

Dispersal behaviors stimulated by habitat alterations in golden snub-nosed monkeys (*Rhinopithecus roxellana*) in the Qinling Mountains, China

DEAR EDITOR,

Combining location data, species distribution modeling (MaxEnt), and major conservation events, we analyzed historical distribution changes in golden snub-nosed monkeys (*Rhinopithecus roxellana*) in the Qinling Mountains of China. Our results indicated that the monkeys have changed their distribution in response to implemented conservation programs, including afforestation, reforestation, farmland to field conversion, and, most importantly, removal of residents from nature reserves. Based on these findings, we propose a conservation strategy to enhance these results to effectively protect this species and other animals in the Qinling Mountains, a global biodiversity hot spot.

Despite its considerable diversity of fauna and flora, China faces unprecedented conservation pressures due to significant environmental devastation during the second half of the last century (Pan et al., 2016). Of particular concern, among the 27 existing species of nonhuman primates in China, 80% are currently listed as threatened and more than half have populations containing fewer than 3 000 individuals (Li et al., 2018).

In acknowledgment of the serious and urgent need for better environmental protection, the Chinese Government has undertaken important measures and key projects to mitigate these issues. Firstly, six Key Forestry Projects have been initiated since 1998, including the conservation and protection of forests, especially primary forests, accounting for 60% of China's total forested area (Zhao et al., 2021), and the banning of natural forest logging for commercial purposes in certain biodiversity hot spots (Zhao et al., 2021). Secondly, the 'returning farmland to the field' project was implemented in 2000, resulting in the formation of 167 new nature reserves, bringing the total number of reserves in China to 1 156, covering some 16 million hectares and accounting for 12.09% of China's land area. Thirdly, the Chinese Government has also carried out a unique ecological emigration project since 2012. For example, in Shaanxi Province, more than 10 million people have been relocated from ecologically fragile but biologically diverse areas to lessen the impact of human activities on the environment. These encouraging conservation advancements in China have aroused considerable attention

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from scientists, conservationists, politicians, and the public. Nevertheless, limited research has been conducted on the impact of these programs, policies, and management practices on animal behavior, habitat utilization, geographic distribution, and animal-human relationships. Such studies are critical to assess whether such endeavors have achieved their desired objectives and to provide scientific feedback to inform and enhance future conservation programs.

As a renowned biodiversity hotspot in central China, the Qinling Mountains have been significantly disturbed by human activities but have also benefited from multiple conservation projects implemented by the Chinese government. As a result, the initiatives carried out in the Qinling Mountains have become a model for biodiversity conservation in China. The endangered golden snub-nosed monkey (*Rhinopithecus roxellana*) was first recorded in the region in 1959, with their habitat severely impacted until the beginning of this century. Based on fieldwork conducted from June 2021 to June 2022 and historical data collection, we analyzed the dynamic geographic distribution of this species over the past 60 years as well as the relationships between their historical distribution and human activities and conservation strategies. Our findings should offer valuable scientific feedback and insights to inform and improve future conservation programs.

To determine the changes in geographic distribution and key variables affecting survival of the monkey population in different periods in the Qinling Mountains, we use the MaxEnt model to reconstruct suitable habitats within the study area. To obtain the necessary data for the model, we conducted a comprehensive literature review and field survey. The literature data included distribution records of the golden snub-nosed monkey from 1959 to 2021. The field survey was conducted from June 2021 to June 2022 to verify previous reports and locate new monkey populations. Because the location data were obtained from multiple impromptu surveys in different periods, we filtered original locations within one km² and classified them into three different time periods, i.e.,

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1980s (82 locations), 2010s (94 locations), and 2020s (176 locations). Environmental variables were divided into three categories, i.e., vegetation types, topographic structures, and human activities. We obtained these variables from official websites and converted the data into the form required by the model (Supplementary Materials).

Prior to the 21st century, golden snub-nosed monkeys in the Qinling Mountains were primarily distributed in five counties, including Zhouzhi, Taibai, Ningshan, Foping, and Yangxian (Li et al., 2001) (Figure 1A). Over time, however, their geographic distribution underwent a significant reduction, decreasing from 30 080 km² in the 1980s to 21 414 km² in the 1990s, resulting in a loss of 8 666 km² of habitat (Figure 1B). This decline was likely due to specific socioeconomic and agricultural activities, including extensive commercial logging, farming, and human migration into conservation areas (Li et al., 2002). Of note, commencing in the 1960s, the Shaanxi Government established six state forest bureaus that engaged in commercial logging of approximately 4 000 km² over nine counties, including natural primary forest habitats of the monkeys and other animals (Li et al., 2001). Furthermore, by the end of 1997, about 1 940 km of roads had been built for the logging industry, producing nearly 2 5471 000 m³ of timber.

As a result, large-scale forest destruction and severe habitat loss occurred, forcing many monkey populations to move to higher elevations.

This concerning decline began to reverse by the end of 1999, with gradual increases in habitat in the 2010s, reaching 21 701.68 km² by 2021 (Figure 1C), as well as the identification of six new populations in Zhashui, Huyi, Meixian, Liuba, Fengxian, and Weibin. These positive changes have been attributed to conservation projects implemented to mitigate the deteriorating status of animal populations in the Qinling Mountains.

From the 1980s to 2010s, the centroid distribution of the monkeys shifted 14.8 km northwest, followed by a period of relative stability, with a slight 0.3 km shift southeast from the 2010s to 2022, likely due to improved habitat and human relocation out of conservation areas (Figure 1D). This migration pattern is likely influenced by the fewer human activities and more extensive primary forests in Taibai Mountain (highest peak in the Qinling Mountains, 3 767 m a.s.l.).

Increasing intraspecific connectivity is critical for maintaining genetic diversity as well as ecological and habitat biodiversity to promote ecosystem potential (McGuire et al., 2016). As

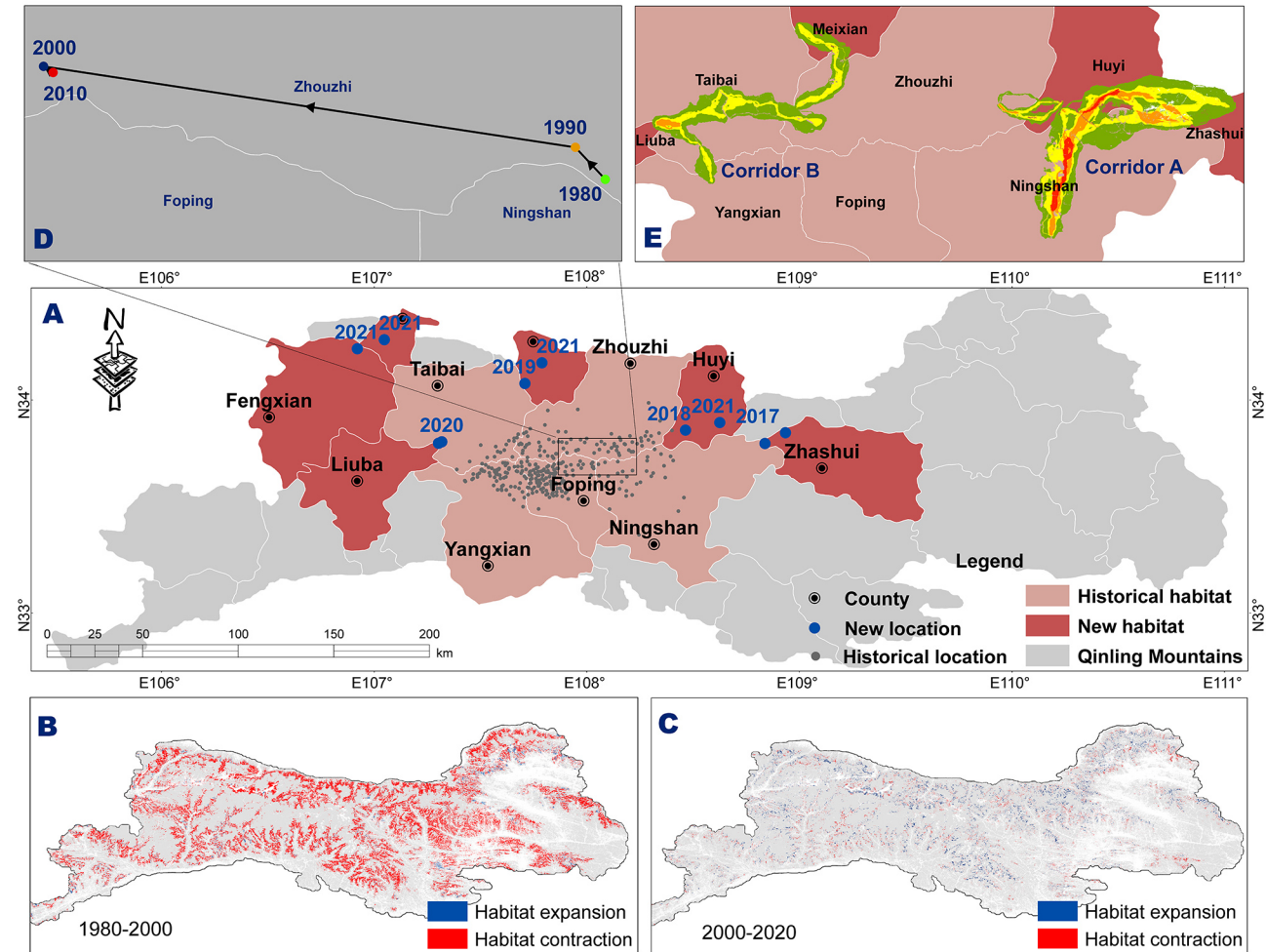


Figure 1 Geographic locations and habitat changes of golden snub-nosed monkeys in the Qinling Mountains, China

A: Current geographic locations and new reported populations in different years. B: Habitat changes from 1980 to 2000. C: Habitat changes from 2000 to 2020. Red is contracted area, blue is expanded area, and gray is area without change. D: Drifting centroid trajectory of monkeys from 1980 to 2021. E: Two migration corridors used by golden snub-nosed monkeys in the Qinling Mountains since the 1980s. Colors represent frequency scales.

illustrated in Figure 1E, two major monkey migration corridors were identified, which have shaped the distribution of the new populations and allow two-way movement. The first corridor links the Huiyi and Zhashui groups to the Ningshan group (A), while the second corridor links the Meixian and Chencang groups to the Taibai group (B). During migration, the monkeys and other animals need to traverse several major traffic areas (Supplementary Table S1), including the express railway from Xi'an to Chengdu and highway from Xi'an to Hanzhong, which cross corridor A to the south. Based on our observations, monkeys move through the mountains above the tunnels, around the border between Ningshan and Huiyi. Corridor B, which runs along Taibai Mountain, is crucial for monkey dispersal and is associated with less human activity, more primary vegetation, and more extensive forests.

Our findings further indicated that elevation (47.9%), tree type in habitats (14.3%), road infrastructure (10.6%), and human footprint (8.3%) were significant variables influencing monkey behavior and selection of habitat type, dispersal direction, migration, and future development (Supplementary Figures S1, S2).

Results also showed that mean elevation of the monkey habitat in the Qinling Mountains has declined from 2 000 m (1 400–2 700 m) a.s.l. prior to the 1980s (Li et al., 2002), to 1 867 m a.s.l. in the 1980s, 1 834 m a.s.l. in the 2010s, and 1 805 m a.s.l. at present (Supplementary Figure S3). Based on our field survey, we propose that this change may be attributed to human emigration out of conservation areas and the conversion of farmland into fields following government-initiated policies, allowing monkeys to extend their habitat to areas previously occupied by humans.

Deciduous broad-leaved forest, evergreen coniferous forest, and mixed coniferous and broad-leaved forest play essential roles in monkey habitat selection (Guo et al., 2008). Interestingly, our results showed that the contribution of tree type varied over time, from 3.7% in the 1980s, 17.4% in the 2010s, and 14.3% in 2021 (Supplementary Figure S2), with a progressively increasing trend before the 2010s. These findings imply that, following the loss of primary forests due to commercial logging, the monkeys primarily sought habitat that retained broad-leaved forests to ensure basic survival. However, after logging was banned and conservation projects were launched, the monkeys had a greater choice of different tree types and habitats, allowing them to extend their distribution and move to lower elevations. As vegetation recovered, the impact of tree type on monkey distribution was no longer a key constraint in the 2020s.

Road infrastructure is another major factor affecting monkey distribution. Historically, from the middle to the end of the last century, only one railway and logging road existed in the Qinling Mountains. However, the construction of several major railways and highways in the last 20 years has resulted in substantial habitat fragmentation and isolation, markedly influencing monkey migration.

Our results also showed that the human footprint, representing the impact of human activities, has played a critical role in monkey distribution. First, a range of socioeconomic factors led to significant natural resource depletion, land conversion, and deforestation in the Qinling Mountains. Notably, commercial logging activities (from 1960 to 1999) and depletion of primary forests forced the monkeys to migrate to higher elevations. Second, increased

deforestation and agricultural development following an increase in human population density occurred in the Qinling Mountains, with the expansion of cultivated lands up to 2 000 m a.s.l. again forcing monkeys to move to higher elevations. Third, the implementation of environmental protection and conservation endeavors, such as the banning of logging and return of farmland to wild fields, allowed monkeys to utilize areas once occupied by local people, thereby significantly changing their distribution.

Our results also indicated that in the case of recovering habitats, the conservation strategies for monkeys should shift from habitat protection to the strengthening of dispersal pathways and migration corridors. In addition to golden snub-nosed monkeys, other mammals, such as takins (*Budorcas taxicolor*), giant pandas (*Ailuropoda melanoleuca*), carnivorans, and artiodactyls, also use corridors (Wang et al., 2021). Therefore, it is essential to implement appropriate management strategies to maintain the corridors identified in this study. Furthermore, tunnels for human traffic could be constructed at elevations between 1 700 m and 2 000 m a.s.l., allowing traffic to pass through the mountain without impacting surface habitats. Vegetation restoration along the corridors should also be promoted to link fragmented areas, thus providing more extensive coverage to monkeys and other animals during their movements.

Finally, while species distribution models can effectively simulate the status of habitats, they cannot accurately simulate the size and distribution range for each population based solely on location data. Therefore, our next step will involve distinguishing between populations and specific external factors according to variations in population dynamics.

SCIENTIFIC FIELD SURVEY PERMISSION INFORMATION

Permission for field survey in the Qinling Mountains was granted by the Shaanxi Forestry Bureau.

SUPPLEMENTARY DATA

Supplementary data to this article can be found online.

COMPETING INTERESTS

The authors declare that they have no competing interests.

AUTHORS' CONTRIBUTIONS

The idea for this study originally came from B.G.L., R.L.P., and C.L.W. Field data were collected by G.H., L.C., X.D.Y., T.W., W.L., H.T.Z., and H.Z. Historical distribution data were collected by Y.R., W.W.F., Y.W., and X.W.W. Statistical analyses were performed by C.L.W. The manuscript was prepared by C.L.W. and W.F.W. with edits and additional suggestions for data analysis and interpretation provided by B.G.L. and R.L.P. The project and all guidance were coordinated by W.F.W. All authors read and approved the final version of the manuscript.

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Supplementary Materials

Dispersal behaviors stimulated by habitat alterations in golden snub-nosed monkeys (*Rhinopithecus roxellana*) in the Qinling Mountains, China

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Supplementary Materials and Methods

Study area

Our survey covered an area of the Qinling (105°30'–110°05'E, 32°40'–34°35'N) in Shaanxi Province, about 400 km–500 km from east to west, and about 150 km – 200 km from south to north, with an area of 53,000 km² (Basic geographical conditions of Shaanxi province, 2011). The vegetation displays a significant vertical differentiation: deciduous broadleaved forests are principally distributed below 2,200m; the coniferous and broadleaved mixed forests range from 2200 to 2600 m; evergreen coniferous forests are found from 2,400 to 3,000; and above 3000 m we met deciduous, coniferous forests and alpine meadow (Liu et al., 2022). It is an area that features remarkable biodiversity hot spot (Wang et al., 2014).

The golden snub-nosed monkeys studied are the only nonhuman primate species in the area (Li et al, 2001), with about 4,000 individuals belonging to 39 troops (populations) before the 21st Century (Li et al., 2001; Li et al., 2002).

In addition to collecting historical distribution locations, the survey included camera traps to identify the current distribution location.

Database collection

Through the literature review, we compiled the data records of monkeys' distribution profiles reported from 1959 to 2020. Because those data were from multiple unplanned surveys in different periods, we filtered original locations within one km² with Spatially Rarely Occurrence Data software in the SDM toolbox to avoid spatial autocorrelation. After the filtering, we got 82 location sites in the 1980s, 94 locations in the 2010s, and 176 locations in the 2020s. Our fieldwork in 2021 aimed to verify the previous reports and found four new monkey populations (Fig 1A).

Environment variables

The environmental variables used in this study to analyze the relationship between ecological factors and monkeys' distribution patterns consist of three parts: vegetation types, topographic structure, and human activities. We obtained the data from Global Geo-information Public Product (<http://www.globallandcover.com>) recorded in 2000, 2010, and 2020, representing the profiles during the 1980s and the 2010s, and the 2020s, separately. The topographic variables include the elevations, slopes, and aspects, extracted from the Digital Elevation Model (DEM) stored in the Chinese Academy of Sciences geospatial database (<http://www.gscloud.cn>). The variables related to human-induced activities include the human footprint index (HFI), the distances of the habitats to human settlement (DS), roads (DR), and water resources (DW). HFI came from the Center for International Earth Science Information Network (http://www.ciesin.columbia.edu/wild_areas) (Venter et al., 2016). DS, DR and DW were calculated according to the Digital vector map from National Geographic Information Resources Directory Service System (<http://www.webmap.cn>).

Environmental variables were resampled to a km² resolution, unified according to WGS_1984 geographic coordinate system, and transformed into ASC format.

Data analysis

Species distribution models (SDMs) has been used to find potentially suitable habitat for the animals (Kuemmerle et al. 2011, Naundrup and Svenning 2015); among

them, the Maximum Entropy Model (MaxEnt) has recently become increasingly popular for such a purpose (Nüchel et al., 2018; Liu et al., 2019). We used this model to identify monkeys' suitability habitats in the Qinling from the 1980s to 2020s. We conducted a subsampling procedure with ten replicates (Khatchikian, 2011). We used 75% of the data as the training set for model construction and 25% as the random test set for model performance.

We also utilized the area under the receiver operating characteristic curve (AUC) to evaluate model validity and accuracy, ranging from 0.0 to 1.0. The larger the value, the more accurate the model (Zhang et al., 2019). We categorized the habitats into three levels: high-suitable, moderate-suitable, and unsuitable (Liu et al, 2022).

Based on the suitable habitat levels, we compared suitable habitat changes during the period to identify the increased or reduced distribution areas, both horizontally and vertically.

We also calculated habitat centroids of the monkeys in different periods – the 1980s, the 1990s, and the 2010s, including 2020-2021, to work out their drifting directions from period to period with a SDM toolbox. The least-cost path tool (SDM toolbox, version 2.5) was used to identify their existing and potential migration corridors in the Qinling.

Supplementary Results

1. Geographical distribution changes of the golden monkey

The newly reported monkeys' locations started in 2017, including Taibai, Zhouzhi, Foping, Yangxian, and Ningshan. Another six populations in Meixian, Huyi, Liuba, Fengxian, and Weibin were found in our survey .

2. MaxEnt model

2.1 Habitat suitability for the model

AUC value of the MaxEnt model from 1979 to 2021 is 0.922, indicating that the model can ideally model the relationship between monkeys' distribution patterns, environmental variables, and human steps.

2.2 Suitable habitat change

The suitable area in the 1980s was 30,080 km², which was expanded in some regions (466.69km²) but contracted in others (8,844.75km²). Thus, by 2021, the total suitable area was 21,701.68 km²

2.3 Centroid changes

In the 1980s, the monkeys' suitable habitat center was located in an area linking Zhouzhi and Ningshan (108.10E, 33.72N). It drifted 1.34km toward the northwest in the 1990s (108.09E, 33.73N), which further moved another 14.8km, reaching the border between Zhouzhi and Foping in 2000 (107.94E, 33.75N). Thus, from the 1980s to the present, the centroid of the golden snub-nosed monkeys moved toward the west, 15.56 km. Such a centroid is now in Zhouzhi county, near the border between Zhouzhi and Foping (107.94E, 33.75N), only a shifting of 0.3km southeast compared with the previous period.

2.4 Migration corridors.

With the application of the least-cost path tool, we generated the two migration

corridors.

2.5 Vertical habitat changes

In addition to horizontal movement, monkeys' habitats also changed vertically. During the 1980s, the average elevation was $1867.55 \pm 265.84\text{m}$, which was reduced to $1834.03 \pm 249.27\text{m}$ in the 2010s, then to $1805.12 \pm 245.25\text{m}$ in the 2020s. Such a reduction reached a significant level (Kruskal-Wallis test, $\chi^2=218.93$, $\text{df}=2$, $p<0.001$).

2.6 Variables playing a significant role in shaping habitat changes

According to the permutation importance test, the variables contributing to shaping monkeys' habitats are illustrated in Fig. 6. Among the nine, the following three were identified to have played significant roles: elevation (47.9%), Habitat tree type (14.3%), Road distance (10.6%), and Human footprint (8.3%)

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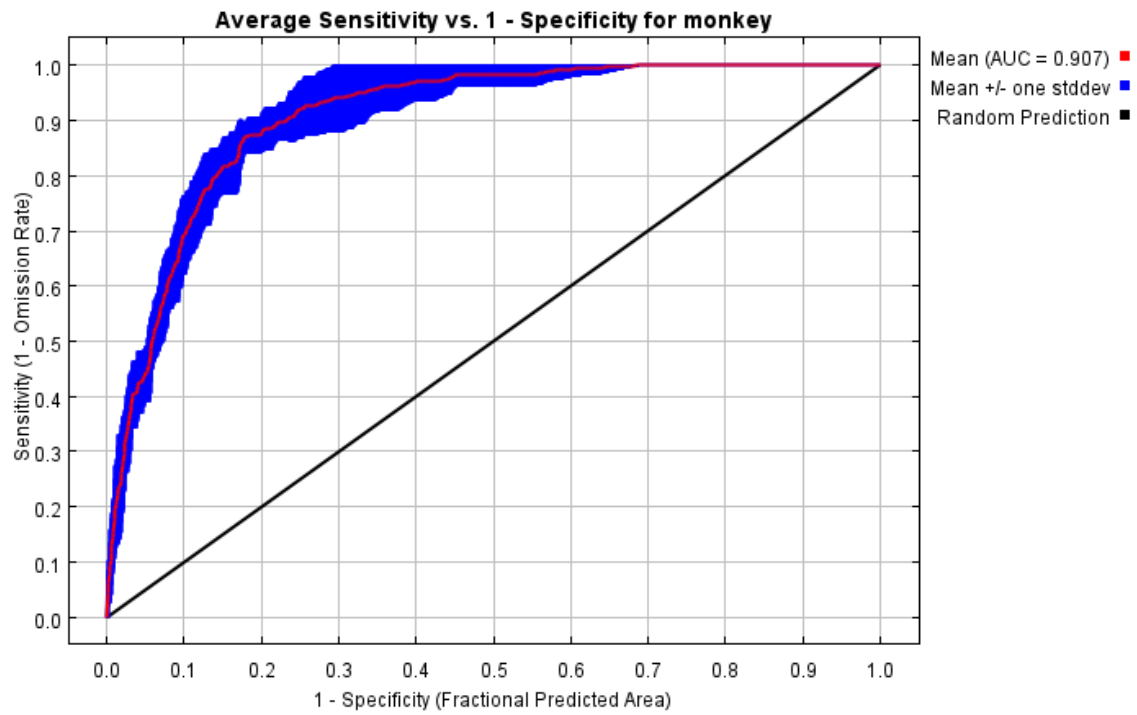
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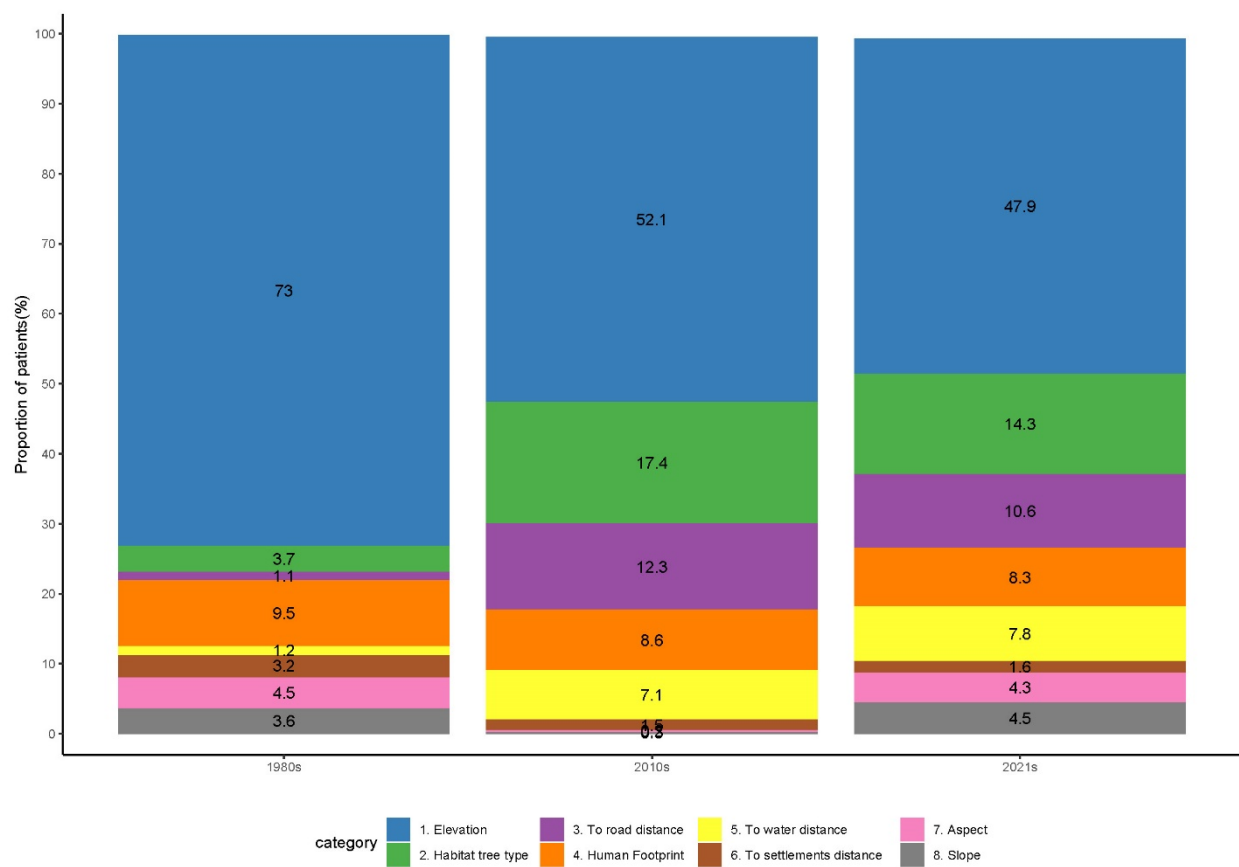
Supplementary Table S1 Road construction in the Qingling since 1958 and a significant increase over the last 20 years.

Types	Built time	From	To	Length within Qinling
Railway	1958	Baoji	Chengdu	346.7 Km
Railway	2001	Xi'an	Ankang	259 Km
Railway	2007	Xi'an	Nanjing	12.268 km
Highway	2009	Xi'an	Ankang	58.261Km
Highway	2007	Xi'an	Hanzhong	258.65 Km
Express railway	2017	Xi'an	Chengdu	135 Km
Logging road	1960- 1999	Low elevation	High elevation	1940 Km

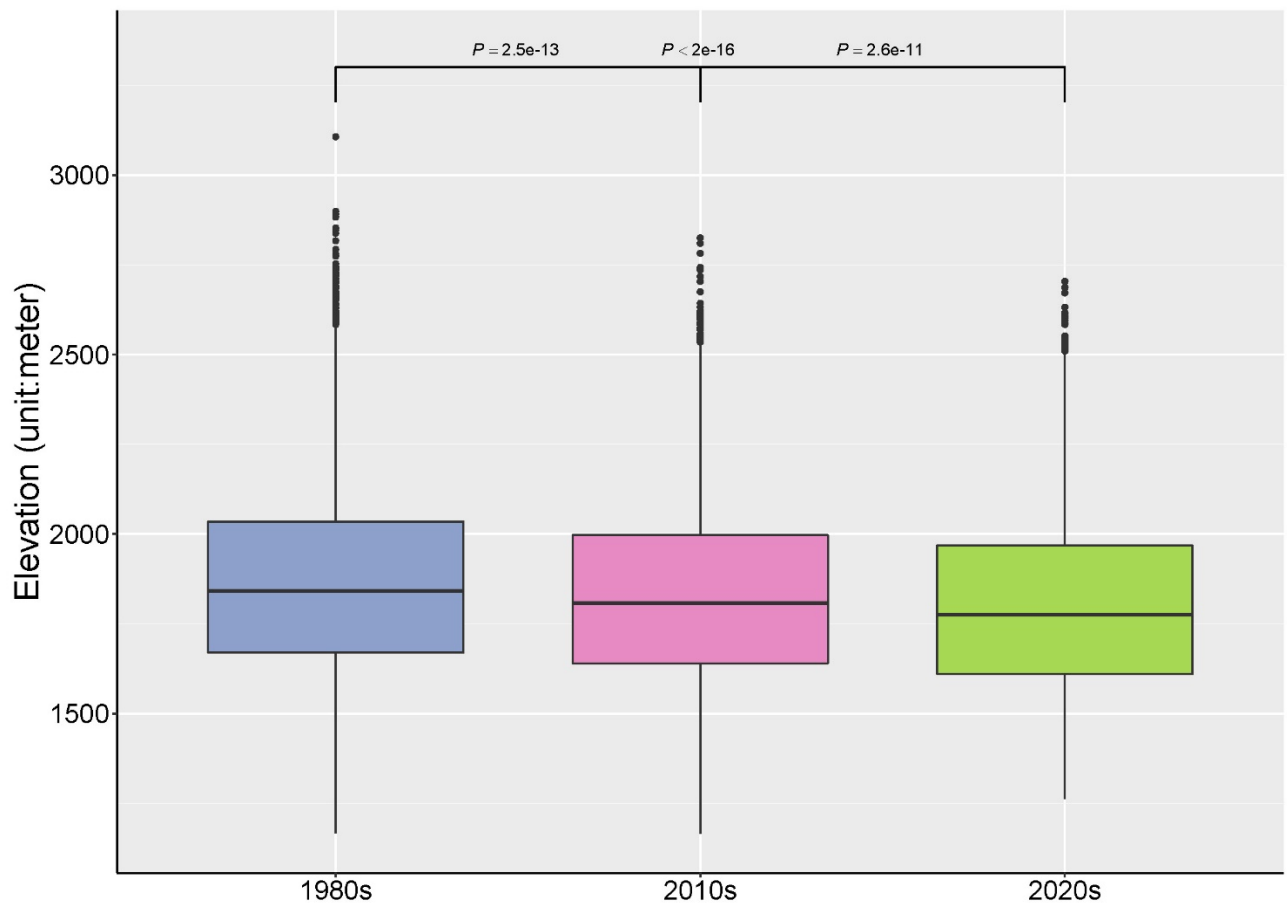
Data from Ding, 2014.



Supplementary Figure S1 The results of receiver operating characteristic (ROC) curve verification in MaxEnt model



Supplementary Figure S2 Contribution percentage of the environmental variables to the MaxEnt model.



Supplementary Figure S3 The average habitat elevations of the golden snub-nosed monkeys in different periods.