



Original Article

## Impacts of Climate Change on the Distribution of the Red-Shanked Douc (*Pygathrix nemaeus*)

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**Abstract:** The Red-shanked Douc (*Pygathrix nemaeus*) is an endangered primate found only in a small region of Indochina, and its populations is believed to have declined at most known sites in recent decades. While the most serious threats to the Doucs to date are illegal hunting and habitat destruction, the potential impacts of climate change on this species are still poorly understood. In this study, we employ MaxEnt, a widely used species distribution modeling method, to predict climatically suitable habitat for *P. nemaeus* at present, and then project the optimal model using a range of future climate change scenarios to understand the possible shifts in response to climate change over the entire range of the Red-shanked Douc. The model results in most climate change scenarios and timeframes show that *P. nemaeus* may experience significant habitat loss and fragmentation within its current range as a consequence of suitable habitat contraction. The climatically stable refugia for the Red-shanked Douc are predicted to consist of protected areas along the Annamite Range that runs between Vietnam and Laos, and we suggest this region to be the focus of the Doucs' conservation effort in the future. To mitigate climate-related risks for the Red-shanked Douc, future cooperation initiatives between Vietnam and Laos' governmental institutions and conservation organizations will be crucial in conserving the remaining habitat of this endangered primate.

**Keywords:** MaxEnt, Red-shanked Douc, Refugia, Species Distribution Modeling, Transboundary conservation.

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## 1. Introduction

The Red-shanked Douc (*Pygathrix nemaeus*) is an endangered primate found in Vietnam, Laos, and Cambodia [1]. The largest populations of the Red-shanked Douc is reported to be in Laos [2], while the Doucs's record in Cambodia is in a restricted region close to the border with Vietnam and Laos [3]. In Vietnam, the Douc is documented to be from Pu Mat National Park, Nghe An to Chu Mom Ray National Park, Kon Tum [4]. *P. nemaeus* is classified as Critically Endangered by IUCN throughout its entire range [1], and currently hunting poses the most serious threat to the Doucs [5]. However, in Vietnam, for the last decades habitat destruction has also been considered as the main threat for the species due to the rapid growth of Vietnam population and economy [6]. There has been no quantitative assessment on the total distribution area of the Red-shanked Douc, but based on extensive field surveys and trade records since the early 1990s, *P. nemaeus* is estimated to have experienced a marked loss of about 50 – 80% of its available habitats [4, 5].

In recent years, the impacts of climate change on biodiversity have raised concerns over extinction risks on many taxa [7, 8], especially for Vietnamese primates [9, 10]. However, the potential impacts of climate change on the Red-shanked Douc and its current habitat have still remained poorly understood. Therefore, *P. nemaeus* will stand a better chance of survival if prioritized conservation efforts will be implemented at climatically stable habitats.

Maximum Entropy (MaxEnt) is a relatively new species distribution modeling approach that can provide insights into patterns and processes in ecology, biodiversity, and conservation [11]. MaxEnt has been used in identifying of suitable habitats for endangered species [12]; determining of conservation priority areas [9]; and assessing of the impacts of climate change on species distribution [10]. Hence, in this paper, we reviewed literature and conducted field surveys in key protected areas of the Central

Annamite Landscape to gather occurrence records of *P. nemaeus*. We then used MaxEnt to predict its current potential distribution using collated distribution data and bioclimate variables, and projected the optimal model using different future climate scenarios to assess the impacts of climate change on the Doucs. Based on the results, we provide recommendations for priority sites to better protect this endangered species.

## 2. Methods

### 2.1. Literature Review

To gather occurrence records, we reviewed the available records of the Red-shanked Douc by searching main biodiversity and research databases using combinations of following keywords: “*Pygathrix nemaeus*”, “*Pygathrix*”, “Red-shanked Douc”, “Douc”, “Chà vá”, “Chà vá chân nâu”, and “Voọc ngũ sắc”. Field notes and reports from research and conservation institutions were also screened. The collected records were then checked following standard protocols [13] to avoid inaccuracies.

### 2.2. Field Surveys

We then used collated records from previous step to identify sites that may still support significant Red-shanked Douc populations. As a result, in 2022 and 2023, we conducted field surveys in following protected areas: Vu Quang and Ke Go (Ha Tinh); Phong Nha – Ke Bang and Dong Chau – Khe Nuoc Trong (Quang Binh); Bac Huong Hoa and Dakrong (Quang Tri); Son Tra (Da Nang); Song Thanh, Elephant Species Conservation, and Quang Nam Ngoc Linh (Quang Nam); and Kon Tum Ngoc Linh (Kon Tum). In each site, the field survey lasted from 5-12 days, using protocol suggested by Nguyen et al., 2022 [14]. All field observations of the Red-shanked Douc were then incorporated in the dataset from literature review to create a comprehensive list of known records for *P. nemaeus* (Figure 1).

### 2.3. Data Pre-processing and Model Tuning

To address spatial autocorrelation, we used the *spThin* package [15] in R [16] to thin out localities within 10 km distance [17], creating the final set of 122 localities. We constructed the model using MaxEnt version 3.4.4 [11], with 19 bioclimatic variables at 30 arc-second resolution from WorldClim 2.1 [18], and restricted the extent by using two degree buffer around minimum convex polygon of the occurrence localities [19]. Those variables included BIO1: Annual Mean Temperature; BIO2: Mean Diurnal Range; BIO3: Isothermality; BIO4: Temperature Seasonality; BIO5: Max Temperature of Warmest Month; BIO6: Min Temperature of Coldest Month; BIO7:

Temperature Annual Range; BIO8: Mean Temperature of Wettest Quarter; BIO9: Mean Temperature of Driest Quarter; BIO10: Mean Temperature of Warmest Quarter; BIO11: Mean Temperature of Coldest Quarter; BIO12: Annual Precipitation; BIO13: Precipitation of Wettest Month; BIO14: Precipitation of Driest Month; BIO15: Precipitation Seasonality; BIO16: Precipitation of Wettest Quarter; BIO17: Precipitation of Driest Quarter; BIO18: Precipitation of Warmest Quarter; and BIO19: Precipitation of Coldest Quarter.

However, as MaxEnt has the tendency to produce overfitting models [20], we performed additional steps of tuning decisions, following protocol listed by Nguyen et al., 2022 [12], with ENMeval package [21].

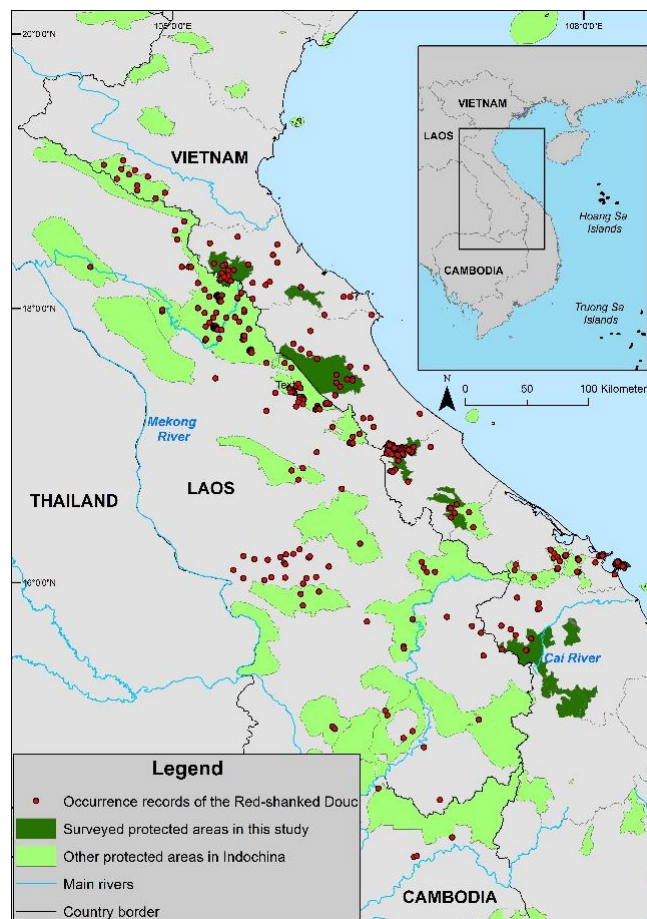


Figure 1. Collated localities from literature and our field surveys for the Red-shanked Douc.

## 2.4. Model Selection and Future Projections

To assess model performance, we used the 10% omission rate threshold to select models that showed the least overfitting. Of this subset, we chose the models with the highest Area Under the Curve (AUC) values. Final models were then compared using the Akaike information criterion, which balances complexity with model fitness [22]. We used the default setting, which is cloglog, for model output, producing model result raster with values ranging between 0 and 1. The value in a particular locality is the probability of the species presence at that location [11]. After selecting the optimal model, we used the 10% training presence threshold to classify suitable areas for the Red-shanked Douc [17]. The optimal model was then projected to three future periods, 2041 – 2060, 2061 – 2080, and 2080 – 2100 using four global climate models (GCM), including ACCESS-CM2, MIROC6, CNRM-ESM2-1, and GISS-E2-1-H [23-27]. For each GCM and timeframe, all four available scenarios that are based on different shared socioeconomic pathways (SSP), including SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5, were included, ranging from SSP1-2.6, which assumes there will be a steady transformation toward environmental-friendly approaches on international scale, to SSP5-8.5, which assumes an ever-increasing pressure for heightened uses of fossil fuels and resource-intensive economic sectors worldwide [28]. The resulting maps for the same GCM in the same timeframe were then summed to create presence probability maps for the Red-shanked Douc.

## 3. Results and Discussions

### 3.1. Field Survey and Distribution Record Results

Our field surveys in 2022 and 2023 recorded the Red-shanked Douc in following protected areas: Vu Quang (Ha Tinh); Phong Nha – Ke Bang and Dong Chau – Khe Nuoc Trong (Quang Binh); Bac Huong Hoa and Dakrong (Quang

Tri); Son Tra (Da Nang); and Song Thanh (Quang Nam). However, we did not record *P. nemaeus* in Ke Go (Ha Tinh); Elephant Species Conservation and Quang Nam Ngoc Linh (Quang Nam); and Kon Tum Ngoc Linh (Kon Tum). All collated records of the species are illustrated in Figure 1.

### 3.2. Species Distribution Modelling Results and Climate Change Assessment

For the current conditions, MaxEnt models showed reasonable prediction power for the distribution of *P. nemaeus*, with the average AUC values > 0.84. The best model had the regularization multiplier value of 3.5 and a combination of linear and quadratic feature classes, and AUC value of 0.864. However, the control parameters for the optimal model also mean that the final model is quite flexible, which might result in overprediction. The final model should therefore be carefully interpreted, as a bioclimatic-based model does not account for other possible interactions such as natural dispersal barriers, adverse species interactions, or human impacts such as hunting pressure and so on (Figure 2). Based on the results, the available habitat area for the Red-shanked Douc in the current climate conditions is approximately 140,000 km<sup>2</sup>. The optimal model covered all known records of the Red-shanked Douc, but also over-extend in the southern limit near the coast of Quang Ngai and Binh Dinh.

Future model projections demonstrate potential shifts in the Red-shanked Douc distribution under a range of climate change scenarios. Changes in the distribution are illustrated in Figure 3, which displays probability density maps, ranked in graduated color scheme, showing the likelihood of the Douc's presence calculated from a large ensemble. Each ensemble is a combination of all four scenarios for one timeframe from one GCM. The highest value (100%) means that area was estimated to be suitable for the Doucs in all scenarios. Although those models' predictions differ insignificantly on the overall locations of changes, there appear two trends for *P. nemaeus*'

range shift in the future. The first trend shows that the distribution is likely to shrink compared to the current predicted range, with the average decrease of approximately 15.5% (standard deviation  $\pm 13.9\%$ ) in terms of total area, even in the best-case scenario (Table 1). Also, for different timeframes, all four GCMs suggested that range contractions of the Doucs will be

highest in 2081 – 2100 period (approximately 38,000 km<sup>2</sup> decrease), following by 2061 – 2080 period (about 23,000 km<sup>2</sup> decrease), and the lowest ones are in 2041 – 2060 period (nearly 17,000 km<sup>2</sup> decrease). Therefore, in long-term, climate change will likely become an escalating threat to the Red-shanked Douc.

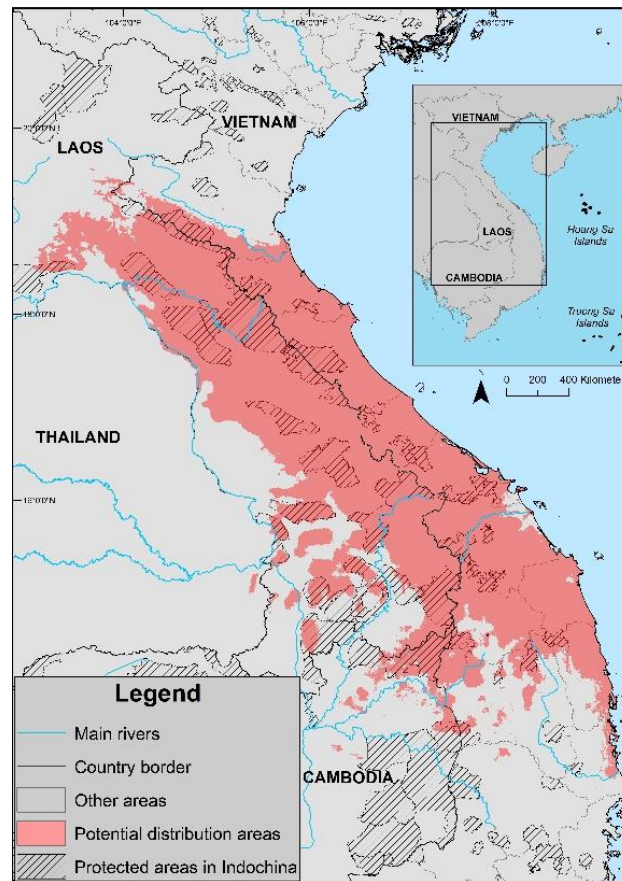


Figure 2. Projected area based on optimal model for current potential distribution of the Red-shanked Douc.

Table 1. The change in projected suitable habitat in different future scenarios for the Red-shanked Douc

Global climate models	2041–2060		2061–2080		2081–2100	
	Area change (km <sup>2</sup> )	Percent change (%)	Area change (km <sup>2</sup> )	Percent change (%)	Area change (km <sup>2</sup> )	Percent change (%)
ACCESS-CM2	-11,257	-6.8	-13,815	-8.4	-32,427	-19.7
MIROC6	-9,418	-5.7	-24,418	-14.8	-37,330	-22.6
CNRM-ESM2-1	-11,314	-6.9	-4,869	-3.0	-27,483	-16.7
GISS-E2-1-H	-34,402	-20.6	-47,151	-28.6	-53,110	-32.2
Average	-16,598	-10.1	-22,563	-13.7	-37,585	-22.8

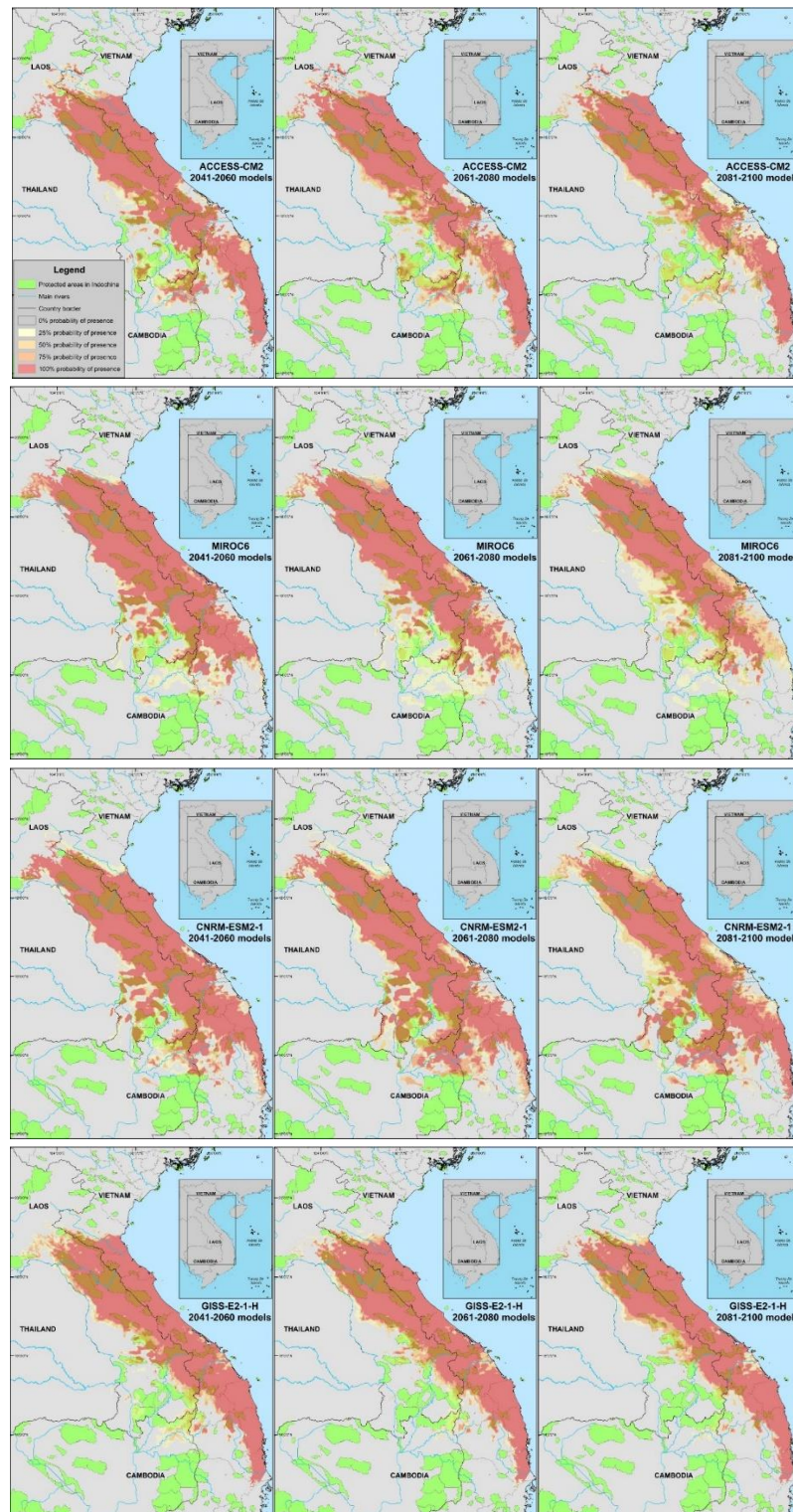


Figure 3. Predicted distributions for the Red-shanked Douc under a range of different future climate change scenarios.

The second trend shows that the species' range may experience habitat fragmentations due to range shift upwards to track the cooler climate, especially in lowland areas, and the southwest region may be the most vulnerable site. As shown in Figure 3, most of the predicted future distributions will be centered around the Northern and Central Annamite Landscapes, and a small portion may be in the Southern Laos Upland Landscape. The populations in lower areas, such as parts Quang Tri - Hue in Vietnam or Savannakhet – Salavan in Laos will become restricted and depend on nearby higher elevation areas. In such case, the Northern and Central Annamite Landscapes, especially region that connects many protected areas that run along the border between Vietnam and Laos, may serve as the main refuges for the species in future.

### 3.3. Discussions

According to our models, we suggest following regions, which lie within the largely continuous and climatically stable habitats of the Doucs, to be prioritized for future conservation measures of the species. They include Vu Quang National Park (Ha Tinh, Vietnam); Phong Nha – Ke Bang National Park and Dong Chau – Khe Nuoc Trong Nature Reserve (Quang Binh, Vietnam); Nakai Nam Theun National Park and Khoun Xe Nong Ma Protected Area (Khammouane, Laos); and Bac Huong Hoa Nature Reserve (Quang Tri, Vietnam): Together they form a large continuous block of forested area, and they are home to the most significant Red-shanked Douc populations. Many areas in this region still retain high quality habitats, and hence they should be considered as priority for any conservation initiatives for *P. nemaeus* in the future [29-31].

Other conservation region, comprising Bach Ma National Park and Hue Saola Nature Reserve (Thua Thien Hue, Vietnam); Quang Nam Saola Nature Reserve and Song Thanh National Park (Quang Nam, Vietnam); and Xe Sap National Park (Sekong, Laos), together form another contiguous forested area, and support the second

most important Red-shanked Douc population. While parts of this region have been severely degraded by human activities, sizable Douc groups are still persist here [32-34]. Therefore, protection and law enforcement activities, if properly conducted, can help assure the long-term survival of the species in this region.

While both Son Tra and Ba Na – Nui Chua nature reserves (Da Nang, Vietnam) are quite isolated from other significant natural habitats of the Doucs, important *P. nemaeus* populations still inhabit both areas [35, 36]. As land demand for infrastructure and tourism activities intensifies, conservation priority for the Red-shanked Douc here should focus on preserving the remaining habitats [6].

Our results for the potential distribution of the Red-shanked Douc in current conditions differ significantly from those in a previous study [37]. In particular, the results in the 2019 study over-predicted the distribution of *P. nemaeus*, and covered areas outside known range of the species in the northern limit such as Pu Hoat and Pu Hu. However, the results also under-predicted the distribution of the Douc in Laos, where important populations in Hin Nam No and Nakai – Nam Theun areas were not within the predicted range. We suggest that in this study, we used a more updated and accurate data set of known records of the Red-shanked Douc, and hence we were able to construct a more reasonable potential distribution in current conditions of *P. nemaeus*. Therefore, our study again emphasize the significance of input data for the model accuracy.

According to our field surveys and interview results, in Song Thanh National Park, Quang Nam, the morphologically typical Red-shanked Douc occurs in the northern side of the Cai River. In the southern side of the river, only the morphologically typical Gray-shanked Douc can be spotted. However, local people also reported the occasional occurrences of Douc groups with mixed morphological characters of the two species in both sides of Cai River. Hence, we propose that Cai River system may act as a 'soft'

natural barrier that promote the speciation between two *Pygathrix* taxa by limiting the gene flow (Figure 1), and other factors may further facilitate to the divergence.

#### 4. Conclusion

In this study, MaxEnt, a machine learning approach, was used to assess the possible impacts of climate change on the Red-shanked Douc, an endangered primate that inhabits parts of the Indochina. The results showed that in most scenarios, the distribution of *P. nemaeus* is likely to shrink compared to the current predicted range, and in long term, climate change will be an ever-increasing threat to the Red-shanked Douc. In particular, based on the optimal model, the suitable distribution range for the Red-shanked Douc in the current climate conditions is approximately 140,000 km<sup>2</sup>, and the available habitat for the Doucs is likely to shrink, with the average decrease of around 15.5% in total area, even in the best-case scenario. Furthermore, the species' range may experience certain levels of fragmentations, and a number of key habitats in areas such as Quang Tri - Hue in Vietnam or Savannakhet – Salavan in Laos will become highly restricted. In such case, the Northern and Central Annamite Landscapes, especially region that connects many protected areas that run along the border between Vietnam and Laos, may serve as the main refuges for the species in future. Therefore, to effectively mitigate climate-related risks for the Red-shanked Douc, future cooperation initiatives between Vietnam and Laos' governmental institutions and conservation organizations will be crucial in conserving the remaining habitat of this endangered primate.

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