Predicting the potential distribution change of the endangered Francois' langur (Trachypithecus francoisi) across its entire range in China under climate change

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Abstract

The Francois' langur (Trachypithecus francoisi) is a rare and endangered and the indicated primate species distributed in karst area in northern Vietnam and southwestern China. However, holistic conservation management has been hampered by research limited to specific nature reserves or sites. Building a comprehensive map of potential distribution for the Francois' langur is essential to advance conservation efforts and ensure coordinated management across regions. Here, we used 82 occurrence records of Francois' langur surveyed in Guangxi, Guizhou, and Chongqing from 2017 to 2020, along with 12 environmental variables to build the potential habitat model under current and future climate (for the periods 2021-2040, 2041-2060, 2061-2080, 2081-2100) using maximum entropy models (MaxEnt). Our results indicated that 1) precipitation- and temperature-associated bioclimatic variables made the greatest contributions to the distribution of Francois' langur, vegetation, water source and anthropogenic variables were also important factors affecting the distribution of Francois' langur; 2) 144207.44 km2 potential Francois' langur suitable habitat across the entire range in China was estimated by the current model, moderate- and high-suitability habitat accounted for only 23.76% (34265.96 km2) of the predicted suitable habitat and mainly distributed in southwest Guangxi, east of Chongqing and the border between Guizhou and Chongqing; 3) the suitable habitats of Francois' langur will dramatically contract under future climate change and the habitat centroid will move in the southeast direction with the shifting distance about 2.84km/year from current to 2100. The habitat prediction of Francois' langur and related drivers proposed in this work will provide essential insights for future conservation of this species, which is, not only existing distribution areas should be monitored and protected, but also conservation beyond existing habitats should be a focus of effort, especially future expansion areas, to ensure effective and timely protection under climate change and anthropogenic pressures.

1 INTRODUCTION

Climate change is one of the most significant contemporary threats to biodiversity worldwide (Isaac & Williams, 2007; Jing et al., 2022) and is already affecting species and ecosystems on a global scale, and these effects are projected to become more rapid and extensive (Field et al., 2014). In particular, many species that are already vulnerable, such as those with limited geographical range and/or restricted habitat requirements, could find their available habitat area reduced or eliminated (Hobbs et al., 2009). And these endangered species may be threatened by a combination of disturbances associated with climate change (such as temperature or precipitation) and ongoing anthropogenic activities (such as habitat fragmentation, pollution, urbanization) (Holling, 1973). For example, deforestation and forest degradation are threatening the survival of about half of all bamboo species worldwide, and climate change may present an additional significant threat, especially, many bamboo species provide essential food and shelter for wildlife species, including one of the most endangered species, the giant panda (Tuanmu et al., 2013). Many species are responding to changing environments by shifting their geographical ranges (Chen et al., 2011; Parmesan, 2006).

Francois' langur (*Trachypithecus francoisi*) is an endangered species endemic to the limestone forests of the tropical and subtropical zones of northern Vietnam and southwestern China (Nadler et al., 2004), with a current estimated global population of approximately 2,000 individuals (Wang et al., 2011; Zeng et al., 2013). In China, the distribution of Francois' langur was largely restricted to areas characterized by karst topography at altitudes of 120-1,800 m in Guangxi, Guizhou and Chongqing (Han et al., 2021). These areas have some unique features that differentiate them from mountain forests, such as steep cliffs, which cover about 10-20% of the area, lack of surface water (Huang, 2002), and relatively poor, but more diverse vegetation (Zhou et al., 2013). Due to forest loss, habitat destruction and fragmentation, some Francois' langur populations have been locally extirpated from some parts of their historic range (Li et al., 2007; Zeng et al., 2013). For instance, this species has become restricted to only five isolated sites in Guizhou (Hu et al., 2011). Although the Francois' langur was listed as endangered on the Red List of the International Union for Conservation of Nature (IUCN, 2020), and was considered a first-grade protected wildlife species in China (Niu et al., 2016; Wang et al., 2011; Wen et al., 2010), little was known about its habitat use and factors affecting habitat selection or association, except for some roost selection and behavioral ecology, moreover, previous studies were limited to specific nature reserves or locations (Hu et al., 2011; Li et al., 2020; Liu & Bhumpakphan, 2020; Zhou et al., 2013, 2018).

Climate change effects on distribution of species, particularly rare and endangered ones, have attracted increasing attention, and predicting how these species will react to climate change is a major current challenge in ecology. Some species, including plants (Mahmoodi et al., 2022; Pan et al., 2020; Wu et al., 2016; Zhang et al., 2020), freshwater fishes (Chu et al. 2005), mammals (Wilkening et al., 2019), coral reefs (Sill & Dawson, 2021) and invertebrates (Martín & Abellán, 2022), have been predicted distribution affected by the climate change with some model methods, such as bioclimatic prediction system (BioCLIM), random forest model (RFM) and maximum entropy models (MaxEnt) (Phillips et al., 2004, 2006). Among these models, MaxEnt is the most accurate and commonly used model (Bellard et al., 2018; Tsoar et al., 2007). The MaxEnt is an open-source software package for modeling species niches and distributions through the application of a machine-learning technique. It combines the current distribution data of the species with the background environmental variables, associates the known occurrences with a set of unique environmental conditions and then predicts the probability of presence for unknown locations via the use of multiple algorithms, and evaluates the importance of environmental variables using jackknife (Yin et al., 2022). Thus, MaxEnt can be applied to well predict the distribution of Francois' langur as well as habitat selection.

In this study, MaxEnt was applied to construct the potential distributions of Francois' langur. The primary objectives were as follows: (1) to model current potential distribution of the Francois' langur habitat across the entire range in China, (2)to explore the relationships among the potential distribution patterns and environments of the Francois' langur and determine relevant influencing variables, (3)to predict potential distribution in the future different periods, and (4)to evaluate how the climate change in the future affect the potential distribution of this species. Additionally, the study aims to provide suggestions and new insights for the biodiversity conservation of rare species.

2 MATERIAL AND METHODS

2.1 Occurrence data of Francois' langur

A total of 171 occurrence records of Francois' langur were obtained from our survey data. From 2017 to 2020, we conducted field surveys in all known distribution areas of the species in Guangxi, Guizhou, and Chongqing provinces, which are located in the southwest China with special ecological environment of karst ecosystem (Figure 1). We recorded the occurrence of species based on direct observations, fecal remains and infrared cameras. To avoid overfitting in the models (Li et al., 2022) and to prevent spatial auto-correlation of raster data, we used the SDM Toolbox v2.4 (spatially rarefy occurrence data) of ArcGIS 10.2 to ensure that there was only one occurrence record for the species in each 1 $\times$ 1 km resolution grid cell (Tu et al., 2021). After selection, 82 occurrence records of Francois' langur were identified for modelling analysis.

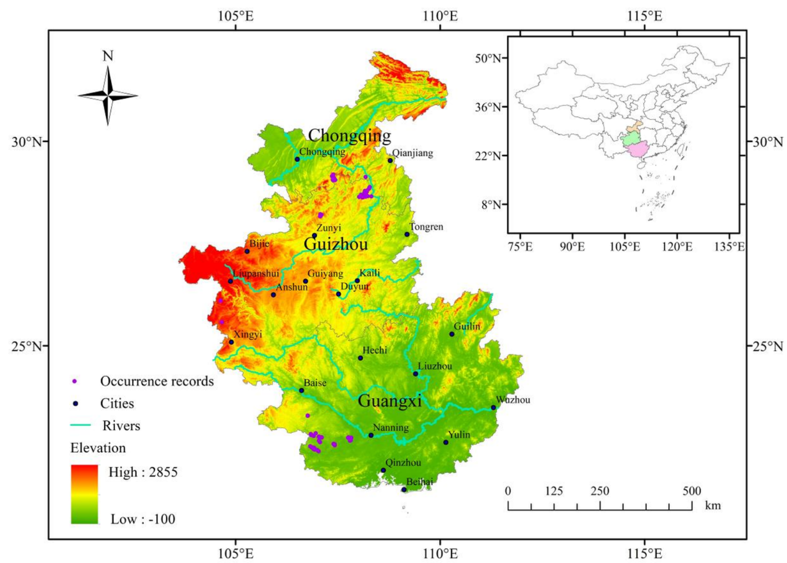

FIGURE 1 Study areas and occurrence records of Francois' langur in the present study

2.2 Environmental variables and data processing

A total of 26 environmental variables, including climate (19 bioclimatic variables), topography (elevation, slope, aspect), vegetation (Normalized Difference Vegetation Index (NDVI)), water sources (distance to river) and human activities (distance to road, distance to housing), were provisionally selected to build the initial models based on previous research on the habitat of Francois' langur.

19 grid-based bioclimatic variable data were downloaded from the WorldClim (www.worldclim.com) dataset. The current climate data were obtained with a spatial resolution of 30 arc-second (approximately $1km^2$) (Li et al., 2022). Future climate data were obtained from the Beijing Climate Center Climate System Model (BCC-CSM) under the Coupled Model Intercomparison Project Phase 6 (CMIP6) global climate model in four periods of 2021-2040, 2041-2060, 2061-2080, 2081-2100 with the shared socio-economic pathways 245 (SSP 245 for moderate scenario). These climatic variables represent annual trends (mean annual temperature and precipitation), seasonality (annual range of temperature and precipitation), and limiting environmental factors (temperature and precipitation of a certain quarter) (Hijmans et al., 2005; Thapa et al., 2018). As the 19 bioclimatic variables were all extended from temperature and precipitation based on different calculations, to avoid the effects of model overfitting caused by multicollinearity of these variables (Zhao et al., 2020), the 19 predictor climatic variables used in this study were tested using Pearson correlation analysis with the 'Cor' function in R 4.3.0 (Team, 2014) (Appendix 1), and variables with high correlation coefficients (| r |[?]0.8) and relatively low contribution rates in the initial models were removed to improve model predictability (Ji et al., 2020; Liu et al., 2022).

Three topography variables including elevation, slope and aspect were derived from Digital Elevation Model (DEM) data, which was obtained from geospatial data cloud (http://www.gscloud.cn) with a resolution of 30m using ArcGIS 10.2. NDVI was downloaded from the Resources Environment Data Center, Chinese Academy of Sciences (http://www.resdc.cn) with a resolution of 500m. River, road and housing data were obtained from the National Basic Geographic Information System, and the Euclidian distance tool of the ArcGIS 10.2 was used to calculate the distance between each grid cell layer and the nearest river, road and housing.

Consequently, five predictor climate variables were retained, namely, the Mean Diurnal Range (Mean of monthly (max temp-min temp)) (Bio2), Min Temperature of Coldest Month (Bio6), Temperature Annual Range (Bio7), Precipitation Seasonality (Coefficient of Variation) (Bio15), Precipitation of Coldest Quarter (Bio19), additionally, elevation, slope, aspect, NDVI, distance to river, distance to road, distance to housing were also used in the model prediction (Table 1). To facilitate spatial analysis within China, all variables selected for modelling were projected to WGS_1984_UTM_Zone_48N and resampled to 30 arc-second (approximately 1 km^2) using the spatial analysis tools in ArcGIS 10.2.

TABLE 1 Environmental variables included in the analysis and their percentage contribution and permutation importance in predicting the current distribution of Francois' langur

Variables	Description	Percent contribution (%)	Permutation importance (%)
Bio2 ()	Mean of monthly (max temp-min temp)	15.6	9.5
Bio6 ()	Min temperature of coldest month	20.4	7.1
Bio7 ()	Temperature annual range	7.4	15.3
Bio15 (mm)	Precipitation seasonality (coefficient of variation)	5.1	10.7
Bio19 (mm)	Precipitation of coldest quarter	14.9	34
Ele	Elevation	4.4	2.3
Slop	Slope	2.3	4.1
Asp	Aspect	0.7	0.3
NDVI	Normalized difference vegetation index	3.2	1.2
Dis_river	Distance to nearest river	2	2.5
Dis_road	Distance to nearest road	20.6	11.7
Dis_house	Distance to nearest housing	3.4	1.4

2.3 MaxEnt modelling

We used the open source software package MaxEnt v.3.4.4, which can be downloaded from http://biodiversity informatics.amnh.org/open_source/maxent/ (Sun et al., 2020). Francois' langur occurrence records and environmental variables were imported into MaxEnt. All models were set random seeds and used 75% of the record data as the training set and the remaining 25% as the test set with 10 replicates and bootstrap as replicated run type (Wang et al., 2020), while the number of modelling iterations was set at 10000 to allow the models to have adequate time for convergence (Young et al., 2011). The jackknife test procedure was used to evaluate the relative importance of each environmental variable. The response curves of environmental variables were used to test the correlation between the variables and the occurrence probability of Francois' langur. Logistic was selected to output results. The default options were used for the other parameters.

2.4 Model evaluation and validation

Receiver operating characteristic (ROC) curve analysis is an effective method for evaluating the accuracy of species distribution models (Liu et al., 2022; Wang et al., 2007). We used the area under the ROC curve (AUC), which is a threshold-independent discrimination metric that represents the probability that a random presence or absence is correctly assigned by the model (Phillips et al., 2006). The AUC values range from 0.5 to 1.0, with AUC $>$ 0.9 indicating excellent performance (Janitza et al., 2013).

The mean value of the 10 replicates from the model was taken as the distribution result, and the value represent habitat suitability index (HSI), which was between 0 and 1. The ASCII output file from MaxEnt was transformed into a raster layer, which was reclassified using the Spatial Analyst tool. At present, the classification of suitable habitat areas is largely based on experience, and there is no unified standard (Sun et al., 2020). We used the Jenks' natural breaks classification in ArcGIS combined with maximum training sensitivity plus specificity (Max TSS), balance training omission, predicted area and threshold value (average TPT) in the MaxEnt output to reclassify the data into four suitability areas for Francois' langur: high habitat suitability, moderate habitat suitability, low habitat suitability, and unsuitable habitat. The spatial analysis tool in ArcGIS 10.2 was used to calculate the areas and proportions of each suitability area.

2.5 Changes in potential distribution and centroid shifts

To construct the core distribution shifts and potential area changes under each future climate model, binary suitable or unsuitable maps were produced using ArcGIS 10.2 to analyse the changes in centroid and potential distributions based on the threshold of unsuitable area. By comparing the suitable/unsuitable potential distributions in different time periods, a total of four types of distribution changes were determined, namely, contraction, expansion, no change and no occupancy (Jose & Po, 2020; Liu et al., 2022). Moreover, because the potential distribution of Francois' langur was scattered and its outline was irregular, centroid shift analysis was conducted based on the potential distribution under different time periods using SDMtoolbox v2.4 (Brown, 2014) to visually show the changing trends of the potential core distribution of Francois' langur.

3 RESULTS

3.1 Model performance

Predicting suitable habitat for Francois' langur with MaxEnt resulted in high model performance. The AUC metric for the ten replicate runs was 0.973±0.006 (mean±SD), indicating a high level of predictive performance in the current period. For future climate models of the Francois' langur distribution, the obtained AUC values in 2021-2040, 2041-2060, 2061-2080, 2081-2100 were 0.977, 0.977, 0.974, 0.975, respectively, all of which were greater than the 0.9 AUC threshold, indicating good model performance.

3.2 Environmental variable contributions

The Jackknife analysis showed the contribution of each variable and their permutation importance in predicting the habitat of Francois' langur. The current prediction was mainly affected by Dis_res (20.6%), Bio6 (20.4%), Bio2 (15.6%), Bio19 (14.9%), Bio7 (7.4%) and Bio15 (5.1%) in decreasing percentage of their contribution towards the prediction model. All other variables contributed less than 16% (Table 1). When considering the permutation importance, Bio19 (34%), Bio7 (15.3%), Dis_road (11.7%), Bio15 (10.7%), Bio2 (9.5%) showed the highest percentage. The Jackknife test also revealed the importance of the variables when used in isolation as well as when each variable was excluded. The variables Bio6, Bio7, Bio2, Bio15, Bio19 registered the highest gain when the variables were evaluated individually, whereas the variables aspect and slop showed the negative gain (Figure 2).

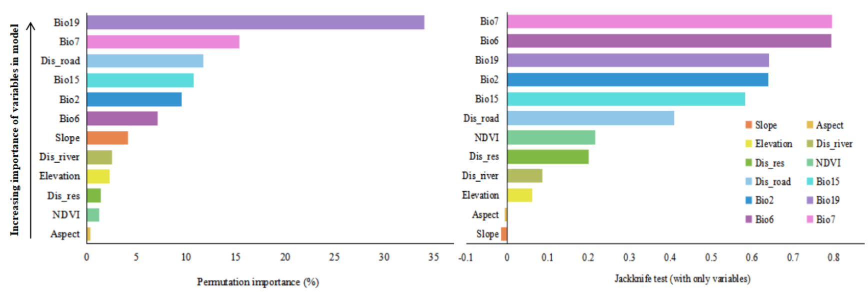

FIGURE 2 The relative predictive power of different environmental variables based on the jackknife test and permutation importance in MaxEnt for Francois' langur

3.3 Response of environmental variables

Species response curves revealed the relationship between environmental variables and the probability of species presence, indicating biological tolerances for target species and habitat preferences. Based on the acquired species response curves (Appendix 2), Francois' langur prefers habitats with mean diurnal range (mean of monthly (max temp-min temp)) (bio2) less than 6*C, min temperature of coldest month (bio6) of 9-11*C, temperature annual range (bio7) of 21-23*C, precipitation seasonality (coefficient of variation) (bio15) less than 65mm, precipitation of coldest quarter (bio19) from 70 to 80mm. Meanwhile, the probability of Francois' langur presence increases with increasing the distance to road in the range of 0-15km, distance to housing in the range of 0-30km and NDVI from 0 to 0.8. The probability of Francois' langur presence decreases as the distance to river increases.

3.4 Current potential distribution

A map of current habitat suitability for Francois' langur based on MaxEnt model predictions is shown in Figure 3; it is based on the 12 environmental variables and the current occurrence data of Francois' langur. All 82 occurrences of Francois' langur fell within the predicted suitable area, again indicating that the model performed well and produced excellent evaluation. The total suitable habitat area was predicted to be 144207.44 km^2 (29.09% of the study area), of which the highly suitable area (0.45-1) covered 13108.55 km^2 (9.09% of the total suitable area); the moderately suitable area (0.25-0.45) covered 21157.41 km^2 (14.67% of the total suitable area) and the poorly suitable area (0.04-0.25) covered 109941.49 km^2(76.24% of the total suitable area). The highly suitable areas were located in a small part of southwest Guangxi, east of Chongqing and on the border between Guizhou and Chongqing. The moderately suitable habitats were close to the highly suitable ones with different expansion. Less suitable areas, which were fragmented, were mainly located in Guizhou, some parts of Chongqing except the northern area and southwest of Guangxi (Figure 3).

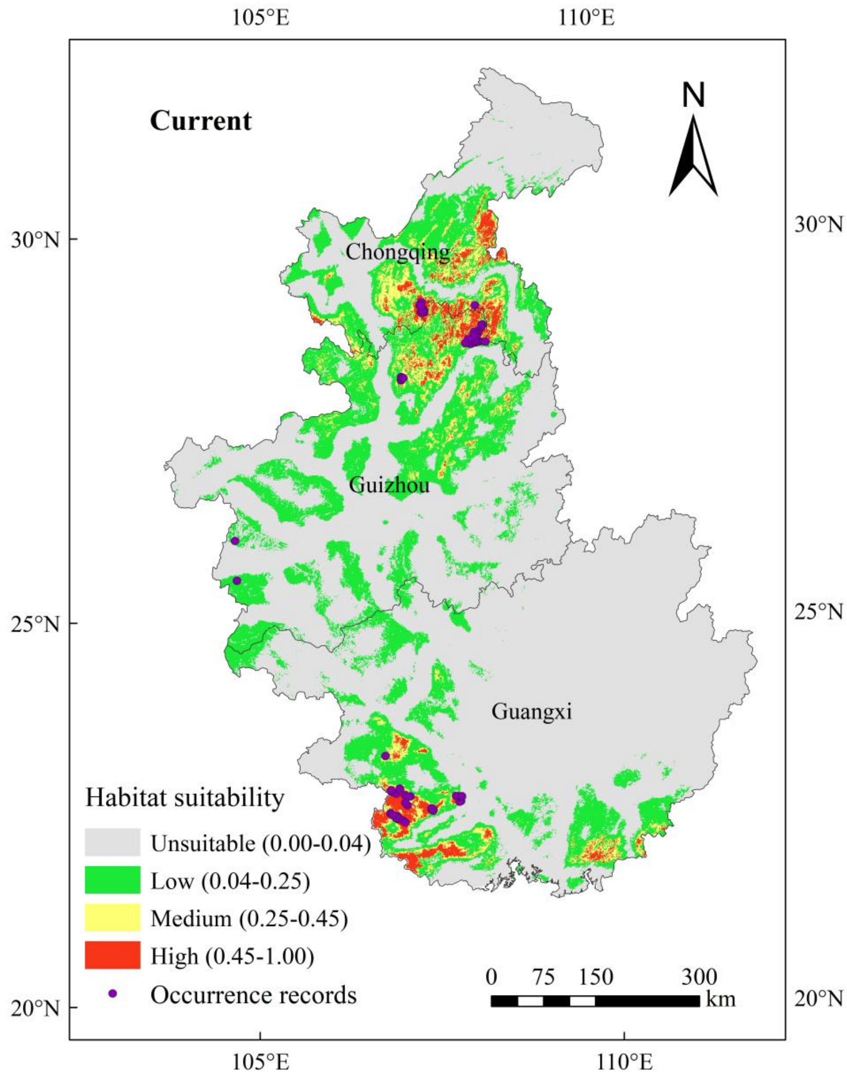

FIGURE 3 The current potential distribution map of Francois' langur

3.5 Future changes in suitable habitat

Under future climate conditions (2021-2040, 2041-2060, 2061-2080, and 2081-2100) in the SSP245 climate scenario, the area of the potential geographical distribution of Francois' langur was predicted to decrease compared to the current situation. Habitat suitability maps for future climate models are shown in Figure 4. By 2021-2040, the high potential suitable area for Francois' langur would decrease by 76.73%. Similarly, the moderately suitable area would decrease by 50.87% and the low suitable area would decrease by 46.22%. By 2041-2060, however, the highly, moderately and poorly suitable areas for Francois' langur would only decrease by 20.47%, 21.42% and 40.81% respectively, revealing an increase in the suitable area for Francois' langur compared to the period of 2021-2040. By 2061-2080, the high suitable area for Francois' langur would decrease by 83.46%, the medium suitable area would decrease by 54.56% and the low suitable area would decrease by 47.39%. A similar pattern was also confirmed for 2081-2100, where the highly, moderately and poorly suitable areas for Francois' langur would decrease by 76.85%, 61.73% and 51.62% respectively (Figure 5).

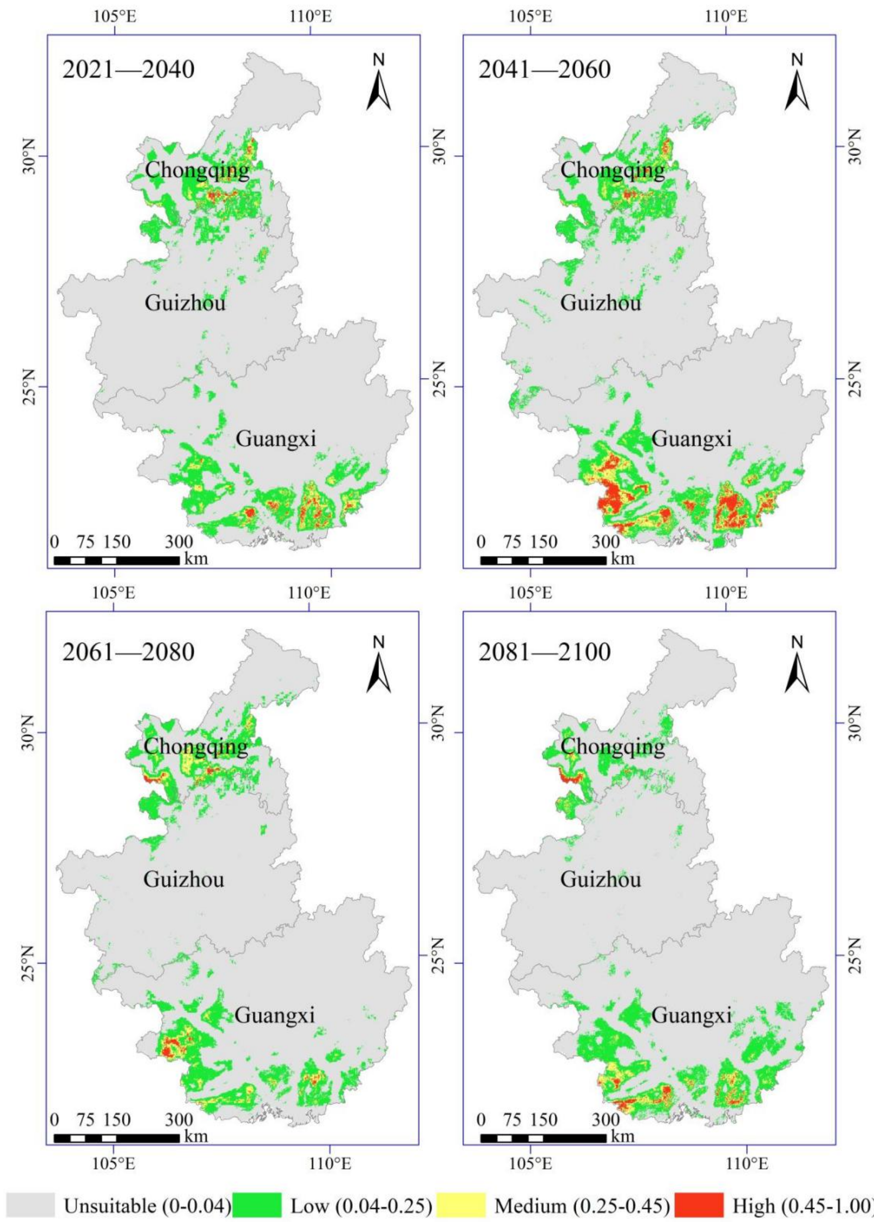

FIGURE 4 Predicted future distributions of periods 2021-2040, 2041-2060, 2061-2080 and 2081-2100 for Francois' langur

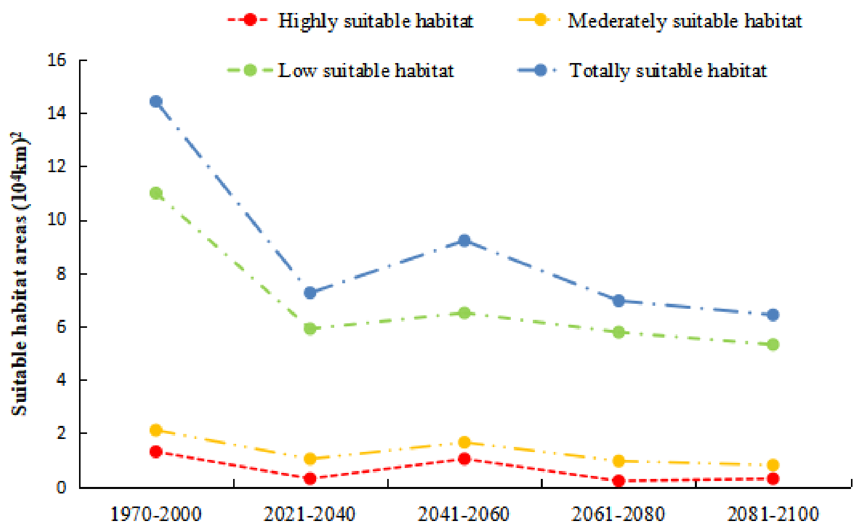

FIGURE 5 Suitable habitat areas of Francois' langur in all different periods

3.6 The centroid distribution shifts

The change in the potential distribution of Francois' langur from 2021 to 2100 is shown in Figure 6. These models predicted that future global change would promote the contraction of the potentially suitable habitats for Francois' langur, with the total suitable habitats decreasing. In particular, most of the suitable habitat in Chongqing and Guizhou would contract sharply. Francois' langur would expand slightly in southwestern Guangxi and western Chongqing. The potential core distribution of Francois' langur would move southeast from southern Guizhou to northern Guangxi under future climate conditions. Furthermore, the distance of the centroid shifts were 109.43km, 145.99km, 82.26km, and 227.09km in 2021-2040, 2041-2060, 2061-2080, and 2081-2100, respectively, compared to the current (Figure 7).

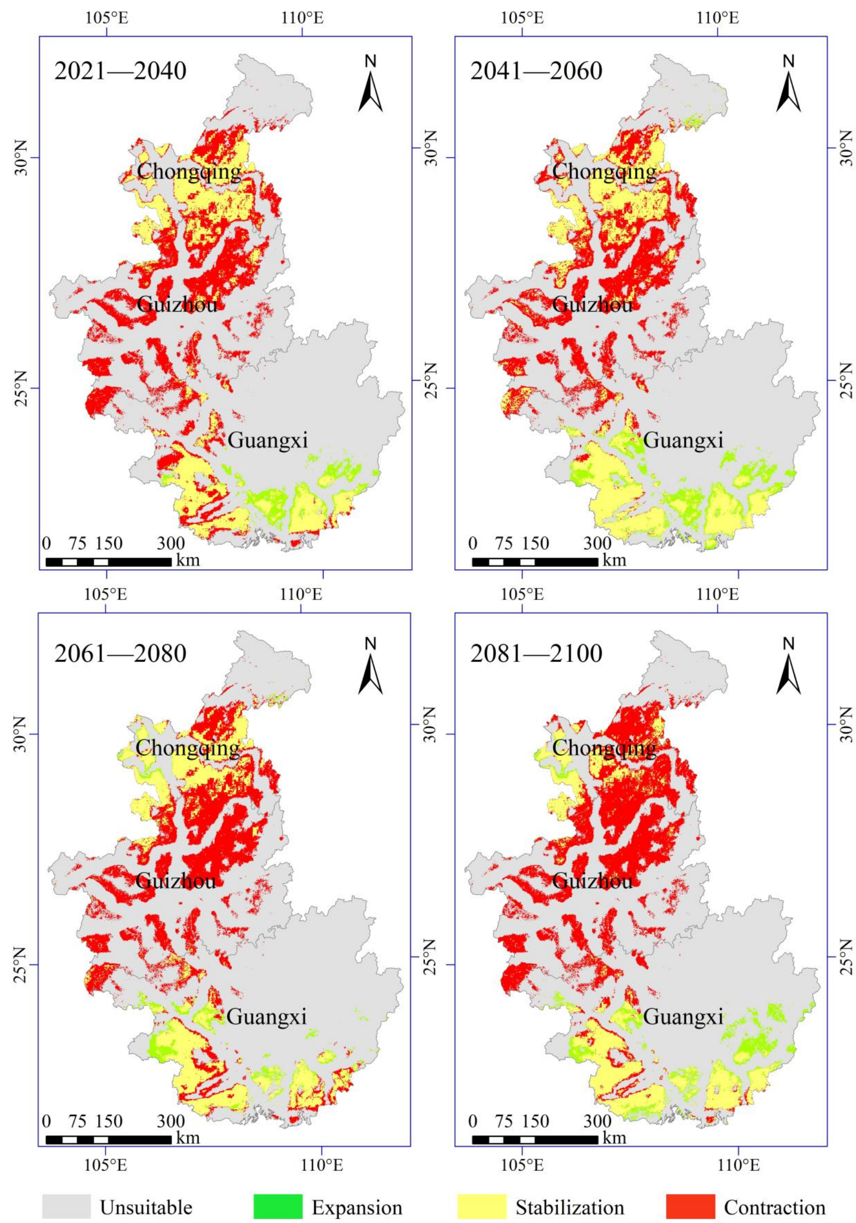

FIGURE 6 Potential distribution changes in the future (2021-2040, 2041-2060, 2061-2080, 2081-2100) compared to current for Francois' langur

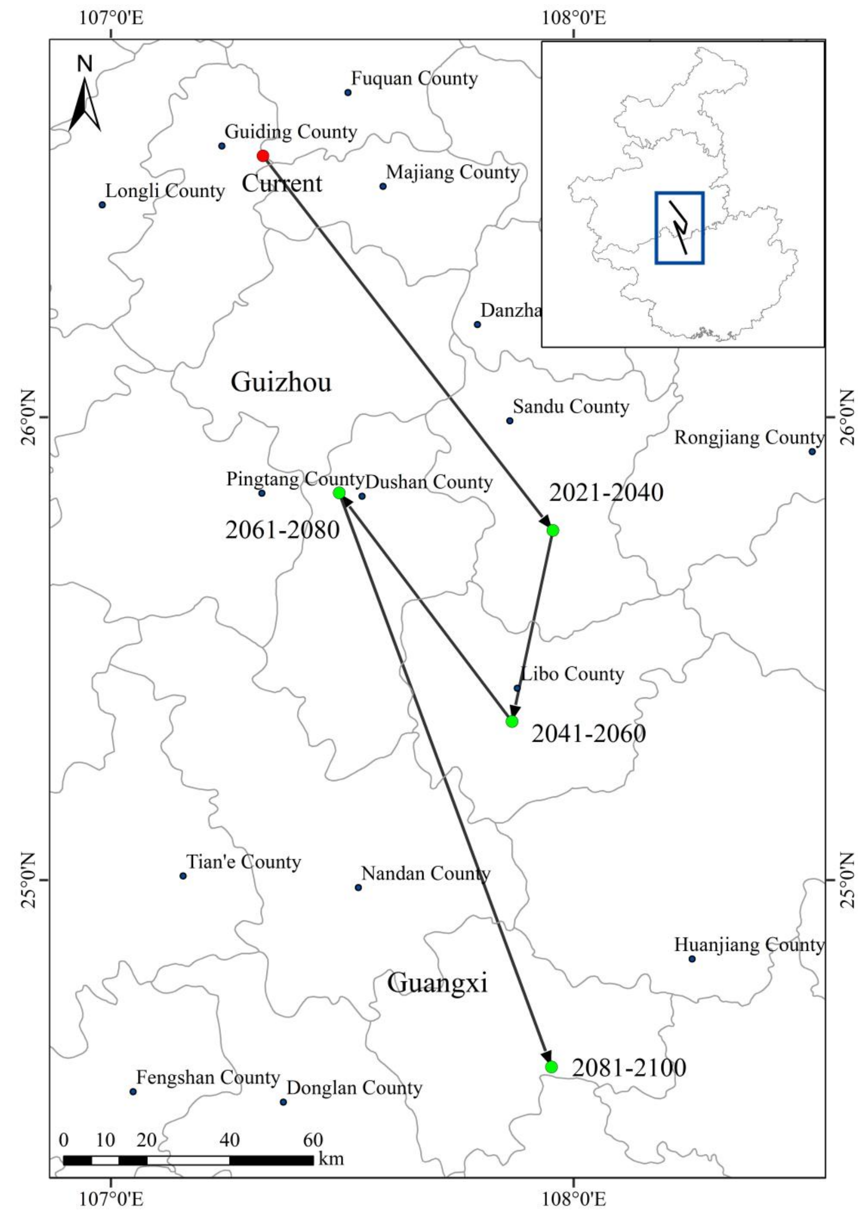

FIGURE 7 Centroid change in the potential distribution of Francois' langur from 2021 to 2100. The distance of the centroid shifts were 109.43km, 145.99km, 82.26km, and 227.09km in 2021-2040, 2041-2060, 2061-2080, and 2081-2100, respectively, compared to the current.

4 DISCUSSION

4.1 Influence of environmental variables

In the field of Francois' langur ecology, habitat selection and use have been an important research topic for researchers. The factors of habitat selection have been divided into biological, geographical, and anthropogenic factors (Han et al., 2023). Our results suggested that bioclimatic variables made the largest contribution to the distribution of Francois' langur, vegetation, water source and anthropogenic variables were also important factors influencing the distribution of Francois' langur. As demonstrated by numerous previous studies,, the distribution of Francois' langur was largely restricted to areas characterized by karst topography, limestone cliffs, and caves with mixed conifer-broadleaf forests as they provided quality food resources and cover for predator avoidance (Wang et al., 2011; Wen et al., 2010; Zeng et al., 2013). Additionally, its distribution was concurrently influenced by various factors, including temperature, precipitation and vegetation (Enstam & Isbell, 2004; Han et al., 2011).

We used the MaxEnt model to construct patterns of habitat suitability for the Francois' langur in China. According to our model prediction, temperature-associated bioclimatic variables were of great importance in predicting habitat suitability for Francois' langur, while precipitation-associated bioclimatic variables were the most important habitat predictor for Francois' langur. Numerous studies have shown that in recent years the frequency of precipitation in southwest China has decreased, while the intensity, total precipitation, and occurrence of extreme rainstorm have increased (Yan et al., 2023; Lu et al., 2022; Ding, 2014; Feng et al., 2012). As a result, river water level have risen, and the original valley area with food and habitat caves for Francois' langur have been flooded, posing a direct threat to the living habitat of Francois' langur. In addition, temperature and precipitation have a great influence on the growth rates of plant species, and fruits, seeds, and especially young leaves are the main food of Francois' langur. Therefore, temperature and precipitation indirectly determined the distribution of Francois' langur by affecting the availability of potential food resources (Huang et al., 2008; Zhou et al., 2011; Zhou et al., 2006). Based on the response curves in our study, the most suitable distribution of Francois' langur exhibited the following temperature characteristics: temperature annual range of 21-23, mean of monthly temperature range (max temp-min temp) of < 6, and minimum temperature of coldest month of 9-11. The precipitation seasonality (coefficient of variation) and precipitation of coldest quarter of Francois' langur's most suitable distribution were < 65 mm and 70-80 mm, respectively. This result is consistent with the climatic conditions of the extant range of Francois' langur (Han & Hu, 2010; Li et al., 2019; Niu et al., 2016).

Vegetation-related variable, the normalized difference vegetation index, was another important variable. Francois' langur prefers areas with relatively high NDVI, which is consistent with Han et al. (2023), Niu et al. (2016), Zeng et al. (2013) and Zeng (2011), who showed that Francois' langur habitat was mainly in the valley areas on both sides of the rivers, covered by evergreen broad-leaf forests with higher tree canopy density and vegetation cover, which provided availability of better food resources and suitable cover for predator avoidance. Meanwhile, distance to rivers and altitude were the less important variables. Previous studies have indicated that Francois' langur was primarily distributed in valleys characterized by dominant evergreen broadleaf forests. These areas offer abundant food and water sources, and culverts and karst caves along rivers provide enough suitable sleeping sites for Francois' langur (Han et al., 2011; Hu, 2011; Wang et al., 2011). In addition, the elevation of Francois' langur distribution ranges from 300 to 1800m, with seasonal changes in climate and food (Li et al., 2019; Li et al., 2015).

For the anthropogenic variables, distance to roads (Including railways) was found to be the more important variable compared to distance to housing. Most previous studies have assessed the impact of linear infrastructure on wild animals and have typically shown that distribution decreases as road density increases (Céline Clauzel et al., 2013; Clauzel et al., 2015). Roads are likely to act as barriers to wildlife movement (Coffin, 2007; Zhu et al., 2011). Therefore, roads may have negative impact on the activity and distribution of Francois' langur. In this study, distance to roads was positively correlated with the occurrence probability of Francois' langur. However, distance to housing had a limited influence on the distribution prediction of Francois' langur. This finding aligns with Han et al. (2023), Zeng et al. (2013), Wang et al. (2011), who reported that Francois' langur has become accustomed to human disturbances, especially, crops grown on agricultural land may supply the food resources for Francois' langurs (Han et al., 2023).

4.2 Characteristics of the current potential distribution

Our model estimated potential suitable habitat of 144207.44 km^2 for Francois' langur across the range, based on the Max TSS and average TPT thresholds in the MaxEnt output. Hu et al. (2011) showed that Francois' langur was restricted to only five isolated sites (Dashahe, Baiqing, Mayanghe, Kuankuoshui and Yezhong) with a total area of about 912 km^2 in Guizhou.Chen (2006) estimated potential Francois' langur habitat in Guangxi at approximately 3216.23 km^2. Han and Hu (2010) confirmed that the distribution area of Francois' langur in Chongqing Jinfo Mountain was about 50 km^2. Our model predicted the largest proportion of Francois' langur habitat in China than the total habitat in three provinces (Guizhou, Guangxi, and Chongqing) in previous studies, which were based on survey records or estimates at a small scale, such as one or more nature reserves. Importantly, our model analysis was based on a machine-learning algorithm, species records from the entire range in China, and a set of environmental variables including climatic factors. Furthermore, our model prediction for the Francois' langur was based on a larger and more comprehensive scale than prior methods (Chen, 2006; Han et al., 2011, 2023; Hu et al., 2011).

Our model predicted a total of 34265.96 km^2 of moderate- and high-suitability habitat for Francois' langur, which only accounted for 23.76% of predicted suitable habitat. The moderate- and high-suitability habitats, primarily located in southwest Guangxi, east of Chongqing and the Guizhou-Chongqing border, was nearly 10 times the area of previous surveys (Chen, 2006; Han & Hu, 2010; Hu et al., 2011). However, the low suitable habitat was distributed over a larger area as fragmentation, which is consistent with Guan et al. (2022) and Niu et al. (2016), who suggested that the Francois' langur habitats presented severe fragmentation, complex patch shape, weak patch aggregation, and decentralization, and typically showed that habitat area decreased and further fragmented with increasing human activities. The current potential distribution in our study basically covered and was larger than the historical distribution areas of Francois' langur recorded in "A guide to the mammals of China" (Smith et al., 2010) and "China' s mammal diversity and geographic distribution" (Jiang et al., 2015). Our results can provide a scientific reference for further field survey on the distribution of Francois' langur in China.

4.3 Distribution change in the future

Our results indicate that, compared to the current potential habitat, the suitable habitats of Francois' langur will decrease in all future periods under climate change. In the future climate prediction, the temperature in southwest China are expected to continue increasing, and show a more obvious difference in the increase between the northern and southern regions (Yang et al., 2022; Zhang, 2020).Climate change will lead to changes in species habitat, such as increased precipitation and more extreme precipitation events (Feng et al., 2023; Yue, 2022). From 2021 to 2100, the area of suitable habitat will greatly contracted, especially in the medium- and high-suitability areas along the border between Guizhou and Chongqing. Moreover, most of the patchy areas of low-suitability will cease to exist. The centroid of habitat shifted to the southeast at a rate of approximately 2.84km/year from current to 2100. Previous studies have indicated that changes in annual precipitation, annual mean temperature, precipitation and temperature seasonality, as well as land use/ land cover changes, could reduce suitable habitat for the large mammals such as Asiatic black bear (*Ursus thibetanus*), Asian elephant (*Elephas maximus*) and western hoolock gibbon (*Hoolock hoolock*), and thus increase their extinction risk (Deb, 2016). In addition, our results are consistent with the description that primates and other large mammals are highly dependent on a complete forest ecosystem for their food and security requirements, and habitat fragmentation will accelerate local population extinctions (Guan et al., 2022). For Francois' langur, habitat fragmentation caused by climate change and anthropogenic disturbance would be the most important factor in changing the distribution of this species.

4.4 Conservation recommendations

Our results showed that the current predicted habitats of Francois' langur were over more than the history areas, but the distribution habitats of Francois' langur would be threatened to contract and fragment dramatically in the future. We suggest to expand the survey range of their habitat, reduce human disturbance and enhance habitat connectivity by establishing ecological corridor especially the border of Chongqing and Guizhou and further protection on these areas. Moreover, conservation of the Francois' langur should not be based only on the existing distribution areas, but should also focus on conservation beyond existing habitats, especially the expansion areas in the study, which should be considered to join the national programme as protected areas.

AUTHOR CONTRIBUTIONS

Yaqiong Wan: Conceptualization (lead); data curation (equal); formal analysis (equal); writing - original draft (lead); writing - review and editing (equal). **Luanxin Li:** Data curation (equal); writing - original draft (equal). **Jiang Zhou:** Investigation (equal); writing - review and editing (equal). **Yue Ma:** Data curation (equal); writing - original draft (equal). **Yanjing Zhang:** data curation (equal); methodology (equal). **Yan Liu:**writing - review and editing (equal). **Jiaqi Li:** Supervision (equal); writing - review and editing (equal). **Wei Liu:**Supervision (equal); writing - review and editing (equal).

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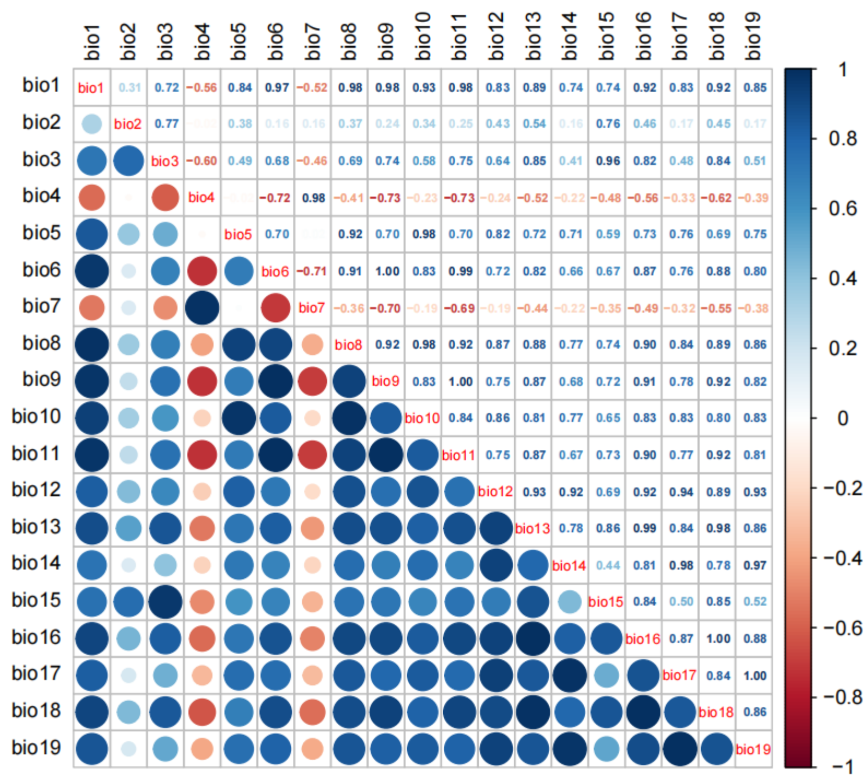
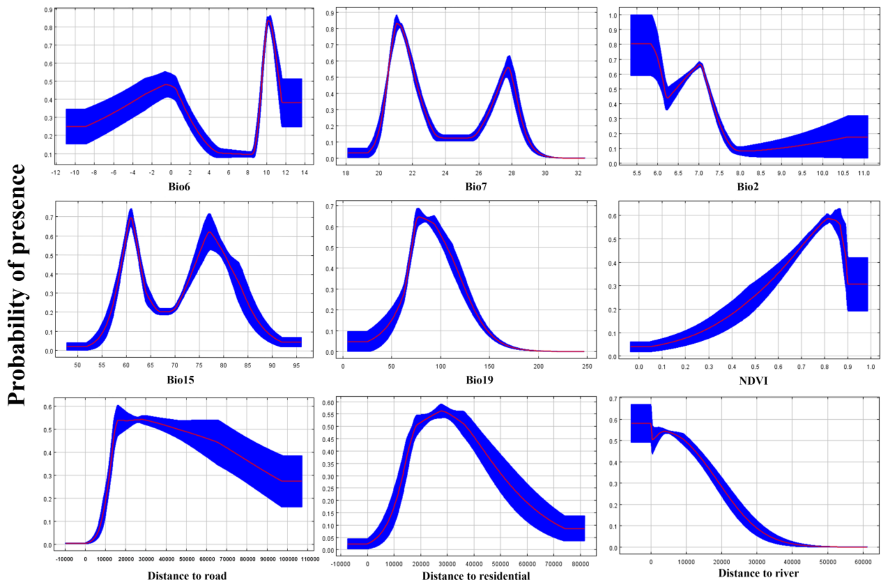
APPENDIXES

APPENDIX 1: Pearson' s correlation coefficients between 19 climate variables, and intensity of color represents greater positive (blue) or negative correlation (orange).



APPENDIX 2: Response curves of environmental variables in the potential distribution model of Francois' langur. Note: The red curves represent average value over 10 replicate runs, while blue margins represented ± SD calculated for 10 replicates



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