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Impacts of changing climate on the distribution of migratory birds in China: Habitat change and population centroid shift

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ABSTRACT

Climate changes are related to the changes in the distribution of migratory species, which irreparably harm biodiversity. In this study, we evaluated the habitat change and population centroid shift for 7 orders and 23 different species on the IUCN (International Union for the Conservation of Nature and Natural Resources) Red List of migratory birds from 2014 to 2017 in current to mid-21st (2041–2700) century by Maximum Entropy method (MaxEnt) model. We found that there is significant spatial variability in geographical suitability, with the Yangtze River basin losing 9.74% of suitable habitat and the Pearl River basin losing 13% of habitat. The area of suitable habitat decreases over 3% of total habitat area in China under the RCP 2.6, and decreases about 10% of total habitat area in China under RCP 8.5 scenario, with the population centroid of habitat moving about 50 km to northeast on average. Furthermore, the mean suitability of migratory birds will decrease over 3% in the future, which means environmental variables are changing in directions that are not suitable for birds. Migratory birds will change their habitat and growth cycle in response to the climate change. The direction and distance of the population centroid are different for every species. Most of the individual species in the study will move over 50 km and all the species will move to places with higher suitability. For the whole of China, the constraint for migratory birds is t_{min} (Minimum temperature). The dominant variable in southeast China is NDVI (Normalized Difference Vegetation Index), while alt (altitude) in the north China. The decline in the suitable habitat area and shift in the population centroid will lead to the changes in the time and distance of the migration process, resulting in more adverse conditions for the survival of migratory birds. Our study proves the adverse role of climate change in species distribution which is a prerequisite for protecting species in the future.

1. Introduction

The number of migratory birds has declined dramatically worldwide since 1970. The key driver of the abundance decline is that climate change exacerbates the survival pressure of migratory birds (Jacome et al., 2019; Jetz et al., 2007; Lehikoinen et al., 2019; Mammola et al., 2018; Pearson et al., 2013; Russell et al., 2015; Saino et al., 2011; Spooner et al., 2018; Wilson et al., 2019; Yalcin and Leroux, 2018; Yu et al., 2019), which will result in the ecological imbalance and the absence of ecological function (Cohen et al., 2018; Hewson et al., 2016; Keogan et al., 2018). It is critical to understand how species spatial distribution changes under the changing climate for protecting biodiversity and formulating effective policies (Northrup et al., 2019; Vickery et al., 2014).

The geographical distribution of birds has changed greatly in past decades. Roberts et al (2019) recorded that the spatial regime boundary of 46 years avian population moved over 200 km in North America (Roberts et al., 2019). Previous studies have made great progress in studying the correlation between species distribution and climate change. Climate change affects organisms by affecting the environment and food (Sanchez-Bayo and Wyckhuys, 2019; Title and Bemmels, 2018). Climate change damages the region's suitable environmental conditions for certain species, which leads to change in their geographic range (Keogan et al., 2018; Saino et al., 2011). Brawn et al (2017)

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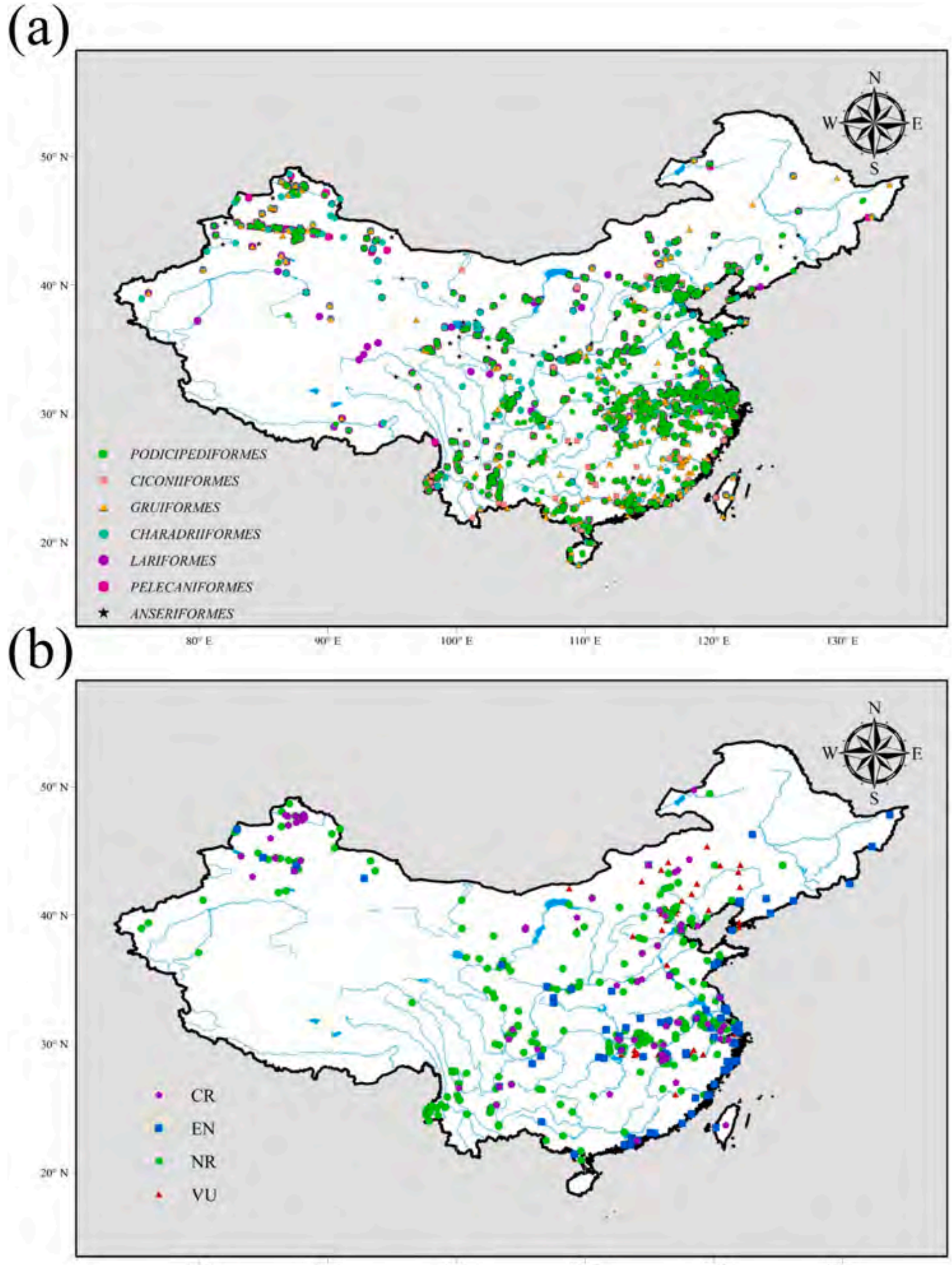

Fig. 1. The locations of (a) 7orders of migratory birds and (b) 23 different IUCN categories species.

illustrated that the population of tropical birds was closely correlated to the climate in the rainfall (Brawn et al., 2017). Climate change makes that the growth cycle of migratory birds hardly keeps the feeding time in sync with and the period of rich food resources (Bowler et al., 2019; Fecchio et al., 2019; Jetz et al., 2007; Kentie et al., 2018; Wilson et al., 2019). Saino et al (2011) confirmed the cause of the population decline of European migratory birds was their migration phenology that mismatches the climate (Saino et al., 2011). Bowler et al (2019) corroborated the general trend that European insectivorous birds communities were confirmed to be the same as insects (Bowler et al., 2019). Despite these lines of evidence, little research has been conducted to identify the effects of individual climate variables on species distribution. Better identification of major climate variables can help to establish effective policies, which is one of the urgent needs for biodiversity conservation (Beringer et al., 2011; Both et al., 2010; Cohen et al., 2018; Dugger et al., 2016; Hoffmann and Sgro, 2011).

Theoretical research on the correlation between species distribution and climate change is meaningful to protect biodiversity. To understand the effect of climate change on the potential distribution pattern of species, the research model has become an important means. The species distribution models (SDMs) are used to simulate the relationship between species distribution and environmental variables (Collins et al., 2017; Dudík et al., 2004; Erauskin-Extramiana et al., 2019; Pacifici et al., 2017; Panda and Behera, 2019; Parmesan, 2007; Pavon-Jordan et al., 2019). Maximum Entropy method (MaxEnt) model is demonstrated to perform well for evaluating the distribution of species at the geographical level since the presence-only data is widely used in the SDMs (Finch et al., 2017; Jacome et al., 2019; Roberts et al., 2019; Saupe et al., 2019). We combined bird sample data with Chinese national scale climate data to build the species distribution models (SDMs) for 7orders of migratory birds and 23 species on different levels of the IUCN red list (Moran and Kanemoto, 2017). The distribution of endangered species is always used in the division of protected areas (Lehikoinen et al., 2019; Manish and Pandit, 2019; Runge et al., 2015; Sang et al., 2011; Shen

Table 1
List of variables used in MaxEnt modelling.

Abbreviation	Variables
bio1	Annual Mean Temperature
bio2	Mean Diurnal Range
bio3	Isothermality
bio7	Temperature Annual Range
bio13	Precipitation of Wettest Month
bio14	Precipitation of Driest Month
bio15	Precipitation Seasonality (Coefficient of Variation)
bio18	Precipitation of Warmest Quarter
NDVI	Normalized Difference Vegetation Index
t_{min}	Minimum temperature
t_{max}	Maximum temperature
LUCC	Land cover
alt	Altitude
dis_p	Distance to the protected area
slo	Slope
prec	Precipitation

et al., 2015; Xu et al., 2017), which identifies areas that need priority protection and has positive implications for planning and constructing of protected areas.

In this study, we explored the current distribution and the drivers by MaxEnt, then discussed where and how the distribution may change in the 2050 s. Firstly, we simulated the current distribution of migratory birds, predicted their distribution under future scenarios and calculated the habitat changes. Habitat change was the most intuitive indicator to describe the survival status of migratory birds. Based on the simulation of birds' distribution, we quantified the movement trend by calculating the species population centroid and identified the individual contribution of environmental variables. The population centroid and its change trajectory can reflect the population distribution status and trend. Secondly, we built the models based on different climate zones and basins to figure out the differences of birds distributions across the different regions. Lastly, we compared the differences between the distribution and the protected areas to discuss the effective methods for the remissions of biodiversity loss.

2. Material and methods

2.1. Species data

Migratory birds transport the energy and nutrients within and between the ecosystems, which is the largest population movement in the world, connecting the world into a huge ecosystem (Bauer and Hoye, 2014; Russell et al., 2015). The population of migratory birds passing through the major flyways has dropped by half over the past 30 years (Runge et al., 2015). Migratory birds get into an unfavorable position in Asia (Kirby et al., 2008).

China, the largest country in Asia, lies in the East Asian-Australasian flyways with high biodiversity (Ma et al., 2019). We compiled migratory bird data from 2014 to 2017 Bird Report (http://www.birdreport.cn/).

Table 3
The shift situation of migratory birds.

Orders	Shift direction	Shift distance (km)
Total migratory birds	Northeast	51. 01
PODICIPEDIFORMES	Northeast	49. 00
CICONIIFORMES	Northeast	24. 88
GRUIFORMES	Northeast	66. 17
CHARADRIIFORMES	Northeast	52. 74
LARIFORMES	Northeast	73. 63
PELECANIFORMES	Northeast	43. 55
ANSERIFORMES	Northeast	45. 04

The Bird Report is the most complete and effective summary of bird watchers in China, accounting for 80% of all bird species, and each birdwatching record is sorted up and reviewed by experts to ensure accuracy. The latitude and longitude of the location were determined by comparing the geographical locations in Google Earth and recorded by ArcGIS10. 2. According to the list of Chinese Birds, there are 12 orders of migratory birds in China (Liang et al., 2018b, 2018c, 2017; Liu et al., 2003; Sang et al., 2011; Xu et al., 2017, 2019). We selected the species with migratory behavior, and combined the selected species to simulate the distribution of total migratory birds. There were 115 selected species classified into 7 orders. The data we used in the study have covered more than half of the migratory bird species, which is representative for the whole of China. We compared the present data and the level on the IUCN red list of each species, then chose 23 species from the data to show the uniqueness. The data of total migratory birds is pooled the 7 orders of birds. The total migratory birds data is a collection of diverse birds, so the simulation of this data is representative and accurate (Fithian et al., 2015). After deleting the duplicate invalid data, we modelled the potential distribution of both 7 orders of migratory birds and 23 different IUCN categories species, including 3 critically endangered (CR) species, 5 endangered (EN) species, 9 vulnerable (VU) species, and 6 near threatened (NR) species (Table S1). The locations of migratory birds are shown in Fig. 1.

2.2. Climate data and the scenarios

We only used static environmental variables to simulate the potential distributions of migratory birds, analyzing the static environmental factors that were known to affect birds' movement and habitat changes (Arribas et al., 2019; Beumer et al., 2019). The data of bioclimate, temperature, and precipitation were imported into the model from Worldclim 1. 4 dataset (http://www.worldclim.org/) with 30 arc-seconds (about 1 km) resolution ratio. Current climate scenario (average 1970–2000) was used to comprehend the latent distribution while two future scenarios (RCP 2.6 and RCP 8.5 during average 2040–2060) were used to estimate the future distribution shift. The RCP 2.6 was an optimistic scenario and the RCP 8.5 was a pessimistic scenario (Boisvert-Marsh et al., 2019; Rosen and Guenther, 2016). The land cover dataset and the NDVI dataset were downloaded from the resource and environment data cloud platform (http://www.resdc. cn/) with a

Table 2
The change of suitable area.

	Current		RCP 2.6		RCP 8.5	
	Percentage (%)	Area (10^4 km^2)	percentage (%)	Area (10^4 km^2)	Percentage (%)	Area (10^4 km^2)
Suitable	16.43	157.73	16.07	154.27	14.69	141.02
Unsuitable	83.56	802.18	83.93	805.73	85.31	818.98
Habitat loss			11.04	17.41	19.00	29.97
Habitat gain			8.82	12.93	8.41	13.27

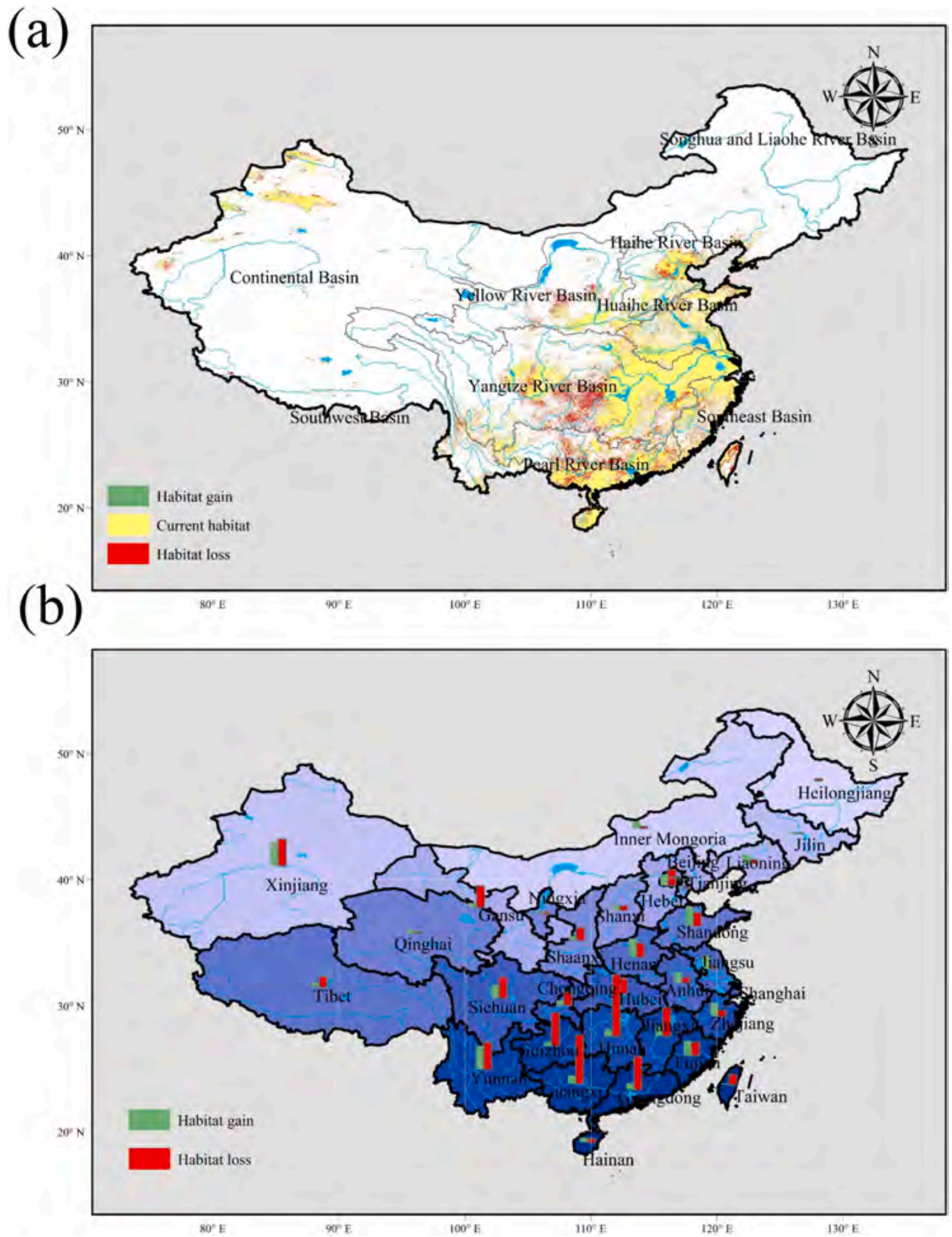

Fig. 2. (a) The habitat change in the future and (b) the statistics of habitat change in province.

resolution of 1 km. The reserves data was from the protected planet (https://www.protectedplanet.net/). The distance of each grid to protected area was calculated by Euclidian distance in ArcMap. Altitude and slope were compiled by using the Digital Elevation Model (DEM) from the Geospatial Data Cloud (http://www.gscloud.cn).

To make the result reasonable, the Pearson Correlation Coefficient (PCCs) was used to remove high correlated variables (Table S3). Moreover, 13 variables were retained in the model (Table1) after removing highly correlated bioclimate variables ($|r| > 0.8$) (see Table 2).

2.3. Species distribution model and inspection

According to a specific method, all SDMs use the correlation between the species sample data and environmental variables to estimate the ecological niche of the species, and show the correlation to the studied area (Panda and Behera, 2019; Thorson, 2019; Wang et al., 2019; Yu et al., 2019). MaxEnt is a widely used model which only needs simple data set. Its operation is simple and its simulation effect is excellent (Manish and Pandit, 2019). It defines the correlation between species and the environment variables, and predicts the distribution according the present sample data (Dudik et al., 2007; Dudík et al., 2004; Phillips et al., 2006; Phillips and Dudik, 2008). The distribution which has the highest entropy is selected to be the optimal distribution of all the eligible distribution (see Table 3).

We used the default settings (10000 background locations, 500 iterations) which was proved to be accurate and divided the data into two parts–75% for modeling and 25% for evaluating (Merow et al., 2013). We chose the logistic output format to improve calibration (Phillips and Dudik, 2008). The pseudo-absence location was generated to supply the true absence records during the modelling (Cheng et al., 2018). The jackknife test was done in MaxEnt to recognize the importance of variables. The benefit of the test was to give the approximate confidence intervals for many parameters (Jacome et al., 2019; Shcheglovitova and Anderson, 2013).

The Area Under Curve (AUC), the proportion under the Receiver Operating Characteristic Curve (ROC), was used to evaluate the

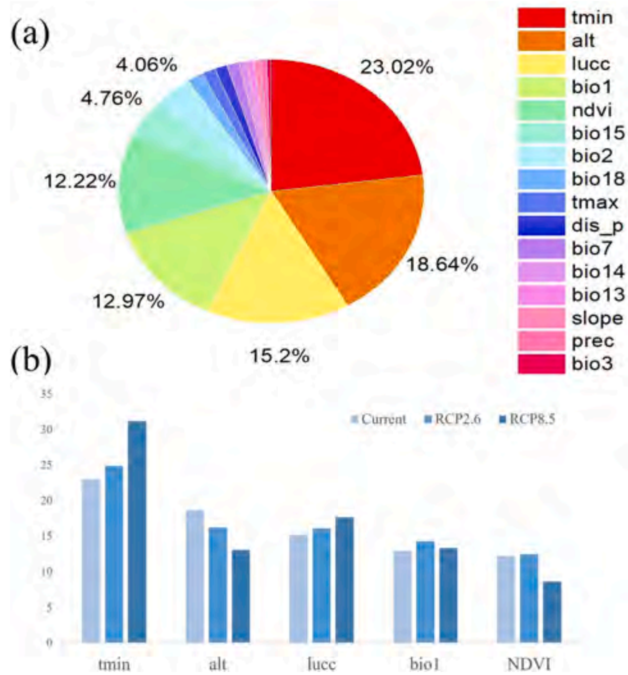

Fig. 3. (a) The percent contribution of the environment variables in current distribution of birds (b) The comparison of percentage contribution of 5 essential variables in different scenarios.

performance of the model (Phillips et al., 2006). The AUC value was positively correlated with the model, so we picked the model with AUC value over 0. 8 seen at Table S2 (Elith et al., 2011; Fourcade et al., 2014).

2.4. Index of habitat change

2.4.1. The habitat loss

The decrease of habitat area is the main threat to the biodiversity which is caused by climate change (Taubert et al., 2018). There was a continuous distribution suitability map coming from the model. To calculate the habitat loss, "maximum training sensitivity plus specificity logistic threshold (MaxSSS)" was used to classify the continuous distribution suitability into the binary distribution map (Saupe et al., 2019; Vale et al., 2014). We also calculated the mean suitability of the map. The calculating of habitat loss was based on the comparison between the suitable area in current and future scenarios. It was described as habitat loss when the suitable area turns to the unsuitable area and the opposite is habitat gain.

2.4.2. The population centroid

The population centroid is regarded as the representative indicator reflecting the population movement process (Collins et al., 2017; Liu et al., 2019). We calculated the population centroid of the habitat for migratory birds in longitude (X) and latitude (Y) to explain the bias in the future. After comparing the population centroid of the species, we took the average offset distance in two scenarios.

$$X = \frac{\sum X_i P_i}{P} \quad Y = \frac{\sum Y_i P_i}{P}$$

where X_i and Y_i are the longitude and latitude of the site, P_i is the sustainability at site, and P is the total sustainability.

3. Results

3.1. Spatial changes of habitat and the shift of population centroid

Based on the current and the two future scenarios, the models simulated the distribution of 7 orders of migratory birds and the endangered birds well by checking the AUC value (Table S1). The current and future potential geographical distribution of birds in China is shown in Fig. S1.

The suitable area of migratory birds in the current climate accounts for 16.43% of the total area of China. In the future scenario, the percentage of the suitable area is 16.07% of the total area of China in RCP 2.6 and 14.69% of the total area of China in RCP 8.5. Compared with the current climate, the suitable area decreases by 0.36% of the total area of China under RCP 2.6 scenario and 1.74% of the total area of China under RCP 8.5 scenario. The habitat transformation in the future is shown in Fig. 2. In accordance with the calculation results, the habitat area will decrease (Rushing et al., 2016; Saino et al., 2011). The habitat change for 7 orders of migratory birds is shown in Fig. S2.

Prediction models for future scenarios show the decrease of suitable regions (Bay et al., 2018). The area most prone to qualitatively change in the future is the boundary zone with low altitude between suitable and unsuitable areas. The most loss of habitat is mainly in the southern China, including Hunan province, Guangxi Zhuang Autonomous Region and Guangdong province. Hunan will be the province with the highest habitat loss in the future with losing 26,361 km^2 accounting for 20.74% of the current total habitat area in Hunan. Guangxi Zhuang Autonomous Region will loss 19,767 km^2 accounting for 18.50% of the current total habitat area in Guangxi. Guangdong province will loss 12,985 km^2 accounting for 11.78% of the current total habitat area in Guangdong. The abatement of habitat is common in China except some places (Fig. 2). The most gain of habitat is in the southeast China, including Jiangsu province, Zhejiang province and Shandong province. The habitat area will rise 5396 km^2 in Jiangsu province, 3460 km^2 in Zhejiang province and 2970 km^2 in Shandong province in the future.

In this study, the research content of 7 orders of migratory birds reveals an obvious bias trend in the population centroid of habitat. In the future climate scenarios, the entire population centroid will move to the northeast, and all the migratory birds will move from their potential habitats to higher altitudes (Pacifici et al., 2017). The declining mean suitability is shown in the future (Fig. S3).

3.2. The importance of environment variables

The percentage contribution of different variables can be seen by the jackknife test in the MaxEnt model. The determination of the leading factor for the migratory birds is derived from the comparison of the contribution rate of the environmental variables involved in the model.

The result of estimating the importance of the variables shows that t_{min} is the most crucial environmental variable for distribution of migratory birds, accounting for 23.02% importance. The LUCC, alt, bio1, and NDVI also make massive contributions to the model, accounting for 15.2%, 18.64%, 12.97%, and 12.22% importance respectively. The sum of the 5 essential variables account for 82.05% of the cumulative contribution. The individual contribution of these variables can be seen in Fig. 3a.

This result indicates the 5 factors are of great significance for the current distribution of birds. In the future scenarios, the most important variable is still t_{min}, of which the percent contribution is 23.89% in RCP

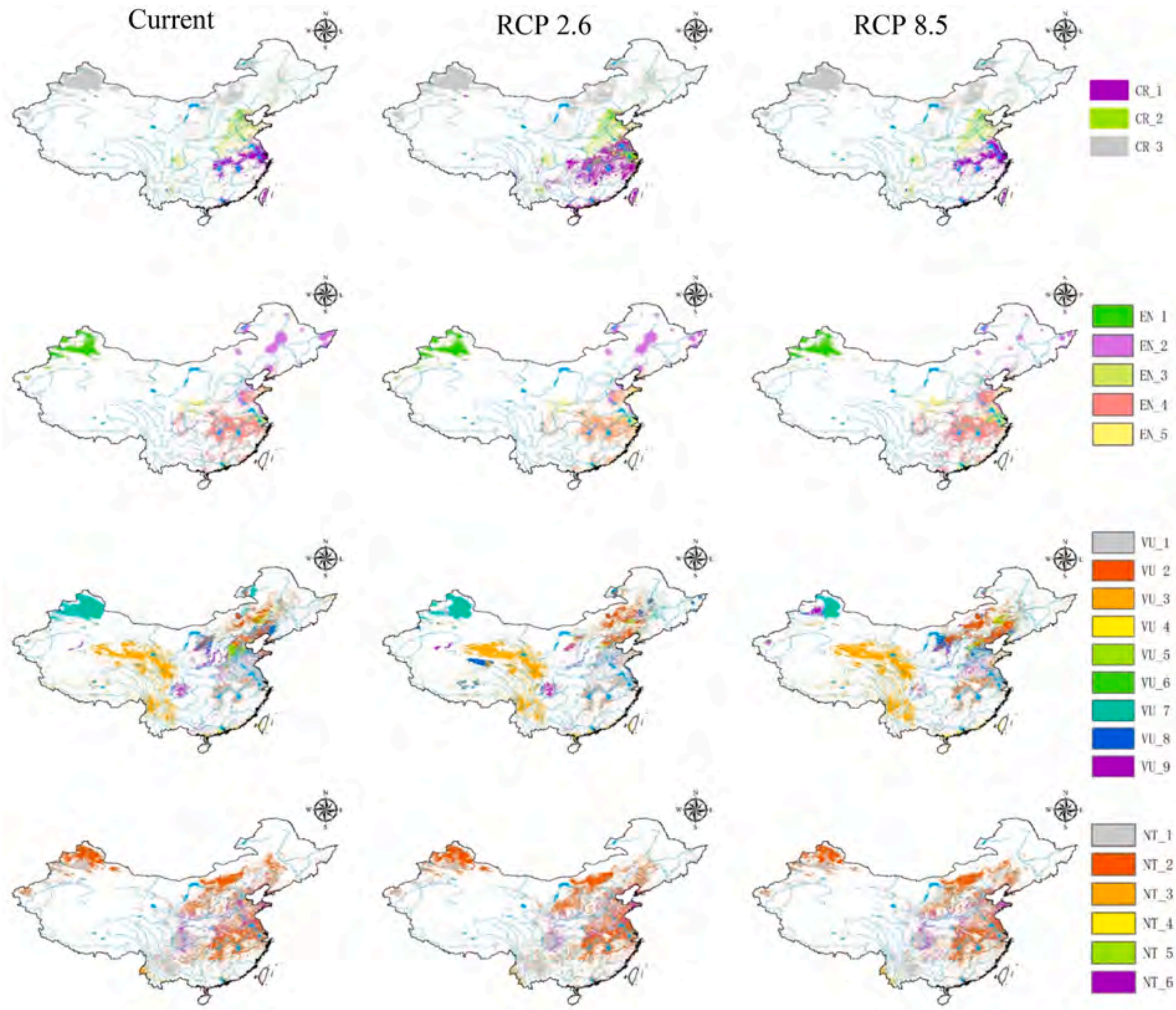

Fig. 4. Habitat of the species groups identified by MaxEnt. Each panel depicts the habitat of each bird group based on the different scenarios.

2.6 and 31.17% in RCP 8.5 (Fig. 3b). It can be seen that the temperature is the main environmental factor that affects the potential distribution area of the migratory birds. The combined percent contribution of all climate variables is 53.59% in RCP 2.6 and 59.13% in RCP 8.5. Climate change still has a great influence on the distribution of migratory birds in the future.

3.3. *The distribution of endangered species*

23 species of different endangered level on the IUCN red list are used in our model to comprehend the current potential distribution and the future habitat. The comparison between the current situation and future distributions of species are shown in Fig. 4.

From the results, it is obvious that the geographical distribution range of bird species of different protection levels is different. The distribution range of bird species of CR and EN levels is small and concentrated in some areas, while most birds of VU and NT levels can live in most parts of China. As the climate changes, the VU and NT levels of birds can still find a suitable environment, but CR and EN levels of birds may lose their habitat, even resulting in a survival crisis (Liu et al., 2003; Pimm et al., 2014).

The distributions of most endangered species have changed by comparing the distributions of present and future climate scenarios. The distributions of 9 species display a distinct reduction and 8 species will maintain their current habitat area. The habitats of CR_3, CR_1, VU_3, and EN_4 decease 56001 km^2, 26,652 km^2, 44,464 km^2, and 56,608 km^2, respectively. The species that maintain the existing habitat area mainly including EN_3, CR_2, and EN_1. Specifically, the habitats of several species will expand under the influence of future climate change. All the expand species are mainly distributed in Shangdong and Hebei province of the middle-eastern China, consistent with the total distribution (Northrup et al., 2019; Shen et al., 2015).

Not only the distribution, but also the population centroid changes greatly (Fig. 5a, the abbreviation of species shown at Table S4). The estimation of birds' population migration direction on a large scale is not effective for small areas. The population centroid of migratory birds, shifting in small scale areas, are easily influenced by the local topography that could not match with the total shift of birds in country scale. The migration direction of each species is different and the offset distance is different.

Species distribution will change obviously in the future by detecting the population centroid. The population centroids of most species

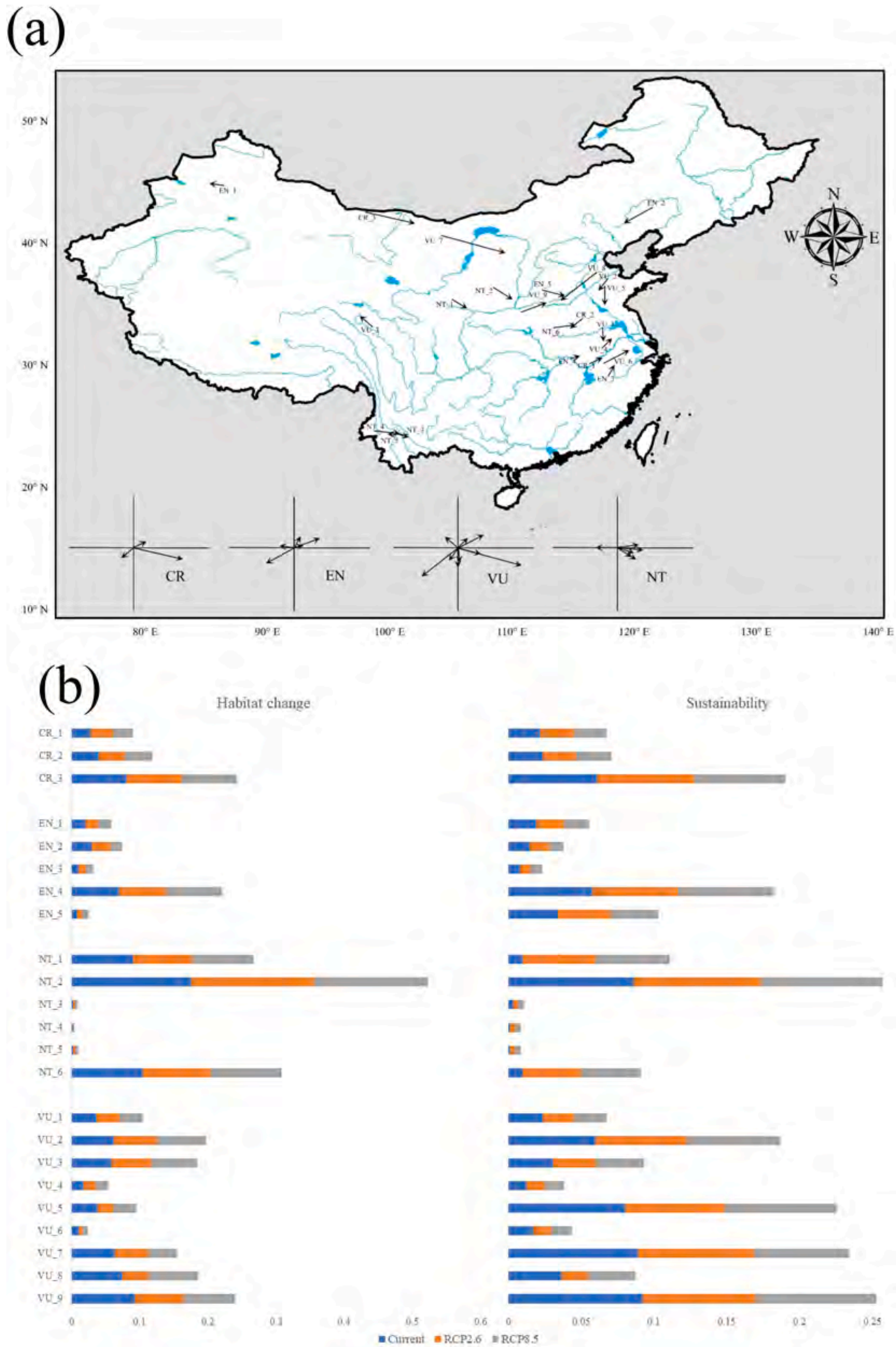

Fig. 5. (a) The shift of the population centroid in the suitable area and (b) mean suitability change and the habitat change in different scenarios.

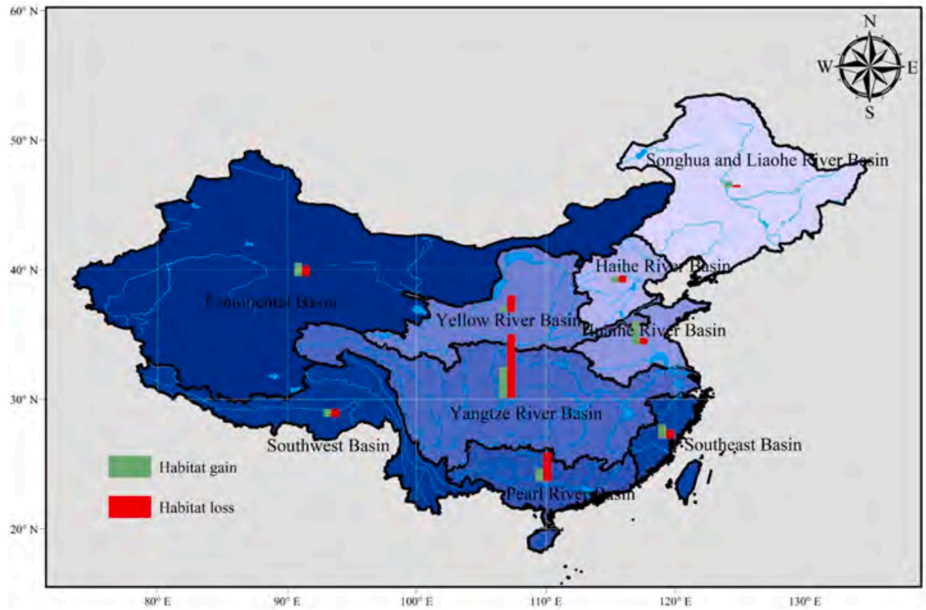

Fig. 6. The change of habitat in different basins.

migrate long distances from the current centroids. In particular, some population centroids of critically endangered species have experienced a huge offset in the future. Especially CR_3 will move 292.88 km to the southeast with the mean suitability decreasing 2.67%, which may exacerbate the survival crisis. The endangered species will also change greatly in the future as EN_2 moving 197.36 km to the southwest and EN_5 moving 174.16 km to the northwest. The most distributions of vulnerable species will move long distances from the current ones and easily get adverse effects under climate change. In the future, VU_8 will move 327.74 km towards southwest with mean suitability decreasing 30.56% and VU_7 will move 419 km to the southeast with mean suitability decreasing 10.82%. In general, species distribution at high latitudes may move southward in the future with the decline in mean suitability. Species distribution at middle latitudes may move eastward. The movement of species means that their habitats are compressed and the living risk rises.

4. Discussion

4.1. The effect of climate change

The result demonstrates that the habitat area of migratory birds will significantly reduce in the future, mainly due to climate change (Gill et al., 2019). Migratory species are more responsive to climate change, as their migration process may be closely related to climate (Dunn et al., 2009).

According to the results 3.1, habitat loss and shift of the population centroid will make the migration process more difficult. The habitat loss also deteriorates the connectivity between different adaptation areas (Finch et al., 2017). The migratory birds have less food on the flyways and have to fly longer distance to achieve the migration. These conditions do not only make the migration process harder, but also make it impossible for many birds to complete. Migratory species require appropriate survival conditions throughout their whole migration process, including the breeding process, the wintering process and the migration between the 2 process (Rushing et al., 2016). Climate change may affect the 3 process all and lead species to spend more energy and time on migrating. With the increasing distance and the instability of food, the difficulty of survival for migratory species will increase (Finch et al., 2017; Rushing et al., 2016; Saino et al., 2011). Especially for the long-distance migration of birds, their risk of death will increase a lot (Bauer and Hoye, 2014; Kirby et al., 2008; Yong et al., 2018).

Result 3.2 shows the appropriate living conditions for the migratory birds which can be viewed through the single-factor response curves of 5 most important environmental variables (Fig. S2). From the 5 most important variables, we can know that birds prefer to live in the plains with a warm climate and abundant water resources (Ma et al., 2019; Yong et al., 2018). Flat terrain means flying distance to search for food is shorter and consuming energy is less. The warm climate and rich water resources mean food resources are rich for the migratory birds (Myers et al., 2000). When the temperature changes, the suitable area of the migratory birds will shift. The transferred area may overlap with the human living space, which will cause the living space for migratory birds to be compressed (Fournier et al., 2019).

Temperature plays a great role in the distribution of migratory birds. Therefore, we investigated the importance of environmental variables in 3 different climate zones (east part of the south temperate zone (STZ), middle subtropical zone (MSZ), and middle tropical zone (MTZ)). Simultaneously, the environment variables differences in 6 basins (Haihe River Basin, Yellow River Basin, Huaihe River Basin, Yangtze River Basin, Southeast Basin, and Pearl River Basin) were also considered. We selected the most important variables firstly and then calculated the percent contribution of variables to figure out the constraint of migratory birds in different regions.

4.1.1. How does climate influence the basins?

The habitat area will decline most in the Yangtze River and Pearl River basins of the south while the area will increase most dramatically in the Huaihe River basins (Fig. 6). The area of habitat in the Yangtze River basin will maximally reduce 58,880 km^2 in the future. The Pearl River basin and the Yellow River basin will decrease 34,589 km^2 and 10,287 km^2 in the future respectively. Yangtze River basin will loss 9.74% of the total habitat area in the basin. Pearl River basin will loss 13.21% of the total habitat area in the basin. Yellow River basin will loss 9.83% of the total habitat area in the basin. The habitat area of the Huaihe River basin will increase 13,218 km^2, accounting for 8.16% of the total habitat area in this basin. The decrement of habitat leads to the living space overlap between birds and humans (Flottum et al., 2016; Short et al., 2011).

The total migration direction of birds is different from that in different regions. The shifts of population centroid in different regions of habitat are shown in the Fig. 7a. The movements of these regions show

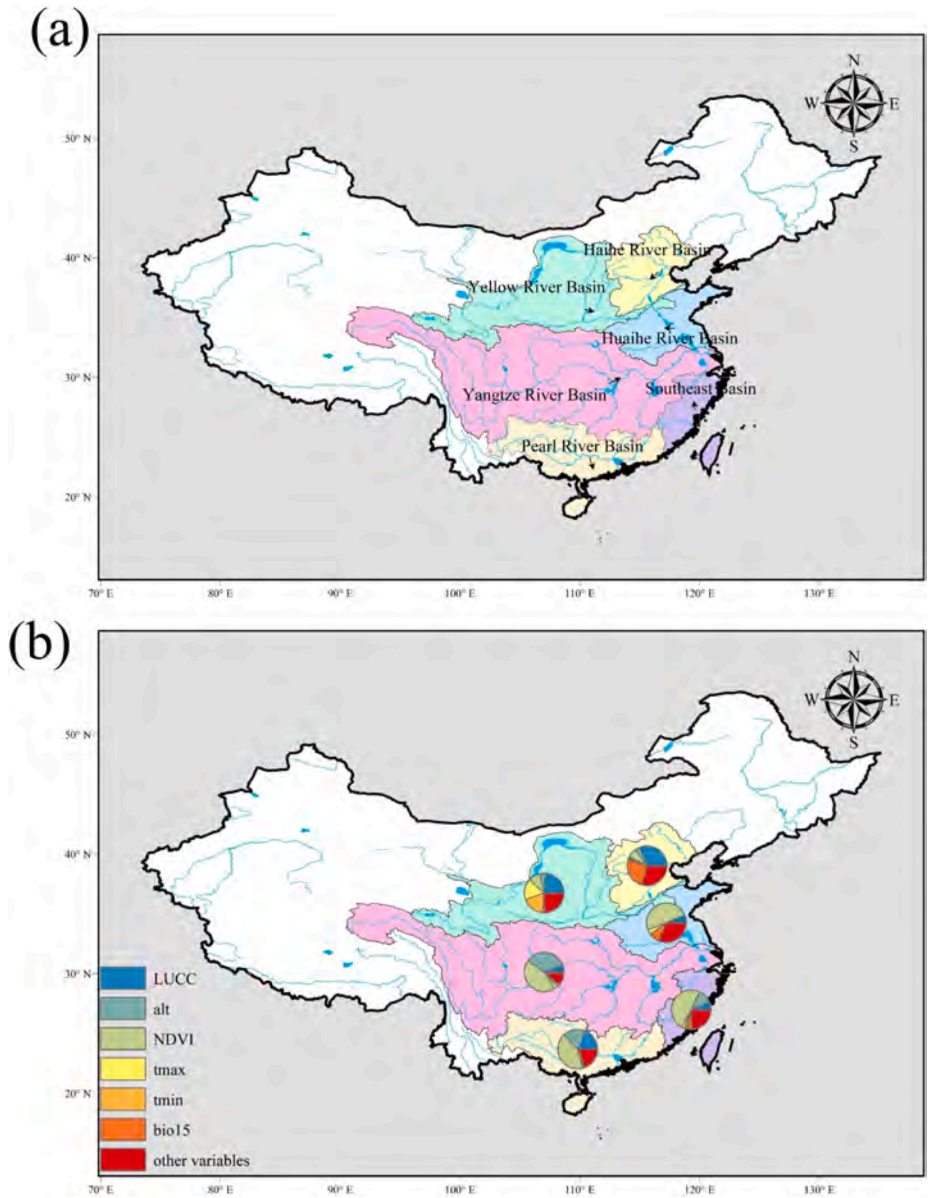

Fig. 7. (a) The shifts of population centroid and (b) the percent contribution of the environment variables in 6 basins.

that the tendency of the distribution is moving towards the mainstream, which also reveals that the distribution of migratory birds in the future scenario will be compressed. The population centroid in Yangtze River basin will move far 44.94 km towards southeast. The population centroids in Haihe River Basin, Pearl River Basin, Yellow River Basin, Southeast Basin, and Huaihe River Basin will move 34.26 km, 31.03 km, 25.33 km, 23.48 km, and 16.68 km respectively.

The result shows that NDVI plays a great role in Yangtze River basin, Huaihe River Basin, Southeast Basin, and Pearl River Basin, in which the percent contribution for distribution is 43.9%, 48.6%, 49.1%, and 43.5% respectively. In these regions, the food is the constraint of the distribution. LUCC is another constraint accounting for 30.9%, 23.8%, and 19.6% importance respectively in Haihe River Basin, Yellow River basin, and Pearl River basin. The human activity plays an important role in the distribution of these regions. Alt is an important variable in Yangtze River basin and Pearl River basin accounting for 34.9% and 13.7%, respectively. These areas have a wide range of elevation.

4.1.2. How does climate change influence the climate zones?

The habitats change mostly in the 3 climate zones (STZ, MSZ, and MTZ). The area of habitat has a significant decrease in these 3 climate zones in the future (Fig. 8). The habitat will lose about 61,247 km^2 accounting for 7.51% of MSZ total habitat area. The habitat area of MTZ will reduce 11.43% about 27,955 km^2 in the future. The habitat area will decrease 6499 km^2 which is about 2.17% of total habitat area of STZ.

The distribution of the STZ will move to the east, which is consistent with MSZ. The population centroid in STZ will move 44.81 km and MSZ will move 59.10 km (Fig. 9a). The distribution in MTZ will move 20.72 km towards south. The distribution will move to a more suitable area in the future.

The constraint of STZ distribution is LUCC accounting for 34.3% importance. The distribution in STZ is also influenced by bio14 and bio15 accounting for 21.6% and 11.4%, respectively. Seasonal rainfall significantly affects the distribution in this region. NDVI is the most important variable in the distribution of MSZ and MTZ whose percent

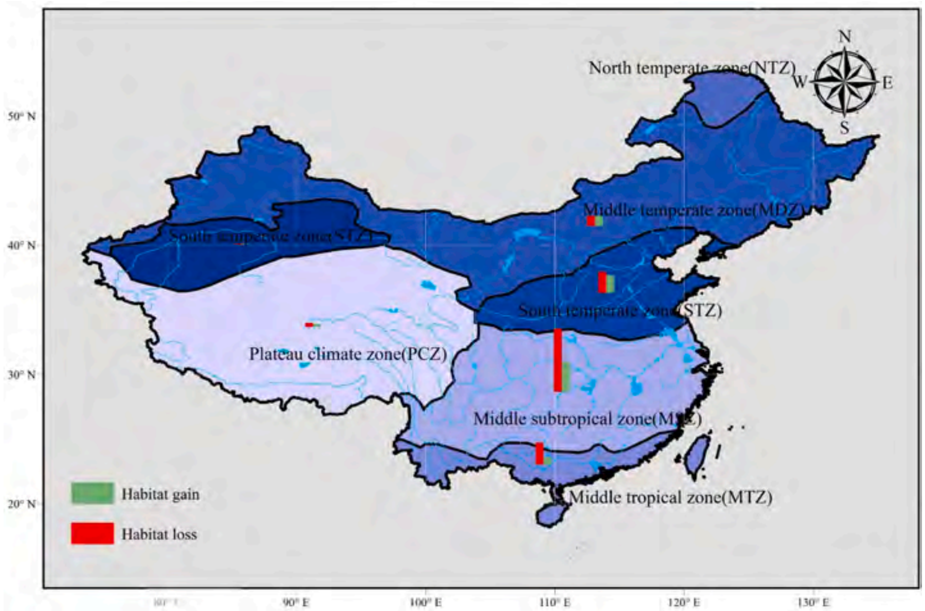

Fig. 8. The change of habitat in different climate zones.

contribution is 51.6% and 55.5% in 2 regions. Alt also plays a great role accounting for 24.6% in MSZ and LUCC accounts for 19.7% in MTZ (Fig. 9b).

The result shows that the reduction of the habitat area and the movement of the population centroid will cause an increase in the distance and the consumption, which forces the birds change their migration time and route. Moreover, some birds may be not even able to achieve migration. The habitat of migratory birds in central China will tend to move towards east in the future, and the habitat of migratory birds in the southern China tends to move towards south.

The result shows that NDVI is an important variable in southern China. The variable shows a great percent contribution to the distribution of migratory birds in southern China, which means the food is the constraint of birds. In the middle of China, LUCC plays a great role in the distribution. Especially in the Haihe River Basin and Yellow River Basin, the importance of LUCC accounts for over 30%, which means human activities influence the distribution greatly. In the Yangtze River Basin of the middle subtropical zone, we can see alt is an important variable to the distribution. Because of the wide area, the altitude varies greatly in the regions.

4.2. Implications of birds protection

4.2.1. The status of birds protection in China

Species with broad tolerance may persist or even expand in the changing environments, but migratory birds are sensitive to the environment (Huang et al., 2017; Runge et al., 2015). It is not effective to protect the biodiversity in China, though the country has committed great contribution in the remission of biodiversity loss (Young et al., 2014). The main measure of protecting the species is establishing the protected area in China. The identification and delineation of habitat is considered as the cornerstone of the establishment of protected areas.

Whether nature reserves work well under climate change has been more important to protect species. Although the number of nature reserves increases recent year, the protective effect is not obvious. The incomplete management of protected areas in China will increase the difficulty of biodiversity protection (Liang et al., 2018c; Ma et al., 2019; Sang et al., 2011). The uncomprehensive classification and ineffective legal mechanism enlarge the difficulty of management (Xu et al., 2019). The types of protected areas established by different department for unique purpose vary widely, and the rights and obligations of relevant departments for protected areas are uncertain, so it is difficult for the government to hold accountable (Liang et al., 2017; Xu et al., 2017, 2019; Yong et al., 2018). It is more difficult to ensure the effectiveness of protected areas since birds move to different places each year.

Considering the climate change and the distribution of the migratory birds, we compared the differences between the nature reserves and suitable areas (Fig. 10). Endangered species are more environmentally sensitive and the population of these species is rare. The migration of these endangered species makes it more difficult for human to protect them effectively.

Comparing the current distribution of birds and the protected area, we can find out that the suitable areas and nature reserves do not match very well. One of mismatch is that the large number of migratory birds lives in the middle and lower reaches of the Yangtze River Plain but protected area is only located around the Dongting Lake and Poyang Lake. The other of mismatch is the position of habitat and the protected area. Lots of habitats are not protected. The distribution of protected areas in different regions of China is very uneven, with large areas of protected areas in western China, but the distribution of birds is mainly concentrated in the eastern of China (Ma et al., 2019). Migratory birds tend to choose plain areas that are easy to fly to and feed successfully, so that they can save energy and have a high probability of survival. The western human population is rare, thus, it is easy to manage the reserves and prevent them from artificial effect. However, the situation in the east is more complex because of its position as the agriculture center and its dense population. The protected areas in the eastern area are scattered and broken, and the connectivity between them is also broken (Sang et al., 2011).

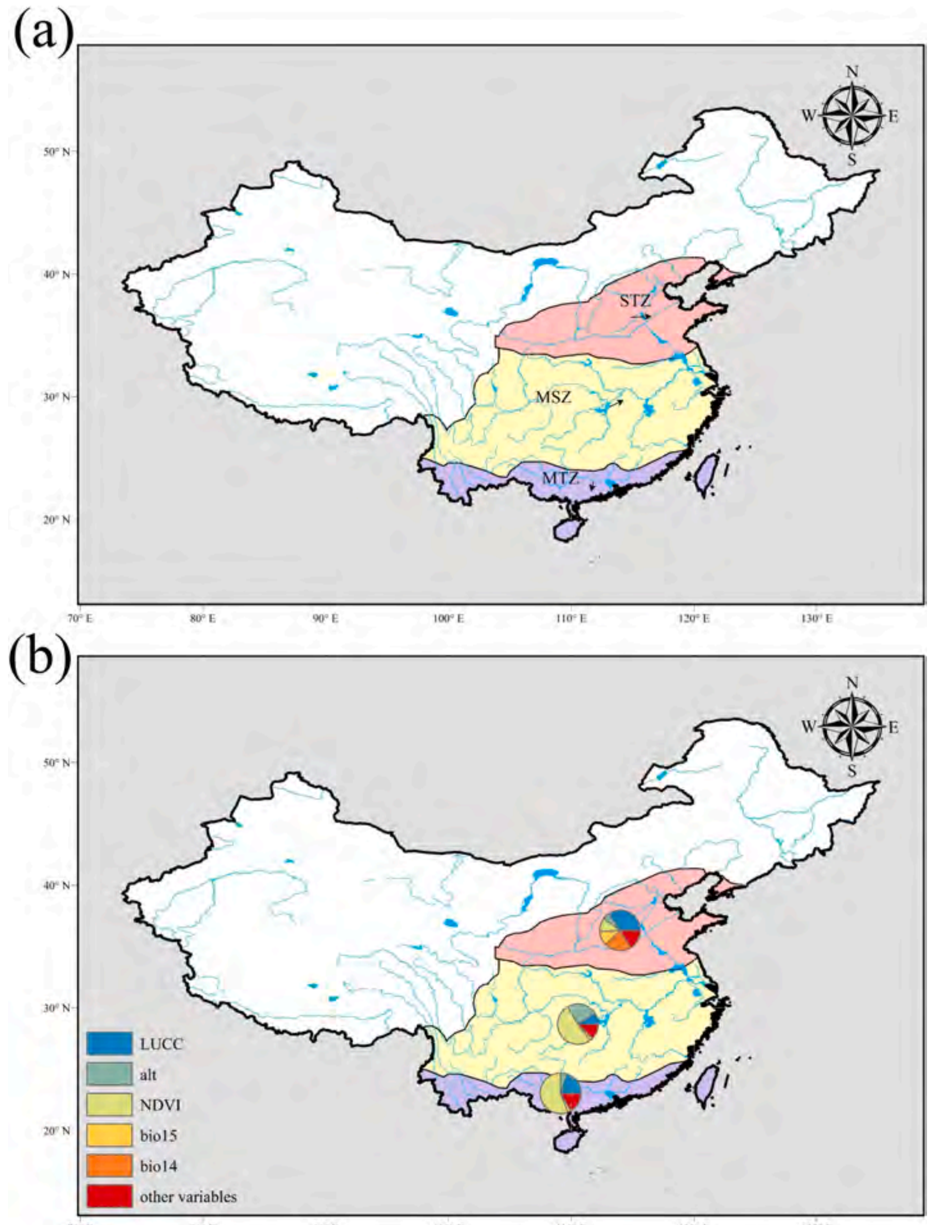

Fig. 9. (a) The shifts of population centroid and (b) the percent contribution of the environment variables in 3 climate zones.

4.2.2. Strategy for birds protection

Our results indicate some new views about the impact of climate change on bird populations. Firstly, an effective regulatory frame should be built based on the establishment of protected areas. The area of nature has reserved in China increases a lot since 2000, but the protective effect is not effective. There are 2 main reasons for this. The first reason is that the location of nature reserves mismatches the distribution of migratory birds (Ma et al., 2019). China is still in the process of high speed development, focusing on the economic activities and the urban expansion, which will reduce the space for birds (Liang et al., 2018b, 2017). The second reason is the lack of rational management of nature reserves. The nature reserves locate in the sparsely populated regions in China, which leads to few workers in the large area (Shen et al., 2015). Effective conservation measures must be established for the protection of species, not only to establish effective nature reserves, but also to take effective policies to reduce the impact of climate change on species distribution.

Secondly, the government should increase the funding used in biodiversity protection. In view of the future direction of bird movement, the species protection in eastern China should be strengthened. Therefore, adequate funding for species conservation should be maintained. The sufficient funding can establish a scientific and effective system to protect the species with great infrastructure and staff (Feng et al., 2020). The government can invest funds to establish a platform for comprehensive assessment of the impact of species protection, which can effectively investigate and monitor the status, changes, and threats of species distribution (Feng et al., 2020; Liang et al., 2018b; Ma et al., 2019; Sang et al., 2011; Xu et al., 2017).

Thirdly, the government should establish the effective legal rules to determine the role, benefit, and responsibility of multiple stakeholders. The nature reserves are established by different departments for various purposes (Lehikoinen et al., 2019; Runge et al., 2015; Xu et al., 2019). Specifically, there are different protection policies to select nature reserves, since China is a wide country with different regulations and standards (Liang et al., 2018a). In addition, the regulations may get conflicts where different types of protected areas overlap. The protected

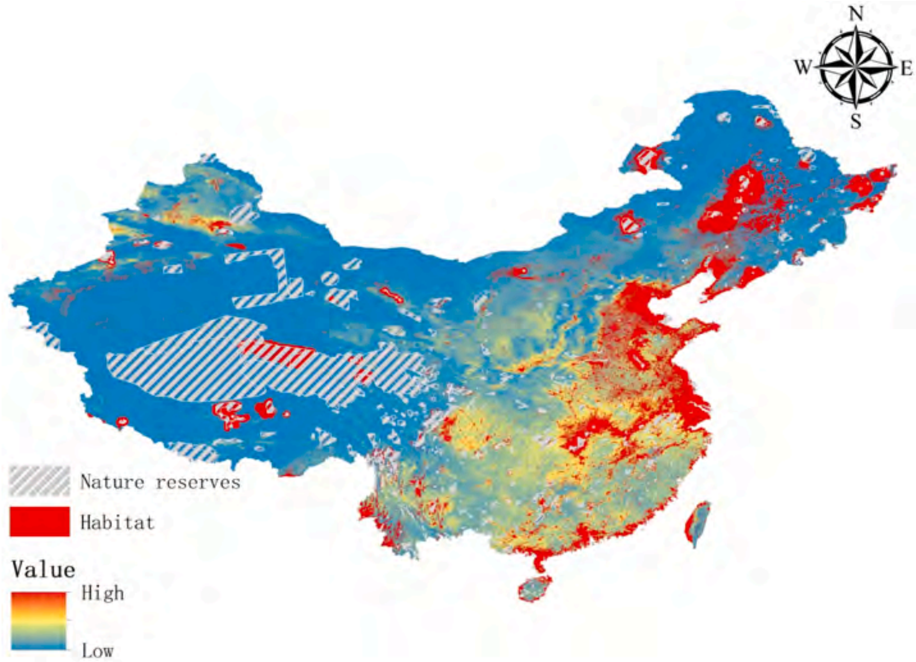

Fig. 10. The comparison of nature reserves and suitable areas in China.

areas among different provinces, climate zones, and the basins are interlacing geographically. Which guidelines should the cross areas follow and what kind of managements should these areas take are not clear. The mismatching borders among province, basins, and climate zones makes it more difficult to manage the cross zones between these areas.

Fourthly, the protection of whole birds and individual birds should be distinguished. According to our research, the influence of climate change on species distribution will rise in the future. Many species of migratory birds will decrease in distribution and population in the future climate scenarios, and may even face the risk of extinction (Pereira et al., 2010; Pimm et al., 2014). Also, some of the species will retain or expand in the future. The distribution of each species is different from other species and changes every year. Considering the suitable conditions for the individual species, we can choose a region for this species and control the environmental conditions to meet demand.

Finally, the effective policies should be taken to combat climate change. Climate change has a critical influence on the distribution of birds, therefore, it is necessary to keep the climate relatively stable by making policies. Temperature is the constraint of birds in the whole China. Because carbon emissions increase the temperature and have a great influence on the distribution of birds, it is necessary to reduce carbon emissions (Beringer et al., 2011). Also, the constraint in southern China is NDVI, which suggests that we should keep forest coverage floating within a certain range. At last, biodiversity loss is a heavy international problem, thus all the countries on earth should unite together to protect biodiversity.

CRediT authorship contribution statement

Jie Liang: Conceptualization, Project administration, Writing - review & editing. **Yuhui Peng:** Data curation, Writing - original draft, Methodology. **Ziqian Zhu:** Visualization, Writing - review & editing, Investigation, Resources. **Xin Li:** Formal analysis, Writing - review & editing, Validation. **Wenle Xing:** Software, Methodology, Validation. **Xiaodong Li:** Formal analysis, Investigation, Resources. **Ming Yan:** Supervision, Investigation, Visualization. **Yujie Yuan:** Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2021.107729.

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