Consideration of climate change impacts will improve the efficiency of protected areas on the Qinghai-Tibet Plateau

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ABSTRACT
The protection of migratory birds and their habitats is important to the ecological stability of the Qinghai-Tibet Plateau (QTP). Currently protected areas (PAs) were designed in accordance with species distribution patterns under current climatic conditions, thus ignoring climate change will lead to a decrease in the protection efficiency of PAs. In this study, using the flagship species Grus nigricollis, as an example, we used the maximum entropy (MaxEnt) model to simulate the distributions and conservation status of G. nigricollis and optimized the existing PA boundaries. The results showed that (1) suitable habitat- for G. nigricollis accounts for 12.48% of the QTP area, and the PAs established under current climatic conditions covered 17.84% of this suitable habitat area; (2) future climate changes will influence the distribution and quality of G. nigricollis habitats, and the average protection efficiency of the current PAs in four climatic scenarios will decrease from 17.84% to 15.31%; and (3) through optimization, the efficiency of existing PAs can be increased by 0.75 times and reach 28.37%, indicating PA planning must consider not only current climate conditions but also the effects of climate changes. Our results aim to address shortcomings in the conservation efficiency of PAs and provide an example for resolving mismatched PA boundaries and habitat changes for species.

Introduction
Migratory birds play essential and indispensable roles in maintaining ecosystem balance and sustainability (Whelan, Wenny, and Marquis 2008). To cope with their high caloric demands during the breeding season, migratory birds travel long distances to their breeding grounds, where they can obtain energy efficiently, thereby controlling the rapid growth of insects and small prey animals in those areas (Dingle 2014; Hu et al. 2016). Moreover, migratory birds act not only as predators but also as prey, increasing the complexity of the food web and increasing ecosystem stability (Bauer and Hoye 2014; Gilg and Yoccoz 2010; Henden et al. 2017; Runge et al. 2015). In addition, migratory birds act as carriers for plant seeds, and microorganisms and can help dismantle geographical isolation to some extent, thus providing increased biodiversity in local ecosystems (Viana, Santamaría, and Figuerola 2016). Due to environmental changes, migratory birds rely on multiple breeding and overwintering habitats across several regions for their survival (Thorup et al., 2007; Knudsen et al. 2011), therefore, migratory birds were always considered as the indicator species of protected areas efficiency (Runge et al. 2015). However, due to rapid climate change and intensive human activities, migratory bird habitats have suffered from serious challenges (IUCN, 2015), and more than 13% of birds worldwide are considered “endangered,” while another 9% are listed as “near threatened” (IUCN 2020), and the situation is even worse for migratory birds. Thus, it is urgent and necessary to protect migratory bird habitats in the face of climate change.

Migratory bird habitats are regulated by multiple factors (Nagy and Grabherr 2009; Ryan Norris and Marra 2007). Among these factors, the most important is ecosystem type and quality (Wiegand et al. 2008); for example, some migratory birds consistently live in high-elevation wetland ecosystems with abundant freshwater and vegetation coverage. Elevation and geological landforms are also important controls for migratory birds that are distributed only within an elevation range of 2500–5000 meters (Song et al. 2014). Human activities (including cattle grazing, urbanization, and ecological engineering) are also important influencing factors that cannot be ignored in most regions (Peng et al. 2020; Quan, Wen, and Yang 2002).

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In addition, ongoing climate change has already profoundly and diversely influenced migratory birds in many ways (Cox 2010; Pearce-higgins et al. 2015) by transforming the spatial distribution of suitable habitats and adjusting the timing of migration (Robinson et al. 2009). Specifically, climate change has led to changes in wetland areas, shifted vegetation distributions and decreased ecosystem stability (Robinson et al. 2009).

Approximately 13% of the world’s land surface has been delineated as protected areas (PAs); these areas play a critical role in protecting migratory birds (Cazalis et al. 2020). To date, most relevant studies have focused on the management, boundaries, and ecological and social benefits associated with PAs (Mackenzie 2012; Xu et al. 2019; Zimmerer, Galt, and Buck 2004), yet gaps in the research still exist on the current and future conservation efficiencies of PAs. For instance, climate changes will affect the habitat of specific species, which will lead to the migration of those species from PAs to their surroundings, resulting in a reduced conservation efficiency of those PAs (Gross et al. 2015; Möller, Rubolini, and Lehikoinen 2008). However, PA planning often focuses on species distributions established under current climatic conditions (Di Marco et al. 2017), ignoring the species distribution dynamics that are predicted under future climate change scenarios. Thus, to avoid the negative impacts of climate change on the habitats of migrating birds, PA planning should be conducted in consideration of not only the current distribution of the birds but also their response to climate change. In brief, determining how to optimize the efficiency of PAs by adjusting their boundaries with consideration of future climate change conditions is currently an urgent issue.

The Qinghai-Tibet Plateau (QTP) is a climate-sensitive region that is considered to be an amplifier of global climate change; thus, this region represents a natural laboratory for studying biological and environmental evolution processes (Baotian and Jijun 1996; Liu et al., 2014). Migratory birds were selected to evaluate PA efficiency, because they are sensitive to changes in their environment (Knudsen et al. 2011), and can accurately reflect rapid changes in climate. The QTP has become an indispensable survival, reproduction, and transit region for migratory birds. Due to the harsh winter climate of the QTP, this region has few resident birds in the winter, but migratory birds are provided with sufficient energy sources and habitat in the summer due to the well-developed water system in the region. As the flagship migratory bird of the QTP, Grus nigricollis, the black-necked crane, was selected as a representative regional migratory bird species in this study; G. nigricollis has both breeding and overwintering areas on the Tibetan Plateau, and there is a sufficient research base on this flagship to support our investigation. The Chinese government has built approximately 48 related PAs on the QTP to protect G. nigricollis habitats. The mismatches between the current and planned PAs and the future effects of climate change on these G. nigricollis habitats are obvious. Therefore, we used the maximum entropy (MaxEnt) modeling method to balance the PA boundaries and future climate change effects. The aims of this study were to (1) map the G. nigricollis distribution under current climate conditions; (2) analyze potential changes in PA efficiency under the current scenario and various future scenarios; and (3) optimize the existing PAs to maintain their stability and efficiency under all potential climate change scenarios. This study not only provides essential data for the planning of PAs but also sets an example for efficiency optimization of PAs in the face of climate change.

Materials and methods

Study area

The QTP is located in southwestern China and comprises the entire Tibet Autonomous Region and Qinghai Province as well as parts of the Xingjiang Uygur Autonomous Region, Gansu Province, Yunnan Province and Sichuan Province (Figure 1). The QTP is the highest plateau in the world, with an average elevation exceeding 4400m above sea level and a maximum elevation of 8844m; therefore, this region has also been called the “roof of world” and the “Third Pole” (Qiu 2008; Yao et al. 2012). The region covers an area of approximately 2.6×10⁶ km², encompassing approximately a fifth of China’s territory. This region is rich in species-specific habitats due to the unique climate conditions on the plateau, and it is famous for both its species richness and biodiversity specificity (Lei et al. 2003; Ouyang et al. 2016). Moreover, two global biodiversity hotspots, the Himalayas and the mountains of South China, are located within this region (Mittermeier et al. 2011; Myers et al. 2000). In addition, the QTP is one of most rich avian biodiversity centers in the world, as an important montane region is located in its southeastern area (Fjeldså, Bowie, and Rahbek 2012; Zhang et al. 2017). More than 830 bird species have been recorded on the QTP (Lu 2018), accounting for more than 50% of the recorded bird species in China, and more than 40% of these species are migratory birds.

To date, more than 150 PAs have been established on the QTP by the Chinese government to protect vulnerable ecosystems and biodiversity (Shen et al. 2021). Among them, 48 PAs have been established directly or indirectly to protect G. nigricollis, together occupying approximately 30.51% of the QTP area; these areas include, for example, the Three Source River National Park, Mapam Yumco National Wetland Nature Reserve and Zoige National Nature Reserve. The PAs on the QTP account for approximately
a third of the area of all PAs in China. (Li et al. 2020). The Chinese government will clearly continue to focus on constructing PAs on the QTP to protect biodiversity in the future. Meanwhile, maintaining high conservation efficiencies at existing PAs is a critical challenge because both warming and concomitant wetting of the climate have been recorded on the QTP in recent years (Gao, Cuo, and Zhang 2014; Li et al. 2010).

**Species distribution model**

Species distribution models (SDMs) that are developed with machine learning techniques can help researchers simulate and predict temporal and spatial changes in the potential distributions of species (Aiello-lammens et al. 2015; Linshan et al. 2017; Na et al. 2018; Zurell et al. 2020). MaxEnt is an SDM, that is based on the algorithm in which maximum entropy modeling of species niches and distributions is implemented (Behdarvand et al. 2014; Merow et al. 2019; Peng et al. 2020; Phillips, Anderson, and Schapire 2006). According to the environmental variables contained in existing “emergence point” datasets for a species, this model extracts constraint conditions and explores the habitat distribution corresponding to maximum entropy under the given constraints. The MaxEnt model (v3.4.4) package was developed by Phillips et al. (2008) based on Java programming.

**Data sources**

(1) Species distribution

The main *G. nigricollis* distribution point data utilized herein were derived from the records of the Global Biodiversity Information Facility (GBIF), an international organization concentrated on making scientific biodiversity-related data available online (Occdownload 2021). As a supplement, we collected 498 *G. nigricollis* occurrence data point from both field observations and the published literature, and through geographical alignment techniques, we converted the occurrence data into latitudinal and longitudinal coordinates.

(2) Environmental variables

Based on the habits of *G. nigricollis* and several references (Han et al. 2018; Song et al. 2014), we collected a total of 26 environmental variables to model the suitable habitats and grouped these variables into three groups, including climatic-, topographical-, and soil-related parameters (Table S1). The soil data were obtained from the Harmonized World Soil Database v1.2 (Nachtergaele et al. 2009). Topographical factors, including the land use and cover change (LUCC), digital elevation model (DEM), slope, and aspect data, were obtained from multiple sources, and climate data were derived from the World Climate dataset (Fick and Hijmans 2017). 26 environmental variables were filtered to 13 environmental variables after considering the habits of *G. nigricollis* and the redundancy among variables. For examples, in 13 of the environmental variables, topsoil gravel content and soil type were selected because the loose wetland soil makes it easier for *G. nigricollis* to forage in deeper layers of the soil (Song et al. 2014; Yang & Zhang, 2014). Climatic factors such as annual mean precipitation and temperature were selected because the habitat ranges of *G. nigricollis*

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**Figure 1.** Location of the study area. The colored points are emergence sites of *G. nigricollis*. (a) shows the distribution of species points, (b), (c) and (d) are photographs of *G. nigricollis* in the field.
were restricted by these variables (Merow et al. 2019; Ruan et al., 2022). The slope, DEM and other topographic factors were considered because the survival and reproduction of *G. nigricollis* prefers flatter areas (Wu et al., 2009). We selected the 2040–2060, 2060–2080 and 2080–2100 time periods (20-year average value was used for each period) and four typical shared socioeconomic pathways (SSPs, namely, SSP1–2.6, SSP2–4.5, SSP3–7.0, and SSP5–8.5) from the Coupled Model Intercomparison Project (CMIP6) to explore the climate change background, characteristics of the protected animals and corresponding PA change patterns (Table 1). Specifically, we chose the three best-performing general circulation models (GCMs, namely, the Canadian Earth System Model version 5 (CanESM5), Instituto Pierre-Simon Laplace Climate Model version 6a with low-resolution (IPSL-CM6A-LR) and Meteorological research Institute Earth System Model version 2.0 (MRI-ESM2.0)) in the Qinghai-Tibet region (Meng et al., 2021; Zhu and Yang 2020). To avoid errors, we chose the mean values of the three models as the future environmental data and corrected the future climate data through overlapping periods (2010–2020) with historical data. Compared to the representative concentration pathway (RCP) scenarios established in CMIP5, CMIP6 not only retained the classical emission pathways of CMIP5 but also added three new emission paths to fill the gaps between the typical CMIP5 paths and meet the research needs associated with some specific problems (O’Neill et al. 2016; Xin et al. 2020). The spatial resolutions of the climate variables were 1 km, and 20-year average values were taken for each period. The topographic and soil variables that changed little over a short period were unified into a 1 km resolution.

**Data processing and model validation**

In this study, duplicate *G. nigricollis* distribution records in each grid cell were first removed; then, environmental variables were selected to avoid correlations. The environmental variable correlations were determined using environmental niche modeling tools (ENMs) (Warren, Glor, and Turelli 2010), which function is same with spThin(Aiello-lammens et al. 2015), and the environmental variable with the lowest correlation (<0.70) was selected as the predictor variable (Figure S1) (Elith et al. 2011; Merow, Smith, and Silander 2013). We also used ENMs to filter the species distribution data to ensure that there was only one point location in a raster to avoid spatial sampling biases, and examined the contribution of each environmental variable to the model by using the Jackknife method (Dorfman, Berbaum, and Metz 1992). In total, the number of optimized *G. nigricollis* distribution points were 386, and 13 environmental variables were utilized (Table 2) to drive the model. We ran the model with 75% of the data as a training sample and 25% as a test sample. The specific modeling steps are described below (Figure 2).

(1) We first used the MaxEnt model to obtain the probability maps of suitable *G. nigricollis* habitat regions on the QTP; then, suitable thresholds (the maximum training sensitivity plus specificity—0.4036) (Phillips 2005) were set to classify the habitat quality into 5 classes, including excellent (0.8-1), good (0.6-0.8), average (0.5-0.6), poor (0.4036-0.5), and unsuitable habitats (<0.4036) (Zhang et al. 2018). Using the layers simulated by the model in combination with the given thresholds, the layers of the Qinghai-Tibet region were binarized into presence and absence and overlaid with the PAs layers to analyze the current efficiency. We referred to the relevant literature and the International Union for the Conservation of Nature (IUCN) classification of the region and migration path (IUCN 2020; Lhendup and Webb 2009; Wang, Mi, and Guo 2020). The breeding and overwintering areas were also divided to assess the current habitat quality and efficiency of the existing PAs.

(2) Driven by future climatic data representing four scenarios, a map of *G. nigricollis* habitat changes was obtained, and the expansion and contraction trends of the overwintering and breeding areas were analyzed. Then, we explored the potential habitat quality changes under different climate change scenarios in the three analyzed time periods.

(3) A comparison of the conservation efficiencies of existing PAs under different future climatic scenarios was carried out. Finally, we tried to optimize and adjust the PA boundaries assuming

**Table 1. Descriptions of the different analyzed SSP scenarios (O’Neill et al. 2016; You et al. 2021).**

| SSP scenario | Socioeconomic development scenarios | Development scenario description | Scenario description |
|--------------|-------------------------------------|---------------------------------|----------------------|
| SSP1–2.6     | SSP1                                | Sustainable development         | Low-forcing scenario, radiative forcing stable at 2.6 W/m² in 2100 |
| SSP2–4.5     | SSP2                                | Moderate trends                 | Medium-forcing scenario, radiative forcing stabilizes at 4.5 W/m² in 2100 |
| SSP3–7.0     | SSP3                                | Fragmented Competition          | Moderate- to high-forcing scenario, radiative forcing stable at 7.0 W/m² in 2100 |
| SSP5–8.5     | SSP5                                | Fossil-fueled development       | High-forcing scenario, radiative forcing stable at 8.5 W/m² in 2100 |
In the current research (Fig. 3), using the ROC, using the difference between the AUC and the overall efficiency, the model derived by the model was considered plausibly (Table 3). The AUC derived in this study was 0.824, indicating that the model results were credible.

The validation of the model was performed by using the receiver operating characteristic curve (ROC), a metric commonly used in machine learning research to verify the credibility of the utilized model. In general, when the projection area under the 1:1 ROC line (AUC) is greater than 0.7, the model is considered plausible (Table 3). The AUC derived in this study was 0.824, indicating that the model results were credible.

### Results

**Protection efficiency of existing PAs under current climatic conditions**

The suitable area for *G. nigricollis* accounts for 12.48% of the total area of the QTP (Fig. 3). Distinct *G. nigricollis* habitat hotspots were located in the Three Rivers Source Region, and the Zoige, Brahmaputra River, Qinghai Lake, Yunnan and Aerjin Mountain regions. Compared to the northwestern region of the QTP, the southwestern region has a greater coverage of PAs, especially in Zoige, Qinghai Lake and the Three Rivers Source Region. These habitats can be divided into breeding and overwintering areas, accounting for 73.85% and 26.14% of the total PA area, respectively. Specifically, the Three Rivers Source Region, Zoige, upstream of Brahmaputra River, Qinghai Lake and Aerjin Mountain are breeding areas, while Yunnan and the midstream reaches of the Brahmaputra River are overwintering areas. Statistically, more PAs were located in breeding areas than in overwintering areas, and the area of the PAs comprised by overwintering habitats was only 22.76% of the size of the breeding area.

The 48 existing PAs protected only 17.84% of the suitable habitat, and the *G. nigricollis* habitat quality was not as good as expected. Only 5.24% of the habitats throughout the QTP were of high quality (include good and excellent), and the existing PAs protected only

### Table 2. List of the 13 selected parameters used in the MaxEnt model.

| Variable | Environmental description | Percent contribution (%) | Spatial resolution (km) |
|----------|---------------------------|--------------------------|------------------------|
| Soil     | Symbol (FAO-90)           | 26.8                     | 1                      |
| Slope    | Soil organic carbon       | 20.9                     | 1                      |
| Bio12    | Annual precipitation      | 17.1                     | 1                      |
| DEM      | Digital elevation model   | 14.2                     | 1                      |
| Ecosystem| Ecosystem types and changes | 9.5                     | 1                      |
| Bio15    | Precipitation seasonality | 2.8                      | 1                      |
| Bio19    | Precipitation in the coldest quarter | 2.1 | 1 |
| Soil_t_gravel | Topsoil gravel content | 1.7                     | 1                      |
| Bio2     | Mean diurnal range        | 1.2                      | 1                      |
| Bio18    | Precipitation in the warmest quarter | 1.1 | 1 |
| Aspect   | Direction of the projection of the slope (normal on the horizontal plane) | 1 | 1 |
| Bio3     | Precipitation in the wettest month | 1 | 1 |
| NDWI     | Normalized difference water index | 0.9 | 1 |

![Figure 2. Simple descriptions of the technological processes in this study.](image-url)

![Table 3. Auc standards used in the evaluation process of the MaxEnt model.](image-url)

| AUC          | Model evaluation |
|--------------|------------------|
| <0.5         | Poor             |
| 0.5 - 0.7    | Common           |
| 0.7 - 0.8    | Credible         |
| >0.8         | Excellent        |
22.76% of the high-quality habitat region (Figure 3). The habitat quality in the breeding areas was better than that in the overwintering areas, with the ratio of excellent habitats being 2.44% higher than that of the overwintering areas. The percentage of areas with excellent and good ratings (3.44%) was barely half of that of the average and poor-rated habitat (6.52%) in the overwintering areas. In the 48 PAs, the habitat quality was excellent in 11.08% of the area, while the remaining suitable areas were rated as good (3.89% of the area), average (5.59%), and poor (7.41%). The area upstream of the Brahmaputra River, Aerjin Mountain and some regions in Yunnan were important potential migration paths or transit regions, and only one PA was established in these regions, presenting an obvious protection need.

Suitable habitat changes under future climatic scenarios

Under the four climatic scenarios, the G. nigricollis habitat either expanded or shrunk in the three analyzed time periods of 2040–2060, 2060–2080 and 2080–2100 (Figure 4). The main losses occurred in Yunnan, the Three River Source Region, Zoige and the Sutlej River; these regions primarily comprised overwintering areas, while the primary habitat expansions occurred in breeding areas, including the area upstream of Brahmaputra River, the Shaquan River, and the northern Three River Source Region. The range of variation in the breeding areas was larger than that in the overwintering areas. Specifically, the expansion and loss of breeding areas were basically offset, although the magnitude of the change was much greater than that in the overwintering areas. It is worth noting that the overwintering areas, although less variable, experienced much more loss than expansion (Figures 4d, 4h, 4l, 4p). This trend led to a gradual northwest shift in the distribution of G. nigricollis, and the magnitude of this movement increased as the scenario worsened.

The total habitat area and quality changed significantly under the future climatic scenarios (Figure 5). The suitable habitat declined continuously over time under the SSP1–2.6, SSP2–4.5, and SSP3–7.5 scenarios, with average rates of decrease of 0.58%, 0.77% and 0.77%, respectively. Under SSP5–8.5, the habitat area first showed an increasing trend and then decreased until 2100. Most of the quality changes occurred in the average-and poor-rated areas; for instance, under the SSP1–2.6 scenario, the excellent and good habitats changed little or not at all, and the changes mainly occurred in poor and average areas, which declined from 7.258% to 6.879% from 2040 to 2100, exhibiting a decrease of

Figure 3. Habitat quality reclassification and regional area statistics of G. nigricollis. The area south of the red line is the overwintering area, and the region north of the red line is the breeding area. This pathway was drawn according to the previous studies of Lhendup & Webb (Lhendup and Webb 2009), Wang et al. (Wang, Mi, and Guo 2020), and IUCN (IUCN 2020).
0.379%. In contrast, two others classes (excellent and good) changed from 5.249% to 5.052%, showing only a 0.197% change.

**Changes in existing PA efficiency under future climatic scenarios**

The average protection efficiency of existing PAs declined from 17.84% to 15.31% under the four analyzed climatic scenarios (Figure 6). The results of SSP1–2.6 differed from those of the three other scenarios. The PA protection efficiency first dropped to 16.97% and then rose to 17.34% from 2080 to 2100. The change rate of the PA efficiency under SSP2–4.5 was almost the same as that under SSP1–2.6 from 2040 to 2060; however, under SSP2–4.5, the PA efficiency decreased at a fixed rate from 2060 to 2100. Under SSP3–7.0, the protected efficiency declined from 17.84% to 15.43% at a fixed rate of 4.5% from 2040 to 2100. Compared to other scenarios, SSP5–8.5 had the worst, protection efficiency, which dropped from 17.84% to 13.98%, and the average decline rate was 7.2% for each period (20 years). Notably, under SSP5–8.5, the rate of decline in the protection efficiency was 3.5% from 2060 to 2080, but this rate increased nearly three-fold (10.89%) in the final stage from 2080 to 2100. Overall, the PA efficiencies decreased under all scenarios; therefore, it is necessary to optimize the existing PAs to improve their resilience to climate change.
Optimization of PAs to cope with future climatic changes

To improve the protection efficiency of existing PAs under future climatic changes, the PA distribution was adjusted under the premise that the total area must remain unchanged to ensure low costs. During this optimization process, only 28.11% of the PA area was changed, but the average protection efficiency of the PAs in the different scenarios increased to 28.37% (Figure 7a). Compared to the average protection efficiency of unchanged PAs, which was 16.24% before the adjustment, the optimized protection efficiency increased by 74.7%. The removed areas were mainly located in the Three River Source National Park; specifically, the northern boundary was adjusted and the western boundary was expanded to accommodate areas that had become unsuitable for G. nigricollis. The newly added PAs were mainly situated in the upstream reaches of the Brahmaputra River, near Aerjin Mountain and on the northern and western QTP, where the main protection gaps were identified. The other hotspots, including the Zoige PA, the Qinghai Lake PA and the PA in Yunnan, were almost unchanged.

The PA efficiency presented a stable performance after optimization, and some differences were found among the four climatic scenarios (Figure 7b). In the SSP1–2.6 scenario, there was an excellent increasing trend in PA efficiency, and the
increasing rate decreased only from 2040 to 2060, after which it increased rapidly again and reached a value of 29.96% from 2080 to 2100. The protection efficiency derived under SSP2–4.5 was similar to that obtained under SSP1–2.6 after optimization, but the rate of increase derived under SSP2–4.5 in the end was much smaller than that of SSP1–2.6. SSP 3–7.0 presented a declining trend from 2040 to 2080 and then increased to 28.78%. Compared to SSP1–2.6 and SSP2–4.5, SSP3–7.0 exhibited more instability. In the worst scenario, SSP5–8.5, the PA efficiency showed a decreasing tendency and became increasingly less efficient with time; however, it still had a higher protection efficiency than the original PAs.

Discussion

In this study, we used the representative flagship migratory bird G. nigricollis to predict current and future migratory bird habitats on the QTP and evaluate and optimize the protected efficiency of existing PAs under current climate conditions and different future scenarios. The results indicated that conservation gaps currently exist mainly in the southwestern part of the QTP; additionally, the future spatial distribution pattern of G. nigricollis showed a tendency to move northwestwards, and the magnitude of this movement that was identified under SSP5–8.5 was greater than that obtained under SSP1–2.6. Even if the total amount of area remains unchanged, the future protection efficiency of existing PAs could be increased from 16.25% to 28.37% by adjusting their boundaries, thus providing support for and examples of addressing climate change risks.

The results of this study are similar to those of previous studies on G. nigricollis. Our results were consistent with these past studies in that G. nigricollis was found to be mainly distributed in the eastern and southern parts of the QTP under current climate conditions (Han et al. 2017; Linshan et al. 2017). In addition, the IUCN’s latest assessment report on G. nigricollis questioned the current increase in the population and suggested that this increase might be transient, which was verified by our study (IUCN 2020). Because G. nigricollis always lives in shallow-water wetlands, climate warming will promote glacier melting and thus expand the suitable habitat area for G. nigricollis; however, as glacial melting accelerates, the shrinkage of shallow-water wetland areas will lead to a decrease in suitable habitat. There were also some differences in the species distributions from those that were derived in different studies; for example, we found that G. nigricollis is widely distributed in Yunnan, but this distribution region has not been detected in other studies (Han et al. 2017) due to the lack of sample sites in the Yunnan region.

The brief increase in the habitat of G. nigricollis, it may be due to the increase in glacial meltwater caused by climate warming, increased surface runoff, and gradual increase in the extent of wetlands, but with the intensification of climate warming, the shallow wetlands that are suitable for the survival of G. nigricollis were projected to decrease, which eventually led to the beginning of the decline in their population.

The results of this study on PAs found that the southern part of the QTP has a remarkable conservation efficiency and currently contains many PAs; in fact, it may contain taking the G. nigricollis as an example, we discussed the approach of PA optimization, but we should consider all the important species in practice. Considering that the PAs in the QTP region are not only established for the protection of G. nigricollis but also

Figure 7. Distribution and efficiency of optimized PAs: (a) PA pattern optimization and adjustment under the condition of no change in the total PAs. (b) changes of optimized PAs efficiency in the future climate scenarios.
that the eastern QTP has a higher biodiversity than does the western QTP (Li et al. 2020; Yu et al. 2021), we optimized the PA boundaries by keeping the PAs in this region as unchanged as possible. Currently, PA gaps are mainly distributed in the upper reaches of the Brahmaputra River and the Aerjion Mountain regions, which are under increasing risk due to the trend of the analyzed species moving to the northwest in the future. Our study indicated that when planning PAs, it is important to include not only the current situation but also to consider risk areas in advance based on projected future changes in species distributions.

Some limitations and uncertainties exist in the current study. First, in terms of the model extrapolation risk, when the model built by the current environmental variables was applied to suitability projections under future climate conditions, a risk of extrapolation was introduced. Further exploration of this is needed in a follow-up study, although we corrected the future climate data through overlapping periods. The second limitation is the lack of highly-precise environmental data and species distribution point data which affected the model results (Long, Zhang, and Ma 2016; Ma et al. 2017; Xie and Xiong 2011). The choice of environmental variables was the third limitation, for example, food and specific timing should be studied, as they could not be considered in this study due to the lack of data. We recommended three directions in future studies. First, establishing a database of alpine migratory birds can make allow migratory bird studies to be conducted in depth in the QTP region. Second, we encourage more research on migratory paths and transit areas of migratory birds, as our research revealed that there may be many potentially unknown important habitats and transit areas that have not been properly protected. Third, we suggest studying more representative migratory birds to deepen the knowledge of regional migratory birds and build a solid foundation to improve their protection. Specifically, G. nigricollis is a short-distance migratory bird that is sensitive to climate change (Butler, 2003; Jonzén et al., 2006; Zurell et al., 2018); however, it is unknown whether other long-distance migratory birds have the same responses to climate change. Therefore, we recommended studying the behaviors of other long-distance migratory birds in the future. Finally, we suggest further detailed research on the migration paths and mechanisms of migratory birds. The study of migratory birds is important because they base the timing of their migration on climate changes, and clarifying the changes in the timing of bird migration will play a major role in exploring the effects of climate change on organisms (Rubolini, Saino, and Møller 2010; Tolvanen et al. 2020).

Conclusion

The current and future distributions of a representative migratory bird species, G. nigricollis, were analyzed on the QTP. The current and future distributions and habitat quality of G. nigricollis were analyzed, the efficiency of the currently relevant PAs was evaluated, and the PA distributions were optimized while maintaining the locations of existing PAs as much as possible. The results indicated that (1) at present, the G. nigricollis are mainly distributed in near the wetlands of the Brahmaputra River basin, the Three River source region and the Ruo’ergai region in the QTP. (2) Climate change has affected the distribution area of G. nigricollis and the conservation efficiency of PAs. (3) Considering the impacts of climate change when adjusting the boundaries of protected areas will improve their efficiencies. This study provides an example for resolving mismatch between PA boundaries and changes in the habitat changes of migratory birds.

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