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Original Article

Modeling Potential Distribution of the Black-shanked Douc (*Pygathrix nigripes*)

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Abstract: The Black-shanked douc - *Pygathrix nigripes* (*P. nigripes*) is an endangered primate found only in a small region between Vietnam and Cambodia. In recent decades, the species populations have been significantly reduced in their common strongholds because of the pressure from illegal hunting and habitat destruction. The actual distribution of this species remains poorly understood. To better understand the distribution patterns of this endangered primate, we collate localities from previous studies and our field surveys to model the douc's potential distribution using MaxEnt, a widely used species distribution modeling method. The model results show that, the main distribution range of *P. nigripes* covers the region of Dak Lak, Khanh Hoa, Lam Dong, and Dong Nai provinces, with an area of approximately 62,000 km^2. Based on the optimal model, we recommend future field surveys in several potential areas to identify unknown populations of the douc. We also suggest possible natural barriers of the Black-shanked douc and its relatives, and its implications for conservation activities.

Keywords: Pygathrix nigripes, MaxEnt, Species Distribution Modeling.

1. Introduction

The Black-shanked douc - *Pygathrix nigripes* (*P. nigripes*) is a highly endangered primate found only in Vietnam and Cambodia. The largest extant populations of the species is found in a relatively large, transboundary continuous block of forest between Seima

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Biodiversity Conservation Area in Cambodia and Bu Gia Map National Park in Vietnam [1]. However, other important populations of the species occur at several sites in Vietnam, such as Cat Tien, Nui Chua, and Phuoc Binh National Parks. *P. nigripes* is classified as Critically Endangered by the IUCN Red List across its entire range, with illegal hunting identified as the most serious threat to its survival [2]. However, in Vietnam, habitat destruction has also been considered the main threat for the species due to the rapid economic development and population expansion over the last decades. Therefore, the Black-shanked douc has been assessed as endangered in the most recent edition of Vietnam's Red Data Book [3].

Despite the species' critical conservation status, important information needed for long-term conservation initiatives, such as the douc's population status and distribution, remains limited. For instance, since the early 2020s, several previously unknown populations of the Black shanked douc have been discovered in fragmented landscapes, sometimes situated at considerable distances from their population strongholds [4]. Therefore, an accurate distribution range is urgently needed for better protecting remaining populations and habitats of the *P. nigripes*.

Species distribution modeling (SDM) represents a suite of analytical methods that identify possible interactions between species occurrence data and relevant environmental variables. Such models have proven essential in advancing our understanding of the spatial ecology of threatened taxa, especially in the context of distribution patterns [5]. SDM can help to identify potential distributions for recently discovered species, design protected areas that account for projected climate change impacts, reveal cryptic species' ecological patterns, and unravel effects of hidden abiotic variables on species distribution [6-9]. One of the most commonly used SDM approaches in recent years is Maximum Entropy (MaxEnt) [10]. MaxEnt has emerged as a powerful SDM method due to its robust predictive performance, even when occurrence records are limited [5, 11]. Therefore, MaxEnt has been recommended as a standard tool in species distribution research, especially for endangered taxa [12].

While there were attempts to use MaxEnt to quantify the range of the species in the past, such studies were plagued with inaccurate occurrence records of the doucs, a more dated version of available bioclimatic variables, and an antiquated modeling approach [1]. For instance, their input localities included records of the Black-shanked douc in Kon Tum and Quang Ngai region, which was far outside the known range of *P. nigripes*, and such localities have been argued to be a misidentification of the related Grey-shanked douc [13]. Also, the modeling method used a more conservative approach, and did not follow the best practice recommendations [14, 15]. Hence, their results were quite overfitted, limiting the ability to determine novel distribution areas where the species may occur [1].

In this study, we amass occurrence records of the Black-shanked douc from previous studies and our field surveys, and then use the comprehensive dataset to construct MaxEnt models for predicting its distribution range and help advance our understanding and support conservation measures for this endangered primate. Unlike previous studies, to ensure robust predictions of our MaxEnt results, we took special precautionary steps to screen the collated occurrence records for accuracies, and we performed modeling protocol following best practice recommendations from modeling experts.

2. Methods

2.1. Literature Review

To gather updated data on the localities of the species, we reviewed the available records of the Black-shanked douc by searching main biodiversity databases using combinations of the following keywords: "*Pygathrix nigripes*", "*nigripes*", "Blacl-shanked douc", "Douc", "Chà vá", "Chà vá chân đen", and "Voọc chà vá". Field notes and reports from research and

conservation institutions were also reviewed and screened. The collected records were then checked following standard protocol outlined by Nguyen (2022a) [7] to minimize duplications and inaccuracies.

2.2. Field Surveys

The occurrence dataset then was used to identify areas that harbor important populations of the Black-shanked douc. Consequently, we selected and conducted field surveys by transect walks based on the method described by Nguyen (2022b) [16], in Cat Tien National Park (Lam Dong and Dong Nai). While past surveys in Cat Tien focused on the eastern and southern parts of the park, we concentrated our survey efforts in the western part of Cat Tien, which is in the former Binh Phuoc area. This part of Cat Tien has received considerably less primate survey attention in the past compared to other areas. All records of *P. nigripes* from our surveys were integrated into the existing dataset to create a more comprehensive list of the species' known localities.

2.3. Model Construction and Evaluation

To ensure prediction accuracy of MaxEnt model, we employed the modeling protocol that was developed and tested by Nguyen (2022) [7]. This approach has been proven to be robust for endangered species [17], and was used to successfully discover unknown populations of elusive mammals [5]. In particular, to mitigate spatial autocorrelation problems, we used the spThin package [18] in R to thin out records within a ten-kilometer threshold. Nineteen bioclimatic variables at 30-arcsec resolution available at the WorldClim 2.1 database [19] were used, and we restricted the study extent by using a three-degree buffer around the minimum convex polygon of the processed localities [20].

We ran all models in MaxEnt version 3.4.4 [12] through ENMeval package [21]. We used all feature classes' combinations, and tested a range of regularization multiplier values from 0.5 to 10.0 with increments of 0.5. All other parameters followed best practice recommendations from previous studies [5, 10, 15]. We then used the fourfold data partition method to construct MaxEnt models. As MaxEnt has a tendency to produce overfitting models [22], we took additional tuning steps to select the optimal model. To assess model performance, we used the 10% omission rate threshold to identify models that showed minimal overfitting. From this set, we then selected the models with the highest Area Under the Curve (AUC) values. The last set of models was then screened based on the Akaike information criterion, which balances complexity with model fitness [23]. For the optimal model, we used the 10% training presence threshold to classify between suitable and unsuitable areas for the Black-shanked douc [11].

3. Results and Discussions

3.1. Distribution Records of the Black-shanked Douc

Figure 1. Collated localities from literature and our field surveys for the Black-shanked douc.

The review process identified 872 known localities of the Black-shanked douc, considerably more than the previous study [1]. New localities of *P. nigripes* that were discovered in recent years in Dak Lak, Lam Dong, and Dong Nai were also included. Our field survey documented three new records of the doucs in Cat Tien National Park. All species records are shown in Figure 1. After preprocessing, from the original 875 records, 68 spatially independent localities were used for model construction.

3.2. Potential Distribution for the Black -shanked Douc

Figure 2. Potential distribution of the Black-shanked douc.

MaxEnt models demonstrated satisfactory prediction power for determining the distribution of the Black-shanked douc, with average AUC values > 0.88. The best model had the regularization multiplier value of 2.5 and a combination of linear and quadratic feature classes, and an AUC value of 0.901. All final models produced broadly consistent predictions of the species' distribution, with only minor differences at the peripheral boundaries of the predicted range.

Nevertheless, the regularization multiplier value of 2.5 for the optimal model suggests a small degree of underfitting in the optimal model. As such, the resulting distribution map should be interpreted as indicative of "potential zones", and it may include regions that are unlikely to be suitable for the Black-shanked douc, especially in the margin regions. We noted that, consistent with limitations inherent to bioclimatic modeling approaches, our results do not incorporate anthropogenic pressures or biotic interactions that may significantly influence the realized distribution of *P. nigripes*. Consequently, the model may overestimate habitat suitability in areas subject to intense human disturbance, and interpretation of the results in such areas should proceed with caution.

The current potential distribution range of the Black-shanked douc can be broadly divided into two regions, with the main one covering around the recorded locations and a smaller breakaway area (Figure 2). The total climatically suitable distribution area of the doucs is estimated at about 79,500 km^2; if the smaller breakaway region is excluded, the main distribution area consists of approximately 62,000 km^2. In particular, the main region is located in the area around Dak Lak, Khanh Hoa, Lam Dong, and Dong Nai provinces and comprises such protected areas as Bidoup – Nui Ba (Lam Dong), Phuoc Binh and Hon Ba (Khanh Hoa), Cat Tien (Lam Dong and Dong Nai), Bu Gia Map and Vinh Cuu (Dong Nai). The second breakaway region, with a total area of about 17,500 km^2, is situated on the northern side of the main region, covering a large part of Quang Ngai Province and the surrounding area. Interestingly, the whole northern part falls totally outside the current reported range of the *P. nigripes*, and well within the southern distribution range of its sister taxon, the Grey-shanked douc [8].

3.3. Discussions

Tran et al., (2020) employed MaxEnt to quantify possible effects of climate change on the distribution range of the Black-shanked douc [1]. Compared to the results in this study, Tran's optimal model was significantly overfitted, and excluded regions from the former Binh Thuan area. Sites in the southern part of Bidoup – Nui Ba National Park (Lam Dong) were also omitted. The difference might stem from the fact that this study employed a more updated locality dataset and environment variables, and we also constructed our MaxEnt models using a more rigorous approach that has been tested and recommended by recent studies [5, 17]. Our results, therefore, emphasize the importance of best practice standards in improving modeling outcomes for future studies.

Based on our MaxEnt optimal model, we recommend several areas that locate within a largely continuous region of suitable habitat for the Black-shanked douc, be the main focus of future field surveys to identify any unknown populations of the doucs. They include Tay Hoa, Deo Ca and Song Hinh Protection Forests (Dak Lak), Thuan Nam Protection Forest (Khanh Hoa), Khanh Vinh Protection Forest (Khanh Hoa), and Bao Loc Protection Forest (Lam Dong).

Consistent with previous studies, which have highlighted issues regarding the unclear natural barrier limit between primate species, our study suggests that environmental variables alone might not be sufficient for the separation between the two species of the *P. cinerea/nigripes* complex [8, 24]. However, as previous ecology and modeling studies have suggested, the biogeographic barrier between two gibbon species, *Nomascus annamensis /gabriellae*, may be the dry deciduous dipterocarp forests, which span from Banlung to Phnom Prich in Cambodia and then expand eastward to Gia Lai and Dak Lak provinces in Vietnam [25, 26]. Such a region also coincides with the barrier region that separates the main and the northern parts in our optimal model (Figure 2). The lack of suitable food sources in the region is perhaps a crucial factor generating this disjunct distribution pattern, especially for a highly folivorous taxon such as *Pygathrix*.

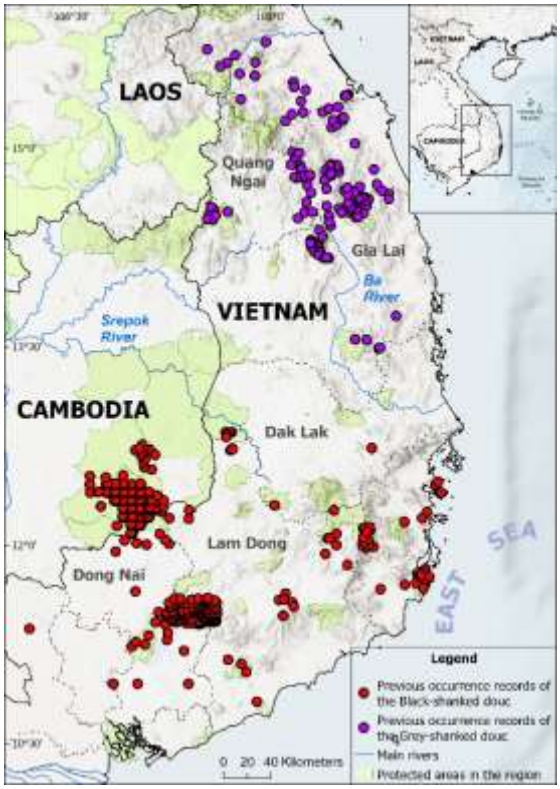

Figure 3. Known records of *P. cinerea/nigripes* species complex.

Our findings suggest that regional river systems may play a contributory role in the speciation processes between the two douc species. All documented occurrences of the Grey-shanked douc are situated north of the Srepok - Ba river system [27], whereas all verified localities of the Black-shanked douc are confined to the southern side of the same hydrological boundary (Figure 3). Although rivers may not constitute absolute barriers to primate dispersal, they can impose significant constraints on movement and, consequently, restrict gene flow between populations [28, 29]. We propose that a combination of habitat characteristics, i.e., dipterocarp forests and river systems, may jointly influence species divergence within the *Pygathrix* genus. While previous studies have indicated the presence of the Black-shanked douc North of the Srepok - Ba river system [13], our results suggest that such records are highly improbable and may stem from inaccuracies in interview-based data collection [30].

4. Conclusion

In this study, we combined occurrence records of the Black-shanked douc from literature and our field survey data to construct MaxEnt models for the species distribution. The optimal MaxEnt model showed reasonable prediction power with average AUC values > 0.88, and the best model had an AUC value of 0.901. The model results suggest that *P. nigripes* is mostly distributed in the region around Dak Lak, Khanh Hoa, Lam Dong, and Dong Nai provinces, Vietnam. Therefore, protected areas in these regions, especially those that form a relatively large and semi-continuous forest such as Bidoup - Nui Ba (Lam Dong), Phuoc Binh and Hon Ba (Khanh Hoa), Cat Tien (Lam Dong and Dong Nai), Bu Gia Map and Vinh Cuu (Dong Nai), will play a crucial role in supporting important populations of the doucs. Future research and conservation initiatives should focus their efforts on such areas to find new populations of the Black-shanked douc, as well as address the outstanding taxonomic issues of this primate clade.

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