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Threatened birds face new distribution under future climate change on the Qinghai-Tibet Plateau (QTP)

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ABSTRACT

The Qinghai-Tibet Plateau (QTP) contains a significant amount of biodiversity which provides a wide range of habitats for a great quantity of wildlife, especially various birds, on account of the unique climatic conditions and geography. However, the QTP has shown more sensitivity and vulnerability to global climate change than other regions, and the change pose a threat to the birds. Here, we used the MaxEnt and the barycenter shift analysis for analyzing the effects of global warming on the potential future habitat of the threatened birds on the QTP by using the ACCESS-ESM1-5 global climate model of the Coupled Model Intercomparison Projects Phase 6 (cmip6) climate pattern with three Shared Socioeconomic Pathway (SSP). The results demonstrated that the climatically suitable habitats for the threatened birds are mainly distributed in the eastern and central regions of the QTP. Moreover, over 81% of the threatened birds would experience a reduction in suitable habitat area within the next 30–50 years in the different future global warming scenario. Satyr tragopan (*Tragopan satyra*) would lose the most habitat (57.15%), while the Tibetan babax (*Pterorhinus koslowi*) would lose the least (0.35%) in comparing to these birds. Nonetheless, some threatened birds showed an increase in their future habitat area because of their physiological characteristics which are more adaptable to a wide range of climate. The climatic suitable habitat for all the threatened birds, except for the Tibetan eared pheasant (*Crossoptilon harmani*), would move to higher altitudes or higher latitudes regions. Simultaneously, the threatened birds in the order of Galliformes had a higher risk of extinction due to their weak flight and extended migratory distances on the QTP in the future. Our study provides provide a data foundation for the conservation of biodiversity and wild birds on the QTP.

1. Introduction

Intergovernmental Panel on Climate Change (IPCC) has concluded that human-induced climate change is increasing the occurrence and magnitude of extreme weather events, including prolonged scorching weather, heavy rainfall, and drought. Moreover, human activity is warming the planet at a faster rate than we have seen in at last 2000 years, with the planet heading for global warming of more than 1.5 °C within the next two decades (Change, 2018; Chen et al., 2018a; Chen et al., 2018b). Meanwhile, the views of changing in the distribution and habitat of creatures were significantly associated with the climate change is obvious (Chuine, 2010; Perry et al., 2005; Thuiller et al., 2005; Velásquez-Tibatá et al., 2013; Wang et al., 2017). An increasing number of studies have shown that a rapid change in climate has altered the ranges and patterns of creatures. It has even accelerated the extinction of a large number of species with low resilience to climate change. For example, the birds in North American have lost about 3 billion individuals since 1970, and the climate change has aggravated this situation (Rosenberg et al., 2019). So far as to the large ungulate, for example, the risk of extinction *Procapra przewalskii*, *Procapra picticaudata*, *Pantholops hodgsonii*, and *Gazella subgutturosa* on the Qinghai-Tibet Plateau (QTP) might be increased on account of climate change (Hu and Jiang, 2011; Zhang et al., 2021). And climate change also has changed the habitat range of birds in England, driving their habitats northward

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(Brommer, 2004; Thomas and Lennon, 1999; Virkkala and Rajasarkka, 2011).

The QTP is the largest and highest plateau on the world, with an average elevation of over 4000 m, and it is known as the “Roof of the World” and the “Third Pole” (Qiu, 2008). Moreover, the unique climate patterns and special geography of the QTP have promoted the diversity and richness of the local species (Favre et al., 2015). Consequently, the QTP has been a research hot spot region for biodiversity research in the world. In recent decades, a rising studies had demonstrated that the QTP is expiring a considerable warming. The QTP has a rate of warming over the past 50 years exceeding the average of global rate by a factor of two (Kuang and Jiao, 2016; Wang et al., 2021). Meanwhile, studies have revealed that the QTP shows more significant sensitivity and vulnerability to climate change than other regions with the rising global temperatures (Yao et al., 2020; Yao et al., 2012; Zhang et al., 2020). The QTP is one of the geographical regions with the largest bird fauna in China. The QTP had a total of over 700 bird species, and it accounting for about half of all the birds in China (Zhang et al., 2017). The unique geographical position and climatic conditions of the QTP had driven the formation of endemic birds, and it also had considerably enhanced the richness of bird species on the plateau (Lei et al., 2014; Zhang et al., 2017). While bird species on the QTP region are highly diversified in China, the birds which reside on the QTP region tend to have a greater proportion of vulnerable species as well as a relatively higher biological endemism (Viterbi et al., 2013). In addition, climate is generally believed to have the most significant effects on the biodiversity of creatures, including birds and reptiles on the QTP (Sun et al., 2021). For instance, the complicated climate of the QTP has contributed to the specific distribution pattern of birds on this region. And this distribution pattern of birds showed that the richness of bird species is highest in the southeastern region on the QTP, and lowest in the central and northwestern parts of the QTP (Zhang et al., 2017). Therefore, when the climate changes, including an increase in temperature and precipitation, it may cause a change in abundance, distribution, and rhythm of birds (Leech and Crick, 2007; Marra et al., 2005; Stephens et al., 2016). Various studies have shown that the response of the most creatures for the global warming was moving to higher altitudes or higher latitudes (Chen et al., 2011; Pauchard et al., 2016; Skarbø et al., 2016). However, the warming might lead to the extinction of species with poor migration capabilities and adaptability on account of their suitable habitat was lost or their migration process was hindered (Cahill et al., 2013; Urban, 2015). Threatened species may become extinct in a near future. These species are in a higher risk of extinction in the face of future climate change than other species for the reasons of their poor population quantity and adaptability (Fortini et al., 2017; Liang et al., 2018a; Morueta-Holme et al., 2010). Thus, the threatened species should be given a further attention in the conservation activities of species diversity. And, advance knowledge and projections of specific areas of changes in the distribution of suitable habitat on spatial and temporal scales for these threatened species under the future climate scenarios is critical for the conservation of species diversity.

Species distribution models (SDM) algorithmically correlate the distribution of a specie with the relevant environment factors of site of the species to calculate the ecological requirements the distribution of the species, and the result of the computation was used to the predict the potential distribution of the species in an area under specific spatial and temporal requirements (Elith and Leathwick, 2009; Lembrechts et al., 2019). Ecologists are in actively employing SDMs to quantify the relationship between species and environment for determining the effects of future climate and habitat changes on species (Howard et al., 2014). And the SDMs has developed into the efficient tools for studying the potential habitat distribution of species and habitat suitability (Raxworthy et al., 2003; Rushton et al., 2004; Williams et al., 2009). MaxEnt model is the species distribution model which was constructed based on the maximum entropy theory (Elith et al., 2011). This model associates the actual distribution records of species with the corresponded environmental factors, and the model predicted the optimal state of species distribution patterns within a certain ecological niche constraint based on the theory that the same species requires the similar climate conditions (Phillips and Dudik, 2008). Among the various SDMs, the MaxEnt model also has prediction results with a high accuracy for species with few positions, localized geographic areas, and limited environmental tolerance (Jiang et al., 2020; Khadka and James, 2017).

In this study, we evaluated the distribution areas of suitable habitats for threatened birds on the QTP on spatial and temporal scales by applying the MaxEnt model. And we assessed for the potential effects of global climate change on the threatened birds on the QTP for the first time. Since some threatened birds on the QTP are migrant bird which is hard to define the real habitat of these birds. Therefore, we exclusively employ the threatened birds that are native, and analyzed the effects of climate change on them. The primary aims of this study were: (i) determining the key areas of suitable habitats for the threatened birds on the QTP and priority areas for conservation; (ii) assessing the effects of climate change on the suitable habitat of the threatened bird on the QTP region; (iii) defining the offset direction of suitable habitat for the threatened bird species on the QTP; (iv) comparing changes and trends in future suitable habitat among the different threatened bird.

2. Raw data and methods

2.1. Occurrence records of birds

The record data of endangered birds applied in this study were obtained from the following two sources: own field survey records (including wild bird species, numbers, and geographic locations) were obtained by recording terrestrial wildlife surveys of nature reserves (including Sanjiangyuan National Nature Reserve, Qilian Mountain National Nature Reserve, and Kunlun Mountain National Nature Reserve) on the QTP from 2016 onwards. All the filed data were obtained by the sample point method and the sample line method. The other part of the bird records come from the website of China Bird Report. The China Bird Report is a national organization whose focus is to provide an internet platform for Chinese birdwatchers to record bird information (https://www.birdreport.cn/ accessed in June 2022) (Li et al., 2013). Then we selected the bird species that were recorded at the International Union for Conservation of Nature (IUCN) Red List of Endangered Species in Near Threatened (NT), Vulnerable (VU), Endangered (EN), and Critically Endangered (CR) levels (The NT species were included because of it is close to qualifying for or is likely to qualify for a threatened category in the near future). Consequently, we selected the threatened birds which is native distributed on the QTP as our experimental subjects. In consequence, 22 native threatened bird species were employed (Table 1). The respective total occurrence records for these 22 species are 235, 687, 359, 108, 114, 80, 169, 34, 1940, 73, 35, 1014, 287, 86, 89, 34, 60, 17, 114, 35, 83, and 200 (STable 1). We used ArcGis 10.8 software to create a grid with 1 km, with a maximum of 1 distribution point per grid. This approach could eliminate the records in close proximity and diminishes the negative effects due to spatial autocorrelation (Kramer-Schadt et al., 2013). All the remaining occurrence records were saved in CSV format.

2.2. Current and future climate data

The current and future climate data of minimum temperature of each month, maximum temperature of each month, precipitation of each month, and bioclimatic variables whose maximum spatial resolutions were 30 s were obtained on the WorldClim Global Climate Data which is available at https://www.worldclim.org/. And the 19 bioclimatic factors correspond to different climatic factors (STable 2). The ACCESS-ESM1-5 global climate models (GCM) was employed on account of it is better adaptively assessing climate simulations on the QTP (Wu et al., 2019). Subsequently, we filtered the climate factors and retained those

Table 1
The endangered status of the threatened birds on the QTP.

English Name	Abbreviated	Scientific Name	Family Name	Order Name	IUCN Level
Steppe Eagle	SE	*Aquila nipalensis*	Accipitridae	Accipitriformes	EN
Saker Falcon	SF	*Falco cherrug*	Falconidae	Falconiformes	EN
White Eared Pheasant	WEP	*Crossoptilon crossoptilon*	Phasianidae	Galliformes	NT
Chinese Grouse	CG	*Tetrastes sewerzowi*	Phasianidae	Galliformes	NT
Tibetan Eared Pheasant	TEP	*Crossoptilon harmani*	Phasianidae	Galliformes	NT
Tibetan Bunting	TB	*Emberiza koslowi*	Emberizidae	Passeriformes	NT
Giant Babax	GB	*Pterorhinus waddelli*	Leiothrichidae	Passeriformes	NT
Yunnan Nuthatch	YN	*Sitta yunnanensis*	Sittidae	Passeriformes	NT
Himalayan Vulture	HV	*Gyps himalayensis*	Accipitridae	Accipitriformes	NT
Ala Shan Redstart	ASR	*Phoenicurus alaschanicus*	Muscicapidae	Passeriformes	NT
Satyr Tragopan	ST	*Tragopan satyra*	Phasianidae	Galliformes	NT
Lammergeier	LA	*Gypaetus barbatus*	Accipitridae	Accipitriformes	NT
Cinereous Vulture	CV	*Aegypius monachus*	Accipitridae	Accipitriformes	NT
Mountain Hawk-Eagle	MHE	*Nisaetus nipalensis*	Accipitridae	Accipitriformes	NT
Tibetan Babax	TBA	*Pterorhinus koslowi*	Leiothrichidae	Passeriformes	NT
White-speckled Laughingthrush	WSL	*Ianthocincla bieti*	Leiothrichidae	Passeriformes	VU
Eastern Imperial Eagle	EIE	*Aquila heliaca*	Accipitridae	Accipitriformes	VU
Collared Crow	CC	*Corvus torquatus*	Corvidae	Passeriformes	VU
Snowy-cheeked Laughingthrush	SCL	*Ianthocincla sukatschewi*	Leiothrichidae	Passeriformes	VU
Sichuan Jay	SJ	*Perisoreus internigrans*	Corvidae	Passeriformes	VU
Beautiful Nuthatch	BN	*Sitta formosa*	Sittidae	Passeriformes	VU
Chinese Monal	CM	*Lophophorus lhuysii*	Phasianidae	Galliformes	VU

with low correlation based on the distribution characteristics of the different species (STable 3). In addition, the SSP 1–2.6, SSP 2–4.5 and SSP 5–8.5 represent the shared socioeconomic pathway with different patterns of economic development and carbon dioxide (CO2) concentration emission scenarios under the future climate scenarios (Hurtt et al., 2020; Popp et al., 2017). And all the climate factors were required to be converted into ASCII format for analysis by MaxEnt (V3.4.4) software.

2.3. Model parameters

We used the MaxEnt model to predict the potential habitat range of the threatened birds on the QTP. The occurrence records and climatic variable of these threatened birds were imported into the MaxEnt. And the 80% occurrence records of 22 threatened birds were used to train the model predictions. And the20% occurrence records were used to test the validity of the model. Replicated run type was Bootstrap. And max number of background points was the default of 10,000. The out format was Logistic (Phillips et al., 2006). The MaxEnt predictions for each species were replicated 10 times (McCune, 2016). Then, the result of habitat predicted by the MaxEnt model were categorized into High, Medium, Low, and Un suitable habitats with standard (Ma and Sun, 2018). We used the area mean (AUC) under the receiver operating characteristic (ROC) curve to assess model performance. The higher AUC values indicate that the model had a greater model prediction accuracy (Gonzalez et al., 2011; Jiménez-Valverde and Biogeography, 2012).

2.4. Distribution barycenter migration of threatened birds

This study used a latitude-longitude grid raster (1 km × 1 km) which was assumed that the area per cell is 1 km^2. And it was used to calculate the distribution barycenter migration of the 22 threatened birds. Assuming the research area is consisted of n latitude-longitude grids. Then, the distribution barycenter was calculated by using the formula $X = \sum_{i=1}^{n} M_i X_i / \sum_{i=1}^{n} M_i$; $Y = \sum_{i=1}^{n} M_i Y_i / \sum_{i=1}^{n} M_i$;$M_i = S_i P_i$. And the P_i indicates the probability that the threatened birds are present, which is obtained by extracting the attribute value of each grid in ArcGIS 10.8. S_i represents the area of per cell. The X_i and Y_i respectively represent the latitude and the longitude of a grid raster. The X and Y indicate the latitude and the longitude of the distribution barycenter of the threatened birds (He et al., 2011; Jiang et al., 2020). Furthermore, the R package "geosphere" was used to calculate the distance between distribution barycenter (Hijmans, 2021). And ArcGIS 10.8 was used to analyze the elevation change by extracting the elevation of each barycenter.

3. Result

3.1. Habitat distribution models for the threatened birds of the QTP

The ROC results indicate that the average training AUC value for the 10-replicate runs in current and future exceeded 0.9 in all the threatened birds on the QTP. Moreover, the standard deviation (SD) values of 10 repetition runs maintained below 0.06 in all the threatened birds on the QTP (Fig. 1). These results demonstrated that the predicted results of MaxEnt model were accurate and had a higher reliability. Therefore, we could proceed with the subsequent analysis.

Current distribution model predictions result showed that the high suitable habitat of the EN birds, including steppe eagle (*Aquila*

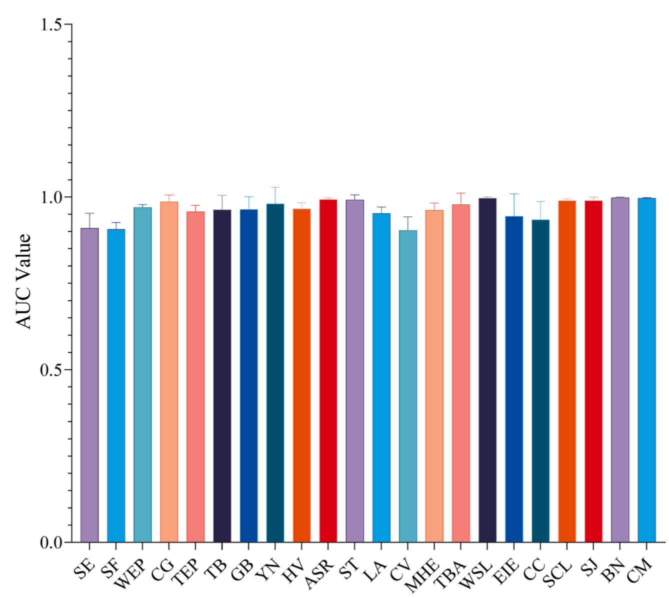

Fig. 1. The simulations AUC values of the MaxEnt for the threatened birds on the QTP.

nipalensis) and saker falcon (*Falco cherrug*), were centrally distributed in the eastern, southern, and central regain of the QTP (Fig. 2A-B). The distribution areas of high suitable habitat of the SE were similar with the SF, however, it for SF was not distributed in the Yunnan Province region on the QTP (STable 4). Furthermore, the SF had a greater area of high and medium suitable habitat than the SE. The high suitable habitats of the VU birds, being similar to the EN birds, preferred to inhabit the eastern and southern region on the QTP (Fig. 2C-I). These regions include Tibetan Qiang Autonomous Prefecture of Ngawa and Tibetan Autonomous Prefecture of Garzê in Sichuan Province, Diqing Tibetan Autonomous Prefecture in Yunnan Province, Qilian Mountains in Qinghai and Gansu Province, and the Gannan Tibetan Autonomous Prefecture in Gansu Province. Notably, collared crow (*Corvus torquatus*) had the largest area, 22.47 × 10^4 km^2, of high suitable habitat in the threatened birds (STable 4). However, the combined area of high and medium suitable habitat of the SF was larger than that of the CC. Then, the high and medium suitable habitat region of white-speckled laughingthrush (*Ianthocincla bieti*) and beautiful nuthatch (*Sitta Formosa*) uniquely distributed in the Southeast of the QTP including Diqing Tibetan Autonomous Prefecture in Yunnan Province and Changdu and Linzhi city in Tibet (Fig. 2C,H). Noteworthy, the BN had the minimum area, only 0.32 × 10^4 km^2 and 0.71 × 10^4 km^2, of high and medium suitable habitat among the threatened birds (STable 4). The high suitable habitat of snowy-cheeked laughingthrush (*Ianthocincla sukatschewi*), Sichuan jay (*Perisoreus internigrans*), and Chinese monal (*Lophophorus lhuysii*) mainly situated in the eastern margin region of the QTP including the border of Gansu and Sichuan Province, Sichuan and Tibet Province, and Yunnan and Sichuan Province (Fig. 2F, H, I).

The current distribution model predictions result showed that the TEP had the largest combine area of high and medium suitable habitat, 40.42 × 10^4 km^2, among the NT birds (SFig. 1A & STable 4). And it primary distributed in the southeastern and southern regions of the QTP, including Tibetan Autonomous Prefecture of Garzê and Tibetan Qiang Autonomous Prefecture of Ngawa in Sichuan Province and Linzhi and Changdu region in Tibet. The high and medium suitable habitats of Chinese grouse (*Tetrastes sewerzowi*), Himalayan vulture (*Gyps himalayensis*), Ala shan redstart (*Phoenicurus alaschanicus*) and cinereous vulture (*Aegypius monachus*) mainly distributed in the northeast region of QTP, including Gannan Tibetan Autonomous Prefecture in Gansu Province, Tibetan Autonomous Prefecture of Haibei and Tibetan Autonomous Prefecture of Hainan in Qinghai Province, and Tibetan Qiang Autonomous Prefecture of Ngawa in Sichuan (SFig. 1B, G, H, K). Furthermore, the high suitable habits of Tibetan bunting (*Emberiza koslowi*) and TBA distributed in the central region of QTP, including Tibetan Autonomous Prefecture of Golog and Yushu Tibetan Autonomous Prefecture in Qinghai Province and Changdu and Naqu region in Tibet (SFig. 1D, M). The suitable habitat of the remaining NT birds concentrated in the southeast of the QTP (SFig. 1). The high and medium suitable habitat area of Yunnan nuthatch (*Sitta yunnanensis*) was minimum in the NT birds, only 5.28 × 10^4 km^2, and it was specifically distributed in the Yunnan Province (SFig. 1F & STable 4).

3.2. Future suitable habitat fluctuations

Future climate model prediction results indicated that the high and medium habitat with medium suitability of the SE, white eared pheasant (*Crossoptilon crossoptilon*), and CV holed expanding in all future climate scenarios with global warming by comparing with the current prediction results (Fig. 3 & SFig. 2). Among these birds, the SE had the greatest increasing high and medium suitability habitat with the fluctuation range of 73.67% ~ 157.55% and 52.33% ~ 97.28%, and both of them reached a maximum in the SSP1-2.6 climate scenario of 2050 (Fig. 3B, SFig. 2B). In addition, the increase future habitats with medium suitability of WEP and CV simultaneously reached the maximum of 45.74% and 22.77% in the SSP2-4.5 climate scenario of 2050 (SFig. 2D). Interestingly, the TBA decreased only 0.35% habitat with medium suitability in the SSP 5–8.5 climate scenario of 2030, however, it increased in the other future climate scenarios, and reached a maximum of 151.93% in

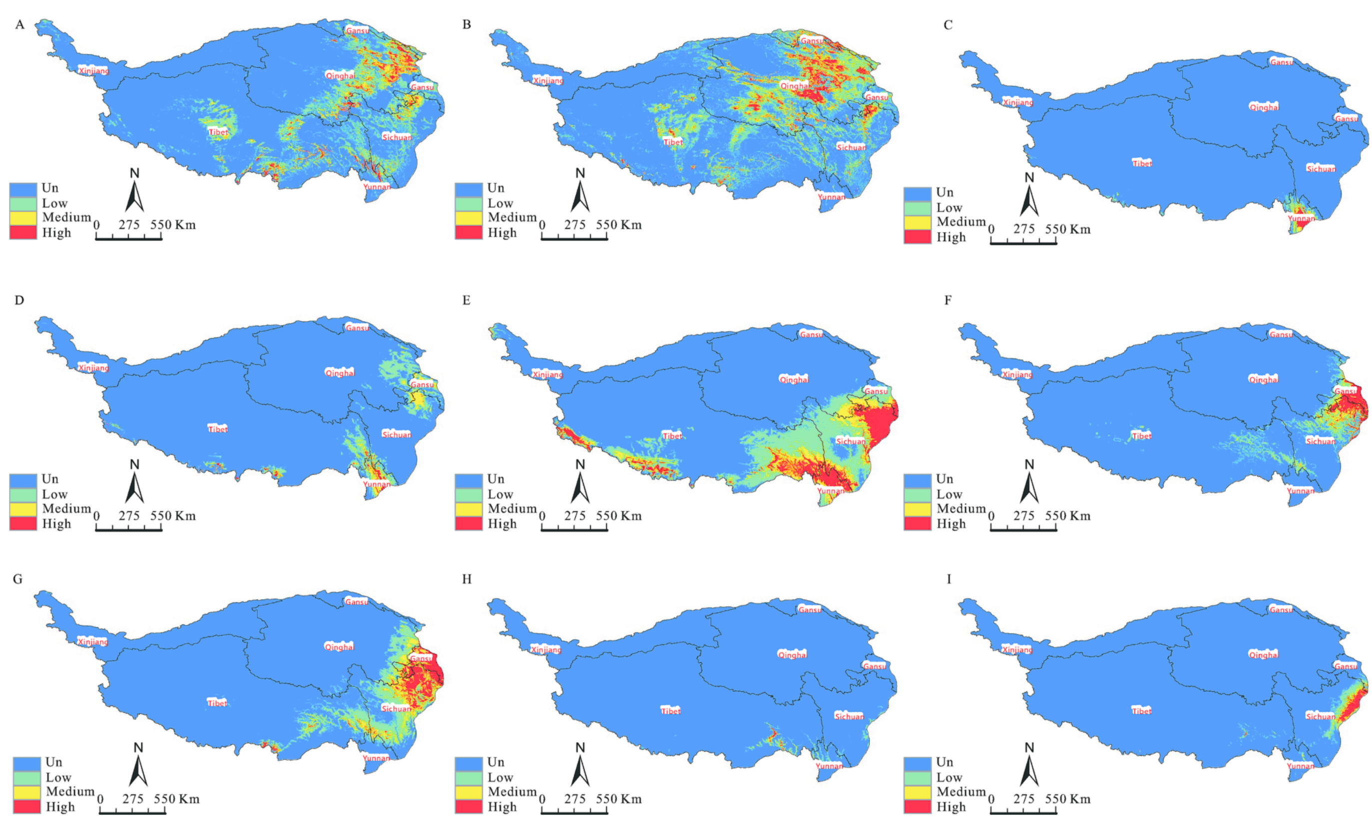

Fig. 2. Habitat distribution of the EN and VU birds on the QTP. (A) SE; (B) SF; (C) WSL; (D) EIE; (E) CC; (F) SCL; (G) SJ; (H) BN; (I) CM.

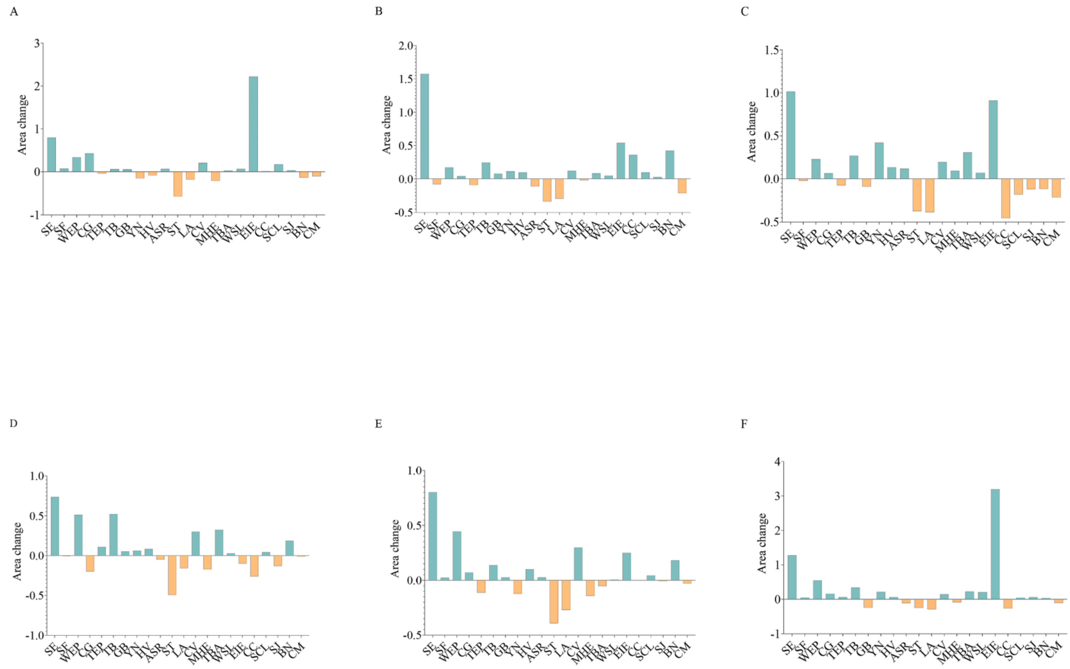

Fig. 3. Area changes of high suitable habitat of the Threatened birds in different climate scenarios on the QTP. (A) SSP 1–2.6 climate scenarios in 2030; (B) SSP 1–2.6 climate scenarios in 2050; (C) SSP 2–4.5 climate scenarios in 2030; (D) SSP 2–4.5 climate scenarios in 2050; (E) SSP 5–8.5 climate scenarios in 2030; (F) SSP 5–8.5 climate scenarios in 2050.

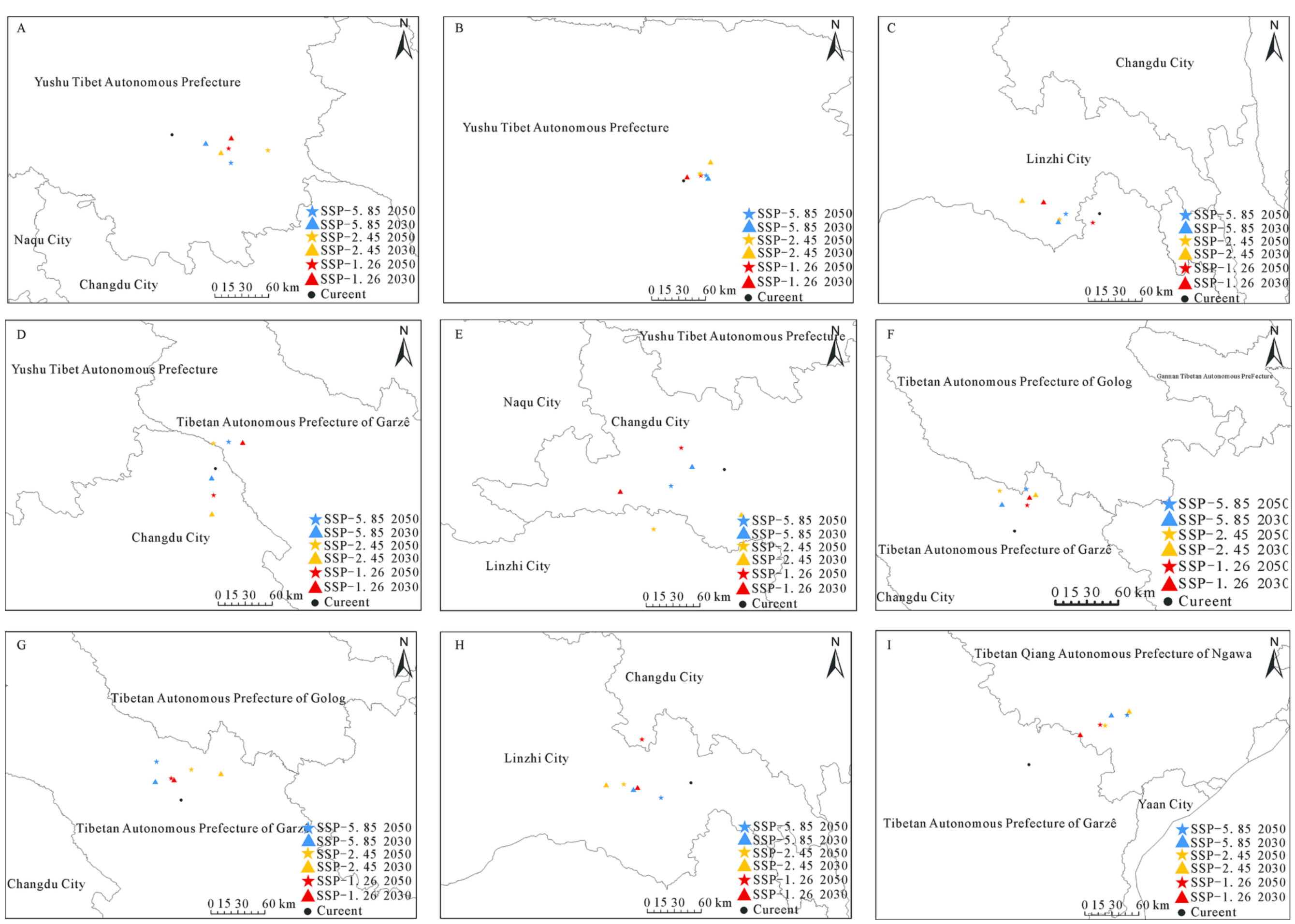

Fig. 4. The barycenter migration of the EN and VU birds in the future climate scenario. (A) SE; (B) SF; (C) WSL; (D) EIE; (E) CC; (F) SCL; (G) SJ; (H) BN; (I) CM.

the SSP2-4.5 climate scenario of 2050 (SFig. 2C, E). Furthermore, the 27.3% threatened birds had a continuously decreased medium suitable habitat in all the future climate scenarios, including SF, ST, lammergeier (*Gypaetus barbatus*), mountain hawk-eagle (*Nisaetus nipalensis*), SCL, and SJ (SFig. 2). And the ST had the largest decrease in the medium suitable habitat among these birds, and it reached a maximum of 54.17% in the SSP1-2.6 climate scenario of 2030 (SFig. 2A). The remaining birds had habitats with medium suitability, which reduced or increased in different future climate scenarios (SFig. 2).

The future climate model prediction of habitat with high suitability results showed that the area of habitat with high suitability of SE, WEP, TB, CV, and WL sustainably increased in all future climate scenarios (Fig. 3). The SE had the maximum increase area of habitat with high suitability, 157.55%, in SSP1-2.6 of 2050 climate scenarios (Fig. 2B). The ST, LA, and CM had a consistently decreased area of habitat with high suitability due to future climate change (Fig. 3). And the decrease areas range of the habitat with high suitability of ST, LA, and CM were 24.34% ~57.15%, 15.87% ~38.60%, and 0.97% ~20.84%, which meet a maximum in the future climate scenarios of SSP1-2.6 of 2030, SSP2-4.5 of 2030, and SSP2-4.5 of 2030, respectively (Fig. 3A, C).

3.3. Future migratory trends of the threatened birds

The results of the barycenter of the threatened birds indicated that the WEP, CG, ST, and CM in the Galliformes order tend to migrate northward in the future climatic scenario of global climate change (Fig. 4I & SFig. 3A, B, I). On the contrary, the TEP in the order Galliformes only had a tendency to migrate to the south in the future distribution model (SFig. 3C). And, the barycenter of giant babax (*Pterorhinus waddelli*) and SE in the Passeriformes order and the Accipitriformes order tended to migrate to southern on account of the global climate change (Fig. 4A & SFig. 3E). The barycenter of the remaining threatened birds, belonging the orders of Passeriformes, Accipitriformes, and Falconiformes, had a trend that north migration in the different future climate scenarios (Fig. 4 & SFig. 3). Distance of barycenter migration results showed that the maximum migration distance of WEP, CG, TEP, ST, and CM in the Galliformes order were 43.3 km, 59.2 km, 36.19 km, 97.7 km, and 111.3 km, separately (STable 6). And the maximum migration distance of TB, GB, YN, ASR, TBA, WL, CC, SCL, SJ and BN in the order Passeriformes were 32.6 km, 48.7 km, 40.7 km, 46.7 km, 26.0 km, 77.2 km, 100.9 km, 47.3 km, 49.1 km, and 82.8 km, respectively. The maximum migration distance of SE, HV, LA, CV, MHE, and eastern imperial eagle (*Aquila heliacal*) in the order Accipitriformes were 91.5 km, 33.3 km, 66.0 km, 30.5 km, 44.2 km, and 49.6 km. Furthermore, the SF in the order Falconiformes had a maximum migration distance of 32.8 km. Moreover, the elevation of barycenter of SF, TEP, CV, SCL, SJ, BN, and CM were persistently decreased due to future climate change (Fig. 5A-F). Both ASR and LA had a consistently increase of elevation of barycenter in all future climate scenarios. The elevation of barycenter of the remaining threatened birds showed increase and decrease in different future climate scenario.

4. Discussion

4.1. Threatened birds distribution and habitat fluctuations

The result of the current suitable habitat distribution model showed that the high and medium suitable habitat of the threatened birds are mainly distributed in the eastern, southern and central regions on the QTP. And the habitats with low suitability and unsuitability were mainly

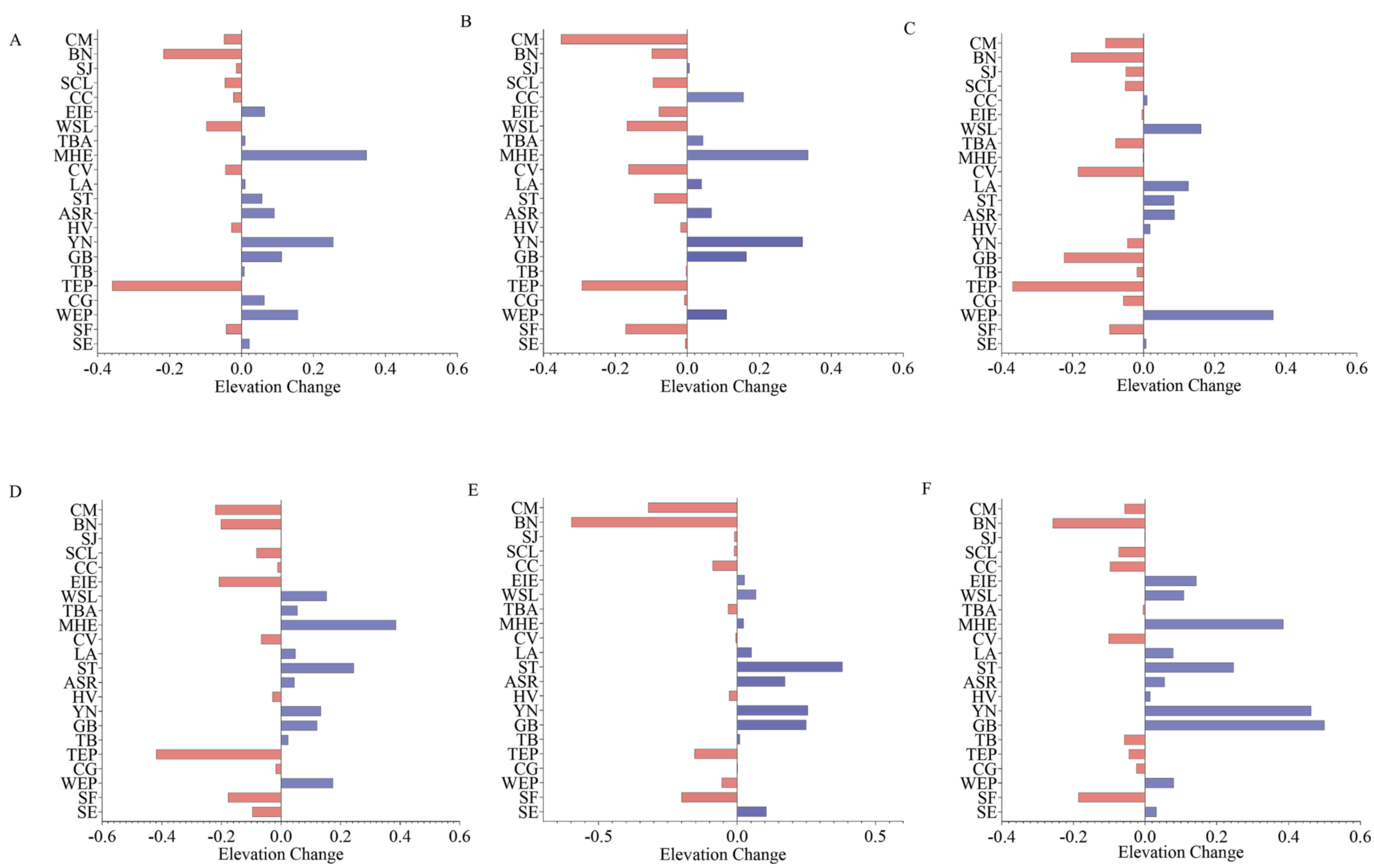

Fig. 5. The barycenter elevation change of the threatened birds on the QTP in the different future climate scenario (A) SSP 1–2.6 climate scenario in 2030; (B) SSP 1–2.6 climate scenario in 2050; (C) SSP 2–4.5 climate scenario in 2030; (D) SSP 2–4.5 climate scenario in 2050; (E) SSP 5–8.5 climate scenario in 2030; (F) SSP 5–8.5 climate scenario in 2050.

distributed on the northwest and southwest and some part of the central regions on the QTP. Recent research indicated that climate is the most significant driver of the biodiversity and species distribution. Elevation increases from southeast to northwest on the QTP. The oxygen content gets lower, in contrast, the solar radiation got higher from southeast to northwest. These means that the climate becomes increasingly unsuitable from southeast region to northwest region on the QTP (Liu et al., 2022). And the climate also affected the vegetation on the QTP (Pan et al., 2017; Pederson et al., 2015). The vegetation coverage was affected to become fewer from east region to west region on the QTP by the unique climate (Fan and Bai, 2021). Therefore, we suggested that these conditions have contributed to the concentration distribution, in the eastern region and southern region on the QTP, of the threatened birds in current unique climate. And we recommend that the biodiversity conservation in the eastern, southeastern, and northeastern regions on the QTP should be strengthened in the construction and management of nature reserves.

The future fluctuations in the suitable habitat of the threatened birds on the QTP results revealed that the 81.82% of the threatened birds showed a reduction in habitat with high and medium suitability in the different future global warming scenario. Among these birds, the area of habitat with high and medium suitability of ST and LA continuously decreased, and both reached a minimum at SSP1-2.6 of 2030 and SSP2-4.5 of 2030 climate scenarios, individually. Furthermore, the future climate scenarios of SSP2-4.5 of 2050 and SSP5.8–5 of 2030 had the greatest members of the threatened birds with the decreasing suitable habitat, and both members of birds were 13. Consequently, we considered that the ST and LA were susceptible to climate change, and both of them deserved more protection and attention under the global change. And the SSP2.4–5 of 2050 and SSP5-8.5 of 2030 climate scenarios should be a focus of the attention concerns on account of the reduction of habitat in the majority of threatened birds in both climate scenarios.

The habitat with medium and high suitability of SE, WEP, and CV were decreased all the time in different future climate scenarios. We used the jackknife test to test the importance of different climate variable in MaxEnt model, and calculated the suitable range of climate factors for the threatened birds (STable 6,7). And the result indicated significant difference in the contribution of climatic factors to birds. And, the SE had a wider range of optimal precipitation (28.09–73.55) in May by comparing with other birds with a maximum contribution of Prec05. In addition, the optimal precipitation range in July of WEP was broader than the other birds with a maximum contribution of Prec07 (117.98–144.04). And the CV also had a wider suitable range of minimum temperature in May in comparison with the other birds with contribution of Prec05 (−7.07 to 10.7). Therefore, we speculate that SE, WEP, and CV had a better capacity to adapt the environment on account of their own particular physiological features. These features led to a further increase of suitable habitat of SE, WEP, and CV with the global warming (Jiguet et al., 2007; Jingsong et al., 2005). And these birds might be more comfortable on the QTP with global Warming.

4.2. Trend in migration of barycenter

The migration of barycenter results indicated that approximately 86.36% of the threatened birds on the QTP trend to resort to migration to northern regions in response to climate change. Meanwhile, the elevation of barycenter results showed that 68.18% of the threatened bird on the QTP had a trend of migrating higher elevation in order to relieve the pressure of climate change. The TEP, GB, and SE tended to continually migrate to lower latitudes under different climatic scenarios among the threatened birds on the QTP. Nevertheless, the GB and SE had an increasing elevation barycenter in different climate scenarios. We speculate that the GB and SE were mainly relieving the effects of global warming on themselves by migrating to higher elevations. Furthermore, both of the ASR and LA trended to migrate to the region with higher altitudes and higher elevation under the future scenario. A growing current study confirmed that creatures will migrate to higher altitudes or higher latitudes in response to the global warming (Inouye et al., 2000; Liang et al., 2018b). And we confirm this perspective with our findings of the threatened birds on the QTP.

The TEP had been not only trended to migrate to the region with lower latitude, but also to the lower elevation region in the global warming. Initially, we found that the Tibetan Buddhist temples have a common habit of feeding TEP. And we considered that the results might be influenced on account of the fact of the artificial feeding of TEP from the Tibetan Buddhist temples (Li et al., 2014; Li et al., 2018; Shen et al., 2012). Then, we tried to remove the point around the Tibetan Buddhist temples of the TEP to reanalyzing. But, the result of the reanalysis was similar with the previously analysis result (SFig. 4). Consequently, we considered that the adaptation strategy of the TEP was significant different from that of the other threatened birds for the global climate change. Meanwhile the TEP need a further attention and protection in the conservation process of endangered species.

The migration distance of barycenter result showed that the CM had a largest migration distance with a distance of 111.3 km. Moreover, the WEP, CG, TEP, ST and CM in the order Galliformes had a longer migratory distances requirement. Birds in the Galliformes order had a weaker flight capability by comparing with the birds in the orders of the Accipitriformes, Falconiformes, and Passeriformes (Keane et al., 2005). Accordingly, the birds in the order Galliformes will face a higher risk of extermination under the global climate change on the QTP. We propose that the government should give more attention to the threatened birds in Galliformes order in the construction of protected areas and the conservation.

5. Conclusion

Simulating the effects of global climate change on the threatened birds on the QTP by using MaxEnt which could be used to conserve the endangered species. In the present study, we determined that the suitable for the threatened birds on the QTP are centered in the eastern and central region of the QTP, including northwestern region in Sichuan Province, eastern and central regions in Qinghai and Tibet Province. Besides, the area of suitable habitat of the over 81% threatened birds on the QTP showed a reduction in different future scenarios. However, the other threatened birds showed an increase in the area of suitable habitat on different degrees because of their greater ability to respond to environmental stressors. Among these threatened birds, the most negatively affected by climate change is ST, which will lose 57.15% of suitable habitat in 2030 when the carbon emissions are at 1.26. And, the least negative effect of climate change is on the SE, whose area of suitable habitat will increase by 118.01% in 2050 when the carbon emissions are at 1.26. Then, we identified that the suitable habitat of all the threatened birds with an exception of the TEP would migrate to higher elevations region or higher latitudes region in the climate change future. Furthermore, we discovered that the species in the order of Galliformes, among these threatened birds, faced a greater risk of extinction under global climate change than the other threatened birds by comparing the offset of suitable habitat. Therefore, we appealed that the species in the Galliformes order should be given more attention in the conservation measures for wild and endangered species on the QTP.

CRediT authorship contribution statement

Bin Li: Methodology, Conceptualization, Software, Formal analysis, Investigation, Writing – original draft, Visualization, Writing – review & editing. **Chengbo Liang:** Software, Investigation. **Pengfei Song:** Investigation, Data curation. **Daoxin Liu:** Investigation. **Wen Qin:** Investigation. **Feng Jiang:** Investigation, Methodology. **Haifeng Gu:** Investigation. **Hongmei Gao:** Investigation. **Tongzuo Zhang:** Conceptualization, Project administration, Funding acquisition, Supervision, Writing – review & editing, Investigation, Methodology.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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