



Suitable habitat prediction of Sichuan snub-nosed monkeys (*Rhinopithecus roxellana*) and its implications for conservation in Baihe Nature Reserve, Sichuan, China

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Abstract

As an endemic primate species with one of the highest priorities in wildlife conservation in China, Sichuan snub-nosed monkeys (*Rhinopithecus roxellana*) have undergone a sharp decline and range reduction in recent centuries. Here, we used maximum entropy modelling (MaxEnt) integrated with four types of environmental variables, including three biological climate variables (Bio17, precipitation of the driest quarter; Bio6, min. temperature of the coldest month; and Bio2, mean diurnal range), three topographic variables (altitude, slope, and aspect), two anthropogenic variables (Human Footprint Index and human disturbance), and three vegetation-related variables (enhanced vegetation index, normalized difference vegetation index, and Wet Index) to identify the spatial distribution of suitable habitats for Sichuan snub-nosed monkeys in Baihe Nature Reserve (BNR), which is located in the Minshan Mountains. The average training AUC of our model performance is 0.929 ± 0.003 . The model predicted 9.6 km² of high suitability habitats and 14.1 km² of moderate suitability habitats for Sichuan snub-nosed monkeys, adding up to only 11.7% of the total area of concern for the study in the BNR. The top four variables ranked in the model (altitude, Human Footprint Index, human disturbance, and Bio17) accounted for relative gain contributions of 23.3%, 19.3%, 14.2%, and 13.4%, respectively. The predicted suitable habitats were confined to an altitude range of 1971–3198 m, Human Footprint Index of mainly 3–5 values, low human disturbance (mainly livestock), and precipitation of the driest (or coldest) quarter of 9–22 mm. Additionally, the suitable habitats were mainly distributed in the core zone (36.1%), buffer zone (26.8%), and experimental zone (29.5%). The remaining habitats (7.6%) were distributed in the 0.5-km buffer zone of the reserve border. The predicted suitable habitats indicated limited suitable habitat space for the Sichuan snub-nosed monkeys, with most of the suitable habitat distributed outside the core zone in the BNR. Our findings highlighted that human activities in all three functional zones could be the most negative factor on suitable habitat distribution of Sichuan snub-nosed monkeys in the BNR.

Keywords Sichuan snub-nosed monkeys · Habitat suitability · MaxEnt · Baihe Nature Reserve · Zoning · Human disturbance

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Introduction

In protection of wildlife community, the protection of rare and endangered animals has become one of the most important tasks. Conservationists and ecologists have recognized that understanding the survival of species requires identification of habitat quality and the dynamic process of spatial distribution (Fahrig and Merriam 1985; Wei et al. 2018; Zhang et al. 2014). Therefore, an assessment of habitat suitability and mapping of optimal habitat is essential for understanding the complex habitat characteristics of wildlife and implementing efficient protection.

Although they serve as one of the main protection strategies, some reserves were established on the basis of limited information or empirical data of the target species (or habitats) at the time of their designation (Hull et al. 2011; Yan et al. 2018). Moreover, functional zoning of the reserves may represent a trade-off between socioeconomic interests and environmental protection (Hull et al. 2011; Xu et al. 2016; Yan et al. 2018). In certain cases, relatively loose mixed zoning schemes were used to balance human needs and conservation goals. These include the strictly protected core zone, the buffer zone allowing limited human activities, and the experimental zones with different land use options (Hull et al. 2011; Xu et al. 2016). Under this situation, the habitat suitability assessment of target species seems more urgent and meaningful for testing the efficacy of the zoning.

Primates are regarded as undergoing many threats. The International Union for Conservation of Nature (IUCN) Red List has assessed 437 known species of primates worldwide and identified more than 67% of those species as threatened or near-threatened (IUCN 2018). With approximately 79% threatened with extinction, the primates in South and Southeast Asia have an even more precarious conservation status (Schipper et al. 2008). In this study, we focused on one group of threatened primates in China: the snub-nosed monkeys (genus *Rhinopithecus*), which are represented by five living species and four of which distribute today in high altitude and mountainous regions of south-west China (Zhao et al. 2018). Sichuan snub-nosed monkeys, a species of the snub-nosed monkeys, also known as Golden snub-nosed monkeys (*Rhinopithecus roxellana*), are well known as an iconic national animal of China (Li et al. 2003). It is listed on the endangered species list of a number of organizations (Chopra 1989; IUCN 2018; Wang and Xie 2004). As an endemic primate species in China, Sichuan snub-nosed monkeys (*Rhinopithecus roxellana*) were once widely distributed in south, southwest, central, and northwest China (Li et al. 2002). However, due to climate change and anthropogenic activities associated with increased human population growth (Zhao et al. 2018), including extensive deforestation, agricultural expansion, hunting, logging, and habitat fragmentation, the population size and distributions of snub-nosed monkey

have undergone a sharp decline and range reduction (Li et al. 2003; Wen and Wen 2006; Wen 2009; Zhao et al. 2018; Zhao et al. 2019). The populations currently inhabit temperate forests in mountainous highlands at altitudes between 1500 and 3400 in Sichuan, Hubei, Shaanxi, Gansu, and Chongqing provinces in China (Kirkpatrick et al. 1999; Li et al. 2002; Ren et al. 2001; Zhao et al. 2016). According to a recent study on the conservation effectiveness of the Sichuan snub-nosed monkeys in Shennongjia Nature Reserve, only 59% of the habitat area and 61% of the predicted potential habitat area are under protection (Yan et al. 2018). Thus, to ensure the survival of this species, habitat conservation and management in all distribution areas, including the Minshan Mountains, should be of the highest priority.

Currently, the core distribution areas of suitable habitat for the Sichuan snub-nosed monkeys are mainly located in the Qinling, Dabashan, and Minshan Mountains (Liu et al. 2017). However, previous studies primarily focussed on Sichuan snub-nosed monkeys in the Qinling region in Shaanxi Province (Wang et al. 2018; Yan et al. 2018). The Minshan Mountains, as core habitat areas of the Sichuan snub-nosed monkeys in Sichuan Province, receive relatively little attention on habitat suitability. Few related research articles have been published, and these include studies on the habitat pattern dynamics of Sichuan snub-nosed monkeys in Baihe Nature Reserve (Gu 2011; Zhao et al. 2016; Li et al. 2016), as well as the latest study of landscape connectivity of Sichuan snub-nosed monkeys in China (Liu et al. 2017; Nüchel et al. 2018). Therefore, more research is necessary on habitat suitability and distribution in these areas for better protection of the Sichuan snub-nosed monkeys. For this purpose, MaxEnt (maximum entropy modelling), which is a niche-based model, is regarded as one of the best-performing methods for species distribution modelling (Phillips et al. 2006; Elith et al. 2010).

MaxEnt is based on the known geographic distribution data and environmental variables that correspond to occurrence points of a target species. The model is able to identify potential suitable habitat where both the biotic and abiotic variables satisfy the requirements of the target species (Elith et al. 2010; Phillips et al. 2006). A spatial map of habitat suitability can also be produced in the GIS framework (Phillips and Dudík 2008; Yan et al. 2018). Furthermore, the results of the MaxEnt model were consistently better than those of models such as Bioclim or DOMAIN (Kumar and Stohlgren 2009). The MaxEnt model has been widely applied in assessing the spatial distribution of potentially suitable habitat for species by calculating the Habitat Suitability Index (HIS) (Chang et al. 2012; Cui et al. 2018; Bai et al. 2018; Liu et al. 2016b; Thapa et al. 2018; Wang et al. 2017). Notably, its application in the study of the primates has been attempted recently (Fang et al. 2018; Liu et al. 2017; Nüchel et al. 2018; Yan et al. 2018; Zhao et al. 2018). Yan et al. (2018) used a niche-based approach with 14 environmental variables to assess habitat usage

of the monkeys and the effectiveness of their conservation in Shennongjia Nature Reserve (SNR) (Yan et al. 2018). Additionally, given that much of the monkey's range has no survey data, this model is a good tool for use in studying the Sichuan snub-nosed monkey habitat distribution. For example, Liu et al. (2017) identified the most suitable habitats of the snub-nosed monkey distributed in the Minshan Mountain by MaxEnt modelling by using occurrence data from published literature and from field observations conducted in several nature reserves (Liu et al. 2017).

In our study, the MaxEnt model was used first to assess the spatial distribution of suitable habitat for the Sichuan snub-nosed monkeys (*Rhinopithecus roxellana*) in the Baihe Nature Reserve (BNR). Eleven explanatory variables, including three bioclimate variables, three topographic variables, two human disturbance variables, and enhanced vegetation index (EVI), normalized difference vegetation index (NDVI), and Wet Index (WI) variables were selected from 29 potential factors and used in the model. Second, we analysed to what extent that suitable habitats of Sichuan snub-nosed monkeys could be covered by different function zones, and its protection effectiveness of the current zoning in our study area. Our study will increase our understanding of the habitat selection factors and potential suitable habitat distribution of Sichuan snub-nosed monkeys in the BNR, while also providing more scientific support for an effective protection strategy for these primates.

Methods

Study area

The study area is located at Baihe Nature Reserve (BNR), Jiuzhaigou County, Sichuan Province, China (104° 02'–104° 12' E, 33° 11'–33° 17' N), covering an area of 162 km² and approximately 18.5 km long and 14.8 km wide. The reserve lies along the northern slope of the Minshan Mountains in the transition between the Sichuan Basin and the Tibetan Plateau (Fig. 1). The reserve belongs to warm, temperate zone, semi-humid climate. The average annual temperature at the time of the study was 11.5 °C, with a minimum temperature of –0.5 °C in January and a maximum of 20 °C in July or August. The average annual precipitation was 610 mm. The elevation ranges from 1240 to 4453 m above sea level. The main vegetation types are temperate deciduous broad-leaf/coniferous forest and evergreen coniferous forest (Kirkpatrick et al. 1999; Li et al. 2016; Chu et al. 2018).

The BNR is regarded as the most representative reserve and holds one of the largest groups of Sichuan snub-nosed monkeys, which are present at a high population density (Li et al. 2016; Wang et al. 2013; Gu 2011). The survey in Baihe Nature Reserve in 2013 reported 7 groups with approximately 1600

individuals distributed in the BNR (Zhang et al. 2013), with the occupants representing up to 10% of all Sichuan snub-nosed monkey populations in the world (Zhang et al. 2013). The BNR is one of the nature reserves whose main species targeted for protection is the Sichuan snub-nosed monkeys, and this reserve has the largest population density of the primate in the distribution area (Li et al. 2016; Wang et al. 2013; Zhang et al. 2013; Gu 2011).

Occurrence data

The main occurrence points of Sichuan snub-nosed monkeys (565 occurrence samples) were collected by field investigation in different seasons from March 2011 to August 2013. The remaining occurrence and human disturbance data were obtained from the 4th National Census of the Giant Panda, which was conducted from 2012 to 2013. The geographic coordinates of the collection points were recorded with hand-held GPS units. The availability of point data for the Sichuan snub-nosed monkeys during the Fourth National Giant Panda Census, plus a number of occurrence points from our field survey during the same period, provided a unique opportunity to explore this topic in depth.

Due to increases in the spatial autocorrelation of localities, occurrence data with sampling biases may lead to overfitting of the model (Boria et al. 2014; Nüchel et al. 2018). Duplicate records within one grid cell (30 × 30 m), which was the minimum spatial resolution for our GIS data, were removed, and only one record was left for each grid cell in our study to reduce spatial bias. Considering that a few records occurred outside but near the border of the BNR, we buffered a 0.5-km zone from the border in ArcGIS 10.5 (ESRI 2017). Therefore, the study area used for analysis included the area up to the buffer zone of 0.5 km distance from the reserve border. The final records fed into the MaxEnt model included 544 samples.

Environmental variables

Four types of environmental variables were selected for identifying potential suitable habitat.

(1) Environmental biological variables

Bioclimatic data have frequently been adopted for use in habitat modelling and have proven to be relatively authoritative environmental biological variables (Cui et al. 2018; Nüchel et al. 2018; Thapa et al. 2018; Wang et al. 2017). In our study, 19 bioclimatic raster layers at a spatial resolution of 30 arc seconds (~1 km²) were obtained from WorldClim version 2 (<http://worldclim.org/version2>) and included average monthly climate data for minimum, mean, and maximum

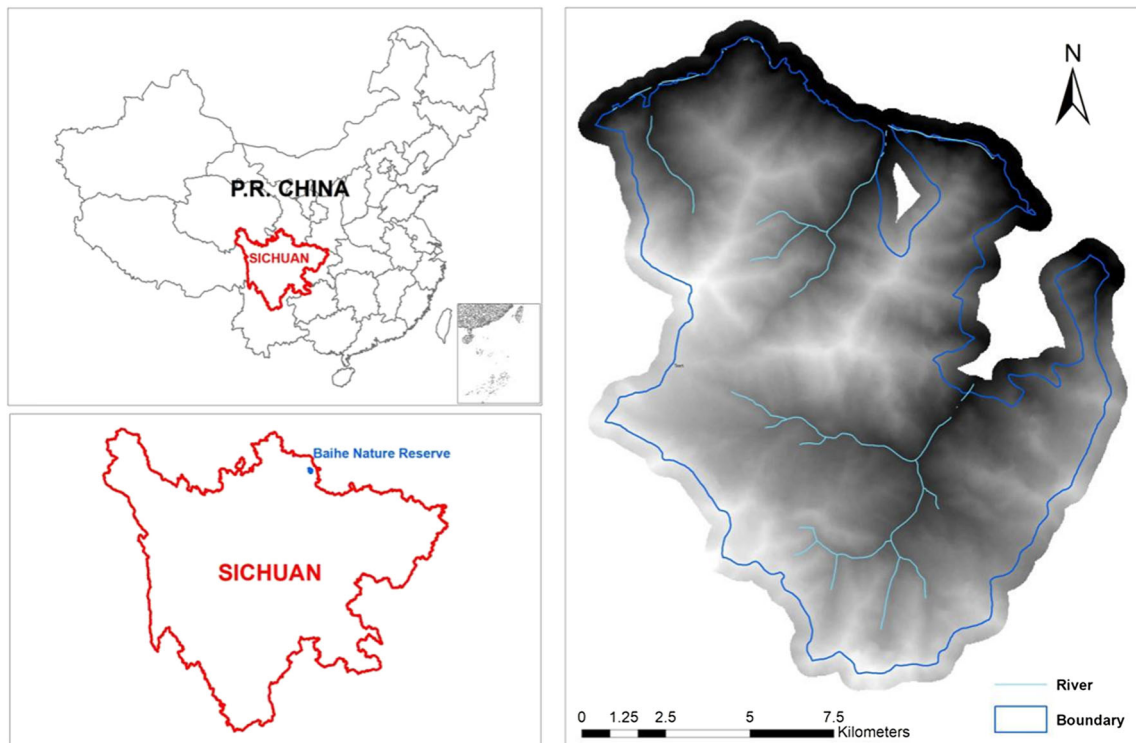


Fig. 1 Map and location of study area, Baihe Nature Reserve

temperature and precipitation for the year 1970–2000 (Fick and Hijmans 2017).

(2) Topographic variables

Three groups of topographic input data, including altitude, slope gradient, and aspect, were selected. The variable layers were extracted from DEM (Digital Elevation Model) by using the spatial analysis tools in ArcGIS 10.5 software (ESRI 2017). The ASTER GDEM DEM data of 30×30 m resolution used in our study were obtained from Computer Network Information Centre, Chinese Academy of Sciences (<http://www.gscloud.cn>) (Geospatial Data Cloud)

(3) Anthropogenic variables

Two measures of anthropogenic disturbance were used in our study. One was 47 human disturbance points including livestock, electric line, roads, fire trace, and hunting in the BNR provided by the 4th National Census of Giant Panda. Distance to the human disturbance layer input in the model was derived through Euclidean linear distance analysis in ArcGIS 10.5. The other was Human Footprint Index (HFI) grids in geographic coordinate system at a spatial resolution of ~ 1 km provided by the 2009 Human Footprint, Last of the Wild Project, Version 3, 2018 Release (LWP-3) (Venter et al. 2018). The HFI expresses the cumulative human pressure on the environment using eight variables, including human

settlement (population density, built-up environments, electric power infrastructure), access (roads, railways, navigable waterways), and landscape transformation (crop lands, pasture lands), and these variables can be used to describe anthropogenic impacts on the environment (Cui et al. 2018; Nüchel et al. 2018; Venter et al. 2018). Gridded data are classified according to their raster value (wild = 0–10; not wild > 10). The value range of the HFI changes from 0 to 50. The larger the value is, the more serious the human pressure is on the environment (Venter et al. 2018). The value of HFI in the BNR was 3–8, 10–12, 14, and 18.

(4) Vegetation-related variables

Five vegetation-related indices derived by remote sensing data were used in our study. The normalized difference vegetation index (NDVI) has been widely used as a typical vegetation cover index (Bista et al. 2018). The enhanced vegetation index (EVI) is more often applied in areas with high vegetation cover. In many cases, NDVI and EVI are highly correlated. Therefore, in our study, we filtered them by correlation analysis. Additionally, we used tasselled cap indicators, including the Wet Index (WI), representing the degree of wetness in the soil; Green Vegetation Index (GVI), representing the degree of vegetation land surface cover; and the Brightness Index (BI), representing the degree of land surface bareness. These indexes were extracted using ENVI 5.3 software (Exelis) from Landsat 8 OLI-TIRS remote spatial data

obtained from the Computer Network Information Centre, Chinese Academy of Sciences (Geospatial Data Cloud), for July 2013.

Data processing and model setting

All raster layers were resampled to 30×30 m spatial resolution in ArcGIS 10.5. We extracted values from all spatial data layers associated with the occurrence points. Here, 19 bioclimatic variable values were analysed through principal component analysis (PCA) in R 3.5.0 software (R Core Team 2017), and we preliminarily selected five candidate variables ranked by the highest standardized loading value: Bio4 (temperature seasonality), Bio17 (precipitation of the driest quarter), Bio19 (precipitation of the coldest quarter), Bio6 (min. temperature of the coldest month), and Bio2 (mean diurnal range) (Appendix 1).

Next, the correlations among all 29 environmental variables were analysed in R 3.5.0 (R Core Team 2017) to eliminate strong collinearity, which affects model performance (Quinn and Keough 2002) (Appendix 2). We chose the environmental variables with correlation values less than $|\pm 0.75|$ and with high standardized loading values (Appendix 1 and 2). Due to a significant correlation between Bio17 and Bio19, only one of those two variables was fed into the model. In addition, in our model, Bio4 was removed because it was correlated to HFI with a correlation value of -0.76 . Bio4 was interpreted as a measure of temperature change over the course of the year based on a calculation of the standard deviation of the 12-month mean (O'Donnell, 2012). In comparison with the HFI, the biological meaning of Bio4 to the Sichuan snub-nosed monkeys seemed not to be significant. Finally, eleven explanatory variables, including three BioClim variables (Bio17, Bio6, and Bio2), three topographic variables (altitude, slope, and aspect), two human disturbance variables (HFI and human disturbance), and EVI, NDVI, and WI variables were selected and then converted to formats that are compatible with the MaxEnt model. Occurrence points and environmental variables, respectively, were used as the independent variable and the dependent variables to estimate the habitat selection index and range of Sichuan snub-nosed monkeys in the BNR using MaxEnt software version 3.4.1.

Most default settings in our model were kept except for the following settings: random test percentage, replicated run type, and the values of the regularization multiplier. We set a random test percentage of 25% with tenfold bootstrapping in our model. Manipulation of regularization multiplier is one of the limitations of the MaxEnt model. A larger regularization multiplier may be a more spread out and less localized prediction (Phillips et al. 2006). Model performance may vary according to the level of regularization (Anderson and Gonzalez Jr 2011; Elith et al. 2011; Nüchel et al. 2018). Additionally, in several cases, the optimal regularization value was different

from the default one (Anderson and Gonzalez Jr 2011). In our study, to detect the regularization value, the regularization multiplier values were manipulated by setting them to 0.5, 1, 2, 3, 4, and 5, according to the recommendations of previous studies (Anderson and Gonzalez Jr 2011; Aryal et al. 2016; Su et al. 2015; Thapa et al. 2018). Our model results under these regularization multiplier values would not change much in contribution variables and AUC values. Thus, to that end, a regularization multiplier of setting 1 (default value) was applied due to its good model performance (Phillips and Dudík 2008). In addition, linear, quadratic, and hinge features were selected in our model to avoid overfitting (Merow et al. 2013; Phillips and Dudík 2008). The remaining parameters followed the default settings of the MaxEnt model.

Habitat suitability classification

The output of the model is the Habitat Suitability Index (HSI), which reflects the suitability of habitat, ranging from 0 (least suitable) to 1 (most suitable) (Yan et al. 2018). Most of the methods for classification of the habitat suitability are experience-based (Liu et al. 2013; Liu et al. 2016a). In a recent study of Sichuan snub-nosed monkeys in Shennongjia Nature Reserve, three habitat classes were also verified by direct field observations (Yan et al. 2018). In a study of the potential distribution of red panda using MaxEnt modelling, the 10 percentile training presence was applied as the suitability threshold to build a potential suitability map, whose prediction was based on a probability above 0.22 (10 percentile logistic threshold) and above 0.5 (core suitable habitat) (Thapa et al. 2018). Therefore, based on previous studies and our model result, we selected the 10 percentile training presence threshold (where habitat suitable index = 0.2918) and minimum training presence logistic threshold (where habitat suitable index = 0.0015) from our model output files for classification of habitat suitability for the map. The HSI map and area in each HSI class were derived using ArcGIS 10.5.

Results

Model evaluation

The curve (AUC) of the receiving operating curve (ROC) is normally used to evaluate the predictive power of a model and to verify the precision of the model forecast. AUC values range from 0 to 1. The higher the AUC value is for a given environmental variable, the better the forecast (Phillips et al. 2006). AUC values > 0.5 indicate that the model is better than the randomly generated model. The models with an AUC value > 0.75 are considered potentially useful, and AUC values > 0.9 indicate very good model performance (Phillips et al. 2006; Phillips and Dudík 2008). In our model, the

average test AUC for the replicate runs is 0.929 ± 0.003 , which is recognized as excellent model performance (Appendix 3).

Environmental variables contributing to the model

Table 1 gives estimates of relative contributions of the environmental variables to our model. Altitude, HFI, human disturbance, Bio17, and Bio06 were major predictors of habitat suitability for Sichuan snub-nosed monkeys, whereas the NDVI and WI show the least contributions. The top four ranked in the model (altitude, HFI, human disturbance, and Bio17) accounted for relative gain contributions of 23.3%, 19.3%, 14.2%, and 13.4%, respectively (Table 1), which added up to more than 70.2% of the habitat suitability prediction for Sichuan snub-nosed monkeys. Livestock (72.3%), electric line (12.8%), roads (8.5%), fire trace (4.3%), and hunting (2.1%) were found in the BNR based on the 4th National Census of the Giant Panda. The estimated response curves show that the probability of presence changes as each environmental variable is varied while keeping all other environmental variables at their average sample value (Fig. 2).

Suitable habitat prediction

The HSI in our model was reclassified to four habitat classes: areas not suitable as habitat ($HSI = 0-0.0015$), low suitability habitat ($HSI = 0.0015-0.2918$), moderate suitability habitat ($HSI = 0.2918-0.5$), and high suitability habitat ($HSI > 0.5$) (Fig. 3a). In the end, the model predicted approximately 9.6 km² high suitability habitats and 14.1 km² moderate suitability habitats for Sichuan snub-nosed monkeys, adding

up to only 11.7% of the total concerned study area. In comparison, approximately 106.6 km² of the low suitability habitat and 72.0 km² of the non-habitat, respectively, occupied up to 52.7% and 35.6% of the total concerned study area (Fig. 3a). These predicted suitable habitats (high and moderate suitability) were confined to an altitude range of 1971–3198 m, with a Human Footprint Index of mainly 3–5 values, low human disturbance (mainly livestock), and precipitation of the driest (or coldest) quarter of 9–22 mm.

Effectiveness of protection zoning

Based on overlay analysis of the function zones coupled with suitable habitat distribution, the predicted suitable habitats ($HSI > 0.2918$) mainly were distributed outside of the core zone of BNR, partly in the buffer zone, and in the experimental zone near the buffer zone (Fig. 3b), with 36.1% suitable habitat occurring in the core zone, 26.8% in the buffer zone, and 29.5% in the experimental zone. The remainder (7.6%) was distributed in the 0.5-km buffer zone inside the reserve border. Our results indicate that only limited suitable space and adverse reserve zoning exists in the BNR for Sichuan snub-nosed monkeys. Additionally, suitable habitats adjacent to the reserve border were not protected under the BNR.

Discussion

Using the MaxEnt model, we constructed patterns of habitat suitability for the Sichuan snub-nosed monkeys in the BNR in the Minshan Mountains, where one of the largest groups of

Table 1 Analysis of relative contributions of environmental variables in MaxEnt model

Variable	Percent contribution	Permutation importance	Jackknife of AUC
Altitude	23.3	15.8	0.824
HFI	19.3	7.6	0.795
Human disturbance	14.2	25.7	0.695
Bio17	13.4	18.7	0.785
Bio06	11.6	18.3	0.785
Bio02	9.5	4.1	0.754
Slope	3.5	2.6	0.634
Aspect	2.4	2.6	0.703
EVI	1.6	2.1	0.634
NDVI	1	1.1	0.704
WI	0.1	1.4	0.707

The relative contribution of each variable to predictive model, shown as mean value of 10 replicates. Jackknife tests of variable importance, expressed as AUC (area under the receiver operating characteristic curve) for models using each variable alone. A higher gain indicates a variable with more information for modelling when used in isolation; *HFI*, Human Footprint Index; *Bio17*, precipitation of the driest quarter; *Bio6*, min. temperature of the coldest month; *Bio2*, mean diurnal range; *EVI*, enhanced vegetation index; *NDVI*, normalized difference vegetation index; *WI*, Wet Index

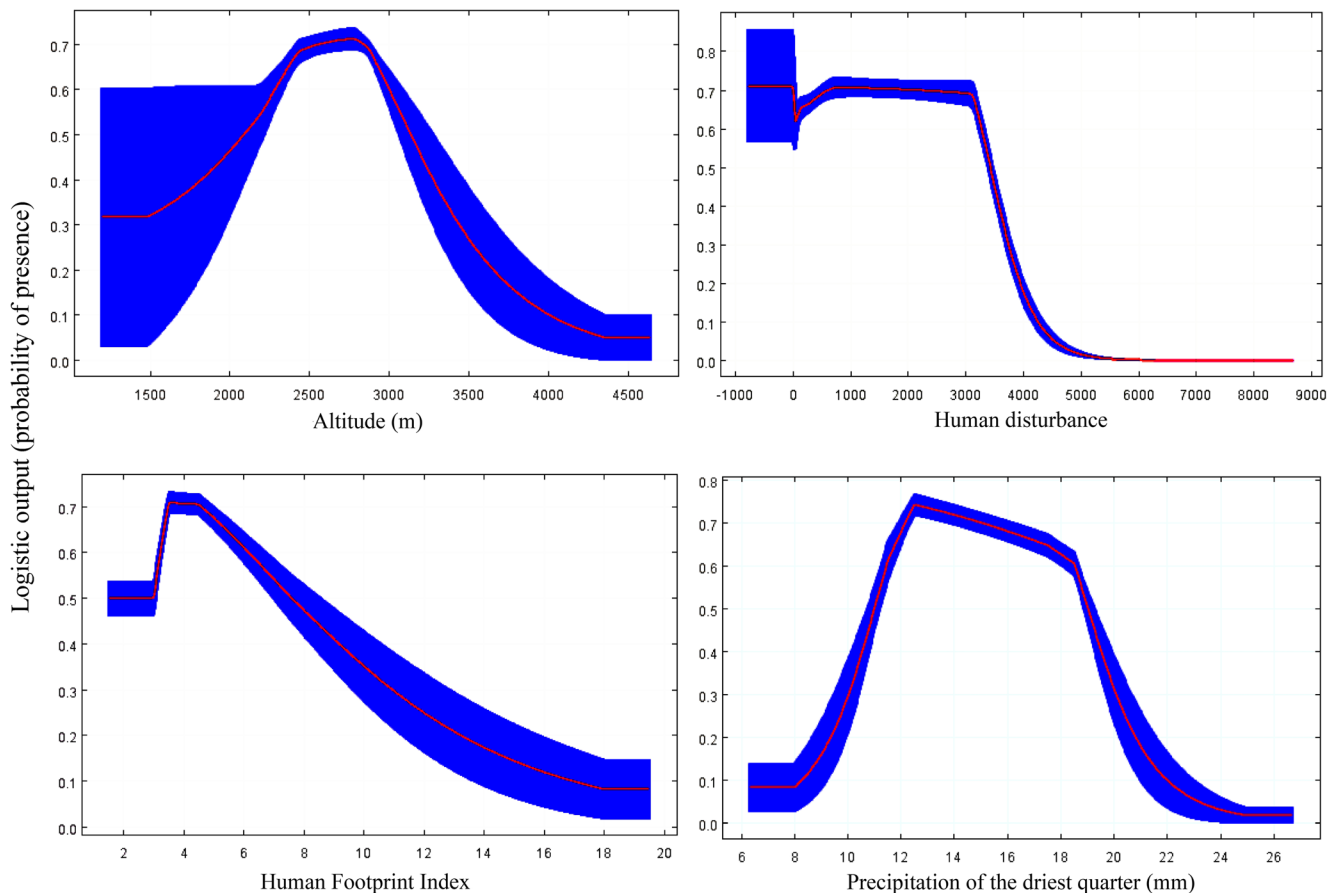


Fig. 2 Estimated responses curves of the ranked first four contribution variables in the MaxEnt model. Note: The mean response of the 10 replicate MaxEnt runs (red) and the mean \pm one standard deviation (blue, two shades for categorical variables)

Sichuan snub-nosed monkeys is found at high population density (Li et al. 2016; Wang et al. 2013).

According to our model prediction, altitude was predicted as the most important environmental variable contributing to the habitat suitability of Sichuan snub-nosed monkeys in the BNR. The predicted suitable habitats (HSI $>$ 0.2918) were confined to an altitude range of 1971–3198 m. This result was basically consistent with findings for Sichuan snub-nosed monkeys in other areas, such as the elevation range of 1400–3400 m in Qingmichuan Nature Reserve (Li et al. 2010) and the elevation range of 1750–3100 m for summer–autumn and 2200–2800 m for winter–spring in the Shennongjia District. The narrower altitude range in the Shennongjia District was most likely caused by human disturbance (Yan et al. 2018). An elevation range of 1700–2600 m was regarded as the most suitable habitat of *Rhinopithecus roxellana* in the Shennongjia District (Wang et al. 2018). In our study area, most human disturbances from the data of the 4th National Census of Giant Panda were found along the riverside (Fig. 4). The altitude range of those human activities shifted from 1973 to 3494 m, which largely overlapped the altitude of suitable habitat distribution (1971–3198 m). This overlap indicated that potential competition existed for

habitats between humans and Sichuan snub-nosed monkeys, although the Sichuan snub-nosed monkeys still share the habitats. In comparison with the current distribution of higher elevations, historical records of snub-nosed monkey occurrence (five snub-nosed monkey species, three of which, including the Sichuan snub-nosed monkeys, are endemic to China) were generally found in warmer and wetter areas and at lower elevation (Li et al. 2002; Nüchel et al. 2018). High rainfall and lower elevation areas were more suitable for agriculture and human settlement. No non-anthropogenic effects or high rainfall were observed to exclude snub-nosed monkey directly. Hence, snub-nosed monkey likely are currently restricted to areas with higher elevation and less accessible because these areas are more difficult for humans to utilize (Nüchel et al. 2018). Therefore, in terms of potential suitable altitude, the prospects are not optimistic for Sichuan snub-nosed monkeys in the BNR.

The bioclimatic variables were important for predicting habitat suitability via indirect influence through vegetation, food, and sleeping sites, etc. (Chu et al. 2018). The species may not respond directly to altitudinal gradients but rather to other abiotic environmental factors regulated by altitude, such as temperature and rainfall, and vegetation type (Hof et al.

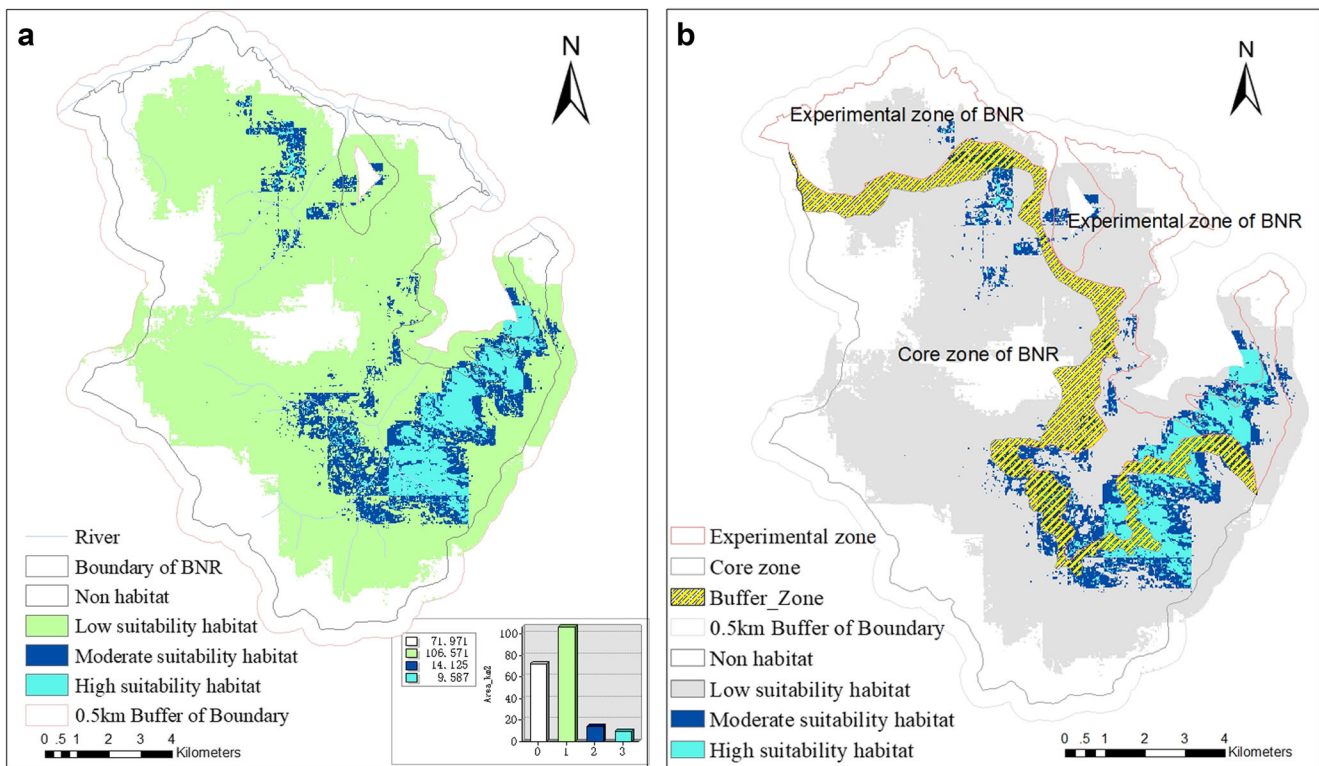


Fig. 3 Suitability of predicted potential habitat of *Rhinopithecus roxellana* in the BNR, Sichuan Province, China. Notes: BNR, Baihe Nature Reserve; non-habitat: HSI = 0–0.0015, areas not suitable as

habitat; low suitability habitat (HSI = 0.0015–0.2918); moderate suitability habitat (HSI = 0.2918–0.5); high suitability habitat (HSI > 0.5)

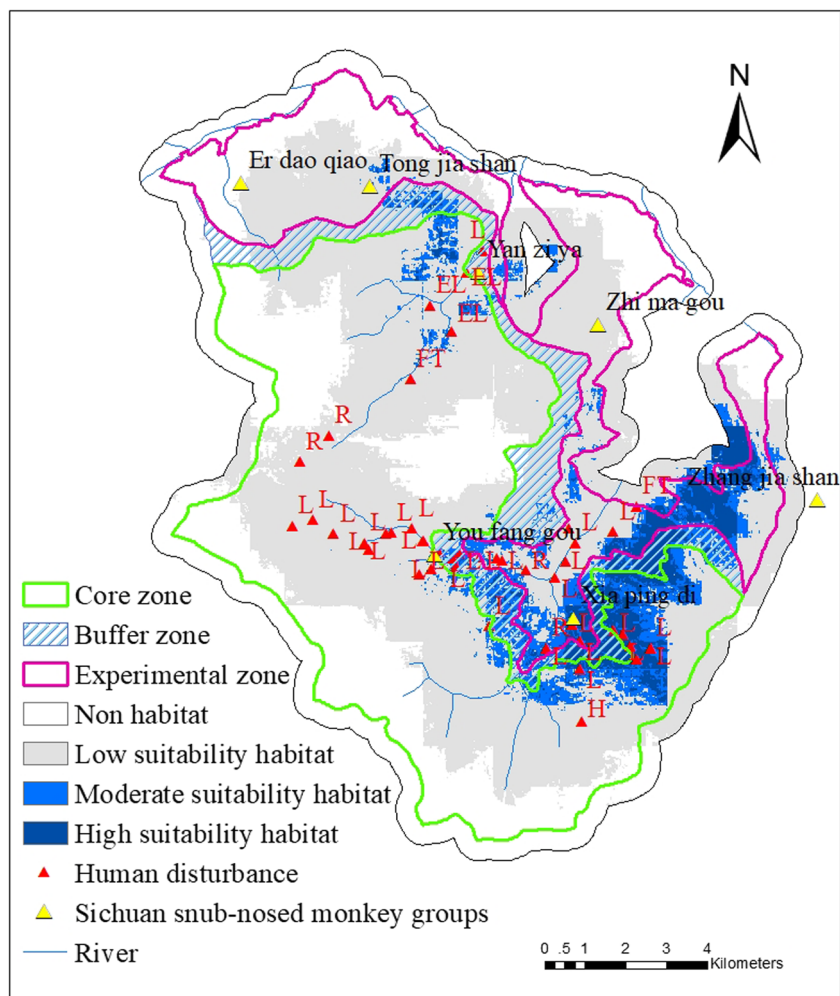
2012; Yan et al. 2018). Regarding those environmental biological variables contributing to our model result, precipitation of the driest or coldest quarter (Bio17 or Bio19) and min. temperature of the coldest month (Bio6) represented extreme climatic conditions. This prediction result was also consistent with findings of Jonas Nüchel et al. (2018), who suggested that the distribution of the snub-nosed monkey (five snub-nosed monkey (*Rhinopithecus*) species, of which three are endemic to China) is best explained by the variable mean temperature of the coldest and warmest quarter, annual precipitation, and precipitation during the driest quarter (Nüchel et al. 2018).

The two anthropogenic variables (HFI and human disturbance) were used in our model. The HFI and human disturbance variables individually represented cumulative human pressure that affected the environmental index and findings based on data collected during an authoritative species on-ground investigation for the 4th National Census of the Giant Panda. These two anthropogenic variables both indicate the importance of human influences on habitat selection of the Sichuan snub-nosed monkeys in the BNR. This result was largely consistent with some previous studies in which elevation and density of the human settlements were the most important factors for identifying suitable habitat (Liu et al. 2017; Wang et al. 2018; Yan et al. 2018; Zhao et al. 2018). A

negative relationship has been reported between the distribution of snub-nosed monkey and anthropogenic variables (Nüchel et al. 2018).

Over the past two millennia, population sizes and distributions of snub-nosed monkey, including Sichuan snub-nosed monkeys, have undergone sharp declines and range reductions (Wen 2009). Climate change and anthropogenic activities are regarded as the two major factors driving these changes (Wen and Wen 2006; Wen 2009). Human-induced habitat fragmentation may cause these species to be disjunct and genetically isolated (Zhao et al. 2018). Therefore, more attention to suitable habitat protection of Sichuan snub-nosed monkeys is urgently needed to stop anthropogenic disturbance, such as that caused by livestock, construction, electric power infrastructure, and access (roads and railways) in the BNR. Since human disturbances were the key environmental contributors to the HSI, we have a reason to believe that part of current low suitable habitats (the largest area with 52.7% in the BNR) could be, to some extent, converted into suitable habitat if human disturbances can be controlled or positively managed. This dilemma is caused by pressure for local socioeconomic development. However, at least 4 groups of Sichuan snub-nosed monkeys (of the 7 groups found, according to a report on Comprehensive Scientific Survey in Baihe Nature Reserve of Sichuan) (Zhang et al. 2013) are distributed in the low-

Fig. 4 Human disturbance and functional zoning in the BNR, Sichuan Province, China. Notes: BNR, Baihe Nature Reserve; human disturbance: from the 4th National Survey of Giant Panda; L, livestock; EL, electric line; R, roads; FT, fire trace; H, hunting



suitable habitats according to the predictions of our model. One group occurred outside the reserve border (Fig. 4). Therefore, the reduction in human disturbances must balance the needs of the local people with the need for the wildlife to survive. A study of the capacity for dispersal of the Sichuan snub-nosed monkeys of BNR is also recommended when assessing habitat quality and fragmentation adjacent reserves and areas in the Minshan Mountains to avoid eventual extinction of isolated monkey populations.

Notably, as a representative reserve, the BNR holds one of the largest groups of Sichuan snub-nosed monkeys with high population density, in the Minshan Mountains, with the Sichuan snub-nosed monkeys being the main protected species. However, with only 11.7% suitable habitats (HSI > 0.2918) found in the BNR, outlooks for survival of the Sichuan snub-nosed monkeys are not optimistic. These suitable habitats are mainly distributed in the core zone (36.1%), buffer zone (26.8%), and experimental zone (29.5%). The remaining habitats (7.6%) are distributed in the 0.5-km buffer zone from the reserve border. Apparently, the suitable habitat

areas within the core zone represented less area than those outside of the core zone. This result indicates that the current reserve zoning design is adverse for protecting suitable habitats of Sichuan snub-nosed monkeys from human disturbance. Furthermore, some suitable habitats adjacent to the reserve border were not protected under the BNR. Moreover, according to data from the 4th National Census of Giant Panda, human disturbance, especially from the main type—livestock—was found in the buffer zone, the experimental zone, and even in the core zone along the river (Fig. 4). Thus, we agreed with other authors that the designation of experimental zones is less effective in controlling livestock than in dealing with houses and roads (Hull et al. 2011). Such designations could lead to suitable habitat areas being further affected by human disturbance under the unreasonable zone classification of the BNR. Our findings highlight the need for appropriate adjustment to the current functions of the zones or the development of management strategies for better conservation. Our research may provide a reference method not only for evaluating species conservation effectiveness of current functional

zones but also for effective planning and designing of reserve zones in the future.

Our study focused on assessing habitat suitability at a time scale of 1 year. However, suitable habitats of Sichuan snub-nosed monkeys may vary somewhat among the different seasons. Suitable habitat during summer–autumn became unsuitable during winter–spring (Yan et al. 2018). A similar shift caused by temperature and food has also been reported for Fanjing Mountain Biosphere Reserve, Guizhou Province, China (Wu et al. 2004). Because our model was based on occurrence data from four seasons, to compare with one season of suitable habitat area being predicted using one season of occurrence data, our model would have given the larger range of habitats, which includes the suitable habitats of all seasons. Therefore, suitable habitats that change in the different seasons cannot be seen in our study, which is a limitation of this study. Further evaluations of seasonal changes of habitat suitability and key environmental contributors are needed in the future since seasonal data of vegetation and human disturbances are available.

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