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Where will threatened migratory birds go under climate change? Implications for China's national nature reserves

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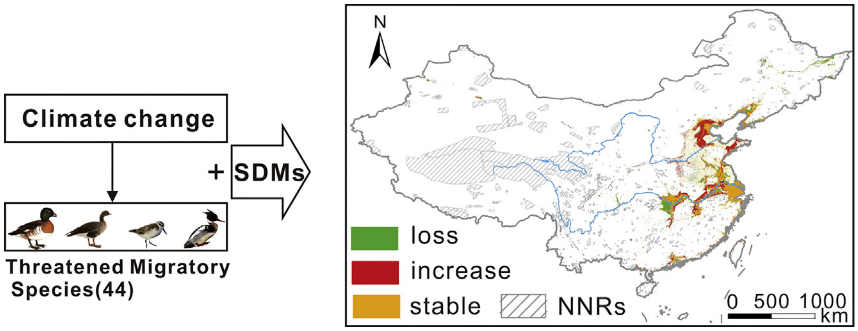
HIGHLIGHTS

- Climate change has impacts on species distributions.
- The species distributions are facing expansion or contraction by 2050 in China.
- Low proportion of hotspots covered by national nature reserves exists by 2050.
- China should increase more nature reserves in the east.
- We emphasize the creation of new and dynamic protected areas in coastal regions.

GRAPHICAL ABSTRACT



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ABSTRACT

Climate change, regarded as one of the major threats to biodiversity and ecosystems, can impact on the distribution and survival of migratory birds. To investigate the threats of climate change to threatened migratory bird distributions, we used species distribution model (SDM) and climatic data under current and future climate scenarios to predict future changes in species distributions and how the geographic distribution of these threatened birds may respond to climate change by 2050. Our results show the hotspots for all species may remain in the lower and middle reaches of the Yangtze River, while more species may dwell in the coastal regions of the Bohai Gulf and the Yellow Sea in the future. Our findings show that the percentage of all species distributions or hotspots for all threatened species covered by national nature reserves (NNRs) in China remain low by 2050. Thus, we propose that China should increase and expand reserves in eastern China. Significantly, we emphasize the creation of protected areas to make it the Ramsar sites in the world and recommend that China should (1) strengthen the cooperation with neighboring countries to share maximum species occurrence data (especially the threatened species), (2) overlay maps of individual species for each taxon to assess the efficiency of coastal nature reserves and predict the hotspots shift under climate change, (3) trade off urban development and ecosystem stability to create new and dynamic protected areas to make it the Ramsar sites, (4) appeal for long-term protection of ecosystem stability to achieve sustainable development in the world.

1. Introduction

Climate change, regarded as one of the major threats to biodiversity and ecosystems, can impact on the distribution and survival of migratory birds (Root et al., 2003; Travis, 2003). It may be profound

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and inevitable that climate change can lead to changes in the spatial distributions of many species (Anderson et al., 2009; Hickling et al., 2005). Thus, it is needed to predict changes in migratory bird distributions in future climate change scenarios for conservation (Rebelo et al., 2010).

Under climate-change scenarios, species may move from their original distribution sites to new adaptable habitats, indicating that they can keep track of their preferred climate niche, with changes in geospatial terms over time (Feeley et al., 2012; Golicher et al., 2012; Tingley et al., 2009). This dynamic process could also lead to local extinctions, especially for species with low dispersal capacities and adaptation (Rebelo et al., 2010; Thomas et al., 2004). Whether a species may adapt to climate change depends on its phenotypic plasticity, genetic changes and equilibrium with climate, otherwise it might go extinct (Feeley et al., 2012). Moreover, the response of species to climate change will depend on certain characteristics such as the size of its geographic range, dispersal capacity, reproductive rates, and its degree of specialized habitat requirements (Feeley et al., 2012). The response for individual species would not be uniform in an independent manner to climate change (Prietotorres et al., 2016). Thus, it is necessary to focus our attention on individual species to predict how their distributions may respond to climate change. The changes in species distributions depend on many climate factors including temperature and precipitation (Vanderwal et al., 2013), but the real challenge that ecologists and conservation biologists face is trying to predict what aspects of climate have greatest effects on species distributions (Bateman et al., 2016).

Recently, advanced methods of modeling species distributions and climate change have guided us to understand potential species distribution changes more deeply (Marmion et al., 2009; Thuiller et al., 2009). In addition, the Maxent model has been demonstrated to perform well for predicting the geographic distributions of species under climate change. (Guevara et al., 2018; Prietotorres et al., 2016). However, considering the overall effects of climate change on species distribution are not static in time (Jentsch, 2007; Mayer and Rietkerk, 2004). The perspective plays an important role in assessing climate change overall impacts on species distributions by overlapping species distributions to obtain maps of the spatial pattern of biodiversity distribution under climate change (Ferrier and Guisan, 2006).

To date the potential impacts of climate change on bird distributions have been studied more such as breeding ranges near polar or wintering ranges (La Sorte et al., 2017; Wauchope et al., 2017), and tropical bird ranges (Prietotorres et al., 2016). Many studies have assumed that coastal wetland losses in the Yellow Sea of China, considered to be critical for foraging habitats that migratory birds dwell, may lead to the declines of birds in the East Asian-Australasian Flyway (Ma et al., 2014; Mackinnon et al., 2012; Rogers et al., 2006). Dongting Lake Wetland and Poyang Lake Wetland in the lower and middle reaches of the Yangtze River, the Ramsar sites are on the decline (Liang et al., 2017; Zhang et al., 2016) and provide important international habitats for migratory birds in the East Asian-Australasian Flyway. A central approach to curbing the threat is establishing protected areas, and the principal protected areas in China are nature reserves. Few researches have assessed biodiversity and efficiency of conservation targets of national nature reserves (NNRs) in China, most of which have been established opportunistically (Liu and Mu, 2016; Naidoo et al., 2008; Wu et al., 2011). It is notable that few studies have predicted changes in species richness or species distributions in China under climate change scenarios (Hu et al., 2017; Liang et al., 2018a). Moreover, migratory birds spend their wintering, breeding or stopover in China. China has the largest human population and the second largest economy in the world, gravely affecting the key stopover habitats of birds, especially of threatened migratory birds. It is really urgent to know how threatened migratory birds may respond to climate change in order to identify conservation hotspots.

Here, our goal in this study is to predict future changes in species distributions and how the geographic distribution of these threatened birds may respond to climate change and then propose recommendations for conservation hotspots. To achieve this goal, firstly, we applied species distribution models (SDMs) and overlapping the 28 species distributions under current and future climate scenarios to obtain the maps of species distributions. In addition, we predict the changes in species distributions and identify the hotspots shift under climate change. Finally, we assess the efficiency of China's nature reserves and propose recommendations for protected areas to make it the Ramsar sites in the world.

2. Materials and methods

2.1. Occurrence records

We selected 44 species in the IUCN Red List (IUCN, 2014)–Critically Endangered (CR, 5 species), Endangered (EN, 15 species) and Vulnerable (VU, 24 species). Occurrence locality records were gathered from two sources: (i) Bird report (http://birdreport.cn/bird/, from 2014 to 2017), collected by birdwatchers; (ii) records obtained from bird survey. With the development of society, the increasing birdwatchers afford many available records. The records were checked by the experienced birders and the bird survey to reduce the errors, then records with ambiguous spatial localities and indefinite records were removed. The latitude and longitude of the localities were obtained from the Google Maps by importing the localities name manually. Sample localities were digitized in ArcGIS 10.2 (ESRI, 2012). Then, to reduce statistical errors connected with small size, the 28 TMBs were applied to construct the species potential distribution model, except those with fewer than 10 independent localities. The remaining 16 species were used to make scatter plots. Occurrence data from birdwatchers has its own limitations. For example, birdwatchers are not uniformly distributed across China, resulting in potential spatial bias in the occurrence data.

2.2. Environmental data

We obtained a total of 23 environmental and bioclimatic variables for projection: 19 bioclimatic variables for both current climatic conditions (average for 1970–2000) and future projections (average for 2041–2060, here after referred to as 2050) from the WorldClim website (http://www.worldclim.org), distance to water and distance to road from the IGRR (Institute of Geography and Resource Research, Chinese Academy of Sciences) by inter-agency letter of agreement, land cover type (GLC-2010) from the GLOBELAND30 website (http://www.globeland30.org), and digital elevation model (GDEMV2 30 M) from the Geospatial Data Cloud (http://www.gscloud.cn), all variables with a 30 arc sec (~1 km) resolution. To predict general future trend, we assessed the possible conservation effects of climate change on species distributions under two Representative Concentration Pathway scenarios. RCP 4.5 is an optimistic scenario where emissions peak around 2040, and RCP 8.5 is a pessimistic scenario where emissions keep rising through the 21st century. For each scenario, we used climate projections from global climate models applied by Commonwealth Scientific and Industrial Research Organization and Bureau of Meteorology (ACCESS1.0). While the potential problems related to the use of global climate change scenarios at local scales, SDMs have been extensively applied in predicting the impacts of future climate change on species and ecosystem distributions, as they represent alternative future scenarios and emphasize the potential threats to species of conservation concern (Baker et al., 2015; Bedia et al., 2013; Ponce-Reyes et al., 2017; Ponce-Reyes et al., 2012). It is well acknowledged that climate data from WoldClim can be used to construct species distribution models in the world (Ponce-Reyes et al., 2017; Prietotorres et al., 2016; Wauchope et al., 2017; Ye et al., 2017).

Prior to the species-climate modeling, we tested for multicollinearity among the 23 environmental variables and found that 11 out of the 23 variables were most correlated with others (Table S2), retaining only those following 12 variables with less than ±0.80 correlation. Mean Diurnal Range (BIO2), Isothermality (BIO3), Max temperature of warmest month (BIO5), Min Temperature of Coldest Month (BIO6), Temperature annual range (BIO7), Precipitation Seasonality (BIO15), Precipitation of warmest quarter (BIO18), Precipitation of Coldest Quarter (BIO19), digital elevation model (DEM), distance to water, distance to road, and Land cover (2010). If two variables were highly correlated, we selected the one we considered had most plausible impacts on species distribution.

2.3. Species distribution models

The relationship between every species' occurrences and climatic conditions can be well established by using the ecological niche modeling software, Maxent (Phillips and Dudík, 2008), and moreover, Maxent has been considered to work better with limited presence-only occurrence data (Merow and Silander Jr., 2014) With Maxent 3.3.3k using the principle of maximum entropy, we obtained individual species distribution map for each species by importing two data: the longitude and latitude of every species' localities and the 12 environmental variables. Models were run with a random sampling of 70% of the locality records as training data and the remaining 30% for model evaluation as testing data. In addition, we ran 1000 iterations and 10 replicates using repeated split sampling, to reduce error (Ye et al., 2017). To investigate which climatic variables contributed most to our SDMs, the permutation importance methods from Maxent outputs were used to obtain the importance of each climate variables. We used the equal training sensitivity and specificity threshold to convert the logistic outputs of models to presence-absence binary maps (Lawson et al., 2014). For our purpose, this threshold is considered suitable and more conservative (Bateman et al., 2016; Freeman and Moisen, 2008; Phillips et al., 2006), which we applied to obtain high-quality distribution area of every species. The other parameters in Maxent were made at default settings. We evaluated the performance of distribution model of each species using area-under-the-curve (AUC) scores of the receiver operating characteristic (ROC) curve. To reduce bias in model performance estimates, we estimated models using 10-fold cross validation (Bateman et al., 2016; Eitelberg et al., 2016; Robert et al., 2013) and considered an AUC above 0.7 to be good model performance (Fielding and Bell, 1997).

2.4. Assessing changes in TMBDs under climate change

We overlaid maps of individual species to obtain maps of CR, EN, VU species and all species respectively under current and future climate change scenarios. Then, we identified the hotspots for CR, EN, VU or all species by defining the top 5% richest areas of each group as the hotspots for each group. Subsequently, we used the map of NNRs in China from the protected planet website (https://www.protectedplanet.net/) to calculate the percentage of distribution range and hotspots of all species covered by NNRs. Finally, to assess changes in species distributions to climate change, we evaluated stable range, gained range and lost range by contrasting hotspots for all species under current and future distribution maps. Moreover, we examined the species richness change by computing the difference between future richness and current richness in each pixel. Species' stable range was figured as the percentage of overlapping area between current and future hotspots in the current. While species' gained or lost range was calculated as the percentage of area predicted to become suitable or unsuitable area respectively in the future compared to the current (Broennimann et al., 2006). We estimated the range change of hotspots for all species by computing the difference between range gain and loss, representing the percentage of their hotspots expansion or contraction between current and future scenarios (Prietotorres et al., 2016).

3. Results

3.1. SDMs, current TMBDs and variables importance

We constructed the 28 SDMs to predict the potential geographic distribution of each species based on environmental variables. All models show high values for the AUC test (0.829-1) (Table S1), indicating that all the models could adequately predict the birds' presence and absence.

The overlap of individual species maps was used to create overall species distribution maps. We discover that the species distribution relative to the species richness seems to decrease with species richness increasing in the overlapping map (Fig. 1). The range of only one species accounts for 33% of all species distributions, and the range where the richness is higher than 5 accounts for merely 30%. It is suggested that species distributions are decentralized in China, and it would be a large challenge for conservation. Moreover, the species distributions with high richness are mostly located in eastern China, and a small part are located in the Xinjiang Uygur Autonomous Region (Fig. 2).

The hotspots for CR species concentrate in lakes or rivers around the lower and middle reaches of the Yangtze River (Fig. 3A). The hotspots for EN species are mostly located in the lower and middle reaches of the Yangtze River, and partly dwelled near the Yellow River Mouth Area (Fig. 3B). For VU species, the majority of hotspots are centered in the lower and middle reaches of the Yangtze River, in the western coast of the Bohai Gulf and in the Northeast Plain (Fig. 3C). The hotspots for all TMBs are also similar to those for VU species (Fig. 3D).

Aiming at biodiversity conservation and secure ecosystem services, a growing number of NNRs have been established in the different regions of China (Xu et al., 2017). However, the NNRs are concentrated in the western China, and some of small NNRs are in the eastern China. There is an alarming lack of large protected areas in the eastern China. The percentage of all species distributions covered by NNRs in China is about 10%, and that of hotspots for all TMBs is 6%.

The permutation importance of each variable varies considerably among species (Table S1). On the whole, Isothermality (BIO3) has the greatest permutation importance, followed by Mean Diurnal Range (BIO2) and Precipitation of Coldest Quarter (BIO19), indicating that temperature is more important than precipitation in the predictive models.

3.2. Changes in species distributions

Table S1 shows the current and future predictions based on Maxent under RCP 4.5 and RCP 8.5 climate-change scenarios by 2050. The potential SDMs for the 2050 climate-change scenarios show significant difference in the current distributions. The RCP 4.5 and RCP 8.5 climate-change scenarios differ in their greenhouse gas concentration. Climate change may have intricate impacts on individual species distribution. Under the two climate-change scenarios, the range change of individual species varies from −78 to 141%. The distribution areas of eight species increase, and The distribution areas of another eight species decrease, and the distribution areas of another seven species have few changes (−15 to 14%) (Fig. 4). It is interesting that range change of the other five species shows opposite trend under the two climate-change scenarios, for example, the range of a species increases under RCP 4.5 climate-change scenario, but it decreases under RCP 8.5 climate-change scenario.

The distribution maps of all species show a relatively small increase (9%, 1%, respectively) under RCP 4.5 and RCP 8.5 by 2050. Species richness of all threatened birds is projected to change under RCP 4.5 and RCP 8.5 climate-change scenarios by 2050 (Fig. 5A–B). The maximum richness values slightly decrease from 26 to 25 and 23 under RCP 4.5 and RCP 8.5 climate-change scenarios by 2050. On the whole, the range of every richness value has little change in China by 2050 (Fig. 1), while some areas have larger species richness (such as the southern coastal areas and the western coast of the Bohai Gulf) and some areas face large decrease (such as the upper and middle reaches of the Yangtze River, especially the northern Guizhou province, the Dongting Lake and the Poyang Lake) (Fig. 5A–B).

The following patterns reveal changes in hotspots by 2050: (i) The hotspots for all threatened species have a range expansion of 12%, 13% under RCP 4.5 and RCP 8.5 respectively, and those for CR, VU, EN species

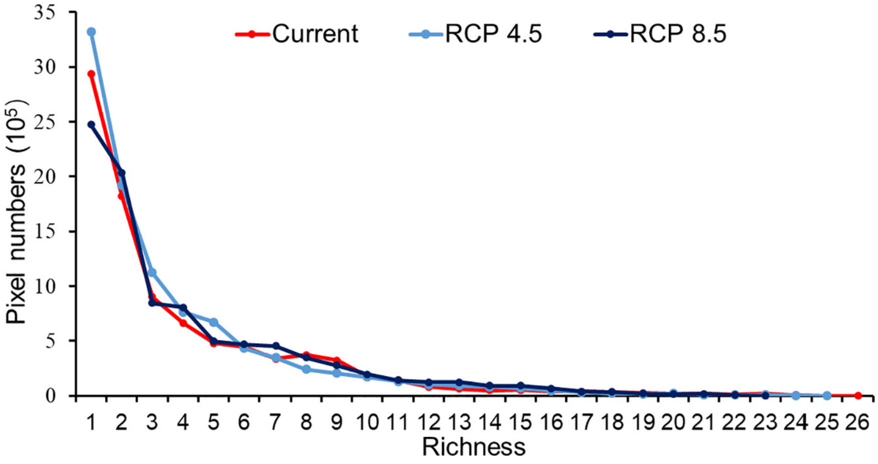

Fig. 1. Number of pixels evaluated on the basis of distribution range of all threatened species in China under current and future climate climate-change scenarios.

decrease by 38%, increase by 29%, decrease by 12%, under RCP 4.5 respectively, increase by 5%, 16%, decrease by 13, under RCP 8.5 respectively; (ii) in general, the hotspots for all threatened species located in the western coast of the Bohai Gulf and in the northern coast of the Yellow Sea mostly increase, but in the western area of the Dongting Lake and the northeastern China decrease dramatically (Fig. 5C–D); (iii) It shows similar to the current scenario that the percentage of all threatened species distributions covered by NNRs in China is 10%, and that of hotspots for all TMBs is 4% under RCP 4.5.

4. Discussion

4.1. Effects on individual species distribution

Overwhelming evidence indicates that anthropogenic climate change will lead to massive species extinctions (Bässler et al., 2010; Thuiller et al., 2010), and the effects of climate change on species distributions should be predicted (Hernandez et al., 2006; Hugo et al., 2010). Moreover, it is very difficult to confirm how species will respond to climate changes which are in absence at present, because successful reproduction and colonization depend on many factors, such as the geographic range, dispersal capacity, reproductive rates, and its degree of special habitat requirements (Feeley et al., 2012; Isaac et al., 2009). Thus, we investigate the potential effects of climate change on 28 species distributions in China. Our results show considerable complexity of changes in species distributions under climate change (Bateman et al., 2016), indicating that these species distributions would face expansion or contraction in China by 2050 (Fig. 4). The complexity observed in our study has also been noted among other regions (Gillings et al., 2015; Pinsky et al., 2013; Vanderwal et al., 2013). Previous results observed that the specific impacts of climate change on individual species distributions were not uniform as they responded in independent manners to climate change (Prietotorres et al., 2016). Moreover, it is possible that species may vary in their adaptive capacity to the climate changes (Saalfeld and Lanctot, 2001), and less adaptable species in regions have low probability of persevering in current localities under

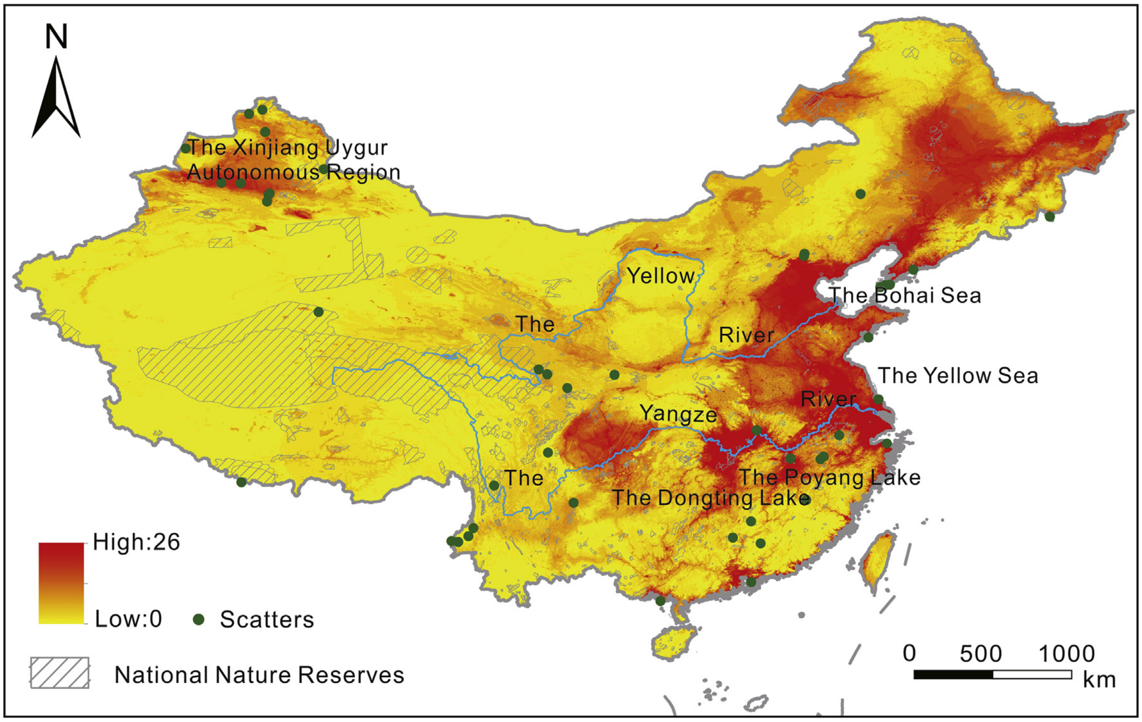

Fig. 2. The map of combining all threatened species distributions in China under current scenario.

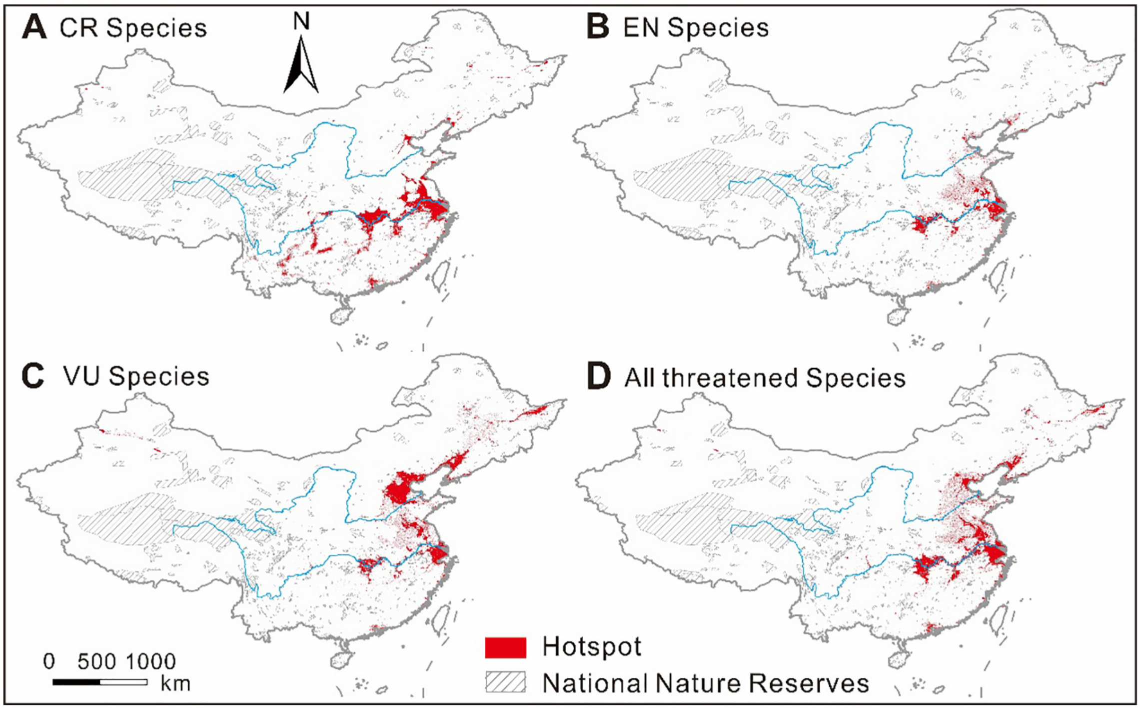

Fig. 3. The hotspots for threatened species in China under current scenario. A–C shows the hotspots for CR, EN and VU species, respectively, D shows the hotspots for all threatened species.

severe climate change. One reason for the complexity could be that different climate variables may dominate on different distributions (ML et al., 2013), where the 28 species distributions may dwell for wintering, breeding or stopover. Climate change may affect the timing of migratory birds' arrival to breeding grounds which plays a significant role on reproductive success, and survivor (Both and Visser, 2001).

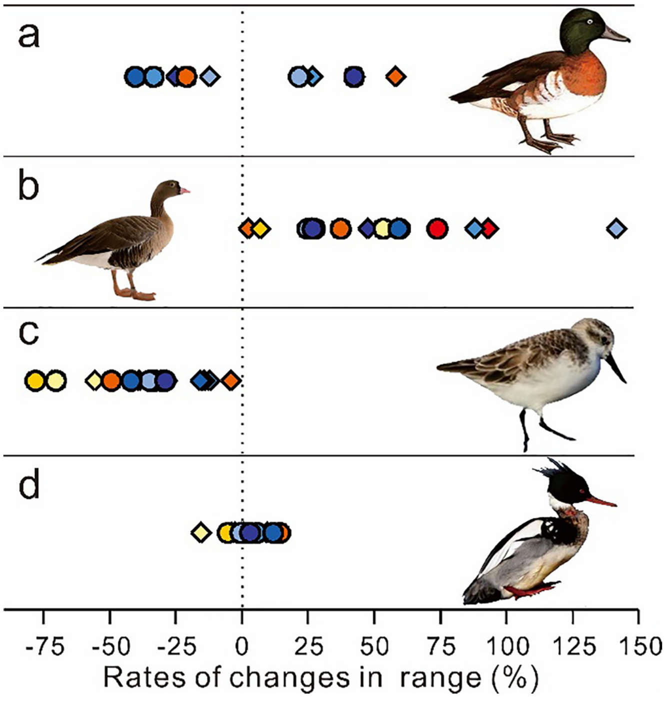

Fig. 4. The rates of changes in range of individual species under RCP 4.5(solid circles) and RCP 8.5 (solid rhombus) climate-change scenarios (%), and the photos of representative birds under every range change trend. a, opposite trend under RCP 4.5 and RCP 8.5 climate-change scenarios (*Aythya baeri*). b, range gain (*Anser erythropus*). c, range loss (*Eurynorhynchus pygmeus*). d, little change (*Mergus squamatus*).

BIO3 is the top variable, indicating that the combination of temperature and precipitation may have more effects on species distributions. Prior results suggested that average temperature alone may not indicate bioclimatic variation well (ML et al., 2013), and precipitation of the driest quarter could play an important role in species distributions. BIO2 (Mean Diurnal Range (Mean of monthly (max temp − min temp))) is the second top variable, and BIO18 (Precipitation of Warmest Quarter) is the third top variable. These are key variables on species distributions, which could make species expand or contract their distributions (Bateman et al., 2016). Thus, our results assume that it is needed to combine precipitation and other climate variables (including extreme conditions) into future predicted species distributions rather than only focusing on rising global temperatures (Pinsky et al., 2013).

4.2. Effects on species distributions

When considering the effects of climate change, the suitable areas for all species distributions will increase (9%, 1%, respectively) under RCP 4.5 and RCP 8.5 by 2050 in China. It is generally consistent with the previous research that modeled the impacts of climate change on Mexican tropical dry forest distributions (Prietotorres et al., 2016). The map of combining all species distributions suggests that the maximum richness values decrease slightly under future climate-change scenarios by 2050. On the whole, Despite our results observe that the species richness will make little change in China, species richness may increase or decrease in some areas, suggesting that more or fewer species dwell there. It has been investigated that both temperature (increase) and precipitation values (decrease) may result in a widespread reduction of current potential species richness in Mesoamerican ecosystems (Gasner et al., 2010). However, species richness results may or may not reflect the real change, and those may be overpredicted for we modeled changes in potential species richness from SDMs (Bateman et al., 2016).

It is observed that the hotspots for all threatened species will have a range expansion of 13%, on average by 2050. However, our results also show loss and gain of species distributions, which will increase in coastal regions of the Bohai Gulf and the Yellow Sea, and decrease dramatically in the western area of the Dongting Lake and northeastern

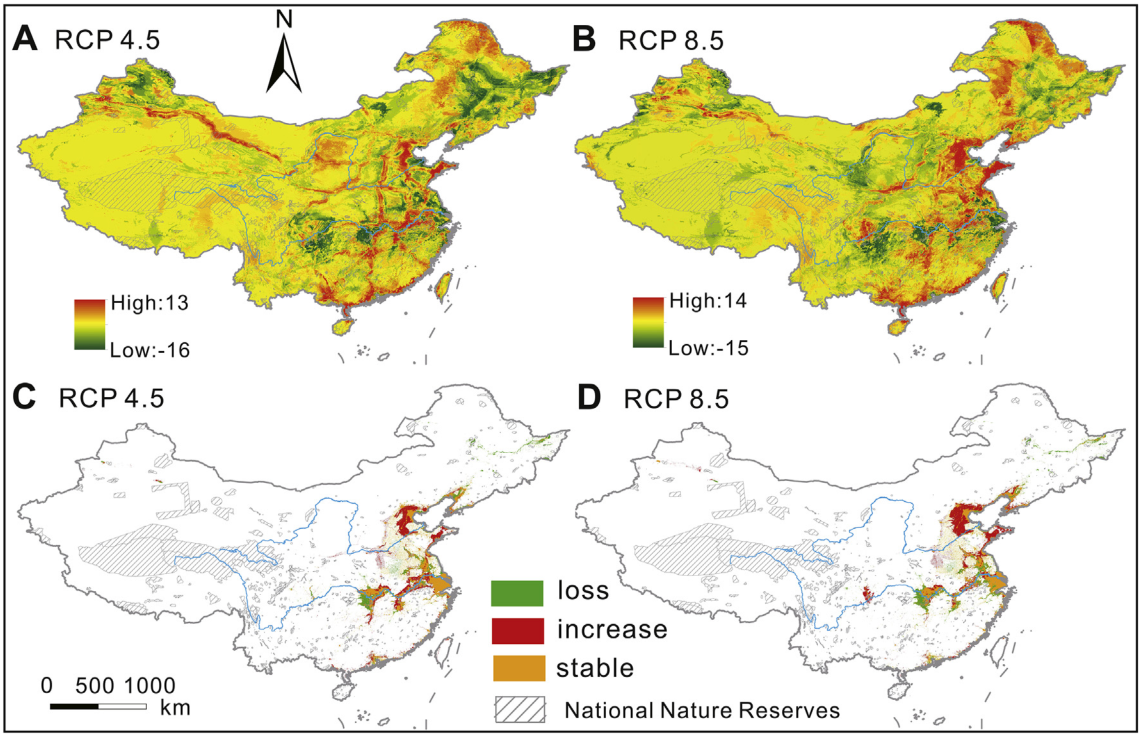

Fig. 5. The distribution range of all threatened species (A–B) and the hotspots for all threatened species (C–D) are projected to change in China under RCP 4.5 and RCP 4.5 climate-change scenarios.

China. It is indicated that a growing number of birds may dwell in coastal regions of the Bohai Gulf and the Yellow Sea, which have been widely considered to be as significant climatic habitats that migratory birds rely on during migrations (Battley et al., 2012; Ma et al., 2013; Rogers et al., 2010). Moreover, the hotspots for CR species will decrease by 38% under RCP 4.5 by 2050, and all of their species distributions will decrease. It is assumed that the climate change would have negative effects on CR species under RCP 4.5, leading to extinction risks that they might die out which regions are predicted to become climatically unsuitable for them in the future (Harte et al., 2004; Ohlemüller et al., 2010). Moreover, an increasing number of hotspots for all species may locate in the Bohai Gulf and the Yellow Sea, where many studies have assumed that the documented declines are likely caused by coastal wetland losses and the loss of tidal flats has been demonstrated (Aharon-Rotman et al., 2015; Ma et al., 2014; Mackinnon et al., 2012; Murray et al., 2014; Ning et al., 2015; Rogers et al., 2006; Wang et al., 2014). It has been mentioned that increasing number of people, urban expansion, boost industry and agriculture has caused attention about integrity of coastal ecosystem and protection of the endangered species in the Bohai Gulf and the Yellow Sea. Thus, the threatened birds in coastal regions of the Bohai Gulf and the Yellow Sea will face more severe extinction risks in the future. Hotspots for all species may remain in the lower and middle reaches of the Yangtze River in the future. Thus, we recommend constructing new and dynamic protected areas in eastern China in the future, especially in coastal regions of the Bohai Gulf and the Yellow Sea.

4.3. Implications for China's national nature reserves

Although, the creation of protected areas is a useful conservation tool, it has been investigated that ineffective governance could undermine the benefits of each conservation efforts aiming at improving biodiversity (Amano et al., 2017). Our results reveal that the NNRs are concentrated in western China, whereas many species distributions are located in the eastern China (Xu et al., 2017). Moreover, the percentage of species distributions for all threatened species covered by NNRs in China are low, and that of hotspots for all species covered by NNRs are lower under current and future climate change scenarios, suggesting that the serious deficiency of NNRs exists in China (Liang et al., 2018b; Wu et al., 2011).Thus, it is an urgent need that China should increase and expand reserves in eastern China (Wu et al., 2011).

It has been mentioned that most of China's nature reserves were established without a clear planning framework (Wu et al., 2011), resulting in "paper parks" instead of realizing sustainable conservation (Liu et al., 2003; Wang et al., 2016).In addition, we predict that not only conservation gaps and deficiency still exists for many species (Huang et al., 2016), but conservation gaps may shift in the future. To address the deficiency, many recommendations have proposed, such as Liang et al., recommended a new framework of China's protected area network composed of conservation priority and ecological corridors in consideration of high connectivity between areas (Liang et al., 2018b), Xu et al., recommended a strategy for establishing a comprehensive national park system to remedy the weaknesses in China's protected area (Xu et al., 2017). However, they hardly emphasized the Ramsar sites conservation, especially in coastal regions of the Bohai Gulf and the Yellow Sea. Our results indicate that hotspots may mostly shift in coastal regions of the Bohai Gulf and the Yellow Sea under climate change by using the occurrence data of threatened migratory bird in China. Thus, we propose the recommendations for creating dynamic protected areas in coastal regions. First, China should strengthen the cooperation with neighboring countries to share maximum species occurrence data (especially the threatened species). Second, SDM (Maxent, the advanced model) should be constructed and overlaid for each taxon to assess the efficiency of coastal nature reserves and to predict the hotspots shift under climate change. Third, the management should trade off urban development and ecosystem stability and create new and dynamic protected areas to make it the Ramsar sites. Finally, we should appeal to people for long-term protection of ecosystem stability to achieve sustainable development in the world.

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Appendix A. Supplementary data

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