beihai National Wetland Park, where salinity is relatively high. Among these three species, *A. marina* was previously found to have the highest salt tolerance, and *A. ilicifolius* was found to have the lowest salt tolerance (Ye et al., 2004), which is consistent with the findings of the present study.
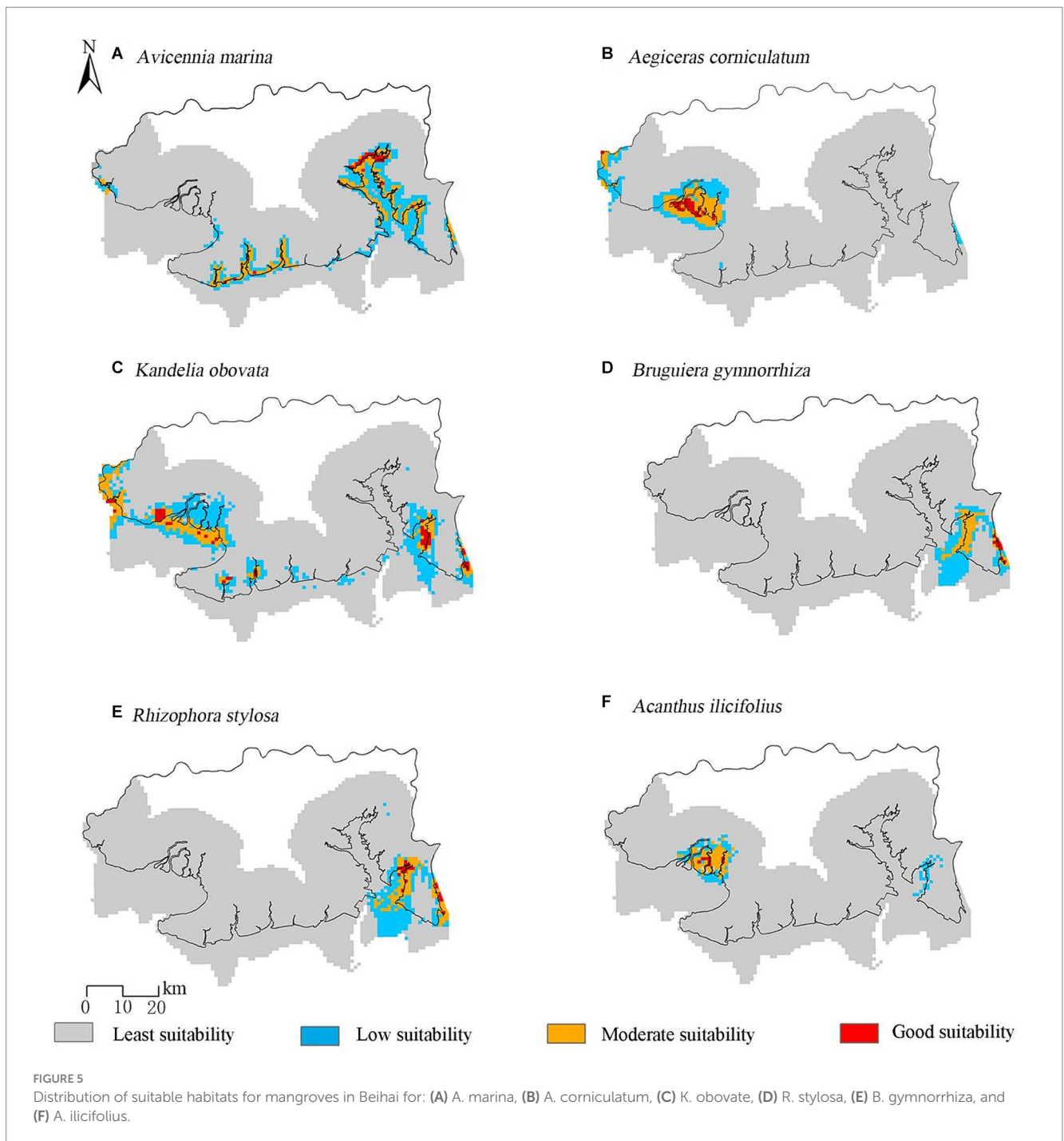
## 4.2 Model applicability

We applied an optimized MaxEnt model in this study to predict the potential spatial distribution pattern of mangroves in Beihai city. The evaluation results can be compared with the current distribution status of mangroves and the area of eugenic zones.

According to the Beihai Mangrove Resource Protection Plan (2020–2030), the suitable area for planting mangroves is 49.52 km$^2$ (Beihai Municipal People's Government, 2021). These data were sourced from the third land survey of China, which mainly employed remote-sensing image interpretation, on-site investigation, and digital image processing techniques. The model results in the present study predicted a similar optimal area for mangrove growth (50.76 km$^2$); thus, the modeled mangrove distribution was consistent with the current situation, which confirmed the accuracy of the optimized MaxEnt model for predicting suitable areas for mangrove growth.

## 4.3 Main land sources for mangrove restoration

Aquaculture ponds have been a focus of attention as potential mangrove restoration sites worldwide (Winterwerp et al., 2005; Matsui et al., 2012). Related research suggests that at a regional-scale in China, approximately 6,400 ha of ponds are used for aquaculture, accounting for 38% of the theoretically recoverable area (Hu et al., 2020b). Loss of mangroves can be attributed to conversion of

FIGURE 5
Distribution of suitable habitats for mangroves in Beihai for: **(A)** A. marina, **(B)** A. corniculatum, **(C)** K. obovate, **(D)** R. stylosa, **(E)** B. gymnorrhiza, and **(F)** A. ilicifolius.

agriculture/aquaculture and dock and road construction, with pond aquaculture being the main cause of global mangrove destruction (Thomas et al., 2017; Elwin et al., 2019), as shrimp pond pollution affects mangrove growth (Zhang and Liao, 2022).

We focused on the overall mangrove forest in our land-use transfer analysis and found that transfer of aquaculture ponds could provide the largest optimal habitat area. The area of aquaculture ponds suited for mangrove growth was $23.71 \, km^2$, while that of wetlands suitable for mangrove growth was $12.25 \, km^2$ (Figure 9), indicating that aquaculture ponds constitute primary and promising candidate areas for mangrove restoration, which is consistent with the findings of a previous study (Su et al., 2022). We analyzed six

mangrove species separately (Figure 8) and found that the transfer of aquaculture ponds was the most suitable for the growth of *A. corniculatum* (with $13.63 \, km^2$). Therefore, *A. corniculatum* can be selected as the primary plant when ecologically restoring aquaculture ponds.

The factors that affected mangrove growth included bioclimate, terrain, substrate type, sea-surface salinity, land-use classification, and SST. However, our assessment was limited in that chemical properties of the soil at the site (e.g., potassium, phosphorus, and lead contents) and hydrodynamic force were not considered. Significant differences may exist between soil samples from natural mangroves and traditional or non-traditional shrimp ponds in terms of pH,
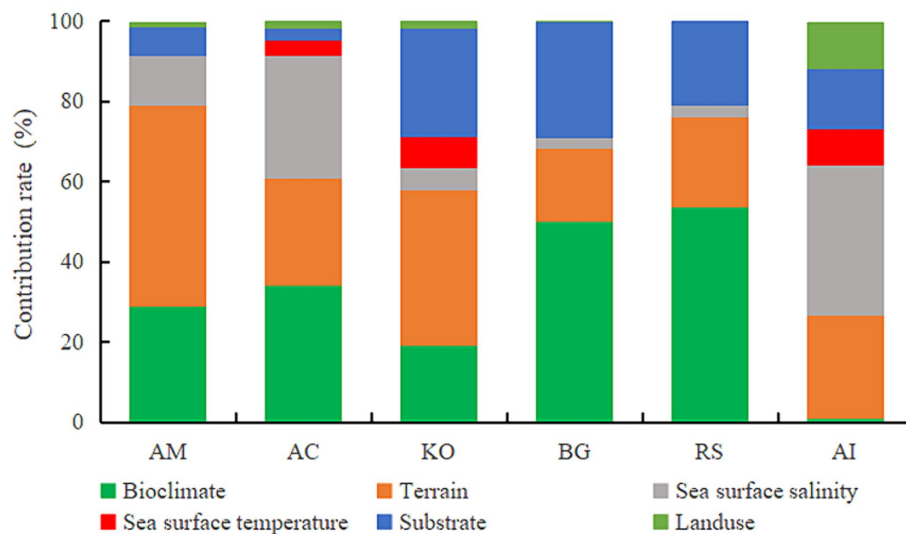
**FIGURE 6**
Contribution of the six investigated environmental variables in predicting the distribution of mangrove species (*A. marina*: AM, *A. corniculatum*: AC, *K. obovata*: KO, *B. gymnorrhiza*: BG, *R. stylosa*: RS, and *A. ilicifolius*: AI).

conductivity, and phosphorus, lead, and chromium contents (Krishnapriya et al., 2023). In the long term, changes in these soil chemical parameters will affect organisms and limit further mangrove restoration. Related studies have shown that ponds located on peat soil are unsustainable and require complete restoration if they are to be converted to mangrove forests, and that ponds on other soil types can be restored into a mixed system of mangrove ponds (Bosma et al., 2012). Owing to differences in soil chemical properties, abandoned ponds may be restored for shrimp and fish production or become targets for mangrove restoration (Aslan et al., 2021). It is difficult to accurately obtain hydrological measurements in mangrove coastal areas, and certain key physical quantities are difficult to parameterize and especially difficult to generalize in hydrodynamic calculations. Thus, in future research, the impact of hydrodynamic force factors on mangroves should be investigated.

## 4.4 Mangrove protection and restoration strategies

(1) In 2013 and 2021, the mangrove forest area in Beihai City was 32.64 km² (Tao et al., 2017) and 41.93 km², respectively. Overall, a growing trend in the area of mangrove forests was observed in Beihai, and local mangroves have been well protected. The model results of this study predict that the suitable forest area for mangrove growth is 50.76 km². Notably, although a large area of suitable forest land remains, the development of shrimp pond aquaculture in the area is taking up the space suitable for the growth of mangrove forests. The proportion of the mangrove breeding shoreline adjacent to Guangxi is far higher than that of natural and reclamation shorelines, and a large area of coastal mudflats has been reclaimed, resulting in the continuous occupation of suitable mangrove forest area (Peng et al., 2016). However, returning ponds to forests is also likely to cause economic losses and livelihood issues for coastal villagers who previously

engaged in aquaculture (Tang et al., 2023). To address these conflicts, relevant departments should prioritize mangrove restoration in shrimp ponds suitable for mangrove cultivation.

(2) Based on the vacancy analysis results, priority should be given to the protection and restoration of mangroves in Lianzhou Bay, Dafeng River, Xichun Port, and Tieshangang Bay. According to literature records, mangroves are present in these areas (Tao et al., 2017). Currently, artificial mangroves, rather than seagrass or salt marshes, are developed. The sedimentary layer of Lianzhou Bay is mainly composed of muddy soil (Wang R. M. et al., 2020). One national level mangrove protection area (Shankou Mangrove Forest Protection Area) is located near Tieshangang Bay. In 2013, the area of mangroves in Tieshangang Bay was 11.12 km² (Tao et al., 2017). The wetlands suitable for transfer into a moderately suitable area for mangrove growth are mainly located in the coastal region of Tieshangang Bay. However, there are only few tree species in Tieshangang Bay, mainly *A. marina*, which is consistent with previous research (Tao et al., 2017). Therefore, we suggest using *A. marina* in Tieshangang Bay for restoration. New wetland parks or protected areas can be constructed in the above-mentioned areas or incorporated into existing protected areas to protect the existing mangroves, and selection of sites within the optimal mangrove habitat should be prioritized to conduct mangrove restoration.

A limitation of this study was that soil chemical properties were not considered among the model's environmental factors. Therefore, in future research, chemical soil parameters in shrimp ponds suitable for mangrove growth should be monitored. Soil properties should be added as influencing factors in model analysis for improving the accuracy of distribution prediction. The present study focused on mangrove species indigenous to Beihai and did not cover the invasive species *Sonneratia apetala*. Future studies should aim to incorporate such invasive taxa, thereby broadening the taxonomic scope and the utility of the predictive model for both conservation and ecological restoration efforts.
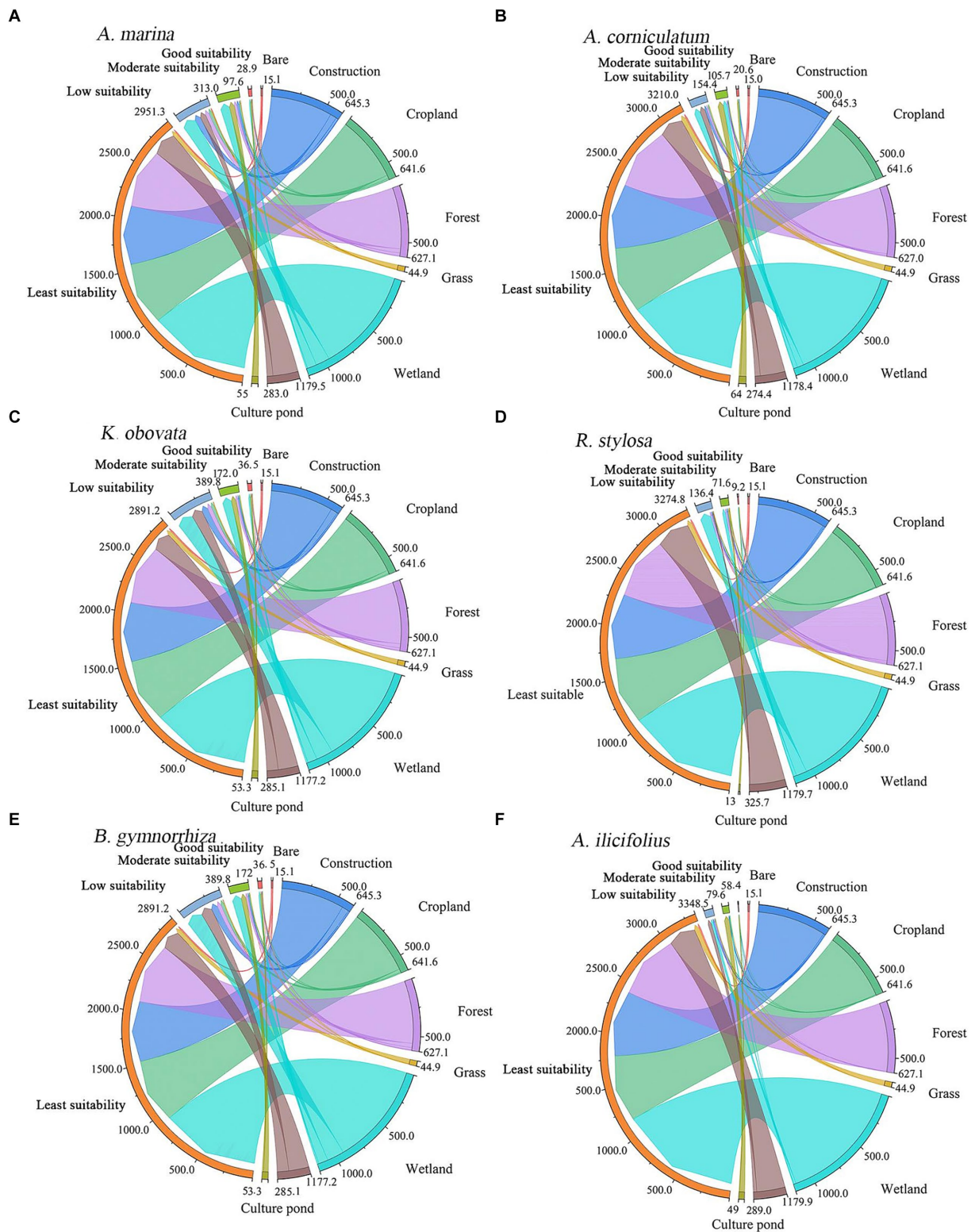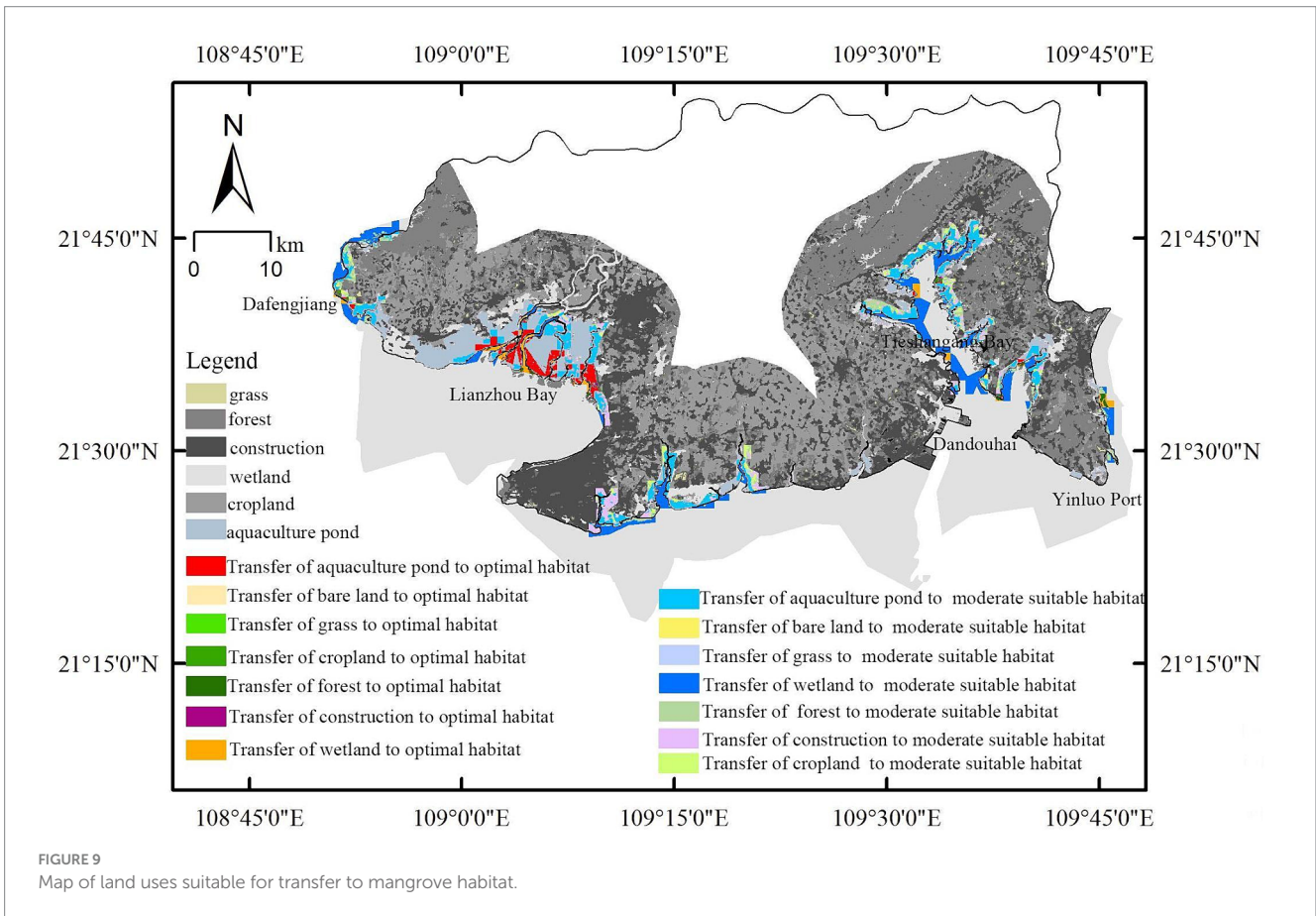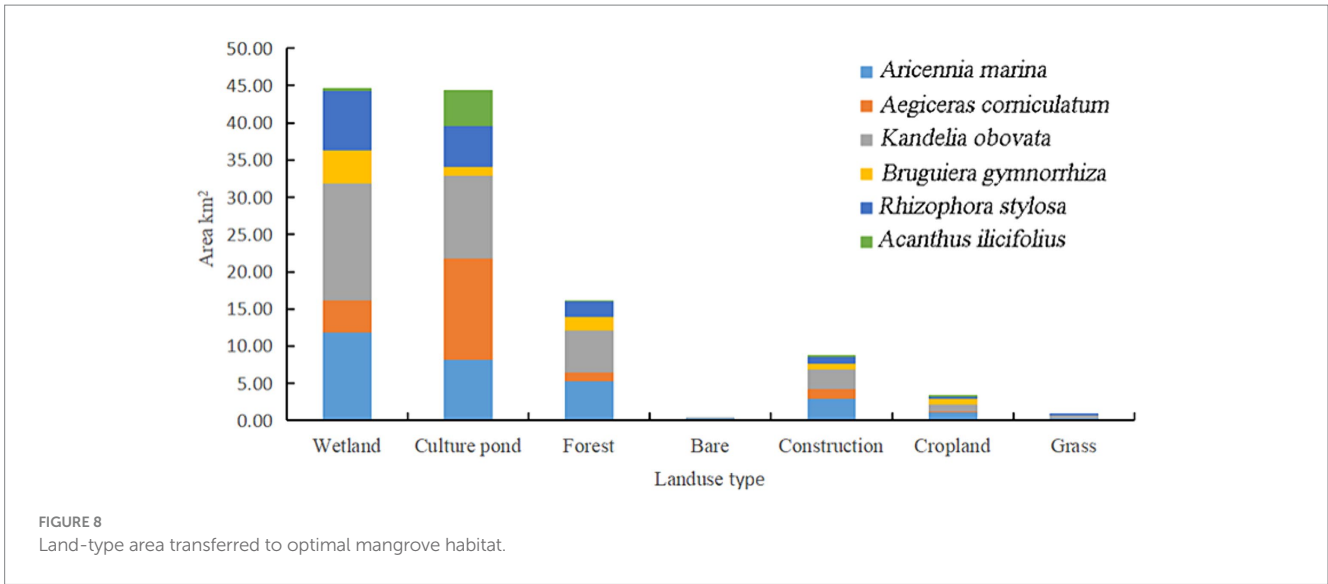
FIGURE 7
Transfer direction between different mangrove habitats and landscape types for: **(A)** A. marina, **(B)** A. corniculatum, **(C)** K. obovate, **(D)** R. st ylosa, **(E)** B. gymnorrhiza, and **(F)** A. ilicifolius.

# 5 Conclusion

Mangrove distribution prediction and identification of suitable land sources are important in mangrove restoration. In this study, we evaluated the suitable environmental conditions for the six main mangrove tree species in Beihai City, Guangxi Province. The results indicated that topographical factors were the strongest drivers of the spatial distribution of *A. marina, A. corniculatum,* and *K. obovata*, and that soil type was more

FIGURE 8
Land-type area transferred to optimal mangrove habitat.



FIGURE 9
Map of land uses suitable for transfer to mangrove habitat.

important for *A. ilicifolius*. We identified the land sources suited as the optimal growth areas for mangroves, and transformation of aquaculture ponds into mangrove habitats appeared to be the most effective ecosystem restoration approach. The aquaculture ponds located in Lianzhou Bay are an important mangrove restoration area, and *A. corniculatum* should be the priority tree species.

The model predictions suggested strategies for targeted mangrove restoration. For example, *A. marina* exhibited a marked preference for littoral zones such as Tieshangang Bay and Jinhai Bay, and *A. ilicifolius* preferred low-salinity environments in Lianzhou Bay. The distribution prediction map of the six main mangrove plants in Beihai City created in this study provides a basis for mangrove restoration and protection. Areas such as Lianzhou Bay, Tieshangang Bay, and Xicun Port were particularly suitable as mangrove habitats. Notably, 55.04% of these areas are already protected.
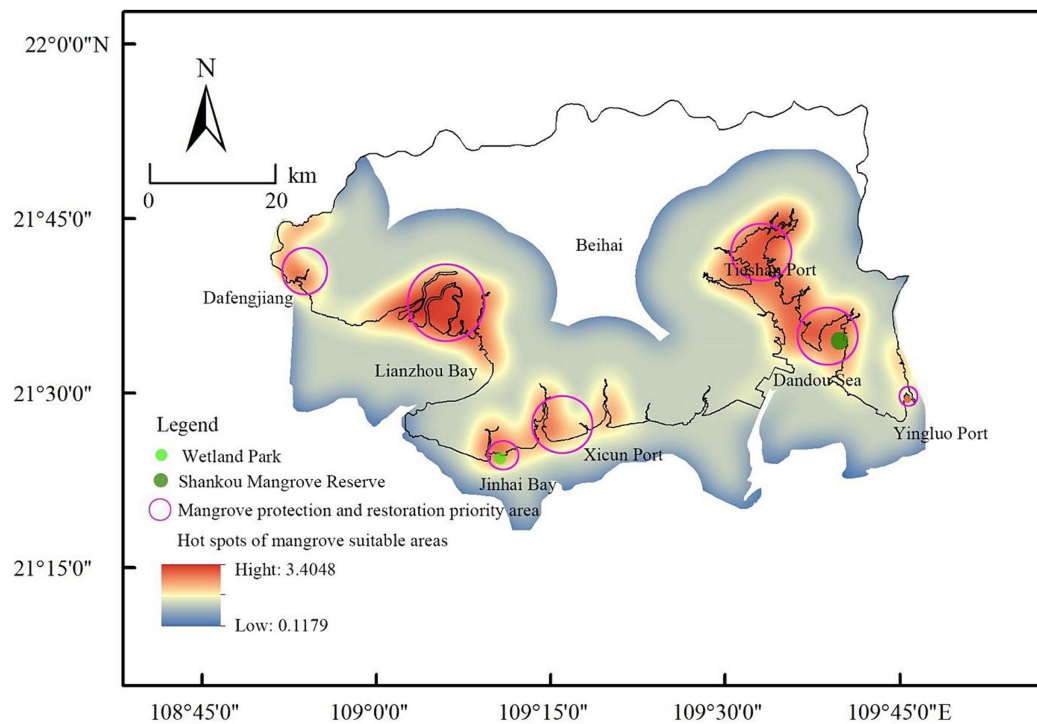
FIGURE 10
Mangrove suitability hotspot map and priority area of mangrove conservation and restoration.

Our findings have potential to provide guidance for the demarcation of future or expanded protection areas, thereby improving effective reforestation management. Our results provide new insights and a theoretical basis for future mangrove protection and restoration.

# Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

# Author contributions

LL: Methodology, Writing – original draft, Writing – review & editing. LW: Funding acquisition, Methodology, Writing – original draft. WM: Methodology, Writing – review & editing, Software. CS: Investigation, Software, Writing – review & editing. LF: Investigation, Software, Writing – review & editing. XX: Investigation, Writing – review & editing. TY: Investigation, Writing – review & editing. XY: Investigation, Writing – review & editing. JW: Investigation, Writing – review & editing.

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# Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. The author(s) declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

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