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Predicted Potential Distributions of Two Rare and Critically Endangered Bird Species in China Based on the MaxEnt Model

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Abstract: Biodiversity loss has become a global ecological crisis, and the conservation of Critically Endangered (CR) species is particularly urgent. In response, this study focuses on two CR bird species with markedly contrasting ecological traits, *Emberiza aureola* and *Aythya baeri*. Using species occurrence records and 22 environmental variables, we applied the MaxEnt model to simulate their potential suitable habitats. The results indicate that: the distribution of *Emberiza aureola* is primarily driven by precipitation of the driest month, precipitation seasonality, and slope. Its habitat suitability shows a unimodal response to isothermality and is enhanced in flat plains characterised by higher precipitation in the driest month and moderate precipitation seasonality. In contrast, *Aythya baeri* is strongly influenced by slope, precipitation of the warmest quarter, and mean temperature of the driest quarter, exhibiting a bimodal response to isothermality. Its suitability peaks under low precipitation conditions in the warmest quarter, reflecting its reliance on shallow, low-disturbance wetlands in open plains. The spatial distribution patterns of the two species differ markedly. Although both are confined to low-relief areas with slopes below 1°, the suitable habitats of *Emberiza aureola* are more extensive and continuous, with high-suitability areas concentrated in the Northeast China Plain and eastern Inner Mongolia. In contrast, the suitable habitats of *Aythya baeri* are highly fragmented and concentrated in the coastal wetlands of Liaodong Bay and the lake systems of the middle and lower Yangtze River Basin. By systematically comparing the distributional patterns of these two CR species at a macroecological scale, this study clarifies the constraints imposed by climatic and topographic factors, providing scientific support for optimising China's protected area networks, implementing targeted wetland restoration, and advancing differentiated habitat management.

Keywords: *Emberiza Aureola*; *Aythya Baeri*; MaxEnt; Potential Suitable Habitat; Critically Endangered Species.

1. Introduction

Biodiversity loss has emerged as a global ecological crisis, where the rate of species extinction now far exceeds natural background levels due to intensified anthropogenic activities [1]. The conservation of rare and endangered species constitutes the fundamental baseline for maintaining ecosystem stability and biosecurity. Consequently, accurately identifying their potential suitable habitats and analysing key limiting factors acts as a prerequisite for the scientific formulation of conservation strategies [2]. China is one of the nations with the richest avian diversity globally, hosting over 1,500 bird species. A significant proportion of these are listed as national key protected species or are considered globally threatened [3]. Among the numerous endangered avian species, the *Emberiza aureola* and *Aythya baeri* stand out as typical Critically Endangered (CR) species. Their populations have exhibited a precipitous decline over the past few decades, rendering them subjects of high global conservation concern [4]. The *Emberiza aureola* was once widely distributed across Eurasia; however, under the dual pressures of habitat loss and excessive hunting, its range has contracted dramatically [5]. Similarly, the *Aythya baeri*, a rare waterfowl endemic to East Asia, has been impacted by wetland degradation and water pollution, resulting in a global population of fewer than 1,000 individuals [6][7]. In the face of an increasingly severe survival crisis, analysing the macro-scale distribution patterns and response mechanisms to environmental changes of these two Critically Endangered species—which possess distinct ecological habits (Passeriformes and Anseriformes)—has become an urgent priority for the formulation of precise conservation strategies.

Although conservation biology research concerning the *Emberiza aureola* and *Aythya baeri* has covered multiple dimensions such as taxonomic status, migration route tracking, population dynamics monitoring, and conservation countermeasures [8]-[9], predictive studies regarding the spatial patterns of their potential suitable habitats remain relatively insufficient. While existing studies have attempted to utilise Species Distribution Models (SDMs) to explore habitat suitability in specific regions, they generally suffer from limitations in spatial scale. These include a focus solely on localised breeding or wintering grounds, the use of singular environmental factors, and a lack of systematic cross-species comparison. Particularly within the context of global climate change and high-intensity anthropogenic disturbance, the ecological niches of species may undergo significant spatiotemporal shifts [10]. However, current academic understanding regarding the identification of limiting environmental factors for these two Critically Endangered birds remains unclear, and systematic predictive research targeting the the *Emberiza aureola* and *Aythya baeri* remains scarce.

In recent years, Species Distribution Models have been widely applied to investigate ecological niche characteristics and predict the potential distributions of species. Among these, the Maximum Entropy Model (MaxEnt) has been extensively utilised in suitability studies for endangered fauna and species with specific habitat requirements, owing to its robust adaptability to small sample sizes and high predictive accuracy [11][12]. The MaxEnt model is capable of integrating existing species distribution data with multi-source environmental factors, such as climate and topography. This facilitates the prediction of potential suitable habitats under varying temporal scales and climatic conditions, thereby providing a scientific basis for the conservation management and habitat restoration of endangered birds.

Consequently, this study focuses on two Critically Endangered bird species distributed within China—the *Emberiza aureola* and *Aythya baeri*. By integrating modern bioclimatic variables with species distribution records, we constructed a MaxEnt-based habitat suitability model to: (1) identify the key environmental factors influencing the distribution of both species; (2) analyse the distribution patterns of potential suitable habitats for these two Critically Endangered birds under current climatic conditions; and (3) compare the differences in their ecological niche characteristics, thereby providing scientific support for in-situ conservation and the optimisation of protected area networks for Critically Endangered birds. The findings of this study offer a significant reference for biodiversity conservation planning at both national and regional levels, holding substantial importance for enhancing the scientific rigour and precision of endangered bird conservation.

2. Materials and Methods

2.1. Species Distribution Data and Processing

In this study, distribution data for the two rare and endangered bird species were primarily obtained from database resources, including the China Bird Report Centre (http://www.birdreport.cn/) and the Global Biodiversity Information Facility (GBIF, https://www.gbif.org), alongside reports from relevant literature. To mitigate high redundancy and spatial autocorrelation within the point data, we utilised the ENMTools package (Version 1.4.3) in the R programming language to perform geographical verification and logical cleaning of the distribution records for each species [13]. We removed noisy data points containing coordinate errors, duplicates, missing values, and invalid entries, ensuring that only one distribution point was retained within each 1 km × 1 km grid cell [14]. Ultimately, a total of 275 distribution points for the *Emberiza aureola* and 524 points for the *Aythya baeri* within China were obtained, as shown in Fig. 1.

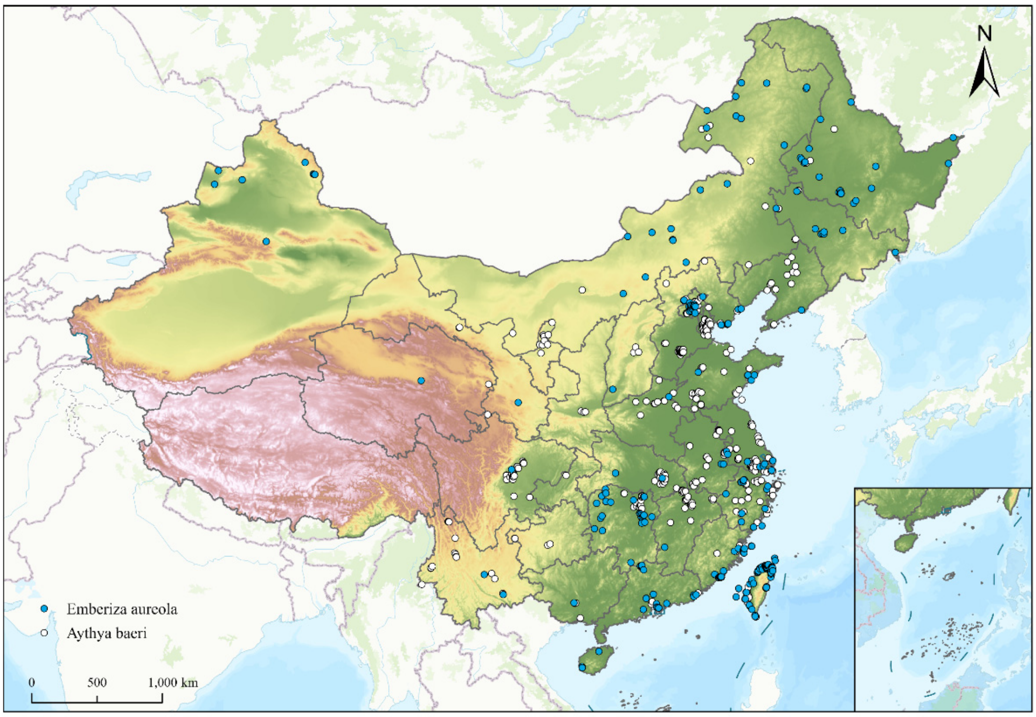

Fig 1. Distribution sites of two rare and endangered bird species in China

2.2. Environmental Variable Selection and Processing

A total of 22 environmental variables were selected for MaxEnt model prediction in this study, including 19 bioclimatic variables and 3 topographic factors (Table 1). The 19 bioclimatic variables were sourced from the PaleoClim database (www.paleoclim.org) at a spatial resolution of 2.5 arc-minutes (approximately 5 km). These bioclimatic factors are specifically designed for constructing Species Distribution Models (SDMs), as they are closely linked to the physiological processes and ecological adaptation of the studied species, thus being highly relevant for predicting potential suitable areas. The topographic factors included elevation, slope, and aspect, all extracted based on Digital Elevation Model (DEM) data from the China Geospatial Data Cloud Platform (http://www.gscloud.org/).To ensure consistency across different data sources, all 22 environmental variables were unified to the same coordinate system (WGS 1984) and spatial resolution (2.5 arc-minutes), cropped using a consistent study area boundary, and ultimately converted to ASCII raster format for use in the MaxEnt model. Furthermore, the administrative boundary data used in this research were obtained from the National Administration of Surveying, Mapping and Geoinformation (https://www.ngcc.cn), with the review number GS(2024)0650, ensuring the accuracy and standardisation of the study area definition.

Since multicollinearity among environmental variables can lead to model overfitting, the Variance Inflation Factor (VIF), implemented via the R package usdm, was used to test for multicollinearity among all variables [15]. A VIF > 10 indicates a high degree of correlation between environmental variables. After calculating the VIF for all variables using the vifstep function, variables with VIF > 10 were sequentially removed, retaining only those with VIF < 10 for input into the model.

Table 1. Summary statistics of environmental variables

Vatiable	Vatiable name	Description	Unit
Bioclimatic variables	bio1	Annual Mean Temperature	℃
	bio2	Mean Diurnal Range	℃
	bio3	Isothermality	%
	bio4	Temperature Seasonality	-
	bio5	Max Temperature of Warmest Month	℃
	bio6	Min Temperature of Coldest Month	℃
	bio7	Temperature Annual Range	℃
	bio8	Mean Temperature of Wettest Quarter	℃
	bio9	Mean Temperature of Driest Quarter	℃
	bio10	Mean Temperature of Warmest Quarter Quarter	℃
	bio11	Mean Temperature of Coldest Quarter	℃
	bio12	Annual Precipitation	℃
	bio13	Precipitation of Wettest Month	mm
	bio14	Precipitation of Driest Month	mm
	bio15	Precipitation Seasonality	mm
	bio16	Precipitation of Wettest Quarter	mm
	bio17	Precipitation of Driest Quarter	mm
	bio18	Precipitation of Warmest Quarter	mm
	bio19	Precipitation of Coldest Quarter	mm
Topographic factors	Altitude		m
	Slope		°
	Aspect		-

2.3. MaxEnt Model Construction and Accuracy Assessment

The filtered environmental variables and their corresponding species occurrence points were imported into the model. The data were randomly partitioned, with 75% of the occurrence points used for predicting potential suitable habitat and the remaining 25% used for assessing model accuracy [11]. Within the MaxEnt model configuration interface, the Jackknife procedure and the plotting of response curves were selected. The model was set to run for 10 replicates, and the mean value across these 10 runs was taken as the final prediction result [16]. The Jackknife test assesses the importance value of various environmental variables on the distribution of the two rare and endangered bird species, *Emberiza aureola* and *Aythya baeri*, simultaneously identifying variables with high contribution and significance. The Area Under the Curve (AUC) of the Receiver Operating Characteristic curve (ROC) is used to denote the predictive accuracy of the model. Model accuracy is categorised into the following levels: failed (AUC ≤ 0.6), poor (0.6 < AUC ≤ 0.7), fair (0.7 < AUC ≤ 0.8), good (0.8 < AUC ≤ 0.9), and excellent (0.9 < AUC ≤ 1) [17].The prediction output of the model ranges from [0, 1], where a higher numerical value indicates stronger habitat suitability for the species. To facilitate the identification of different grades of potential suitable areas, this study employed the Natural Breaks classification method on the MaxEnt model output raster to delineate the species' habitat suitability levels. The potential habitats were classified into four grades: unsuitable area (0 ~ 0.1), low-suitability area (0.1 ~ 0.2), medium-suitability area (0.2 ~ 0.5), and high-suitability area (0.5 ~ 1) [18][19].

3. Results and Analysis

3.1. Model Accuracy Evaluation and Key Environmental Influencing Variables

The MaxEnt model was used to simulate the distributions of the *Emberiza aureola* and *Aythya baeri* over 10 replicates. The mean AUC values were 0.921 and 0.923, respectively, indicating that the model predictions achieved an excellent level of accuracy (Fig. 2).

Analysis of the contribution rates for the nine selected environmental variables, based on the Jackknife procedure, revealed that the primary variables influencing the distribution of the *Emberiza aureola* were, in descending order: Precipitation of Driest Month (38.27%), Precipitation Seasonality (14.03%), Slope (12.22%), Isothermality (10.38%), Precipitation of Warmest Quarter (8.74%), and Mean Temperature of Driest Quarter (6.46%). These six factors accounted for a cumulative contribution rate of 90.10%.

The dominant factors influencing the distribution of the *Aythya baeri* were, in descending order: Slope (44.72%), Precipitation of Warmest Quarter (24.43%), Mean Temperature of Driest Quarter (15.21%), Precipitation Seasonality (6.66%), Isothermality (3.94%), and Mean Diurnal Range (2.69%). The cumulative contribution rate of these factors reached 97.64% (Fig. 3).

The overall results demonstrate that the distributions of both rare and endangered bird species are driven by the combined effects of multiple environmental factors, with the primary influencing factors showing divergence between the two species.

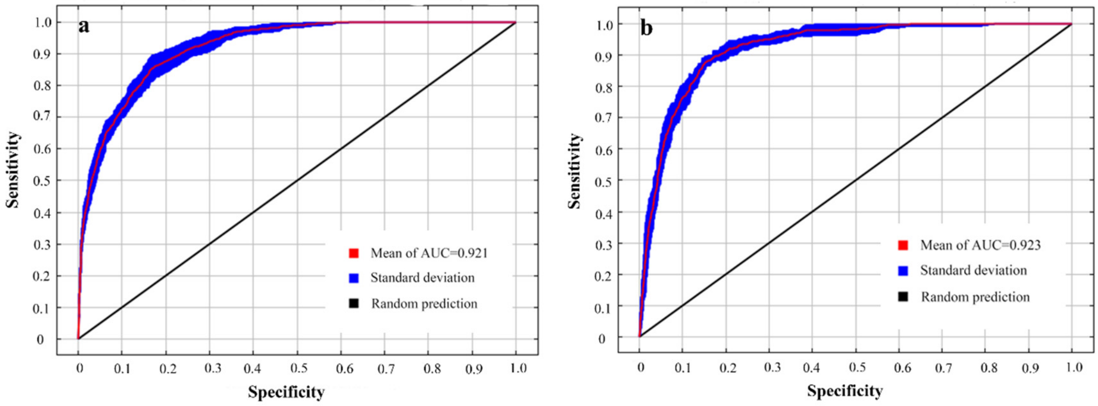

Fig 2. Receiver operating characteristic curve of maximum entropy model. a. *Emberiza aureola*; b. *Aythya baeri*.

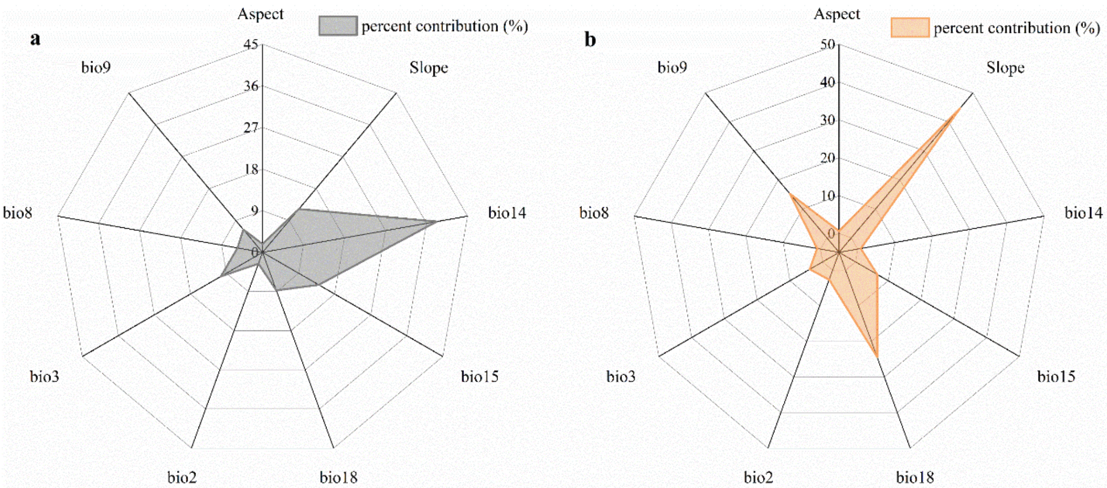

Fig 3. Relative contributions of environmental variables selected by MaxEnt models for two rare and endangered bird species. a. *Emberiza aureola*; b. *Aythya baeri*.

3.2. Environmental Variable Response Curves

The study results indicate a clear divergence in the predicted survival probability response of the *Emberiza aureola* and *Aythya baeri* to various environmental variables (Fig. 4). Notably, the predicted suitability probability of *Aythya baeri* was generally higher than that of *Emberiza aureola* for key climatic factors such as Mean Diurnal Range (bio2), Isothermality (bio3), and Precipitation of Warmest Quarter (bio18), and *Aythya baeri* exhibited a broader tolerance range for temperature factors. Both species showed a decrease in survival probability as the Mean Diurnal Range increased. *Emberiza aureola* reached its maximum at 5.17℃ (0.36), while *Aythya baeri* peaked at 4.97℃ (0.72).The response of *Emberiza aureola* to Isothermality was unimodal, peaking at 21.32% (0.38). In contrast, *Aythya baeri* exhibited a bimodal response, reaching peaks at 21% and 48% (0.89 and 0.72, respectively). The survival probability for both species increased with increasing Mean Temperature of Wettest Quarter. *Emberiza aureola* reached its maximum when the temperature exceeded 32℃ (0.38), whereas Aythya baeri peaked at 24.46℃ (0.34). *Emberiza aureola*'s response to Mean Temperature of Driest Quarter was U-shaped, reaching its minimum near 0℃ (0.16) and stabilizing at 0.95 when the temperature exceeded 20℃. *Aythya baeri* stabilized at 0.77 when the temperature exceeded 20℃.

Both species showed an increase in survival probability with increasing Precipitation of Driest Month. *Emberiza aureola* reached its maximum when precipitation exceeded 200 mm (0.35), and *Aythya baeri* similarly reached its maximum when precipitation exceeded 200 mm (0.75). The response of both species to the Coefficient of Variation of Precipitation Seasonality was U-shaped. *Aythya baeri* reached its minimum at 70 mm (0.23) and its maximum at 138 mm (0.93). *Emberiza aureola* reached its minimum at 70 mm (0.15) and its maximum at 135 mm (0.99). The survival probability for both species initially decreased and then levelled off as Precipitation of Warmest Quarter increased. *Emberiza aureola* reached its maximum when precipitation was less than 110 mm (0.27), and *Aythya baeri* reached its maximum when precipitation was less than 113 mm (0.68). The suitability response to Aspect showed a consistent trend for both species: *Aythya baeri* peaked at an aspect of 350°(0.44), and *Emberiza aureola* peaked at 344°(0.22). Suitability for both species decreased as Slope increased, peaking when the slope was less than 1°(*Aythya baeri* at 0.48, *Emberiza aureola* at 0.26), and tending to stabilize when the slope exceeded 2°.

3.3. Potential Suitable Habitat Distribution

The potential suitable habitats for *Emberiza aureola* and *Aythya baeri* exhibit distinct spatial differentiation across China, showing a consistent overall pattern but with variations in core areas and suitability gradients (Fig. 5). The suitable habitat for *Emberiza aureola* is distributed as a continuous belt extending from Northeast China southwards through North China to Central China, demonstrating a typical latitudinal gradient. The area of its High Suitability Zone is 32.97×10^4 km^2, primarily concentrated in the northern and western parts of the Northeast Plain, including most of Heilongjiang and Jilin provinces and eastern Inner Mongolia, with a few fragmented high-suitability patches occurring in the southern North China Plain. The Medium Suitability Zone covers an area of 57.64×10^4 km^2, encircling the high-suitability areas and extending towards Liaoning, central Inner Mongolia, and the North China Plain, also covering parts of the plains along the middle and lower reaches of the Yangtze River. The Low Suitability Zone spans an area of 136.78×10^4 km^2, forming a continuous transition zone connecting Northeast, North, and Central China. Most of Western China, the Qinghai-Tibet Plateau, and Southern China are classified as Unsuitable Areas.

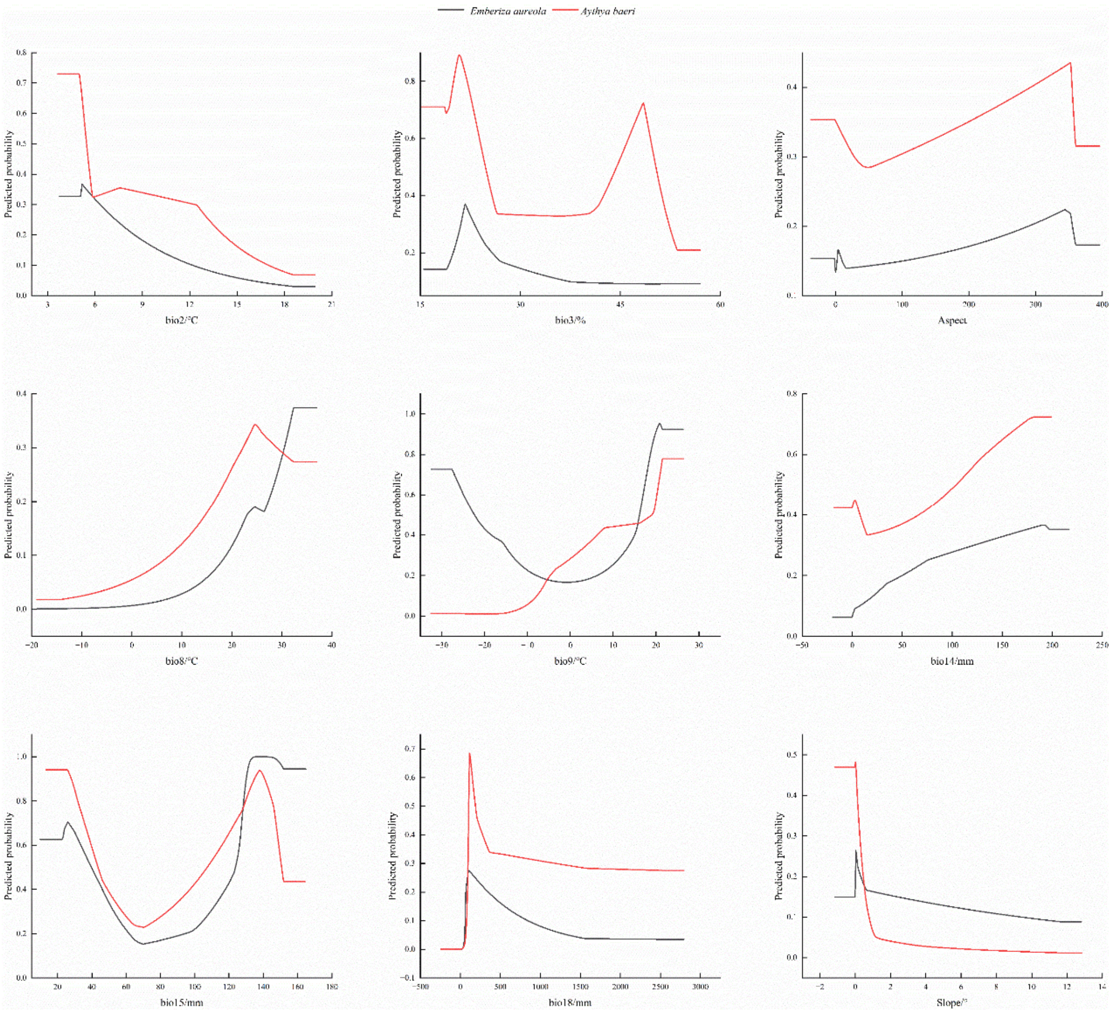

Fig 4. Environmental variable response curves of *Emberiza aureola* and *Aythya baeri*

In contrast, the suitable habitat for *Aythya baeri* is more dependent on wetlands, displaying a fragmented pattern concentrated along coasts and lakes. The area of its High Suitability Zone is 34.48×10^4 km^2, mainly concentrated in two major regions: the coastal areas of Liaodong Bay in the Northeast and the wetlands bordering Heilongjiang and Jilin; and the lake clusters from the eastern North China Plain down to the middle and lower reaches of the Yangtze River, including the Shandong Peninsula, the northern coast of Jiangsu, and large lakes in Anhui, Hubei, and Jiangxi provinces. The Medium Suitability Zone covers 33.76×10^4 km^2, primarily distributed in the gradient transition zones around the high-suitability areas, being particularly evident in North China, Shandong, Jiangsu, and Anhui, while also extending to northeastern Inner Mongolia and central Heilongjiang. The Low Suitability Zone spans 51.43×10^4 km^2, scattered across regions connecting the Northeast, North China, Central China, and the Southeast coastal areas. Western China and the Qinghai-Tibet Plateau are also classified as Unsuitable Areas. Overall, the suitable habitat distribution of *Emberiza aureola* is broader and more continuous, whereas the suitable areas for *Aythya baeri* are wetland-dependent, exhibiting a more pronounced fragmentation and regional concentration.

4. Discussion

4.1. Environmental Drivers of the Distributions of the Two Rare and Threatened Species

This study revealed differing environmental thresholds for habitat suitability between *Emberiza aureola* and *Aythya baeri*, reflecting distinct niche characteristics. Climatic variables — particularly metrics related to temperature variability and the temporal distribution of moisture — appear to play a dominant role in determining the distributional patterns of both species [20]-[22].

As a typical waterbird, *Aythya baeri* exhibited a bimodal response to isothermality in our models, which accords with previous findings that diving ducks and other waterfowl may have seasonal shifts in thermal requirements tied to their life-history cycle [23][24]. In our results the first bio3 peak (contributing 21%) likely corresponds to the breeding-season preference for a relatively stable thermal regime, whereas the second peak (48%) plausibly relates to wintering-season reliance on comparatively warmer water bodies.

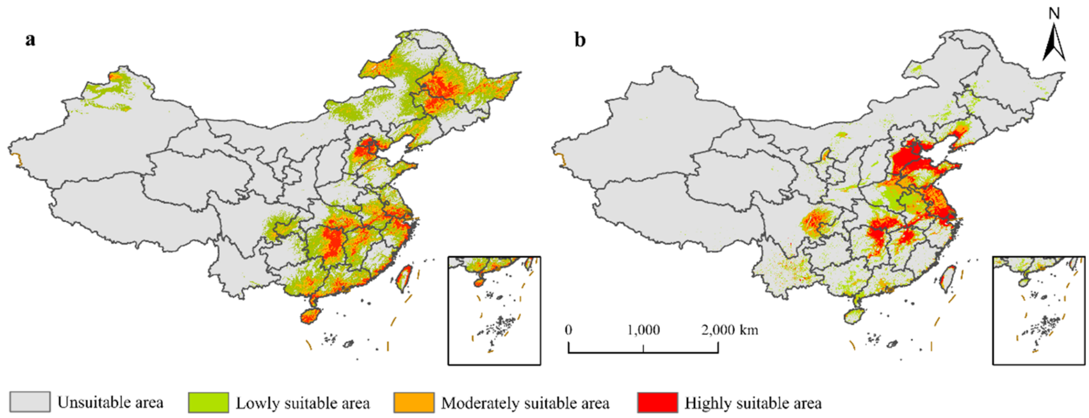

Fig 5. Potential suitable habitats for two rare and endangered bird species. a. *Emberiza aureola*; b. *Aythya baeri*.

Furthermore, the species' high and relatively stable suitability values under mean temperature of the driest quarter (bio9 > 0.77) suggest a winter thermal requirement that helps maintain open, unfrozen waters or limits energetic stress during cold months [24][25]. By contrast, *Emberiza aureola* displayed a single-peaked response to bio3 (peak suitability ~0.38) and a narrower tolerated range for mean diurnal temperature range (bio2), indicating higher climatic sensitivity than *Aythya baeri* — a pattern consistent with *Emberiza aureola*'s recognised vulnerability and its listing as Critically Endangered [5][20][26][27].

Regarding moisture-related variables, both species showed a pronounced U-shaped response to precipitation seasonality (bio15) in our models: moderate seasonal variability (around bio15 = 70 mm) was associated with lower suitability for both taxa. This could be explained ecologically by the fact that intermediate levels of seasonal fluctuation may either desiccate key wetland habitats or, conversely, produce episodic flooding — both of which can undermine the persistence and availability of food resources for breeding or overwintering [23][24]. Notably, *Aythya baeri*'s suitability with respect to precipitation in the warmest quarter (bio18) peaked at relatively low values (< 113 mm), which is compatible with its preference for shallow inland wetlands rich in aquatic vegetation; excessive precipitation can raise water levels and reduce shallow-foraging habitat availability — a response reported for some waterbird species [23][28].

Topographic factors exerted clear and similar constraints on both species: both are highly suited to very low-slope, flat areas (< 1°), directly reflecting their dependence on open plains, floodplain wetlands and shallow water bodies and avoidance of the microclimatic complexity and scarcity of water bodies in steep montane terrain [20][24].

4.2. Distributional Patterns and Spatial Change of the Two Rare and Threatened Species

Maps of habitat suitability for *Emberiza aureola* and *Aythya baeri* clearly projected the environmental thresholds and ecological habits revealed by the models. High-suitability areas for *Emberiza aureola* concentrated on the Northeastern Plain, consistent with earlier studies identifying this region as a core breeding area [20][21]. The region's summer climate and extensive meadows and agricultural wetlands provide abundant insect and seed resources. Southward extensions of suitability correspond to migratory routes and wintering areas, which explains the continuity of suitability patches along those corridors [5][20]. By contrast, *Aythya baeri* showed a more patchy, wetland-dependent pattern. High-suitability clusters occur in northeastern wetland complexes, the Bohai Rim wetlands and the middle–lower Yangtze floodplain lakes — areas that correspond to China's major natural lakes and important migratory/wintering wetlands [24] [28]. This pattern is consistent with the species' diving foraging ecology and its need for unfrozen winter water.

Under equivalent climatic gradients (for example along bio14), *Aythya baeri* often had higher predicted suitability probabilities than *Emberiza aureola*; yet the total mapped suitable area for E. aureola (sum of low, medium and high suitability = 22,738,000 km²) exceeded that of *Aythya baeri* (11,967,000 km²) in our outputs. This discrepancy is primarily attributable to differing spatial availability of preferred habitat types: *Aythya baeri*'s dependence on wetlands — which are naturally patchy and limited in area — constrains its realised distribution despite high climatic suitability in many places. In contrast, *Emberiza aureola* favours grassland and agricultural landscapes that are more continuously distributed across large areas, producing a larger potential suitable extent overall [20] [24] [28]. Both species were classified as unsuitable across western regions (e.g., the Tibetan Plateau and Xinjiang), indicating that extreme climatic conditions are likely primary range limits in those areas [11] [22].

4.3. Conservation Recommendations

Drawing on the habitat suitability patterns and key limiting factors revealed in this study, we recommend the implementation of a refined, spatially stratified conservation strategy. First, the Northeast China Plain, the Bohai Rim region and the lake complexes of the middle and lower Yangtze River should be designated as priority conservation units. Land-use change must be strictly regulated in highly suitable areas for threatened bird species to prevent the loss of core habitats caused by urban expansion [29]. Given the highly specialised dependence of *Aythya baeri* on stable wetland and aquatic environments, we recommend the establishment of wetland protection and restoration programmes aimed at maintaining water-level stability in key lakes and marshes. The construction of wetland ecological corridors is also essential to alleviate the effects of habitat fragmentation on population connectivity [30][31].

For *Emberiza aureola*, which occupies a wider geographic range and relies on open habitats, and considering that much of its suitable habitat overlaps with farmland and meadow landscapes, we recommend promoting wildlife-friendly agricultural practices across the Northeast and North China Plains. Measures such as reducing pesticide use and maintaining vegetated field margins can facilitate the coexistence of agricultural production and biodiversity conservation [32][33]. Furthermore, as both species exhibit sensitivity to climatic factors—including temperature variability and precipitation fluctuations—there is an urgent need to establish long-term "climate–habitat–population" monitoring schemes. Such systems would enable timely assessment of how extreme climatic events influence the carrying capacity of core habitats, providing a scientific basis for adaptive conservation planning [34][35].

Acknowledgments

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