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Identification of Ecological Conservation Priority Areas for Key Terrestrial Wildlife in the Guangdong–Hong Kong–Macao Greater Bay Area

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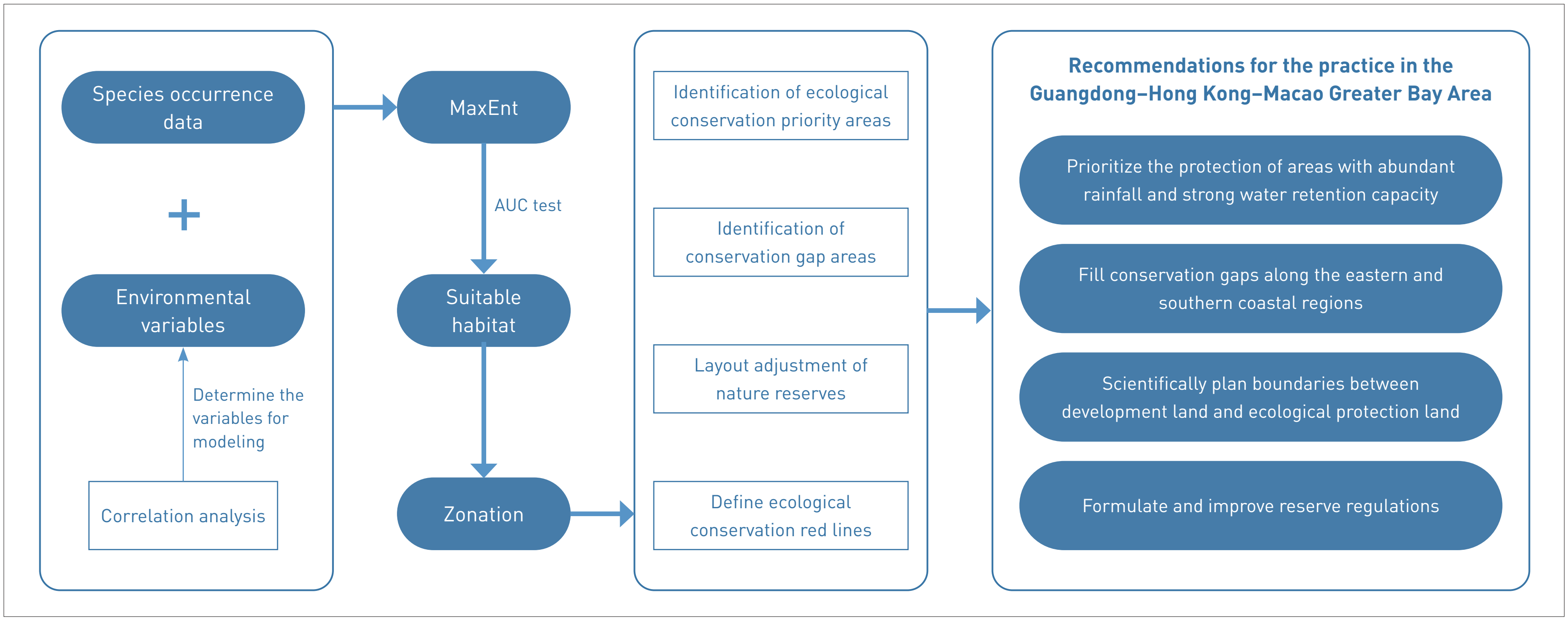
GRAPHICAL ABSTRACT



ABSTRACT

Identifying ecological conservation priority areas (ECPAs) for key terrestrial wildlife species is vital for advancing biodiversity protection. However, existing studies often focus on a single taxon, overlooking the holistic features and interrelationships of biodiversity. This research centers on the Guangdong-Hong Kong-Macao Greater Bay Area (the GBA) and targets 32 primary terrestrial wild species. By integrating the MaxEnt and Zonation models, this research predicts the ECPAs for these species and overlays the results with existing nature reserves to identify the conservation gaps, thereby proposing optimization strategies. The results show that: 1) Precipitation seasonality has a significant impact on the potential distribution of the species, and the suitable areas are mainly concentrated in areas with abundant precipitation and strong water retention capacity. 2) The ECPAs are mainly located in the northern and central mountainous and forested areas of Zhaoqing; the coastal areas of Jiangmen; the central to southern coastal areas of Zhuhai; the central and northeastern parts to coastal areas of Zhongshan; the central to coastal areas of Huizhou; the southeastern Dongguan; the central, western, and coastal areas of Shenzhen; the northern and southern Macao; and the coastal area of Hong Kong. 3) The ECPAs predicted by Zonation overlap with most of the established nature reserves, but there are still gap areas in the eastern and southern coasts of the GBA. These findings offer valuable references for ecological conservation in other regions and underscore the importance of incorporating dynamic variables such as climate change and human activities into future conservation planning. It provides effective approaches to biodiversity protection and scientific support for decision-making in nature conservation management.

KEYWORDS

Nature Reserve; Zonation; MaxEnt; Species Distribution; Biodiversity; Terrestrial Wildlife; Climate Change

HIGHLIGHTS

- Integrates the MaxEnt–Zonation model to predict potential distributions of key species
- Identifies conservation gap areas for four groups of terrestrial wildlife: mammals, birds, reptiles, and amphibians
- Finds that the areas with abundant precipitation and strong water retention capacity are suitable habitats

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1 Introduction

As an important foundation for the survival and development of society, biodiversity has an irreplaceable role in maintaining ecosystem stability[1]. However, the rapid urbanization and high intensity of human activities have resulted in the increasing loss of biodiversity in urban environments, which has become a common problem worldwide[2]. High-quality planning and construction of nature reserves has become an effective way to protect biodiversity[3]. Since 1956, China has established 2,750 nature reserves at various administrative levels, covering a total area of 1.47 million km^2, which accounts for about 15% of the national land cover[4]. However, in the early stage of reserve establishment, the lack of scientific assessment of conservation priorities has resulted in the overprotection of several species and insufficient protection of some key species in part of protected areas[5].

Ecological conservation priority area (ECPA) identification is a quantitative technique that designates a priority network of protected areas based on specific conservation objectives, thus providing data support for regional ecological and environmental planning[6]. In terms of technical operation, foreign scholars began early on to use systematic conservation planning software in biodiversity conservation planning and research. For example, Marco Girardello et al. combined ecological niche modeling and Zonation model to establish important areas for butterfly conservation in Italy and set corresponding conservation priorities[7]. Juliette Delavenne et al. assessed the prioritization of marine biological reserves in the eastern English Channel by comparing the simulation results of Marxan and Zonation models[8]. Currently, most of the domestic studies have applied ECPA identification to delineate biological habitats and proposed corresponding conservation strategies based on the biodiversity impact assessment. Jia Tang et al. analyzed the distribution characteristics of nature reserves in Hubei Province from five perspectives, i.e., dominant ecosystems, special ecosystems, endemic ecosystems, ecosystems with high species richness, and special habitats, and then pointed out the protection vacancies that existed in the current priority forest ecosystems[9]. Fukang Chen et al. took the Guangdong–Hong Kong–Macao Greater Bay Area (the GBA) as the research area and constructed a set of ECPA identification methods applicable to urban agglomerations by integrating ecosystem services and ecological vulnerability indicators[10]. Focusing on the Minshan Region, Jing Xiao et al. identified the ECPAs for rare and endangered species on the basis of MaxEnt and Zonation modeling results, and proposed a spatial optimization solution[11]. Using a species distribution and systematic conservation planning model, Jian Zhou et al. recognized the ECPAs for terrestrial vertebrates in Yunnan Province and evaluated the status quo by dissecting their spatial distribution patterns[12].

In terms of species selection, existing studies tend to consider a single species or taxon as the research object. For instance, Qiqi Luo et al. modeled the spatial distribution pattern and hotspots of waterbird diversity in the GBA using MaxEnt[13]. Utilizing the same model, Trent D. Penman et al. predicted future distributional changes in snake habitat under a climate warming scenario[14]. Further, Jiali Zeng et al. identified the suitability distribution of mangrove forests in coastal wetlands[15]. Nevertheless, this single-taxon perspective often overlooks the holistic features and interrelationships of biodiversity, hindering a comprehensive understanding of the structure, function, and dynamic changes of biomes[16]. It also hampers the ability to uncover species interactions, patterns of niche differentiation, and the underlying ecological processes, thereby limiting the scientific basis for ecosystem protection and restoration.

Consequently, this research focuses on the terrestrial wildlife in the GBA, including mammals, birds, amphibians, and reptiles. By applying the integrated MaxEnt–Zonation model, it aims to predict the potential distribution pattern of priority terrestrial wildlife that are highly valuable for conservation or severely threatened in the GBA, to identify the prioritized distribution characteristics of the nature reserves and the spatial gaps of existing protected area distribution, thereby proposing an optimization plan for nature reserve construction. The results can contribute to the advancement of biodiversity conservation methods, provide critical support for effective conservation and management of biological resources, and offer referable experiences and methods for sustainable development in other countries or regions.

2 Study Area

The GBA is located in South China, including Hong Kong Special Administrative Region, Macao Special Administrative Region, and cities of Guangzhou, Shenzhen, Zhuhai, Foshan, Huizhou, Dongguan, Zhongshan, Jiangmen, and Zhaoqing in Guangdong Province, covering 56,000 km^2[17]. It is characterized by high-density urban development, a large population, and a robust economy. Specifically, according to relevant data from the Guangdong Provincial Bureau of Statistics, the population density of the GBA has reached as high as 1,548 people/km^2[18], with a GDP of 13 trillion yuan[19]. Given its vast territory and the significant topographical variation, i.e., mountains in the north and flat plains in the south, this region has a wide variety of habitat types, including seas, rivers, lakes, wetlands, mountains, and forests. The moderate mean annual temperature (22.9°C), abundant precipitation, and water–heat redistribution facilitated by the Nanling Mountains in the GBA have led to the formation of multiple vegetation types, such as southern subtropical evergreen broadleaf forests and mid-subtropical evergreen broadleaf forests[20]. These habitats effectively facilitate survival, reproduction, and migration of species, resulting in a rich species diversity, including mammals, birds, amphibians, reptiles, fish, and invertebrates. Among them, there are 77 rare species, encompassing *Sousa chinensis*, *Paramesotriton hongkongensis*, *Platalea minor*, *Chelonia mydas*, *Prionailurus bengalensis*, *Periophthalmus cantonensis*, *Lutra lutra*, *Emberiza aureola*, *Manis pentadactyla*, and *Pelodiscus sinensis*, which are flagship species endemic to the GBA. These species exhibit a unique distribution across the region's various ecosystems, forming a complex and diverse ecological network[21].

However, the rapid urbanization over the past 40 years has led to a dramatic increase in urban population size and density. Simultaneously, extensive areas of natural and agricultural land have been converted into construction land with heightened land fragmentation, causing problems such as resource depletion and degradation of ecological functions and placing substantial pressure on the environment[22]. Although establishing a biodiversity conservation system and enhancing the overall ecosystem quality have been included as key tasks in the *Outline Development Plan for the Guangdong–Hong Kong–Macao Greater Bay Area*, there is still a lack of research on the ECPA identification in the GBA that focuses on multiple species categories. Therefore, it is necessary to carry out a specialized study of the ECPA planning in the GBA to formulate scientific conservation and management strategies that support the holistic conservation of biodiversity in the region.

3 Materials and Methods

This research first predicted the potential distribution ranges of the studied species using the species distribution prediction model, MaxEnt, based on species occurrence data and regional environmental variable data. Then, combined with the spatial conservation planning model, Zonation, the ECPAs of multiple species were identified, which were further utilized to optimize the spatial layout of the nature reserves in the GBA and to rationally delineate the ECPAs.

3.1 Data Sources and Processing

3.1.1 Key Terrestrial Wildlife Species

Within the geographic range of the GBA, this research first screened 457 terrestrial wild vertebrates from *The International Union for Conservation of Nature (IUCN) Red List of Threatened Species*, *The List of Wild Animals Under State Priority Conservation*, and *The List of Wild Animals Under Priority Conservation of Guangdong Province*, which included 28 amphibian species, 64 reptile species, 307 bird species, and 58 mammal species. Subsequently, species occurrence data were obtained through the Global Biodiversity Information Facility and the website of China Bird Report. These records were supplemented with data from the

Second National Survey of Terrestrial Wildlife Resources and field sampling data from previous literature. Finally, this research obtained 32 species after manual removal of the species with fewer than five occurrence points, including 7 mammals, 13 birds, 5 amphibians, and 7 reptiles (Table 1).

3.1.2 Environmental Variables

Environmental variables have significant impacts on species distribution[23]. Based on existing studies and considering the environmental characteristics of the target species' habitats and data availability in the study area, this research selected three categories of environmental variables, namely meteorological variables, topographical variables, and anthropogenic disturbance variables (Table 2). The corresponding sources were: 1) 19 meteorological data for the year 2020 (1 km resolution) were downloaded from WorldClim[24]; 2) Land use/land cover data for the year of 2020 (30 m resolution) were acquired through the GlobeLand30 dataset[25]; 3) Digital elevation data (DEM) were accessed through geospatial data cloud (GDEM V3, 30 m resolution); 4) Road data at all levels were obtained from Baidu API, including railroads, highways, expressways, and national highways; 5) Administrative boundary vector ranges for the GBA were derived from the Public Map Service System of Guangdong Province, map No. GS Yue (2023) 1032; 6) Population density data sourced from the 1 km population density dataset of China on WorldPop.

Data preprocessing was conducted using ArcGIS 10.8. First, the national administrative boundary vector data were used as a mask to extract the meteorological variable, topographic variable, and anthropogenic disturbance variable data (30 m resolution) of the GBA in 2020. Second, hydrologic analysis was performed with DEM data, and the Euclidean distance between the corresponding grid and the water system was calculated. Third, the built-up area was extracted from the land use/land cover type data, and the Euclidean distance between the corresponding grid and the grid of built-up area was calculated. Finally, all raster data were converted to ASCII format.

3.2 Research Methods

3.2.1 Operation and Optimization of the MaxEnt Model

The MaxEnt model was used to simulate the maximum entropy distribution probability and to predict the potential distribution of target species based on occurrence data under the assumption of maximum entropy under various conditions[26]. Specifically, it applies the convex hull method to generate the distribution area of pseudo-occurrence points (background or pseudo-absence points) within the study area, making the result more reasonable and consistent

Table 1: The key terrestrial wildlife covered by this research

Category	No.	Species
Mammal	1	*Herpestes javanicus*
	2	*Lutra lutra*
	3	*Manis pentadactyla*
	4	*Muntiacus reevesi*
	5	*Muntiacus vaginalis*
	6	*Prionailurus bengalensis*
	7	*Viverricula indica*
Bird	8	*Aerodramus brevirostris*
	9	*Aythya nyroca*
	10	*Calidris pygmeus*
	11	*Centropus sinensis*
	12	*Charadrius placidus*
	13	*Corvus pectoralis*
	14	*Emberiza tristrami*
	15	*Garrulax canorus*
	16	*Lophura nycthemera*
	17	*Milvus migrans*
	18	*Platalea minor*
	19	*Terpsiphone atrocaudata*
	20	*Zapornia fusca*
Amphibian	21	*Hoplobatrachus chinensis*
	22	*Kalophrynus interlineatus*
	23	*Leptobrachella laui*
	24	*Megophrys mangshanensis*
	25	*Quasipaa exilispinosa*
Reptile	26	*Bungarus fasciatus*
	27	*Coelognathus radiates*
	28	*Gekko melli*
	29	*Mauremys sinensis*
	30	*Pelodiscus sinensis*
	31	*Platysternon megacephalum*
	32	*Python molurus bivittatus*

Table 2: Environmental variable data

Code	Variable	Unit
Meteorological variable		
Bio1	Annual mean temperature	℃
Bio2	Monthly mean diurnal temperature range	℃
Bio3	Isothermality	%
Bio4	Standard deviation of temperature seasonal change	—
Bio5	Max temperature of the warmest month	℃
Bio6	Min temperature of the coldest month	℃
Bio7	Range of annual temperature	℃
Bio8	Mean temperature of the wettest quarter	℃
Bio9	Mean temperature of the driest quarter	℃
Bio10	Mean temperature of the warmest quarter	℃
Bio11	Mean temperature of the coldest quarter	℃
Bio12	Annual average precipitation	mm
Bio13	Precipitation of the wettest month	mm
Bio14	Precipitation of the driest month	mm
Bio15	Coefficient of variation of precipitation	—
Bio16	Precipitation of the wettest quarter	mm
Bio17	Precipitation of the driest quarter	mm
Bio18	Precipitation of the warmest quarter	mm
Bio19	Precipitation of the coldest quarter	mm
Topographical variable		
DEM	Altitude	m
Slope	Slope	°
Aspect	Aspect	—
Anthropogenic disturbance variable		
Landuse	Land use/land cover type	—
Dis_river	Distance to water body	m
Dis_build	Distance to built-up area	m
Dis_road	Distance to road	m
People	Population density	people/km^2
Buildland	Distribution of built-up area	m^2

NOTE

All precipitation-related variables in the table were mean values.

with actual environmental conditions. This approach effectively enhances the model's ability to learn from environmental variables, thereby improving its capacity to accurately simulate species distribution patterns[27]. To ensure model accuracy and reduce spatial overfitting, ENMTools was employed to consolidate multiple occurrence records of the same species within each 1 km × 1 km grid into a single one, resulting in 1,891 valid species occurrence records. Species with five or more valid occurrence records, along with environmental variables, were imported into the model. Of these, 75% of the data were randomly selected as training data for prediction, while the remaining 25% were used for model validation. Unless otherwise specified, all other parameters were kept at their default settings. Then, the Jackknife method was applied with 10 replicates. The average predicted probability of species occurrence for each grid was obtained. Model performance was assessed using the Receiver Operating Characteristic (ROC) curve, with the Area Under the Curve (AUC) as the accuracy metric. The AUC was interpreted as follows: 0.6 to 0.7 indicates poor performance, 0.7 to 0.8 moderate, 0.8 to 0.9 good, and 0.9 to 1.0 excellent[28]. After excluding species with AUC values below 0.7, the final predictions of potential distribution areas were retained for the each species.

3.2.2 Relevance Assessment of Environmental Variables

To improve model accuracy and reduce overfitting errors due to variable covariance[29], this research analyzed the contribution and permutation importance of 28 environmental variables by the Jackknife method and removed those with a contribution rate of less than 1 in the pre-simulation experiments. Meanwhile, Pearson correlation analysis was performed among the environmental variables using ENMTools to calculate the autocorrelation coefficients between the variables. Existing studies commonly exclude less contributing variables with the absolute correlation coefficient smaller than 0.7, thereby ensuring that the environmental variables ultimately modeled for the experiment are reasonable[29]. However, the environmental variables in this research fluctuated modestly, with the internal correlations showing a relatively stable pattern. Using the 0.7 threshold would lead to the premature exclusion of certain valuable variables, causing the loss of valid information. Therefore, the threshold of 0.8 was applied in this research to identify highly correlated variables.

3.2.3 Operation and Optimization of the Zonation Model

Zonation, Marxan, and C-Plan are current systematic conservation planning tools widely used in research and practice[6,30–31]. Zonation has mostly been used to model large-scale layouts of conservation priority[32]. Compared with other software, it is able to identify ECPAs for single or multiple species and emphasizes landscape connectivity, maximizing the value of biodiversity conservation[33]. In this research, Zonation v4 software was used to conduct ECPA planning for key terrestrial wildlife in the GBA. First, using the core area Zonation method, the least valuable grids for species suitability (e.g., poor environment, lack of food resources) were removed while retaining the core distributional area of the studied species. Second, edge removal was employed to eliminate the least valuable grids from the landscape edges to maintain structural connectivity[34]. During the computation, the value of warp factor determined the number of grids removed every time[12], a default value of 1 was applied for the warping factor in this research.

In addition, considering that the built-up area may significantly affect the classification of ECPAs of the species, this research applied the erase by the mask function in Zonation to exclude the undesirable areas and improve the simulation accuracy. All other parameters were set to their default values. This setup can improve the model's reliability while taking into account the specific characteristics of the study area.

As the conservation value of different species varies, the rarer the species, the higher weight should be given to the model predictions. Therefore, before the identification of multi-species ECPAs, the protection level of each species must be clarified and the corresponding weights must be set[11,35]. In this research, weights were set according to the rarity and endangerment levels of different species and their economic and social values (Table 3).

Human activities have a significant impact on ecological land use designation[36]. The rapid growth of population and economic activities since the 20th century has caused problems such as habitat modification, increased invasive species, climate change, and environmental pollution[37], which have led to biodiversity crises[38]. Thus, it is important to consider the potential impacts of anthropogenic activities or land expansion on the ecosystem in ecological studies. Internationally, scholars have included land values or land use fees as variables for model prediction[39]. In contrast, related studies in China have seldom included human activities in predicting parameters. Moreover, due to the complexity of the situations in each region, it is difficult to accurately calculate the use fee per unit of land. Therefore, to enhance the accuracy and reliability of findings, an innovative approach was adopted in this research. By utilizing the erase by mask approach and taking the distribution of existing built-up area as a variable, the impacts of human activities were rationally incorporated into the identification of the ECPAs.

This research then used R language statistical software to plot the landscape degradation rate–risk of habitat loss curve for different categories of species separately, enabling a comparative analysis of how various species respond to landscape degradation. Meanwhile, key data points were labeled on the curves, such as turning points where the risk of species habitat loss begins to increase significantly when landscape degradation reaches a certain level. Further, the quantitative relationship between landscape degradation and the risk of habitat loss was identified by calculating parameters such as the slope and curvature of the curve. This step served to assess the increasing rate and trend of risk, to identify key factors affecting the risk curve, and to provide a scientific basis for the development of targeted conservation strategies. For example, if the analysis indicates that the risk of habitat loss for a species is most sensitive

Table 3: Basis for species weight setting

IUCN Endangered class/national protection class	Weight
Critical Risk (CR)/national first-class protected species	8
Endangered (EN)	4
Vulnerable (VU)/national second-class protected species	2
Near Threatened (NT)	1
Least Concern (LC)	1

NOTES

1. The weighting of species in this research made comprehensive reference to *The IUCN Red List of Threatened Species*, *The List of Wild Animals Under State Priority Conservation*, and *The China's Red List of Biodiversity*. *The China's Red List of Biodiversity* applies the IUCN endangered rank classification names.
2. If multiple weights were assigned to the same species when referring to different classification criteria, the highest weight was selected for setting.

to a particular indicator (e.g., loss of vegetation cover), then conservation efforts should prioritize monitoring and implementing restoration measures accordingly.

Building on this analysis, the research further identified the critical threshold of remaining habitat proportion for conservation. On the one hand, this threshold ensures that conservation priority areas can effectively protect species distributions, maintain basic biodiversity stability, and prevent severe threats to species survival caused by excessive habitat loss. On the other hand, from the perspective of rational resource use, it enables effective protection of key species and ecosystems while keeping costs manageable and promoting efficient resource allocation.

According to the global 2030 ecosystem conservation target issued by the *Convention on Biological Diversity* in 2022, by 2030 at least 30% of terrestrial and inland water and marine and coastal areas should be effectively conserved and managed, and restoration measures should be undertaken for at least 30% of degraded terrestrial and inland water ecosystems and marine and coastal ecosystems[40–42]. In line with these targets, this research selected the top 30% grids with the highest conservation value from the Zonation results as the conservation priority areas. To optimize resource allocation and accurately protect ecologically critical areas, this research integrated ecological sensitivity, ecosystem integrity, and threat level of different areas to designate the top 10%, 20%, and 30% conservation value areas as the primary, secondary, and tertiary ECPA, using the reclassification tool in ArcGIS 10.8.

4 Results and Analysis

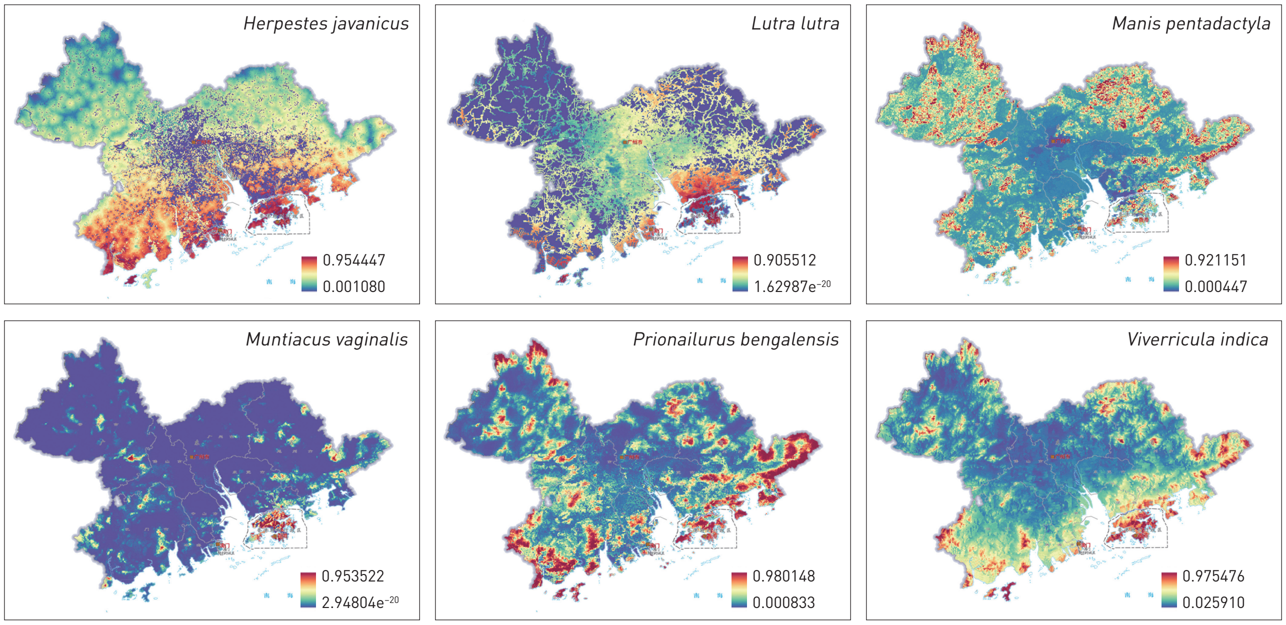
4.1 Evaluation of MaxEnt Model Simulation

This research calculated the relative contributions of environmental variables to the MaxEnt model. As the results indicated, for mammals, the contribution and permutation importance of altitude, distribution of built-up area, and coefficient of variation of precipitation were more significant. For birds, the contribution and permutation importance of the coefficient of variation of precipitation, precipitation of the coldest quarter, and distance to water body were more prominent. For amphibians, the coefficient of variation of precipitation, precipitation of the driest quarter, and distance to water body were more influential. For reptiles, the contribution and replacement importance of slope and the distribution of built-up area was higher.

4.2 Potential Habitat Distribution

Figures 1 ~ 4 present the potential habitat distribution for mammals, birds, amphibians, and reptiles, respectively. The red colors on the maps represent areas that are highly suitable for species to inhabit, indicating the potential presence of abundant food sources, suitable climatic conditions, or better ecological conditions. Blue color shows the habitats of lower suitability, where environmental conditions may be less favorable for species survival. The darker the red, the higher the habitat suitability; the darker the blue, the lower the habitat suitability.

Fig. 1 Potential habitat distribution for mammals.



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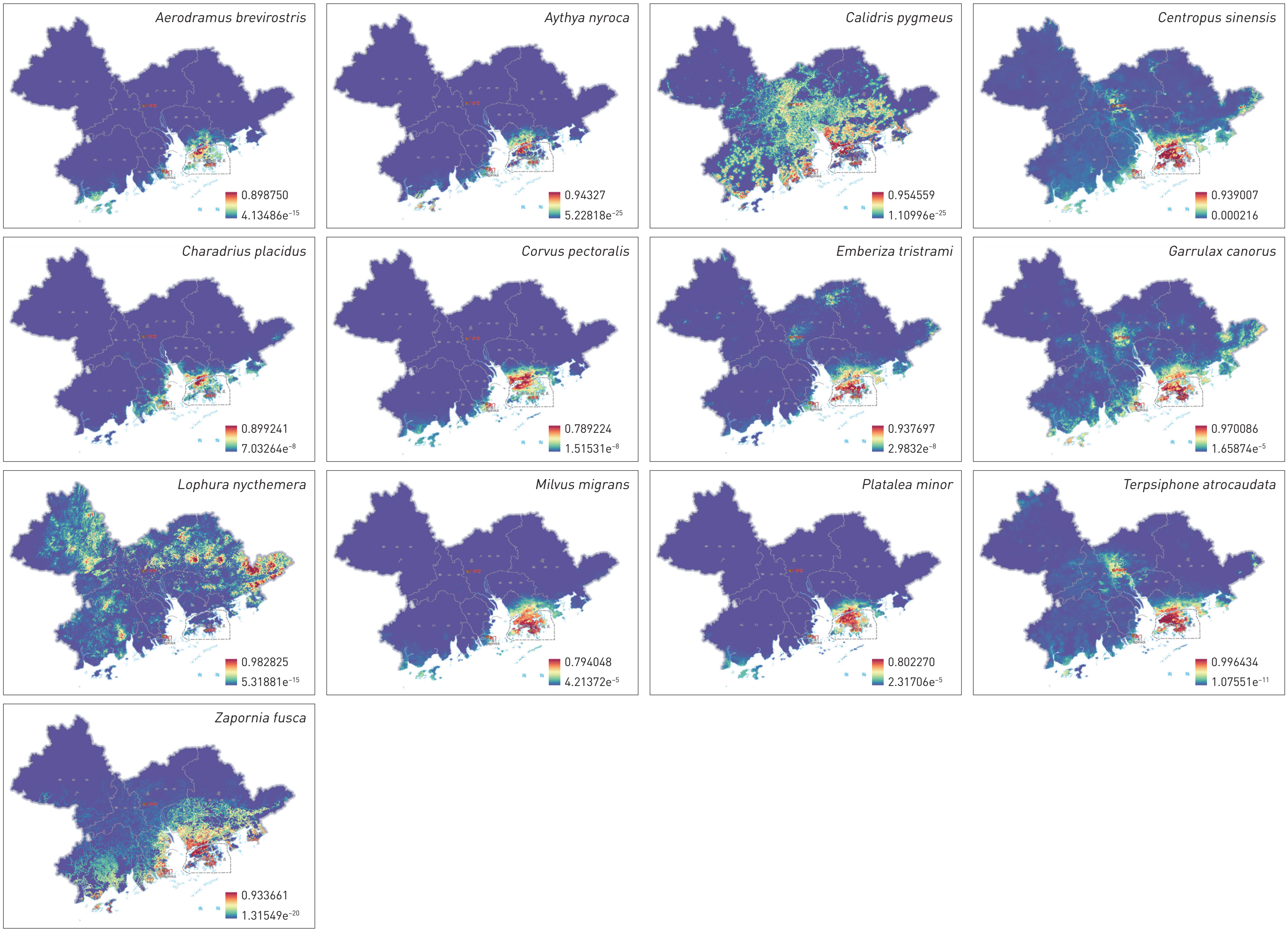

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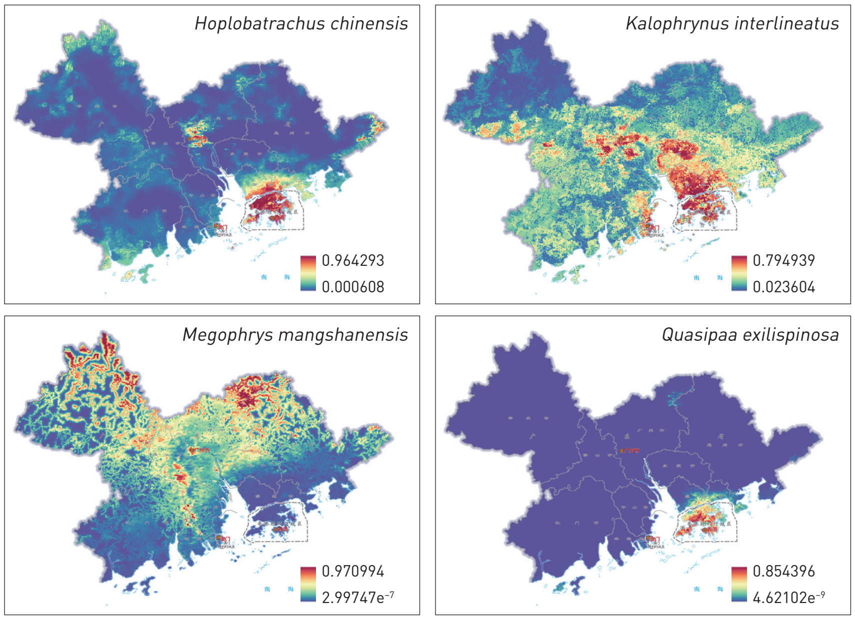

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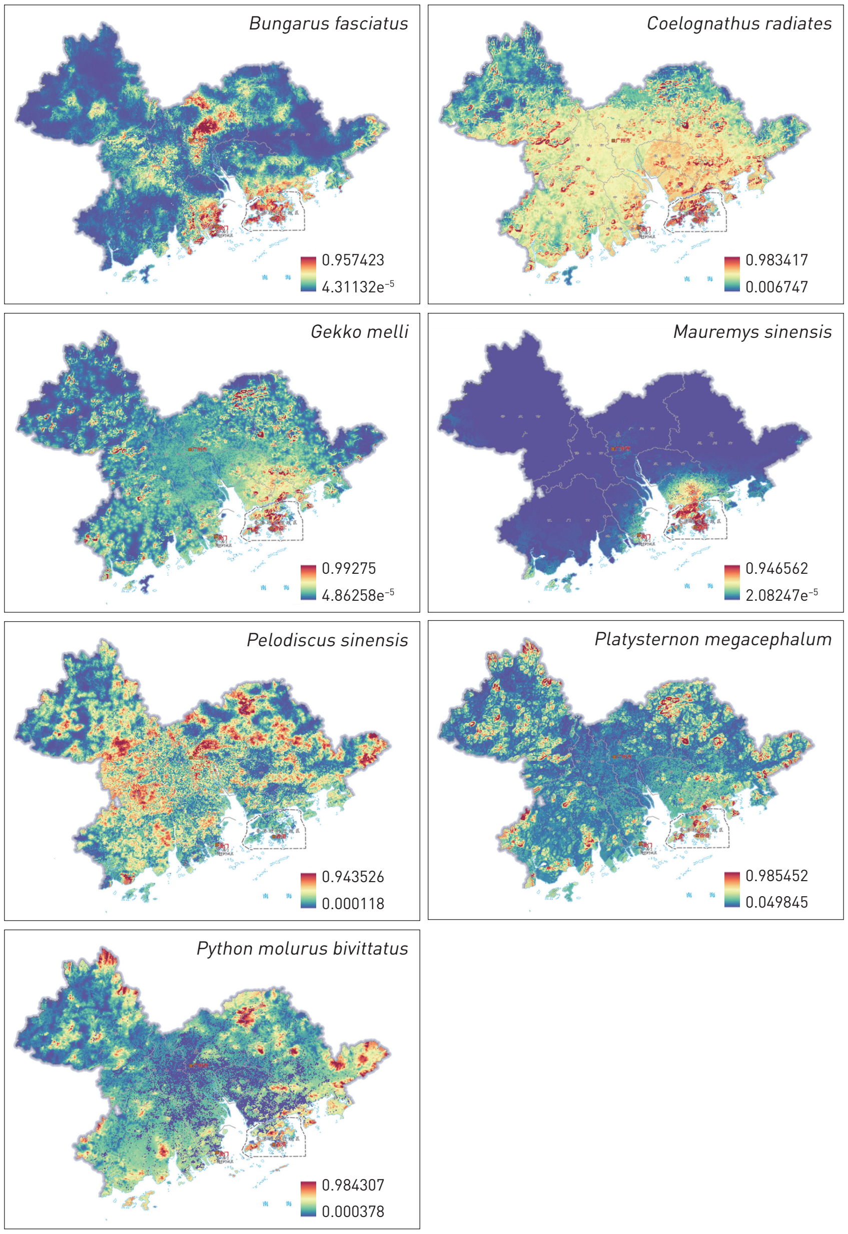
Fig. 2 Potential habitat distribution for birds.

Fig. 3 Potential habitat distribution for amphibians.



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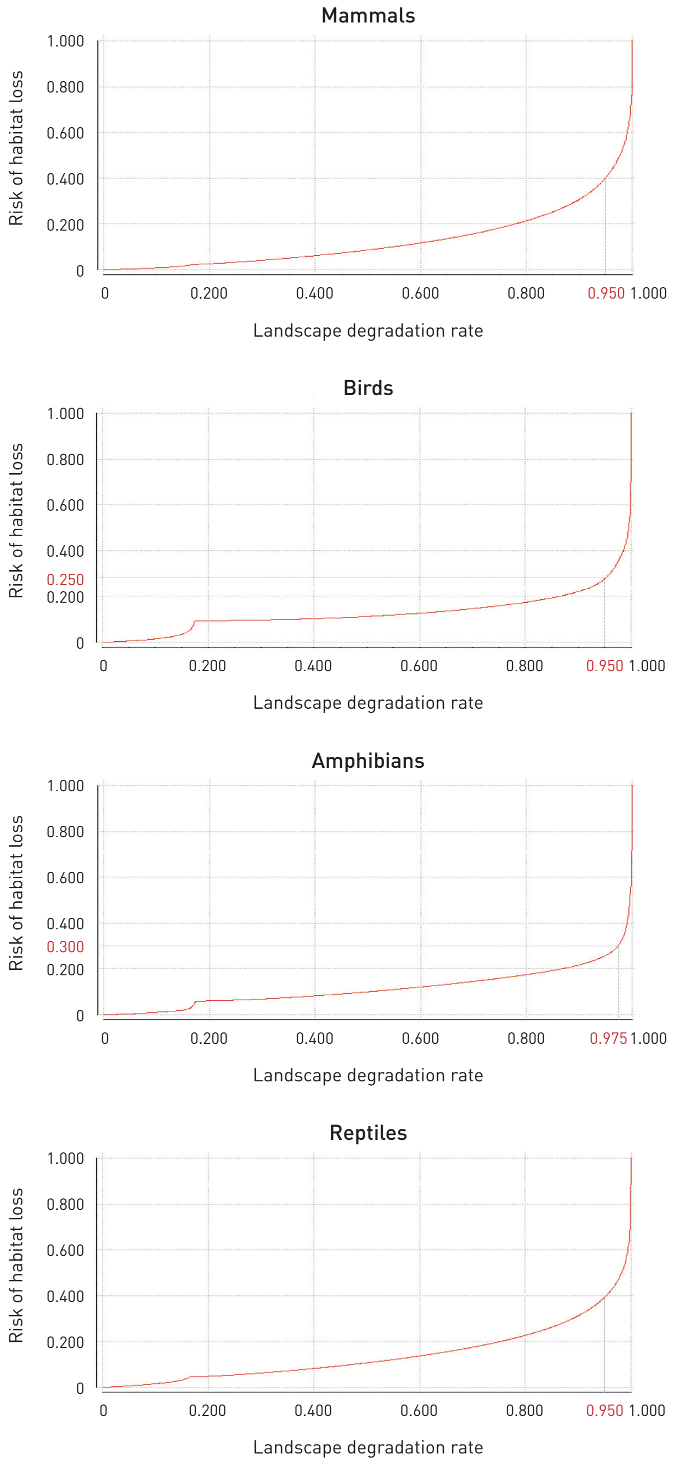
4.3 Spatial Conservation Priority Pattern

4.3.1 Habitat Assessment

Raster data representing the potential distribution of 32 key terrestrial wildlife species were input into Zonation by species category. In turn, the spatial conservation priority pattern and the landscape degradation rate–risk of habitat loss curve for the four species categories in the study area were obtained (Fig. 5). Overall, as the landscape degraded, the risks of habitat loss for species in the study area increase. For mammals, the rate of increase in habitat loss risk remains relatively stable when landscape degradation is below 20%; when the degradation reaches 95%, the average risk of habitat loss rises to 40%, after which it accelerates sharply, eventually reaching 100%—indicating an extinction of existing species. For reptiles, the average risk of habitat loss rises to 40% when landscape degradation reaches 95%, followed by a sharp rise to 100%. In contrast, birds and amphibians face a comparatively lower risk of habitat loss. The average risk of habitat loss for birds reaches 25% when the proportion of degraded landscape reaches 95%, and for amphibians, the risk stays below 30% until the

Fig. 4 Potential habitat distribution for reptiles.
Fig. 5 The landscape degradation rate–risk of habitat loss curves.



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degradation reaches 97.5%. Beyond these thresholds, they both experience a phase of sharp increase.

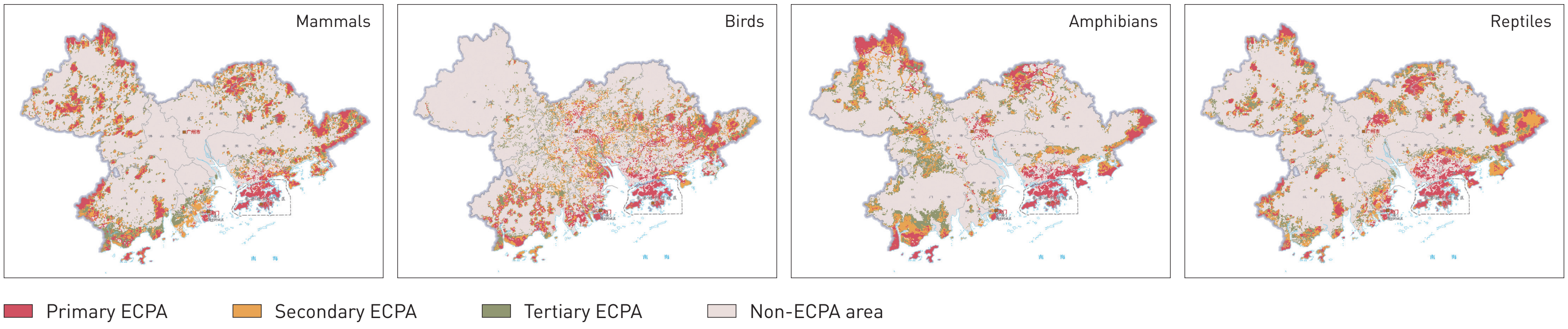
According to the results, when the landscape degradation rate stays below 70%, the proportion of preserved habitat for each category of species remains consistently above 70%. As degradation continues to increase beyond this point, significant changes occur in habitats and the distribution pattern of the species, leading to a decline in conservation effectiveness. Therefore, this research identifies the 70% landscape degradation rate as a critical threshold for achieving effective conservation.

The primary, secondary, and tertiary ECPA results (Fig. 6) show that mammal habitats generally avoid high-density built-up areas and are mainly concentrated in areas with complex and diverse topography, including lowland wetland ecosystems in the Pearl River Estuary, nature reserves along the coastal zone, and mountainous forests and secondary woodlands in the northern GBA. These areas provide rich food resources and less disturbed living environments for mammals, specifically including Dinghu Mountain area in northern Zhaoqing; Luofu Mountain area in northern Huizhou; Futian Mangrove Nature Reserve, Wutong Mountain, and Dapeng Peninsula in Shenzhen; wetlands and mangrove forests close to the Pearl River Estuary in Zhongshan; the coastal areas in western and southern Jiangmen; the coastal areas in the central and southern parts of Zhuhai; the green spaces in northern and southern Macao; and the pristine forests and coastal areas in Lantau Island and UNESCO Global Geopark (Sai Kung) in Hong Kong.

Bird habitats are widely distributed at coastal wetlands and mangrove forests, as well as alluvial plains and paddy fields along the rivers, which supply essential stopover and nesting sites for various migratory birds. Meanwhile, inland open woodlands and grasslands are also important habitats for niche-dependent ground-nesting birds. Nansha Wetland Park in Guangzhou; Lianhua Hill Park and Dapeng Penisula Nature Reserve in Shenzhen; wetland parks in Jinwan District and the mangrove area in Doumen District in Zhuhai; the coastal areas in Haojiang District and Nan’ao Island Nature Reserve in Shantou; Danxia Mountain in Shaoguan; the wetland parks in Xiqiao Mountain and Shunde District in Foshan; Guifeng Mountain National Forest Park in Jiangmen; Dinghu Mountain in Zhaoqing; Xihu Lake and Loufu Mountain area in Huizhou; Wugui Mountain and the wetland areas along the Peral River in Zhongshan; Songshan Lake Eco-Park and the coastal wetlands of Humen Town in Dongguan; the wetlands and rural mountains in Macao; Lantau Island, Meiwo, and Global Geopark (Sai Kung) in Hong Kong are potential bird habitats in the GBA.

Amphibians and reptiles share similar living habits, favoring areas with abundant water resources such as streams, lakes, and wetlands, especially those rich in aquatic plants, while also commonly found in hilly and low mountainous forests. These areas can provide suitable thermal conditions and diverse habitats for breeding and foraging. The Qixingyan Scenic Area, Xing Lake, and Dinghu Mountain in Zhaoqing; the wetlands in the Pearl River Estuary area along the western coast and Tai Mountain in the south, and Kaiping watchtowers and ancient villages in the central and eastern inland, and the river and wetland areas of Enping in Jiangmen; Hengqin Island, Jiuzhou Island in Zhuhai, and the mangroves and coastal wetlands in their surroundings; Baiyun Mountain, Dafu Montain forested area, and Huadu Wetland Park in Guangzhou; Huiyang District, Daya Bay, and Luofu Mountain Huizhou; Songshan Lake in southeastern Dongguan; Wutong Mountain and Dapeng New Area in Shenzhen; the country parks in northern Macao, and the wetlands in the south; and the Lantau Island, Global Geopark (Sai Kung), and Hong Kong Wetland Park in Hong Kong are all major potential distribution areas for amphibian and reptile species habitats in the GBA.

Fig. 6 The primary, secondary, and tertiary ECPAs of four species categories.



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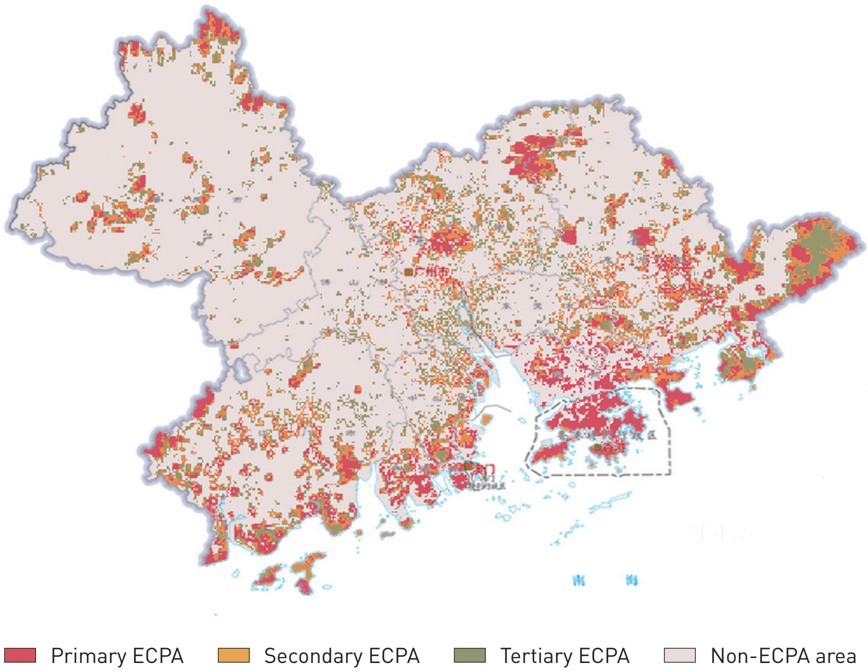
4.3.2 Distribution of ECPAs

The overall distribution of ECPAs for of key terrestrial wildlife species in the GBA were delineated by inputting the potential distribution data of the 32 species into the Zonation and assigning appropriate weights to each grid (Fig. 7). The results show that most of the ECPAs distribute in three types of zones with distinctive geographic features, including mountainous forested areas, coastal and seashore areas, and nature reserves on the outskirts of cities. The mountainous forested areas in the northern and central parts of Zhaoqing (e.g., Dinghu Mountain, Qixingyan scenic area) and the Luofu Mountain in Huizhou provide habitats and refuges for diverse terrestrial wildlife. Coastal wetlands and mangroves of the Pearl River Estuary in Jiangmen, Zhongshan, and Zhuhai, as well as the coastal areas from central and western to eastern Shenzhen, are vital for maintaining the ecosystem balance and biodiversity. Songshan Lake Eco-Park in Dongguan, the country park in Macao, and coastal national parks such as Lantau Island and Global Geopark (Sai Kung) in Hong Kong, although situated in urban fringes, offer valuable habitats for wild animals.

By overlaying the overall distribution of ECPAs with the established nature reserves in the GBA (Fig. 8), it is found that most of the ECPAs overlap with the existing nature reserves, but there are still some uncovered conservation gaps.



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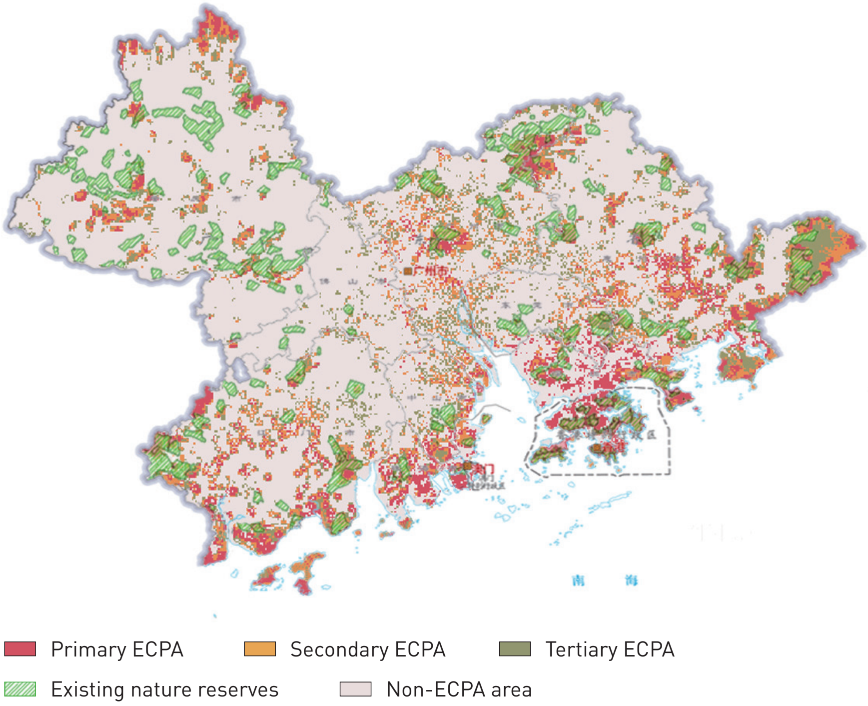

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Fig. 7 Overall distribution of ECPAs of key terrestrial wildlife species in the GBA.
Fig. 8 Distribution comparison of predicted ECPAs of key terrestrial wildlife species and established nature reserves in the GBA.

5 Discussion

5.1 Impacts of Precipitation Seasonality on the Potential Distribution of Key Terrestrial Wildlife Species

According to the analysis results of environmental variables affecting the distribution of key terrestrial wildlife species, this research found that the impact intensity of the meteorological variables on species distribution is stronger than that of topographical variables and anthropogenic disturbance variables. Among them, precipitation seasonality (i.e., Bio16, Bio17, Bio18, Bio19) stands out as the dominant environmental variable shaping the potential distribution of relevant species, reflecting the critical role of precipitation in ecosystem structure and ecological functions[43].

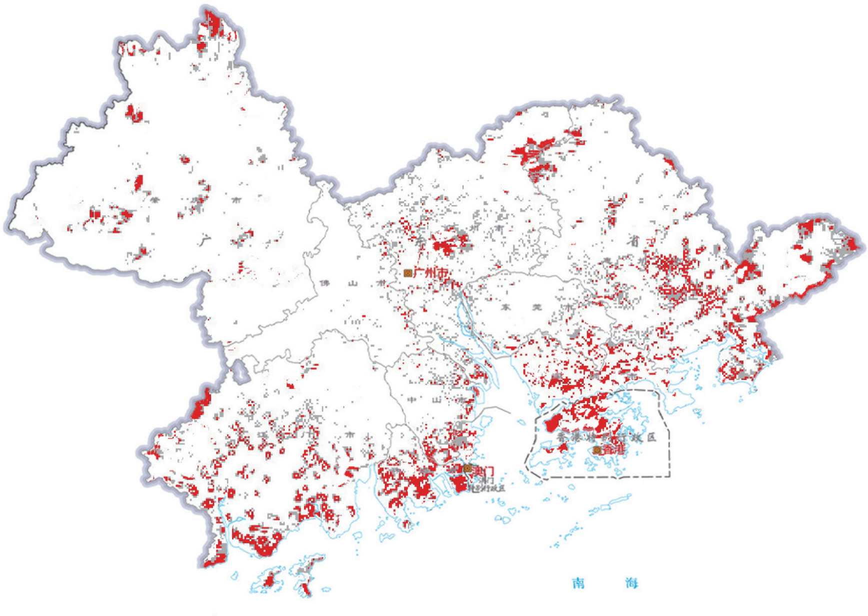
Precipitation seasonality plays a critical role in ecosystems by affecting water availability, food chain relationships, reproduction, habitat suitability, and species tolerance, and contributes significantly to species habitat distribution. First, an adequate and stable water supply is fundamental to the survival of many organisms. However, seasonal fluctuations in precipitation can directly affect water supply or lead to water shortages during certain periods. This water supply–demand mismatch is a major determinant of species distribution. Second, precipitation seasonality affects the growth and distribution of vegetation[44–45], influencing the habitat selection and distribution of the animal species that feed on it. Furthermore, the reproductive activities of many species (e.g., mating, incubation, juvenile development) are closely related to seasonal rainfall. Favorable precipitation patterns can provide optimal breeding conditions, and vice versa can limit the species' distribution. In addition, different precipitation patterns can create diverse habitat types, including wetlands, forests, and grasslands, the suitability of which directly determines the species' habitat distribution. Ultimately, there are significant differences in species' sensitivity to precipitation seasonality. For example, small changes in precipitation may be beyond the adaptive range of species that are highly sensitive to rainfall variability, limiting their habitat distribution.

In summary, future terrestrial wildlife conservation and management efforts should take into account seasonal variations in precipitation and implement timely measures to protect and restore the wildlife habitats and maintain the regional biodiversity and ecological balance. Similarly, future research should also explore in depth the specific impact mechanisms of precipitation seasonality on wildlife population size, distribution range, and migratory behavior to provide a scientific basis for biological conservation and management.

5.2 Optimization of Spatial Layout

In comparison with the existing nature reserves, this research identified the conservation gaps for key terrestrial wildlife in the study area, which are concentrated in the built-up areas with intense human activities in the eastern and southern GBA (Fig. 9). The three major cities, namely Shenzhen, Dongguan, and Hong Kong, have a denser distribution and higher prioritization of ECPAs. However, the available land for further urban development is limited. Thus, how to properly deal with the relationship between urbanization and ecological conservation has become a common development challenge for these cities. To avoid the encroachment of built-up area into ecologically valuable areas, it is essential to define land use boundaries rationally and formulate and refine regulations on conservation areas. In practice, a proportion of dividends from economic development can be invested in ecological protection and restoration, to coordinate the relationship between economic development and ecological protection, as well as to realize their mutual development. Additionally, innovative technologies such as vertical greening can be implemented to create more habitats within the built-up areas to protect and enhance biodiversity, realizing the sustainable urban development and objectives of ecological conservation and promoting the harmonious coexistence of human beings and nature.

Fig. 9 Conservation gaps for key terrestrial wildlife in the GBA.



▨ Conservation gap 🟥 Essential conservation gap

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5.3 Reasonableness and Limitations in Incorporating Anthropogenic Disturbance Variables

By using the erase by mask approach and treating the distribution of built-up area as an environmental variable, this research effectively eliminated existing development areas and improved the accuracy of conservation area calculations, thereby rationally incorporating the impacts of human activities into the process of identifying ECPAs. However, this method also presents certain limitations. First, as built-up areas are primarily used for residential and industrial purposes, their internal environments are highly influenced by human activities, making it difficult to maintain original natural ecosystem functions. Therefore, removing them helps improve the ecological integrity and effectiveness of conservation area calculations, contributing more to achieving the goal of ecological conservation. However, it is somewhat reductive to assume that built-up areas are unsuitable as habitats. In fact, some species may have gradually adapted to the developed environment. Arbitrarily excluding these areas may overlook their internal ecological potential and result in the omission of potential conservation areas.

6 Conclusions and Prospects

Taking the GBA as the study area and 32 key terrestrial wildlife species as the research object, this research successfully predicted the ECPAs in this region by integrating the species distribution prediction model MaxEnt and the multi-species conservation planning model Zonation. The conclusions drawn are as follows. 1) Precipitation seasonality has a significant impact on the potential distribution of the species, and the suitable areas are mainly concentrated in areas with abundant precipitation and strong water retention capacity. 2) The ECPAs are mainly located in the northern and central mountainous and forested areas of Zhaoqing, the coastal areas of Jiangmen, the central to southern coastal areas of Zhuhai, the central northeastern parts to coastal areas of Zhongshan, the central to coastal areas of Huizhou, the southeastern Dongguan, the central, western, and coastal areas of Shenzhen, the northern and southern Macao, the coastal area of Hong Kong. 3) The predicted ECPAs overlap with most of the established nature reserves, but there are still gap areas in the eastern and southern coasts of the GBA.

The results of this research can provide valuable references for advancing ecological conservation in other regions. Nevertheless, this research is only a conceptual planning attempt, and several factors need to be considered when developing concrete planning objectives. First, the species occurrence data should be collected and surveyed in a more detailed and comprehensive manner. The studied species only covered key terrestrial wildlife and has not yet included all protected species in the study area. Meanwhile, the occurrence data used are based on partially available public sources and are mostly about planned conservation areas or where observers have presented. More infrared camera monitoring or field surveys are needed, particularly in areas beyond existing reserves and in less accessible regions to further clarify species distribution information. Second, dynamic factors such as future urban expansion and climate change should be incorporated into the planning of nature reserves. The impact of population growth and rapid urbanization on urban ecology cannot be ignored. In addition, in the context of global warming, environmental variables (e.g., precipitation pattern, temperature) will continuously change. As a coastal region, the GBA is vulnerable to the impacts of climate-related risks (e.g., sea level rise, storm surge). Therefore, the combined effects of these factors must be considered in future planning to ensure the sustainability and adaptability of nature reserve designation.

ELECTRONIC SUPPLEMENTARY MATERIAL

Supplementary material is available in the online version of this article at https://doi.org/10.15302/J-LAF-0-020026.

Competing interests | The authors declare that they have no competing interests.

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粤港澳大湾区重点陆生野生动物生态保护优先区识别

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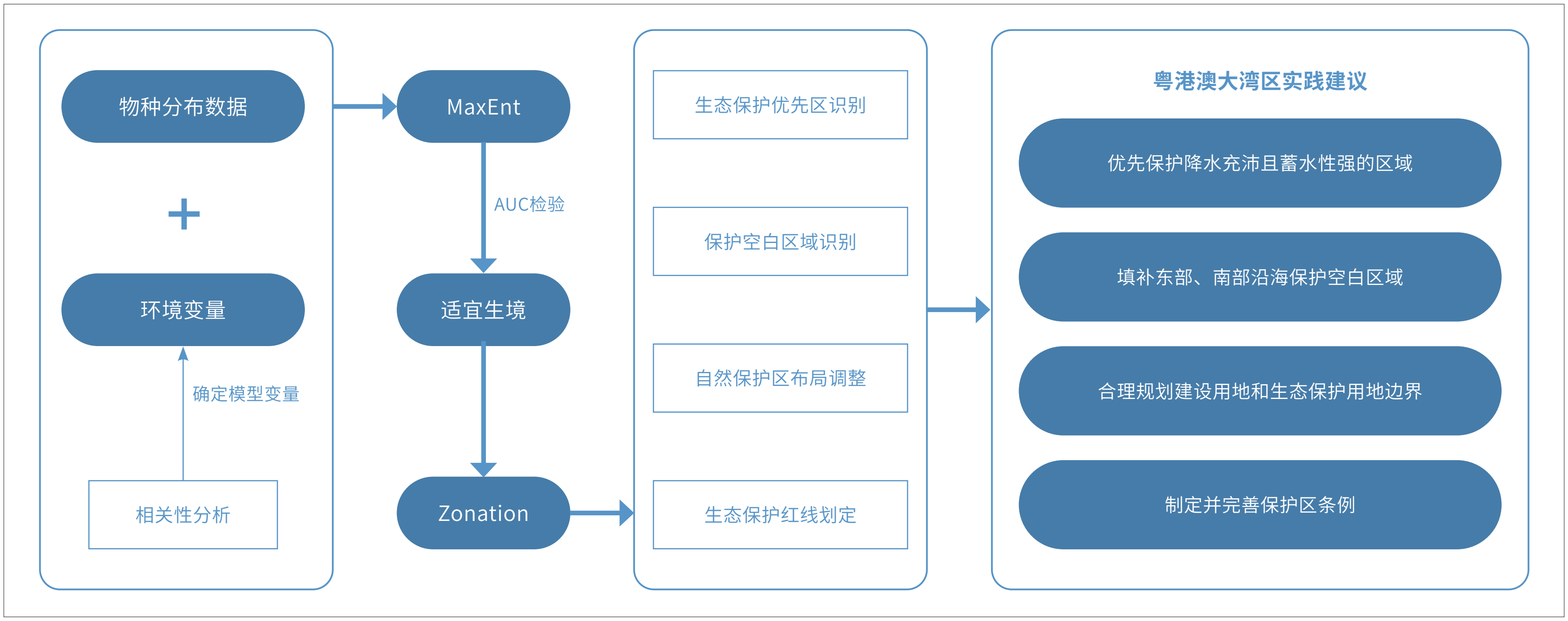
图文摘要



摘要

识别重点陆生野生动物的生态保护优先区对于生物多样性保护具有重要意义。然而，现有研究往往将单一类群作为研究对象，忽略了生物多样性的整体特征和相互关系。本研究聚焦粤港澳大湾区及其32种重点陆生野生动物，综合运用MaxEnt与Zonation模型预测生态保护优先区，进而与现有自然保护区叠加分析，以识别保护空白区域并提出自然保护区优化方案。结果表明：1）降水季节性对物种潜在分布具有显著影响，物种适宜栖息地主要集中在降水充沛且蓄水性较好的区域；2）生态保护优先区分布主要位于肇庆市北部和中部山林区域，江门市沿海区域，珠海市中部至南部沿海区域，中山市中部、东北部至沿海区域，惠州市中部至沿海区域，东莞市东南部，深圳市中西部及沿海区域，澳门北部及南部区域，以及香港沿海区域；3）Zonation预测的生态保护优先区域与大部分已建立的自然保护区重合，但在大湾区东部、南部沿海仍存在保护空白区域。本研究的结果可对其他地区推进生态保护提供有益参考和借鉴，有助于将气候变化及人类活动因素纳入保护区规划工作中，为生物多样性保护提供有效方法，为自然保护管理者提供科学决策依据。

关键词

自然保护区；Zonation；MaxEnt；物种分布；生物多样性；陆生野生动物；气候变化

文章亮点

- 集成MaxEnt–Zonation模型预测关键物种的潜在分布和保护优先区
- 识别哺乳类、鸟类、爬行类和两栖类4类野生陆生动物的保护空白区域
- 发现降水充沛且蓄水性较好的区域为物种适宜栖息地

基金项目

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- 中央高校业务费项目“快速城市化背景下广东省生态保护优先区识别”（编号：CGPY202409）

编辑 高雨婷，马锡栋

1 引言

生物多样性作为社会生存发展的重要基础，对维持生态系统稳定性具有不可替代的作用[1]。快速城镇化发展和高强度人类活动致使城市环境生物多样性日趋丧失，这已成为全球范围内普遍存在的问题[2]。高质量的自然保护区规划和建设是保护生物多样性的有效方式[3]。自1956年起，中国已累计设立各级自然保护区共2 750处，总面积1 470 000 km^2，约占全国陆地总面积的15%[4]。然而，由于创建初期缺乏对保护优先性的科学评估，一些保护区出现了对部分物种过度保护而对部分重点物种保护不足的现象[5]。

生态保护优先区识别是一种定量技术，可根据特定保护目标来确定保护区优先网络，从而为区域生态和环境规划提供数据支撑[6]。在技术操作层面，国外学者较早开始使用系统保护规划软件来辅助开展生物多样性保护的规划研究。例如，马可·吉拉德洛等采用生态位模型和Zonation模型确定了意大利蝴蝶保护的重要区域，并设定了相应的优先保护级别[7]。朱丽叶·德拉文等通过比较Marxan和Zonation模型的模拟结果，对英吉利海峡东段海洋生物保护区进行了优先级评估[8]。目前国内相关研究多将生态保护优先区识别应用于划定生物栖息地，以及基于生物多样性影响评估提出相应保护策略。唐佳等从优势生态系统、特殊生态系统、特有生态系统、物种丰富度高的生态系统和特殊生境5个角度，分析了湖北省自然保护区的分布特点，进而指出当前优先保护森林生态系统中所存在的保护空缺[9]。陈富康等以粤港澳大湾区为研究对象，综合生态系统服务和生态脆弱性指标构建了一套适用于城市群的生态保护优先区识别方法[10]。肖静等聚焦岷山地区，基于MaxEnt和Zonation模型计算，识别该地区的珍稀濒危物种生态保护优先区，据此提出空间优化方案[11]。周键等应用物种分布和系统保护规划模型判识了云南省陆栖脊椎动物的生态保护优先区，并通过剖析其空间分布格局进行了现状评估[12]。

在物种选择层面，现有研究往往将单一物种或单一类群作为研究对象，如罗绮琪等使用MaxEnt模型分析了粤港澳大湾区水鸟多样性的空间分布格局及热点地区[13]；特伦特·彭曼等使用同一模型预测了气候变暖情景下蛇类栖息地的未来分布变化[14]；曾佳丽等则识别了沿海湿地中红树林的适宜性分布状况[15]。然而，这种关注单一类群的研究视角常常忽视了生物多样性的整体性特征和相互关系，既无法全面了解生物群落的结构、功能及其动态变化[16]，也难以揭示物种间的相互作用、生态位分化格局及其背后的生态过程，为生态系统保护和恢复提供科学依据。

因此，本研究重点关注哺乳类、鸟类、两栖类、爬行类等陆生野生动物物种，旨在通过集成应用MaxEnt–Zonation模型，预测粤港澳大湾区保护价值较高或受威胁程度严重的重点陆生野生动物的潜在分布格局，识别自然保护区的优先化布局特征和现有保护地分布的空缺，进而提出自然保护区建设的优化方案。本研究可以促进生物多样性保护方法发展，为有效保护和管理生物资源提供重要支持，并为其他国家和地区的可持续发展提供可借鉴的经验和方法。

2 研究区域

粤港澳大湾区（以下简称“大湾区”）位于中国华南地区，包括香港特别行政区、澳门特别行政区和广东省广州市、深圳市、珠海市、佛山市、惠州市、东莞市、中山市、江门市、肇庆市，总面积56 000 km^2[17]。大湾区城市高密度发展、人口密集、经济发达。广东省统计局相关数据显示，大湾区人口密度高达1 548人/km^2[18]，GDP高达13万亿元人民币[19]。得益于其地域广阔、南北地形差异显著（北部山区、南部平

原），该区域拥有多样的栖息地类型，包括海洋、河流、湖泊、湿地、山地、森林等。大湾区全年平均温度为22.9℃，降水充沛，南岭山脉促进的水热再分布，使其形成了南亚热带常绿阔叶林、中亚热带常绿阔叶林等多种植被类型[20]。这些栖息地有效促进了物种的生存、繁衍和迁徙，形成了丰富的物种多样性，包括哺乳动物、鸟类、两栖动物、爬行动物、鱼类和无脊椎动物等。其中珍稀物种77种，包括中华白海豚（*Sousa chinensis*）、香港瘰螈（*Paramesotriton hongkongensis*）、黑脸琵鹭（*Platalea minor*）、绿海龟（*Chelonia mydas*）、豹猫（*Prionailurus bengalensis*）、广东弹涂鱼（*Periophthalmus cantonensis*）、欧亚水獭（*Lutra lutra*）、黄胸鹀（*Emberiza aureola*）、中华穿山甲（*Manis pentadactyla*）、中华鲎（*Pelodiscus sinensis*）等大湾区特有的旗舰物种。这些物种在该地区的不同生态系统中独特分布，形成了一个复杂而多样的生态网络[21]。

然而，过去40年间的快速城镇化致使致使城市人口数量急剧增长、密度大幅上升；同时，自然与农业用地被大量转化为建设用地，土地破碎化程度加剧，造成资源消耗、生态功能削弱等问题，给环境带来了沉重压力[22]。虽然构建生物多样性保护体系、提升生态系统整体质量已被纳入《粤港澳大湾区发展规划纲要》的重点任务，但仍缺乏以粤港澳大湾区为背景、同时关注多类别物种的保护区识别研究。故而，有必要开展大湾区生态保护优先区的专项规划研究，以制定科学保护策略和管理措施，实现该地区生物多样性的整体性保护。

3 研究材料与方法

本研究首先基于物种分布数据和区域环境变量数据，运用物种分布预测模型MaxEnt预测研究物种潜在分布范围。而后结合空间保护规划模型Zonation，识别多物种的生态保护优先区，进而优化大湾区自然保护区空间布局，合理划分保护区。

3.1 数据来源与处理

3.1.1 重点陆生野生动物物种

以大湾区地理范围为限定，研究首先从《世界自然保护联盟濒危物种红色名录》《国家重点保护野生动物名录》《广东省重点陆生野生保护动物名录》中筛选出457种陆生野生脊椎动物，包括两栖动物28种、爬行动物64种、鸟类307种、哺乳动物58种。随后，通过全球生物多样性信息网络和中国观鸟记录中心网站获取物种分布数据（分布点），并利用全国第二次陆生野生动物资源调查数据和既往文献的实地采样数据对上述数据进行补充；最后，在人工删除分布点数量低于5个的物种后，共确定了32个物种作为研究对象，其中哺乳类7种、鸟类13种、两栖类5种、爬行类7种（表1）。

表1：本研究所涵盖的重点陆生野生动物

类别	序号	名称	拉丁名
哺乳类	1	爪哇獴	*Herpestes javanicus*
	2	水獭	*Lutra lutra*
	3	穿山甲	*Manis pentadactyla*
	4	小麂	*Muntiacus reevesi*
	5	赤麂	*Muntiacus vaginalis*
	6	豹猫	*Prionailurus bengalensis*
	7	小灵猫	*Viverricula indica*
鸟类	8	短嘴金丝燕	*Aerodramus brevirostris*
	9	白眼潜鸭	*Aythya nyroca*
	10	勺嘴鹬	*Calidris pygmeus*
	11	褐翅鸦鹃	*Centropus sinensis*
	12	长嘴剑鸻	*Charadrius placidus*
	13	白颈鸦	*Corvus pectoralis*
	14	白眉鹀	*Emberiza tristrami*
	15	画眉	*Garrulax canorus*
	16	白鹇	*Lophura nycthemera*
	17	黑鸢	*Milvus migrans*
	18	黑脸琵鹭	*Platalea minor*
	19	紫寿带	*Terpsiphone atrocaudata*
	20	红胸田鸡	*Zapornia fusca*
两栖类	21	虎纹蛙	*Hoplobatrachus chinensis*
	22	花狭口蛙	*Kalophrynus interlineatus*
	23	刘氏掌突蟾	*Leptobrachella laui*
	24	莽山角蟾	*Megophrys mangshanensis*
	25	小棘蛙	*Quasipaa exilispinosa*
爬行类	26	金环蛇	*Bungarus fasciatus*
	27	三索蛇	*Coelognathus radiates*
	28	梅氏壁虎	*Gekko melli*
	29	花龟	*Mauremys sinensis*
	30	中华鳖	*Pelodiscus sinensis*
	31	平胸龟	*Platysternon megacephalum*
	32	蟒蛇	*Python molurus bivittatus*

3.1.2 环境变量

环境变量对物种分布结果存在重要影响[23]。综合前人的研究基础，结合目标物种栖息地的环境特征与研究区数据可获取性等因素，本文选取气象变量、地形变量和人类活动干扰变量3类环境变量（表2），具体来源为：1）由世界气候数据库（WorldClim）下载19项2020年气候数据（分辨率为1 km）[24]；2）通过GlobeLand30数据集获取2020年土地利用／覆被数据（分辨率为30 m）[25]；3）通过地理空间数据云获取数字高程数据（DEM）（GDEM V3，分辨率为30 m）；4）各级道路数据获取自百度API，包括铁路、公路、高速、国道；5）大湾区行政边界来自于广东省公共地图服务系统，审图号为GS粤（2023）1032号；6）人口密度数据源于WorldPop中国1 km人口密度数据集。

研究借助ArcGIS 10.8完成数据预处理。首先，利用全国行政边界矢量数据对研究区域进行掩膜提取，获得大湾区2020年的气象变量、地形变量及人类活动干扰变量数据（分辨率为30 m）；其次，基于DEM数据进行水文分析，计算相应栅格与水系的欧氏距离；随后，从土地利用覆盖类型数据中提取建设用地，计算相应栅格与建设用地的欧氏距离；最后，所有栅格数据转换为ASCII格式。

3.2 研究方法

3.2.1 MaxEnt模型的运行与优化

MaxEnt模型用于模拟最大熵分布概率，利用目标物种的存在信息预测其在各种条件下满足最大熵时的潜在分布[26]。具体而言，利用凸包方法在研究区域内生成伪观测点（背景点或伪缺失点）的分布区域，使其更合理、更贴近实际环境条件。这种方法能够有效增强预测模型对环境条件的学习，可更准确地描述物种的分布规律[27]。为确保模型精度并减少空间过度拟合，本研究使用ENMTools将每个栅格（1 km×1 km）中同一物种的多个分布点压缩为1个分布点，最终得到有效物种分布数据1 891个。随后，将有效物种分布数据（有效分布点≥5）和环境变量导

表2：环境变量数据

代码	变量名称	单位
	气象变量	
Bio1	年均温	℃
Bio2	昼夜温差月均值	℃
Bio3	等温性	%
Bio4	温度季节性变化标准差	—
Bio5	最暖月最高温	℃
Bio6	最冷月最高温	℃
Bio7	气温年较差	℃
Bio8	最湿季均温	℃
Bio9	最干季均温	℃
Bio10	最暖季均温	℃
Bio11	最冷季均温	℃
Bio12	年均降水量	mm
Bio13	最湿月降水量	mm
Bio14	最干月降水量	mm
Bio15	降水量变异系数	—
Bio16	最湿季降水量	mm
Bio17	最干季降水量	mm
Bio18	最暖季降水量	mm
Bio19	最冷季降水量	mm
	地形变量	
DEM	高程	m
Slope	坡度	°
Aspect	坡向	—
	人类活动干扰变量	
Landuse	土地利用/覆被类型	—
Dis_river	距水体距离	m
Dis_build	距建设用地距离	m
Dis_road	距道路距离	m
People	人口密度	人／km^2
Buildland	建设用地分布	m^2

注

表格中所有降水量相关的变量都为均值。

入模型，而后随机选用75%的分布点作为训练数据进行分布预测，其余25%用于模型验证测试。除特别说明外，其余模型参数均采用默认设置。随后，采用刀切法进行10次重复实验并计算每个栅格的物种分布概率平均值。使用受试者工作特征曲线（Receiver Operator Characteristic，ROC）对模型进行评估，以ROC下的面积值（Area Under the Curve，AUC）衡量模型预测准确度，评估标准为：0.6～0.7为较差，0.7～0.8为一般，0.8～0.9为良好，0.9～1.0为优秀[28]。在删除AUC结果小于0.7的物种分布数据后，最终确定了各物种的潜在分布区预测结果。

3.2.2 环境变量相关性评估

为提升模型准确性、减少环境变量共线性带来的过度拟合误差[29]，本研究通过刀切法分析28种环境变量的贡献率及置换重要性，并去除预模拟实验中贡献率小于1的变量。同时，使用ENMTools对环境变量进行皮尔逊相关性分析，以计算变量间的自相关系数。现有研究常以相关性系数绝对值大于0.7为标准，剔除贡献率不足的变量，以确保最终用于实验建模的环境变量的合理性[29]。然而，本研究的环境变量数据波动相对较小，内部关联性呈现出较为稳定的态势。若采用0.7作为阈值，会过早地剔除一些有价值的变量，致使模型损失部分有效信息。因此，本研究最终选用0.8作为识别高度相关变量的阈值。

3.2.3 Zonation模型的运行与优化

Zonation、Marxan和C-Plan是当前研究与实践中广泛运用的系统性保护规划工具[6,30-31]。Zonation多被用于模拟大尺度空间的保护优先化布局[32]。相较于其他软件，它能够识别单一或多个物种的生态保护优先区，并且强调景观连通性，能够最大化突显生物多样性保护的价值[33]。本研究中使用Zonation v4软件进行大湾区重点陆生野生动物生态保护优先区规划。首先，运用核心区移除的方法，在保留研究物种分布核心区的同时，移除物种适宜性最小价值栅格单元（如环境恶劣、缺乏食物资源）；其次，采用边缘移除的方法从景观边缘移除价值最小的栅格，使其保持结构连通性[34]。计算过程中，翘曲因子数值决定了每次移除的栅格数量[12]，本研究中翘曲因子采用默认值“1”。

考虑到建设用地或将显著影响物种保护区域划分，研究选用Zonation中的删除掩膜功能来排除不良区域，从而提升模拟结果准确性。其他参数均设置为默认值。此种设置方式在兼顾研究区域特殊性质的同时，也可一定程度提高模型可靠性。

因不同物种的保护价值各异，物种越珍稀，越应在模型预测时被赋予更高的权重。因此，在进行多物种生态保护优先区识别之前，需明确各物种保护级别并设置相应权重[11,35]。本研究依据不同物种的稀有性、濒危等级及其经济社会价值等方面设置权重（表3）。

人类活动对生态用地划分具有重要影响[36]。20世纪以来，人口和经济活动的急速增长已造成栖息地改变、入侵物种增加、气候变化及环境污染等问题[37]，进而引发了生物多样性危机[38]。因而，在生态研究中必须考虑人为活动或用地扩张对生态环境的潜在影响。在国际相关研究中，许多学者将土地价值或土地使用费纳入模型预测变量[39]。相较之下，中国相关研究则较少将人类活动纳入预测参数；且由于各区域情况的复杂性，难以精确计算单位土地的使用费。因此，本研究为增强研究结果的准确性和可靠性，采用了一种创新方法——利用删除掩膜方式将现有建设用地分布作为变量，由此将人类活动的影响合理地纳入优先区识别中。

研究随后利用R语言统计软件，对不同类别的物种分别绘制景观退化－物种栖息地消失风险比例曲线，以对比分析不同物种对景观退化的响应差异。同时，在曲线上标注关键数据点，如景观退化达到一定程度时，物种栖息地消失风险开始显著增加的转折点。研究进一步通过计算曲线的斜率、曲率等参数，识别景观退化与物种栖息地消失风险之间的定量关系，评估风险增加的速率和变化趋势，确定影响风险比例曲线的关键因素，并为制定针对性的保护策略提供科学依据。例如，若分析结果表明某一物种的栖息地消失风险对特定指标（如植被覆盖度下降）最为敏感，则应在保护工作中应重点监测并制定相应恢复措施。

在此基础上，本研究进一步识别景观退化比例阈值为保护基准。一方面，保证在该阈值下的生态保护优先区能够有效保护物种分布，维持生物多样性的基本稳定，避免因栖息地丧失过多导致物种生存面临严重威胁。另一方面，从资源利用的合理性角度出发，在实现对关键物种和生态系统有效保护的同时控制成本并实现资源的合理分配。

根据2022年《生物多样性公约》发布的全球2030年生态系统保护目标，届时需实现有效保护和管理至少30%的陆地和内陆水域、海洋和沿

表3：物种权重设置依据

IUCN濒危等级／国家保护等级	权重
极危（CR）／国家一级保护动物	8
濒危（EN）	4
易危（VU）／国家二级保护动物	2
近危（NT）	1
无危（LC）	1

注

1. 本研究物种权重设置综合参考IUCN红色名录、《国家重点保护野生动物名录》和《中国生物多样性红色名录》，其中《中国生物多样性红色名录》使用了IUCN濒危等级命名方式。
2. 若同一物种基于不同分类标准对应多种权重，则选取最高权重值进行设置。

海区域，并至少对30%的已退化陆地和内陆水域生态系统、海洋和沿海生态系统采取修复措施的目标[40–42]。因此，本研究选取Zonation模型结果中保护价值前30%的栅格作为保护优先区域。为优化资源配置，精准保护生态关键区域，本研究结合不同区域的生态敏感性、生态系统完整性及受威胁程度，在ArcGIS 10.8中使用重分类工具对模型计算结果进行分级，将保护价值前10%、20%和30%的区域分别设立一级、二级和三级生态保护优先区。

4 结果与分析

4.1 MaxEnt模型模拟评价

根据环境变量对MaxEnt模型的相对贡献值结果可知，对哺乳类动物而言，高程、建设用地分布及降水量变异系数的贡献率和置换重要性较为显著；于鸟类而言，降水量变异系数、最冷季降水量和距水体距离的贡献率和置换重要性则较为突出；于两栖类动物而言，降水量变异系数、最干季降水量和距水体距离的影响较大；于爬行类动物而言，坡度和建设用地分布的贡献率和置换重要性较高。

4.2 潜在栖息地分布

图1 ~ 4分别呈现了哺乳类、鸟类、两栖类、爬行类的潜在栖息地分布。图中红色区域代表高度适宜物种栖息的地区，说明该区域可能拥有丰富的食物来源、适宜的气候条件或较好的生态条件。蓝色区域则代表适宜性较低的栖息地，其环境条件或不利于相应的物种生存。图中红色越深表示栖息地适宜性越高，蓝色越深表示栖息地适宜性越低。

4.3 空间优先保护格局

4.3.1 栖息地评价

将32种重点陆生野生动物潜在分布的栅格数据按照分类分别输入Zonation模型，获得研究区域内4类物种的空间优先保护格局及景观退化 – 物种栖息地消失风险比例曲线（图5）。研究区域内各类物种栖息地消失的风险会随着景观退化比例的提高而逐渐上升。就哺乳类动物而言，当景观退化的比例低于20%，其栖息地消失风险的增长率较平稳；当景观退化比例达到95%，其栖息地的平均消失风险将上升至40%；而后，其消失风险会迅速升高，直至景观退化比例增至100%后，现有物种将全部灭绝。对爬行类动物而言，当景观退化比例达到95%时，其栖息地的平均消失风险升至40%；随后，栖息地消失风险将快速增长至100%。而鸟类与两栖类物种的生存环境面临的风险相对较低，即直至景观退化比例分别为95%和97.5%时，两者栖息地平均消失风险才达到25%和30%，而后则进入锐增阶段。

在本研究中，当景观退化比例保持在70%以下时，各类物种栖息地保留比例始终稳定在70%以上。当景观退化比例持续增加，会导致物种栖息地和分布情况发生明显变化，保护效果下降。因而，本研究选定70%的景观退化比例为实现物种有效保护的关键阈值。

一级、二级、三级生态保护优先区结果（图6）显示，哺乳类动物栖息地总体上都避开了建筑高密度地区，主要集中于地形复杂多样的区域，包括珠江口的低地湿地生态系统、沿海岸带的自然保护区及大湾区北部的山区森林和次生林地。具体分布于肇庆市北部鼎湖山一带，惠州市北部罗浮山区，深圳市福田红树林自然保护区、梧桐山和大鹏半岛，中山市靠近珠江口的湿地和红树林，江门市西部和南部沿海区域，珠海市中部和南部沿海区域，澳门北部及南部绿地，以及香港大屿山和联合国教科文组织世界地质公园（西贡园区）原始森林与沿海岸线区域。这些区域为哺乳动物提供了丰富的食物来源和受干扰较少的生活环境。

鸟类栖息地分布较为广泛，主要分布于为多种候鸟提供了重要的停歇和筑巢地点的沿海岸线的湿地和红树林，以及河流周边的冲积平原和水田。同时，对于依赖特定生态位的地栖鸟类而言，内陆的开放林地和草地亦是重要栖息地。具体而言，广州市南沙湿地公园，深圳市莲花山公园和大鹏半岛市级自然保护区，珠海市金湾区湿地公园和斗门区的红树林区，汕头市濠江区沿岸和南澳岛自然保护区，韶关市丹霞山区域，佛山市西樵山和顺德区的湿地公园，江门市圭峰山国家森林公园，肇庆市鼎湖山，惠州市西湖和罗浮山区域，中山市五桂山和沿珠江湿地，东莞市松山湖生态园和虎门镇沿海湿地，澳门湿地和郊区山地，香港大屿山、梅窝及世界地质公园（西贡园区）皆是大湾区内鸟类栖息地的潜在分布区域。

两栖类与爬行类物种的生活习性相似，二者均偏好溪流、湖泊和湿地等水系丰沛的地区，拥有丰富水生植物者尤甚；同时常见于丘陵和低山森林。这些区域能够为其提供适宜的温度条件，以及用于繁殖和觅食的多样生境。肇庆市七星岩、星湖和鼎湖山区域，江门市西部沿海的珠江口湿地和南部台山、中东部内陆的开平碉楼与古村落及下辖恩平市的河流和湿地区域，珠海市横琴岛、九州岛及其周边红树林、沿海湿地，广州市白云山、大夫山林区、花都湿地公园，惠州市惠阳区、大亚湾和罗浮山区域，东莞市东南部松山湖，深圳市梧桐山及大鹏新区，澳门北部郊野公园、南部澳门湿地，香港大屿山、世界地质公园（西贡园区）、香港湿地公园等沿海区域均是大湾区两栖类和爬行类物种栖息地的主要潜在分布地区。

4.3.2 生态保护优先区分布

研究将32个物种的潜在分布数据输入Zonation模型，并为各栅格赋予相应权重，获取大湾区重点陆生野生动物整体生态保护优先区划分结果（图7）。可见，生态保护优先区大多分布于山区森林地带、沿海及海岸带、城市近郊的自然保护区这3类具有明显地理特征的区域之中。肇庆市

鼎湖山、七星岩等位于中部和北部的山林，以及惠州市交界处的罗浮山地区都为多种陆生野生动物提供了栖息地和避难所。江门市、中山市和珠海市的珠江口沿海湿地和红树林，以及深圳市中西部至东部的沿海地区，则是众多水栖和陆生动物的关键栖息地，于维持生态系统的平衡和生物多样性具有重要价值。东莞市松山湖生态园，澳门郊野公园，以及香港大屿山、世界地质公园（西贡园区）等沿海国家公园等地，虽地处城郊，但皆为动物提供了宝贵的栖息空间。

通过将生态保护优先区与大湾区已建成的自然保护区叠加对比发现（图8），大部分生态保护优先区与现有自然保护区重合，但仍存在部分尚未覆盖的保护空白区域。

5 讨论

5.1 降水季节性对重点陆生野生动物潜在分布的影响

根据影响重点陆生野生动物分布的环境变量分析结果，研究发现气候变量对物种分布的影响强度高于地形变量与人类活动干扰变量。其中，降水季节性（即最湿季降水量、最干季降水量、最暖季降水量和最冷季降水量）是影响相关物种潜在分布的主导环境变量，体现了降水量在生态系统结构和生态功能中的关键作用[43]。

降水季节性通过影响水资源供给、食物链关系、繁殖方式、生境适宜性及物种耐受性等多个层面，在生态系统中发挥着至关重要的作用，对物种栖息地分布的贡献率极高。首先，充足且稳定的水源是许多生物赖以生存的基础，而降水季节性的变化可直接影响水资源供给或导致季节性水资源短缺。这种水资源供需矛盾是决定物种分布的重要因素。其次，降水季节性影响着植被的生长和分布[44-45]，进而影响以植物为食的诸多动物的栖息地选择和分布格局。此外，很多物种的交配、孵化、幼仔成长等繁衍活动都与季节性降水关系密切。适宜的降水模式可为其提供良好的繁衍环境，反之则会限制物种分布范围。另外，不同的降水模式可以形成多样的栖息地条件，如湿地、森林、草原等，其适宜性也直接决定了物种栖息地的分布。最后，不同物种对降水季节性变化的敏感程度也存在显著差异，例如，微小的降水变化便可能超出对降水极其敏感的物种适应范围并影响其栖息地分布。

综上所述，未来的陆生野生动物保护和管理工作应考虑降水季节性变化，及时采取措施保护和恢复野生动物栖息地，以确保地区生物多样性和生态平衡稳定。同样，未来研究还应深入探讨降水季节性对野生动物种群数量、分布范围和迁徙行为等方面的具体影响机制，为生物保护和管理提供科学依据。

5.2 优化空间布局

对比现有自然保护区，本研究识别了研究区域内重点陆生野生动物的保护空白——集中于大湾区东部、南部人类活动频繁的建成区（图9）。深圳市、东莞市及香港3座城市的生态保护优先区分布较密集且优先级较高，但可继续用于城市建设开发的土地面积有限。因此，如何妥善处理城镇化与生态保护之间的关系是这些城市共同面临的发展难题。为避免建设用地侵占生态用地，应当合理规划用地边界、制定并完善保护区条例。在实践中，为协调经济发展和生态保护的关系，可将经济发展带来的红利投入到生态保护和恢复工作中，以实现二者共同发展。此外，还可发展垂直绿化等创新技术，在建成区内打造更多生物栖息地，保护和提升生物多样性，实现可持续城市发展和生态保护目标，促进人类与自然和谐共存。

5.3 纳入人类活动干扰变量的合理性与局限性

本研究通过使用删除掩膜的方式，将建设用地分布视为环境变量，在成功剔除既存开发区的同时提高了保护区计算的准确性，从而将人类活动影响合理纳入生态保护优先区识别过程中。然而，本方法也存在一定局限性。首先，由于建成区通常以人口居住和产业发展为核心需求，其内部环境受人类活动影响较大，难以维持原有的自然生态系统功能。因此，将其排除在外有助于提升保护区计算的生态完整性和有效性，以更好地实现生态保护的目标。然而，简单地认为建成区不适宜作为栖息地的观点或有些片面。实际上，一些物种可能已经适应建成区环境，武断地将建成区排除可能会忽视其内部生态保护潜力，造成潜在保护区域的遗漏。

6 总结与展望

本研究以粤港澳大湾区为背景，以32种重点陆生野生动物物种为研究对象，通过集成物种分布预测模型MaxEnt与多物种保护规划模型Zonation，成功预测了该地区重点陆生野生动物的生态保护优先区。所得结论如下：1）降水季节性对物种潜在分布具有显著影响，物种适宜栖息地主要集中在降水充沛且蓄水性较好的区域；2）生态保护优先区分布主要位于肇庆市北部和中部山林，江门市沿海区域，珠海市中部至南部沿海区域，中山市中部、东北部至沿海区域，惠州市中部至沿海区域，东莞市东南部，深圳市中西部及沿海区域，澳门北部及南部区域，和香港沿海区域；3）预测的生态保护优先区域与大部分已建立的自然保护区重合，但在大湾区东部、南部沿海仍存在保护空白区域。

本研究的结果可对其他地区推进生态保护提供有益参考和借鉴。然而，本研究仅为一项概念性规划的尝试，在制定实际规划目标时还需要考虑如下因素。第一，应更详尽、全面地收集调查物种分布信息。本研究仅考虑了重点陆生野生动物，尚未涵盖研究区内所有受保护物种。同时，分布点数据只包含部分已公开信息，且相关数据大多分布于已规划

的保护区或有观测者出现的区域。还需针对现有保护区之外和人迹罕至的区域开展更多的红外相机监测或野外调查，以进一步获取物种分布信息。第二，应将未来城市扩张及气候变化等动态因素纳入自然保护区规划过程。人口增长和快速城镇化对城市生态带来的影响不容忽视，且在全球气候变暖背景下，降雨模式、气温等环境因素也会发生动态变化。作为沿海区域，大湾区还面临海平面上升、风暴潮等气候变化带来的影响。因此，未来规划中须兼顾这些因素的综合影响，以确保自然保护区划定的可持续性与适应性。

补充材料

可通过https://doi.org/10.15302/J-LAF-0-020026查看本文补充材料。

图 1. 哺乳类潜在栖息地分布结果
图 2. 鸟类潜在栖息地分布结果
图 3. 两栖类潜在栖息地分布结果
图 4. 爬行类潜在栖息地分布结果
图 5. 景观退化 - 物种栖息地消失风险比例曲线
图 6. 4 类物种一级、二级、三级生态保护优先区分布图
图 7. 大湾区重点陆生野生动物生态保护优先区分布图
图 8. 大湾区重点陆生野生动物生态保护优先区与现有自然保护区的分布对比
图 9. 大湾区重点陆生野生动物保护空白区域