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Identifying potential refugia and corridors under climate change: A case study of endangered Sichuan golden monkey (*Rhinopithecus roxellana*) in Qinling Mountains, China

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Climate change threatens endangered species and challenges current conservation strategies. Effective conservation requires vulnerability assessments for species susceptible to climate change and adaptive strategies to mitigate threats associated with climate. In this paper, we used the Maxent to model the impacts of climate change on habitat suitability of Sichuan golden monkey *Rhinopithecus roxellana*. Our results showed that (i) suitable habitat for Sichuan golden monkey was predicted to decrease by 37% in 2050s under climate change; (ii) the mean elevations of suitable habitat in the 2050s was estimated to shift 160 m higher; (iii) nature reserves protect 62% of current suitable habitat and 56% of future suitable habitat; and (iv) 49% of current suitable habitat was predicted to be vulnerable to future climate change. Given these results, we proposed conservation implications to mitigate the impacts of climate change on Sichuan golden monkey, including adjusting range of national park, establishing habitat corridors, and conducting long-term monitoring.

KEYWORDS
climatic refugia, conservation implications, corridor, habitat suitability, Maxent, nature reserves

1 | INTRODUCTION

Climate change poses one of major threats to global biodiversity (Garcia, Cabeza, Rahbek, & Araújo, 2014) and will impact species geographical distributions (Brown et al., 2016; Ribeiro, Werneck, & Machado, 2016), population dynamics (Townsend et al., 2016; Uboni et al., 2016), phenology (Charmantier & Gienapp, 2014; Tomotani, Gienapp, Beersma, & Visser, 2016), biotic interaction (Meserve, Kelt, Gutiérrez, Previtali, & Milstead, 2016; Stenseth et al., 2015), and evolution (Waples & Audzijonyte, 2016). Furthermore, such impacts are expected to increase severity in the future (Bellard, Bertelsmeier, Leadley, Thuiller, & Courchamp, 2012). The resilience/vulnerability to climate change of species depends on their ability to minimize or

avert the adverse effects of climate change by dispersing to suitable habitat, or by deploying plastic ecological and evolutionary responses (Nicotra, Beever, Robertson, Hofmann, & O'Leary, 2015; Schloss, Nuñez, & Lawler, 2012). Species unable to respond to conditions with rapid climate change are vulnerable and have an increased probability of extinction (Urban, 2015). The Intergovernmental Panel on Climate Change (IPCC) assessed that 20–30% of all species are at grave risk of extinction due to increasing global warming (IPCC, 2014).

The potential high risk of species extinction requires us to implement adaptive conservation strategies to mitigate the harmful impacts of climate change (Arribas et al., 2012; Shen et al., 2015), and there is a pressing need to identify the species, habitats, and

regions that are most likely to be effected by climate change (Balzotti, Kitchen, & Mccarthy, 2016). A few approaches for assessing species' vulnerability to climate change have been developed, such as vulnerability indices (Bagne, Friggens, & Finch, 2011), the mechanistic niche model (Schloss et al., 2012), and the bioclimatic envelope model (Forrest et al., 2012; Willis et al., 2015), among which bioclimatic envelope models are commonly used (Sinclair, White, & Newell, 2010) because they generally only require current species range and associated climate conditions (Rowland, Davison, & Graumlich, 2011). Predicted shifts in the species' range under future climate scenarios can identify at-risk species (Bellard et al., 2012) and contribute essential information to prioritize conservation strategies (Foden, Young, & Watson, 2016).

The Sichuan golden monkey (*Rhinopithecus roxellana*) is a primate species endemic to central and west-central China (Li, Jia, Pan, & Ren, 2003) and is classified as endangered by International Union for Conservation of Nature (IUCN) (Long & Richardson, 2008). Its current habitat is restricted to elevations of 1,400–3,400 m above sea level in temperate Montane forests located in Gansu, Shaanxi, Hubei, and Sichuan Provinces (Li, Pan, & Oxnard, 2002). Over the past several decades, the species has faced conditions detrimental to their survival, such as deforestation, tourism, and hunting (Guo, Ji, Li, & Li, 2008; Huang et al., 2016). As a result, the population has declined more than 50% over the past half-century (Li et al., 2002; Long & Richardson, 2008). Chinese government has implemented a number of conservation programs including the Grain-to-Green program and the Natural Forest Conservation Program (Li et al., 2013; Zhang et al., 2007) to protect and improve habitat for wildlife including the Sichuan golden monkey which serves as a recognizable flagship species for conservation in China preserve the species. At present, most pre-existing key threats and limiting factors for the species have been mitigated, and populations are now beginning to increase (Chang et al., 2012). However, climate change will pose serious threats that will degrade and fragment suitable habitat for Sichuan golden monkey (Li et al., 2016; Luo et al., 2016). The consequences of climate change on Sichuan golden monkey may pose major challenges to current conservation efforts (Luo, Liu, Pan, Zhao, & Li, 2012; Luo et al., 2015), but are poorly understood. Therefore, it is important to investigate the potential impacts of climate change on distributions of Sichuan golden monkey so that adaptive conservation strategies can be developed to promptly respond to and reduce the impacts of rapid climate change (Guisan et al., 2013; Wheatley et al., 2017) on this endangered species.

In the present research, we used the maximum entropy model (i.e., Maxent Version 3.3.3k, Phillips, Anderson, & Schapire, 2006) to make predictions on habitat suitability, to examine the species' vulnerability to climate change, to evaluate conservation effectiveness of existing nature reserves, and to identify possible climatic refuges and corridors for Sichuan golden monkey. Based on our results, we propose appropriate conservation strategies for the species in the Qinling Mountains of China.

2 | METHODS

2.1 | Study area

The study site is located in the Qinling Mountains (106°30′–108°05′ E, 32°40′–34°35′ N), Shaanxi Province, China. The Qinling Mountains is considered as a natural boundary separating temperate and subtropical zones (Zhao, Zhang, & Dong, 2014). The mountain rises to over 3,000 m, with a more gradual gradient on the south slopes; however, its north slopes are steep (Pan et al., 2001). It is typically warmer and moister in the south slopes than in the north, and climatic conditions are largely dependent on elevation (Pan et al., 2001). An isolated subspecies of Sichuan golden monkey, *R. roxellana qinlingensis*, occupies the Qinling Mountains (Li, Chen, Ji, & Ren, 2000). Qinling Mountains is the northern most range of the species, and approximately 4,000 individuals belonging to 39 troops inhabit this area (Li et al., 2000, 2001). Nineteen nature reserves have been established in the area and provide protection for the giant panda (*Ailuropoda melanoleuca*), Sichuan golden monkey, and other sympatric species (Fang, Xu, Zhang, Xiao, & Zhang, 2017; Xu et al., 2014).

2.2 | Data preparation

Occurrence records of Sichuan golden monkey (N = 350) were obtained from camera-trap monitoring, field surveys of nature reserves, and published literature in Qinling Mountains (see details in Appendix S1; Figure 1). Because these localities are from multiple unplanned surveys, the localities likely display spatial autocorrelation (Radosavljevic & Anderson, 2013). To lessen this autocorrelation, we filtered occurrence records by randomly choosing one locality within each 1-km^2 grid (Kramer-Schadt et al., 2013; Liu, Mcshea, & Li, 2016). After filtering, 291 unique localities remained. To calibrate the effect of selection bias on predictive performance, we created 10,000 random points as pseudo-absence data (Phillips et al., 2009) from the study area excluding a buffer area which was 10 km from occurrence points of the species in the Qinling Mountains (Vanderwal, Shoo, Graham, & Williams, 2009).

Nineteen bioclimatic variables (at 30 s resolution) were extracted from the WorldClim database for both current (average for 1950–2000; available at http://www.worldclim.org) and future climatic conditions for 2050s (average for 2041–2060). The future climate data used for this study consisted of IPCC-CMIP$_5$ climate projection (Wu, Chen, & Wen, 2013) from the Met Office Hadley Center for atmosphere-ocean coupled model (HadGEM$_2$-AO) under the representative concentration pathway (RCP4.5). The average global temperature increase of 0.9–2.0 °C under RCP4.5 would fall within a 2 °C global warming limit for the 2050s (UNFCCC, 2015). The time horizon 2050s was selected because it represents a time far enough in the future for marked climatic changes to have taken place (Young et al., 2012).

Additional environmental variables were combined to create distribution models for Sichuan golden monkey (Appendix S2). The density of settlements, roads, and rivers were retrieved via a
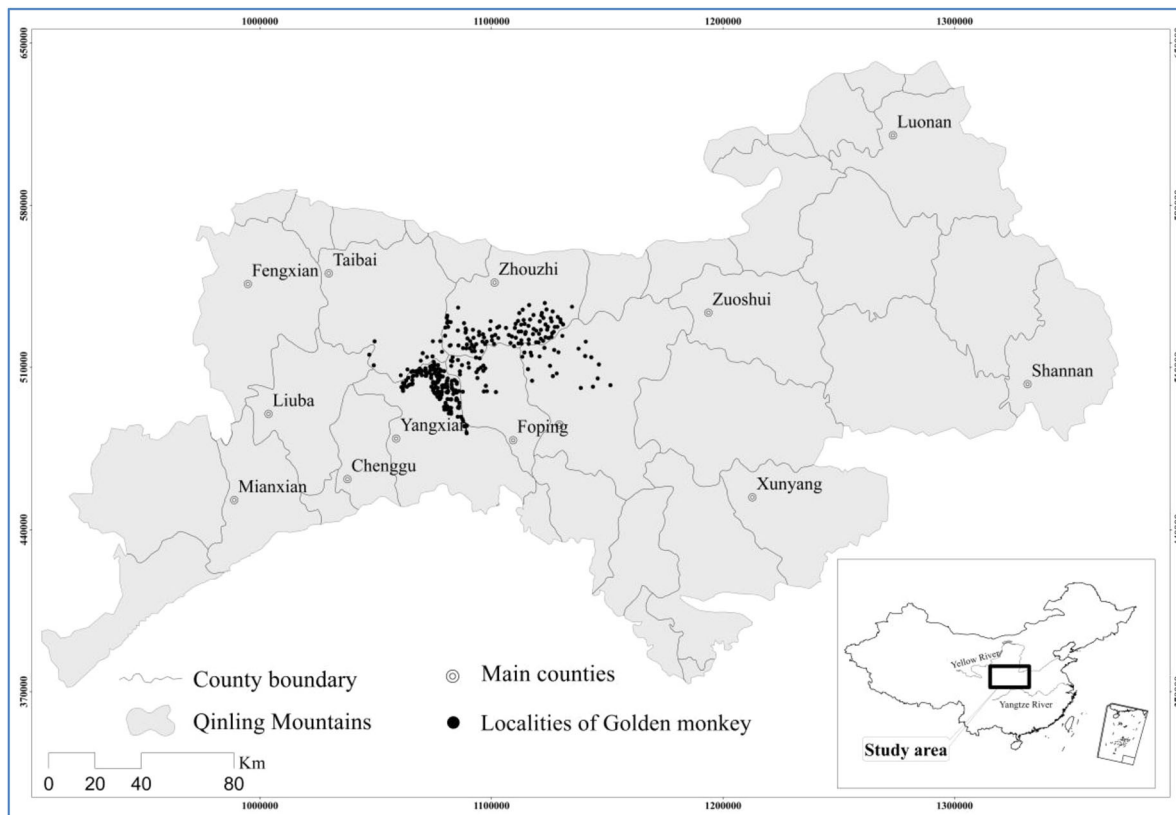
FIGURE 1 Localities of Sichuan golden monkey in Qinling Mountains

1:1,000,000 scaled map of China (National Geomatics Center of China, available at http://atgcc.sbsm.gov.cn). Elevation was obtained from a digital elevation model (DEM) at 30 s resolution, taken from the WorldClim database. Non-climate variables (i.e., density of settlements, roads, and rivers) are unavailable for 2050s, and thus we kept these variables static in our projections (Stanton, Pearson, Horning, Ersts, & Akçakaya, 2012).

Spatial variables was resampled to 1 km^2 resolution, and projected to the same projection (*Asia_ North_Albers_Equal_Area_Conic*) by ArcGIS 10.1 (ESRI Inc., Redlands, CA). Multicollinearity of variables was reduced, by eliminating relational variables where Pearson's | r| > 0.8 (Appendix S3; Cord, Klein, Mora, & Dech, 2014; Li, Liu, Xue, Zhang, & Li, 2017). We retained the most important biologically meaningful variables for building models.

2.3 | Habitat suitability model

Maximum entropy models (Maxent) are considered as very useful tool especially to predict species distribution with presence-only data (Elith, Phillips, Hastie, Dudík, & Chee, 2011; Phillips & Dudík, 2008). We ran Maxent with the following settings: random test percentage (25%), regularization multiplier (1). We ran 15 replicates and conducted a subsample type (Vedel-Sørensen, Tovaranonte, Bøcher, Balslev, & Barfod, 2013) with other recommended default settings (Phillips et al., 2006; Phillips & Dudík 2008). Maxent also estimated the importance of variables based on the percent contribution (Jenks et al., 2012).

We used the area under the receiver operating characteristic curve (AUC) which is threshold-independent to measure model performance. The AUC ranges from 0 to 1, with a value of 1 signifying perfect model performance (Phillips et al., 2006). The Maxent output consisted of continuous values between 0 and 1 representing species' occurrence probabilities. We converted these values to presence and absence, based upon threshold values in which sensitivity equals specificity (Liu, Berry, Dawson, & Pearson, 2005; Tytar, Mezhzherin, & Sobolenko, 2015). Cells with probability values greater than the threshold value were considered as suitable habitat for the species. We next withdrew patches with area <7.4 km^2 and distance from the nearest patch >2.1 km based on the minimum home range size and daily path length of the species (Tan, Guo, & Li, 2007). A Mann–Whitney *U*-test was used to assess the difference in average suitable habitat elevation between current and the 2050s. Statistical analyses were carried out with SPSS 19.0 software (IBM Inc., New York, NY).

2.4 | Gap analysis of nature reserves

Gap analysis serves as the first step in assessing biodiversity on a coarse-filter scale (Li et al., 2016; Scott et al., 1993). Suitable habitats, both current and future, were overlapped with nature reserve borders to investigate the ability of these reserves in promoting conservation through protection of Sichuan golden monkey post-climate change events (Feeley & Silman, 2016).

2.5 | Vulnerability assessment

We assessed changes in available suitable habitat between the present time frame and the 2050s and specified the habitat into the following categories:

1. Vulnerable habitat: the area in which current suitable habitat was projected to be unsuitable in the 2050s;
2. Climatic refuge: the area where current suitable habitat overlapped with predicted suitable habitat for the 2050s;
3. New suitable habitat: the area where current unsuitable habitat was predicted to become suitable by the 2050s;
4. Unsuitable habitat: the area where current unsuitable habitat overlapped with habitat predicted to remain unsuitable for the 2050s.

Three indicators were used to examine climate change impacts on suitability of Sichuan golden monkey habitat: (i) percentage of area change (AC); (ii) percentage of current suitable habitat area loss (SH_c); and (iii) percentage of increased suitable habitat area for the 2050s' (SH_f) (Duan, Kong, Huang, Sara, & Xiang, 2016; Li, Liu, et al., 2017; Thuiller, Lavorel, & Araujo, 2005). Indicators were calculated as follows:

$$AC = (A_f - A_c)/A_c \times 100\% \qquad (1)$$

$$SH_c = (A_c - A_{fc})/A_c \times 100\% \qquad (2)$$

$$SH_f = (A_f - A_{fc})/A_f \times 100\% \qquad (3)$$

For the formulas above, A_f is the predicted area of suitable habitat considering the 2050s' climatic scenario for Sichuan golden monkey; A_c is the predicted area of current suitable habitat; and A_{fc} is the area of suitable habitat found for both the current and the 2050s' scenario.

2.6 | Habitat corridor analysis

Graph theory has become a popular tool for modeling the connectivity between suitable habitat patches (Foltête, Clauzel, & Vuidel, 2012;
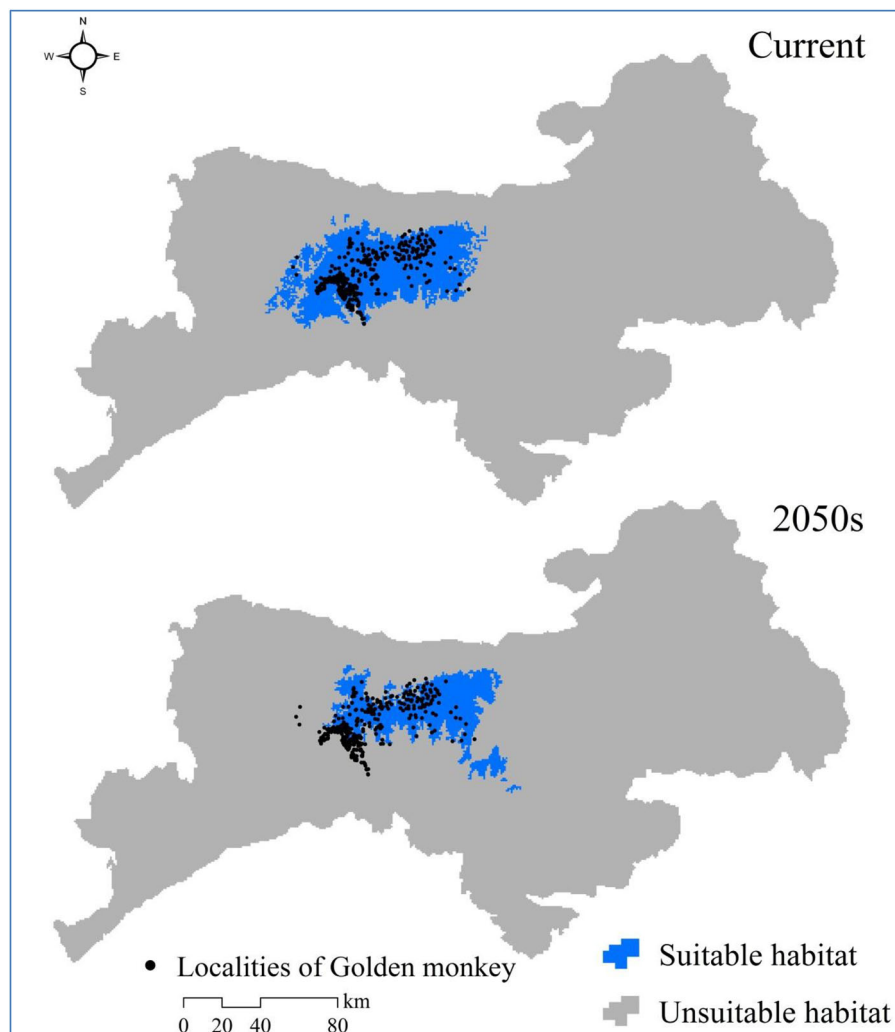

FIGURE 2 Predicted suitable habitat of Sichuan golden monkey under current and the 2050s' climate scenarios in Qinling Mountains

Foltête, Clauzel, Vuidel, & Tournant, 2012). We respectively used the inverse of the habitat suitability map as a resistance surface (Wang et al., 2014) and identified least-cost paths (Li, Clauzel, et al., 2017) to identify the current and future potential habitat corridors for Sichuan golden monkey. All analyses were performed using Graphab 2.2 software (available at https://sourcesup.renater.fr/graphab/en/home.html) (Clauzel, Deng, Wu, Giraudoux, & Li, 2015).

3 | RESULTS

3.1 | Species distribution model

Distribution models for Sichuan golden monkey were made with eight variables (Appendix S2). The average training AUC value was 0.985 ± 0.0001 and the average testing AUC value was 0.982 ± 0.004. The percent contribution of model variables ranked from the highest to the lowest were: mean diurnal range (24.1%), density of rivers (23.4%), precipitation seasonality (20%), density of roads (15.9%), annual precipitation (8.7%), minimum temperature of coldest month (4.4%), density of settlements (3.1%), and elevation (0.3%). The average threshold value for probability of presence at sensitivity equals specificity was 0.204. We classified cells with probability values greater than 0.204 as suitable habitat for the species.

3.2 | Change in suitable habitat

The area of current suitable Sichuan golden monkey habitat is 4,580 km^2, and mainly distributed in Chenggu, Foping, Huxian, Ningshang, Yangxian, Taibai, and Zhouzhi counties (Figure 2). By the 2050s, the areas of suitable habitat were predicted to be 2,880 km^2 with a reduction of 37% area (AC) (Figure 2). The mean elevation of suitable habitat in the 2050s was predicted to be 1,947 ± 332 m, which was significantly higher ($Z = -22.28$, $P \leq 0.001$) than that of current suitable habitat (1,786 ± 362 m).

3.3 | Coverage of nature reserves

The results revealed that current nature reserves protected 62% of the current suitable habitat area and 56% of the 2050s' suitable habitat area (Figure 3). However, Sichuan golden monkey was predicted to suffer habitat loss across twelve nature reserves by the 2050s, with the loss of suitable habitat area ranging from 10% to 100% (Table 1).

3.4 | Vulnerability assessment

Our model predicted that 2,247 km^2 (SH$_c$ = 49%) of current suitable habitat for Sichuan golden monkey would be vulnerable to climate change. Unchanged suitable habitat (i.e., climatic refuge) covers an area of 2,333 km^2. Interestingly, our results suggest there will be an increase in suitable habitat (new suitable habitat, 555 km^2, SH$_f$ = 19%) in Ningshan county (Figure 4).
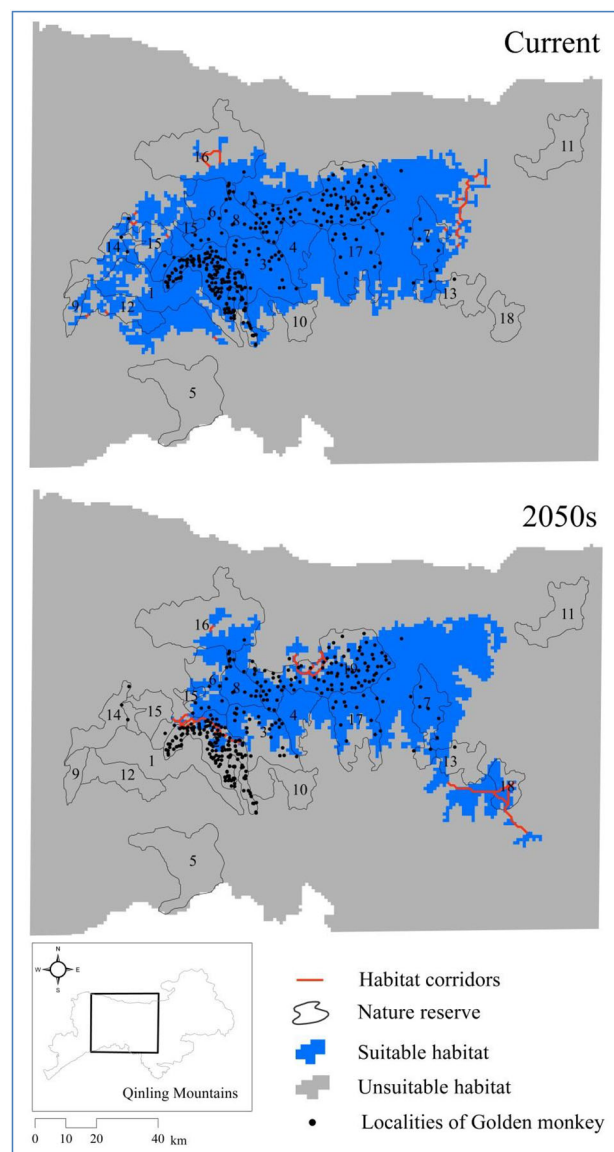

FIGURE 3 Gaps between nature reserves for conserving Sichuan golden monkey, and suitable habitat patches of species connected by least-cost paths in Qinling Mountains

3.5 | Potential habitat corridors

Suitable habitat patches for Sichuan golden monkey that connected by least-cost paths representing potential movement paths between patches. The graphab modeling presented 23 least-cost paths between current Sichuan golden monkey's suitable habitat, and 32 paths in future (Figure 3).

4 | DISCUSSION

Our model projected that, even under a mild climate change scenario, there would be 49% of reduction in suitable habitat area for the Sichuan golden monkeys in the Qinling Mountains. The IUCN suggests that species having a predicted loss of 30–50% in suitable habitat should be considered threatened (IUCN, 2001). Since the Sichuan

TABLE 1 Projected change in suitable habitat of Sichuan golden monkey in nature reserves

Code	Nature reserve	Suitable habitat area/(km²)		Percentage of area change (AC) (%)
		Current	2050s	
1	Banqiao	261.75	0.00	−100.00
2	Changqing	305.86	76.53	−74.98
3	Foping	300.35	148.01	−50.72
4	Guanyinshan	148.44	132.06	−11.04
5	Hanzhongzhuhuan	–	–	–
6	Huangbaiyuan	205.42	136.77	−33.42
7	Huangguanshan	175.55	166.85	−4.96
8	Laoxiancheng	120.57	118.75	−1.51
9	Motianling	19.20	0.00	−100.00
10	Niangniangshan	77.04	0.00	−100.00
11	Niubeiliang	–	–	–
12	Panlong	117.96	0.00	−100.00
13	Pingheliang	11.27	21.04	86.63
14	Sangyuan	66.88	0.00	−100.00
15	Taibainiuweihe	92.86	8.47	−90.88
16	Taibaishan	126.44	129.33	2.29
17	Tianhuashan	285.70	196.64	−31.17
18	Yingzuishi	–	68.14	100.00
19	Zhouzhi	522.43	422.34	−19.16

golden monkeys were predicted to lose 49% of suitable habitat, the species would be specified as threatened according to above IUCN suggestion and conservation actions are needed.

Based on our results, habitat connectivity in the southwestern portion of Qinling Mountains was relatively low, and this area was predicted to lose the greatest area of suitable habitat by the 2050s. Thus, effective conservation strategies for this area should include the construction of corridors for the species to disperse between suitable habitat patches. At the same time, the new suitable habitats of Sichuan golden monkeys are projected to occur in Ningshan County. However, Sichuan golden monkey will be impeded by natural and artificial barriers (e.g., rivers, agriculture, logging, and roads; Fan et al., 2011; Li et al., 2002; Sun et al., 2007) if they attempt to expand to new suitable habitats in the future. Thus, we propose proactive measures (e.g., forestry planning) to improve the connectivity of habitat, and constructing migration corridors to assist populations of Sichuan golden monkey to expand to and utilize these new habitats in the future.

Nature reserves are a key component in conservation, yet they are under increasing threats from rapid climate change (Gross, Watson, Woodley, Welling, & Harmon, 2015; Nori et al., 2016). Most nature reserves were established decades ago without considering the impact of climate change (Araùjo, Alagador, Cabeza, Nogues-Bravo, & Thuiller, 2011; Li et al., 2015), and conservation effectiveness of these reserves will be negatively affected by climate change. The results revealed that current nature reserves protected 62% of the current suitable habitat area and 56% of the 2050s' suitable habitat area (Figure 3). However,

Sichuan golden monkey was predicted to suffer more than 10% habitat loss across 12 nature reserves by the 2050s (Table 1). Three nature reserves (i.e., Huangguanshan, Pingheliang, and Yingzuishi) are isolated from other nature reserves and they currently protect a small population of Sichuan golden monkeys (Gao & Kang, 2007; Meng, 2008), thus in advance of habitat corridors construction should be conservation planning for those nature reserves facing climate change.

Assessments of vulnerability can provide information regarding future impacts of climate conditions on species (Pacifici et al., 2015), thereby allowing managers to make appropriate conservation action plans (Arribas et al., 2012). Our results identify the possible climatic refuges for Sichuan golden monkey within Qinling Mountain range, and will provide scientific data which can be used to take into account in establishing new national parks for protecting the species. Protection of these areas will facilitate the long-term survival of this species.

Validation of our model revealed that there was good concordance between the known distribution of Sichuan golden monkey in Qinling Mountains and the suitable habitat predicted by the model. Nevertheless, there are limitations and uncertainties. First, habitat for Sichuan golden monkeys is affected by many other physical and biological factors. However, data on spatial variation of these other biotic and abiotic factors within our study area are limited, which restricted our choice of variables for building the models. Second, our findings highlighted the risks of ignoring the intersection of ecology process and dynamic threats in response to climate change for Sichuan golden monkey. Though we could not include all variables in the model,
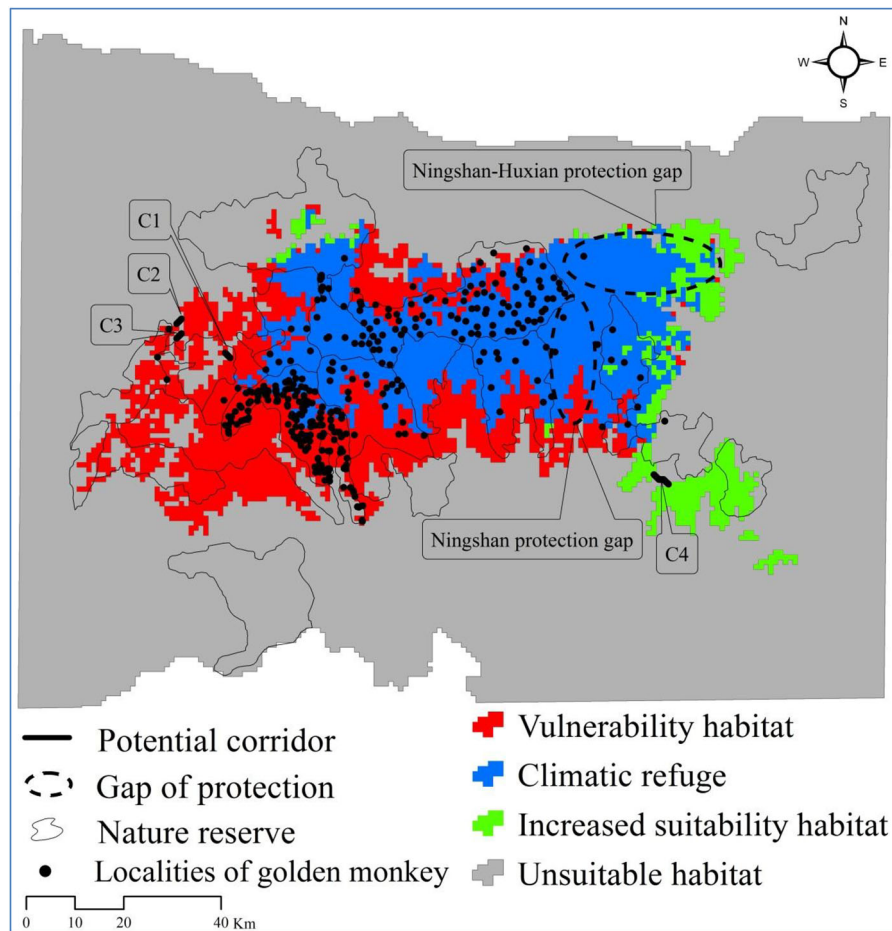
FIGURE 4 Vulnerability levels of suitable habitat for Sichuan golden monkey, and protection gaps and potential corridors for species in the Qinling Mountains. C1–C4 indicate locations for constructing habitat corridors

our results represented the reliable analysis of the impacts of climate change on golden species' distributions and are based on the best data available for the species. We believe that it is likely a good representation of how climate change will affect the patterns and distributions of Sichuan golden monkey's habitat.

5 | CONSERVATION IMPLICATIONS

As a species of public interest and national pride, Sichuan golden monkey is a focus of conservation effort (Chang et al., 2012; Huang et al., 2016; Xu et al., 2014). The government of China has listed the Qinling Mountains as priority areas for biodiversity conservation plans (2011–2030) (Ministry of Environmental Protection, 2011), and will establish a national park to further strengthen conservation for giant panda and other species including Sichuan golden monkey in the Qinling Mountain range (State Forestry Administration, 2016). Thus, our assessment of the vulnerability of Sichuan golden monkey provides valuable information for formulating strategies to meet the future challenges brought on by climate change. To help mitigate the impacts of climate change on Sichuan golden monkey in the Qinling Mountains, we propose the following recommendations.

5.1 | Including new suitable habitat into planning of the national park

Suitable habitat for Sichuan golden monkey predicted for 2050s revealed large gaps in the conservation network (Figure 4). The gaps in Ningshan county should be covered by the proposed national park to improve habitat connectivity for the species.

5.2 | Establishing habitat corridors

Although we produced a map of least-cost paths for Sichuan golden monkey's movement, the establishment of all potential corridors will be a long-term process, which does not meet the urgent needs for conserve Sichuan golden monkey. Perhaps first and foremost, promoting habitat corridors should be based on (i) increasing chances for the known isolated populations to shift to larger suitable habitat patches in Taibai county (C1, C2, and C3) and (ii) assisting dispersal of population to new suitable habitat in 2050s in Ningshan county (C4; Figure 4).

5.3 | Strengthening monitoring on Sichuan golden monkey

Many nature reserves were in preliminary stages of adopting strategies for the repercussions of climate change when their

master plans were formulated (Xu et al., 2017). However, it is at the time impossible to fully understand how the species will respond to current strategies and what management measures will be most effective. Therefore, long-term standardized monitoring programs should be carried out after the new Qinling National Park is established to monitor the changes in populations and habitats of this endangered species which was predicted to be vulnerable to climate change.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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