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Range-wide prediction of habitat suitability for king cobras under current and future scenarios

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Abstract

Ophiophagus hannah, commonly known as the king cobra, is listed as vulnerable by the International Union for Conservation of Nature (IUCN) and is protected under national laws in most countries. This charismatic species faces multiple threats, including habitat loss, human persecution, illegal trafficking, and climate change. Due to the king cobra's sensitivity to environmental conditions, its population status and trends are barely understood. This study used the MaxEnt algorithm to predict the potential distribution of king cobras across Asia, a method that has been successfully implemented in modeling distributions of various species in the region. The findings showed that Evergreen Broadleaf Trees emerged as the most influential variable for the distribution of *Ophiophagus hannah* with a 27.3% contribution, followed by the Mean Diurnal Range and Urban/Built-up areas. Jackknife analysis identified the Mean Diurnal Range as having the highest testing gain. Approximately 413,268 km^2 were found to have the most suitable climatic conditions for sustaining this species. Countries such as India, Myanmar, Bangladesh, Vietnam, Cambodia, Indonesia, and Malaysia were identified as having favorable conditions. Under the future climate scenario SSP5-8.5, the extent of suitable habitats (maximum) for the king cobra is projected to decrease in the periods 2041–2060 and 2081–2100. This report provides valuable insights that could inform conservation strategies for *O. hannah* in these regions.

KEYWORDS

bioclimatic variables, consensus land cover variables, conservation, MaxEnt

Plain language summary

This study aims to predict distribution patterns of *Ophiophagus hannah* across Asia for both current and future scenarios by using a modeling program called MaxEnt. To predict the distribution pattern of *O. hannah* in future scenarios, a framework known as Shared Socioeconomic Pathway 5-8.5 (SSP5-8.5) was chosen for the periods between 2041–2060 and 2081–2100. SSPs offer narrative descriptions and quantifications of potential developments in socio-economic variables, such as population growth, economic development, and the rate of technological change. SSP5-8.5 is a high-path scenario characterized by rapid economic and technological development and medium to high climate change vulnerability. These characterizations highlight the challenges to both mitigation and adaptation efforts. Anthropogenic activities, particularly the burning of fossil fuels, deforestation, and other industrial processes, release greenhouse gases into the atmosphere, leading to an enhanced greenhouse effect and global warming. The SSPs consider various future scenarios concerning how these human activities might evolve, affecting the trajectory of climate change. The king cobra is categorized as vulnerable by the International Union for Conservation of Nature (IUCN), and most countries have established national laws or regulations to protect it. This reptile species faces multiple threats, including habitat loss, human persecution, illegal trafficking, and the impacts of climate change. Due to its high sensitivity to environmental conditions, proper understanding of its population status and trends remains limited. Therefore, the present study aims to determine how changes in environmental conditions affect the potential distribution of this reptilian species across Asia.

1 | INTRODUCTION

The king cobra, *Ophiophagus hannah* (Cantor, 1836), is the world's longest venomous snake and one of its most iconic reptiles. According to Whitaker and Captain (2004), it belongs to the family Elapidae, which also includes other highly venomous species such as cobras, mambas, and sea snakes. As its name suggests, *O. hannah* feeds primarily on other snakes, including venomous ones (Bhaisare et al., 2010). It can reach up to 5.5 m in length, is oviparous in nature, and builds nests for life (Aagaard, 1924; Daniel, 2002; Whitaker & Captain, 2004). It has a distinctive hood that it can enlarge when threatened or when displaying aggression. The hood is marked with a pair of striking white bands that resemble eyes (Sarkar et al., 2018). *O. hannah* is widely distributed across tropical and subtropical regions of Asia (Gowri Shankar et al., 2013), inhabiting various habitats such as forests, grasslands, agricultural fields, and mangrove swamps (Gowri Shankar et al., 2013). King cobras are known to nest, mate, and produce offspring between altitudes of 1000 and 1500 m (Sapkota et al., 2021). However, *O. hannah* is facing threats from habitat loss, human persecution, illegal trade, and climate change (Sapkota et al., 2021). It is listed as vulnerable by the International Union for Conservation of Nature (IUCN) and is protected under national laws in most of its range countries (Gowri Shankar et al., 2013).

The distribution of the king cobra is poorly understood due to its secretive nature and low encounter rate. More research and conservation efforts are needed to ensure the survival of this magnificent species. In this study, the MaxEnt algorithm was employed to identify suitable habitats for the king cobra across Asia. The MaxEnt algorithm, which operates on presence-only data, establishes a nonlinear relationship between predictor and response variables (Gupta et al., 2023). The MaxEnt-based species distribution model (SDM) is commonly applied to predict suitable habitats or appropriate areas for flora and fauna across different geographical and temporal scales (Phillips & Schapire, 2004).

Practitioner points

- *Ophiophagus hannah*, commonly known as the king cobra, is classified as vulnerable by the International Union for Conservation of Nature (IUCN) and is protected under national laws in most countries. This species faces various threats, including habitat loss, human persecution, illegal trafficking, and climate, all of which affect its distribution and survival.
- Due to its elusive nature and low encounter rate, the distribution of the king cobra is not well understood. Increased research and dedicated conservation efforts are needed to ensure the continued survival of this magnificent snake.
- Utilizing maximum entropy modeling to analyze distribution helps to identify suitable habitats for the king cobra across Asia, information that is key for developing effective conservation strategies tailored to protect and support this species.

In Asia, MaxEnt-based SDMs have been successfully employed to predict the distributions of several species, including the pangolin (Suwal et al., 2020), the Golden Langur (Thinley et al., 2019), the Himalayan Musk Deer (Lamsal et al., 2018), bat species (Thapa et al., 2021), and various terrestrial reptilian species (Alatawi et al., 2020).

Recent studies have used shared socioeconomic pathways (SSPs) to predict distribution patterns under future climatic scenarios (Purohit & Rawat, 2021; Rawat et al., 2022). SSPs offer narrative descriptions and quantitative assessments that outline potential socioeconomic developments, including variables such as population growth, economic development, and the rate of technological evolution. These scenarios characterize challenges related to both mitigation and adaptation efforts in response to climate change.

The aim of this study is to predict the potential distribution of *O. hannah* in Asia under current environmental conditions that are capable of supporting its existence, while also emphasizing the influence of environmental factors on this reptilian species. Furthermore, the study intends to forecast suitable areas for *O. hannah* in Asia by using a shared socioeconomic pathway (SSP5-8.5) for the period of 2041–2060 and 2081–2100. The results of the distribution analysis under future climatic scenarios illustrate the impact of human-induced climate change on the distribution of *O. hannah* across Asia.

2 | MATERIALS AND METHODS

2.1 | Occurrence points

Occurrence points for *O. hannah* in Asia were sourced from the Global Biodiversity Information Facility (GBIF) (GBIF.org). The data set contained a total of 916 occurrence points. To mitigate geographical biases, a spatial thinning process (5 km × 5 km) (Gupta et al., 2023) of the occurrence points was applied through the spThin package in R v4.2.2. Subsequently, outliers—such as points located at sea or those missing essential environmental data—were removed manually. After these adjustments, 185 occurrence points remained and were used to develop the final model (Figure 1).

2.2 | Environmental data

Information on bioclimatic and topographic variables was obtained from the WorldClim v2.1 database (http://www.worldclim.org), and information on the consensus land-cover variables was obtained from EarthEnv (https://www.earthenv.org/) (Table S1). All files were downloaded in GeoTiff format with a 30 arc-second resolution. Information for Asia's environmental variables was extracted using QGIS (http://qgis.osgeo.org/). Bioclimatic variables demonstrate mean monthly temperature and precipitation trends, including extremes and seasonal variations (Kumar et al., 2021; Rawat et al., 2022), and are continuous in nature. The 12 land-cover variables, expressed as eight-bit values,

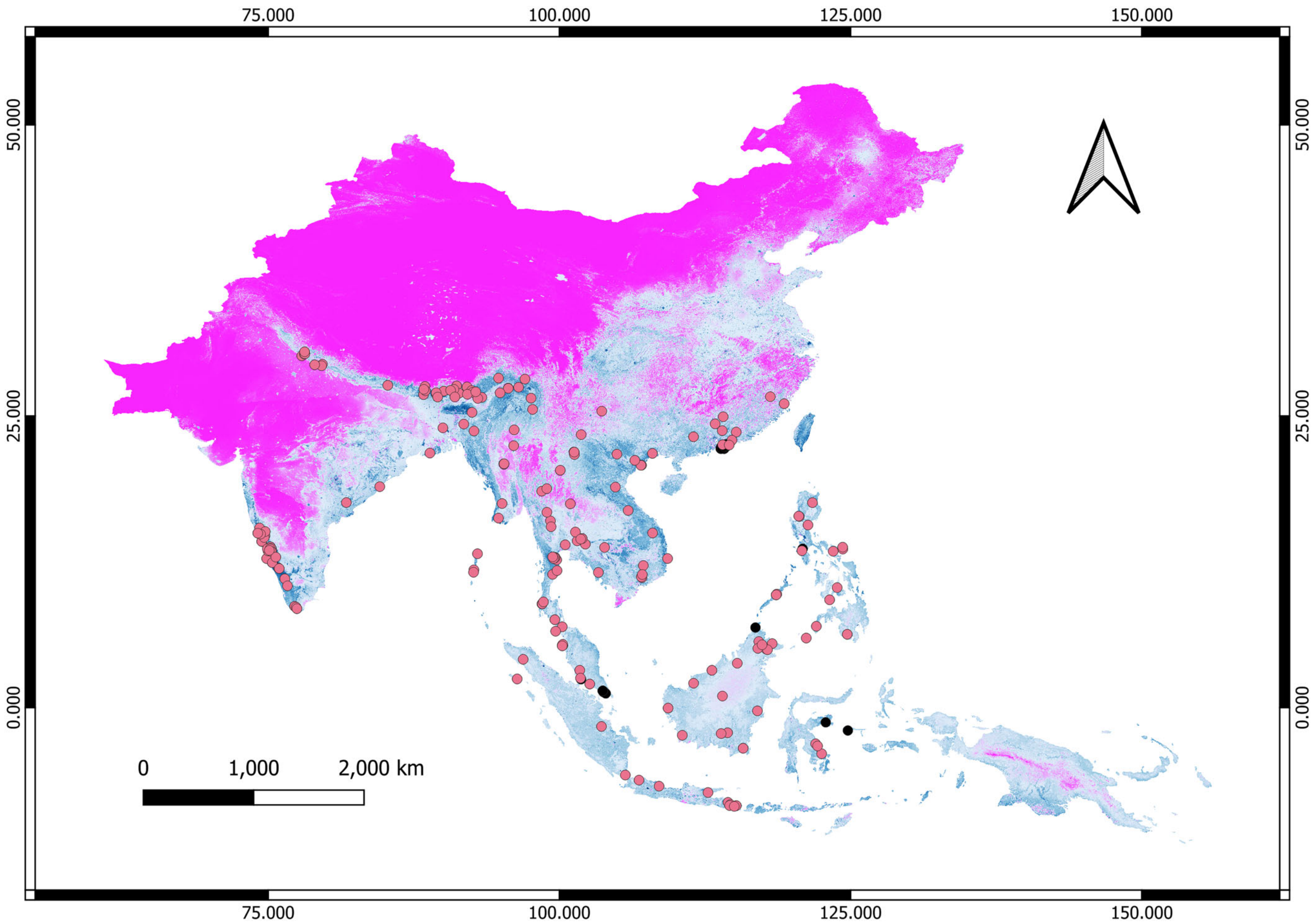

FIGURE 1 Map showing occurrence points of *Ophiophagus hannah* across Asia before (black) and after (pink) spatial thinning. Background color of the map demonstrating the lowest to highest habitat suitability of king cobra where pink represents the lowest habitat suitability and blue represents the highest habitat suitability.

TABLE 1 Correlation coefficient between 15 predictor variables that are used for final model development.

	Mean Diurnal Range	Precipitation Seasonality	Precipitation of Warmest Quarter	Evergreen/ Deciduous Needleleaf Trees	Evergreen Broadleaf Trees	Deciduous Broadleaf Trees	Mixed/ Other Trees	Shrubs	Herbaceous Vegetation	Cultivated and Managed Vegetation	Regularly Flooded Vegetation	Urban/ Built-up	Snow/Ice	Barren	Open Water
Mean Diurnal Range	1	0.5350	−0.6594	−0.0857	−0.4838	−0.0780	−0.2076	0.0243	0.3166	−0.1781	−0.1356	−0.0399	−0.0110	0.5814	−0.0825
Precipitation Seasonality	0.5350	1	−0.3710	−0.0365	−0.5414	0.0791	0.0142	0.0506	0.1593	0.2091	−0.0886	0.0260	−0.0205	0.0854	−0.0026
Precipitation of Warmest Quarter	−0.6594	−0.3710	1	0.0969	0.5500	0.0712	0.2090	0.0208	−0.2439	0.0334	0.0912	0.0082	−0.0778	−0.4873	−0.0009
Evergreen/ Deciduous Needleleaf Trees	−0.0857	−0.0365	0.0969	1	−0.0518	0.0422	0.4498	−0.0180	−0.0844	−0.1742	−0.0085	−0.0265	−0.0309	−0.1417	−0.0271
Evergreen Broadleaf Trees	−0.4838	−0.5414	0.5500	−0.0518	1	−0.0592	−0.0939	−0.0266	−0.2421	−0.2873	0.0600	−0.0514	−0.0622	−0.2419	−0.0459
Deciduous Broadleaf Trees	−0.0780	0.0791	0.0712	0.0422	−0.0592	1	0.3020	0.0466	−0.1190	−0.1142	−0.0266	−0.0232	−0.0352	−0.1308	−0.0317
Mixed/Other Trees	−0.2076	0.0142	0.2090	0.4498	−0.0939	0.3020	1	0.0890	−0.2058	−0.1944	−0.0297	−0.0482	−0.0641	−0.2391	−0.0550
Shrubs	0.0243	0.0506	0.0208	−0.0180	−0.0266	0.0466	0.0890	1	−0.0484	−0.2297	−0.0227	−0.0355	−0.0038	−0.0419	−0.0408
Herbaceous Vegetation	0.3166	0.1593	−0.2439	−0.0844	−0.2421	−0.1190	−0.2058	−0.0484	1	−0.2213	−0.0528	−0.0427	0.0628	−0.0268	−0.0476
Cultivated and Managed Vegetation	−0.1781	0.2091	0.0334	−0.1742	−0.2873	−0.1142	−0.1944	−0.2297	−0.2213	1	−0.0462	0.0129	−0.1230	−0.4708	−0.0854
Regularly Flooded Vegetation	−0.1356	−0.0886	0.0912	−0.0085	0.0600	−0.0266	−0.0297	−0.0227	−0.0528	−0.0462	1	0.0133	−0.0147	−0.0523	0.1341
Urban/ Built-up	−0.0399	0.0260	0.0082	−0.0265	−0.0514	−0.0232	−0.0482	−0.0355	−0.0427	0.0129	0.0133	1	−0.0143	−0.0519	0.0127
Snow/Ice	−0.0110	−0.0205	−0.0778	−0.0309	−0.0622	−0.0352	−0.0641	−0.0038	0.0628	−0.1230	−0.0147	−0.0143	1	−0.0178	−0.0116
Barren	0.5814	0.0854	−0.4873	−0.1417	−0.2419	−0.1308	−0.2391	−0.0419	−0.0268	−0.4708	−0.0523	−0.0519	−0.0178	1	−0.0542
Open Water	−0.0825	−0.0026	−0.0009	−0.0271	−0.0459	−0.0317	−0.0550	−0.0408	−0.0476	−0.0854	0.1341	0.0127	−0.0116	−0.0542	1

range from 0 to 100, representing the percentage prevalence of each type (Tuanmu & Jetz, 2014). To prevent model overfitting due to multicollinearity among variables (Cao et al., 2021), the ENM Tools package (Warren et al., 2021) in R v4.2.2 was used to analyze the correlation between raster layers. Pairs of variables exhibiting a correlation coefficient ≥ ±0.8 were removed from the analysis (Table 1) (Cao et al., 2021; Purohit & Rawat, 2021). The remaining variables were then used to develop the final model.

2.3 | Future environmental variables

This study utilized the BCC-CSM2-MR model, based on CMIP6 data, to develop future climatic scenarios (http://www.worldclim.org). The model, developed by the Beijing Climate Center in China, is renowned for its accurate predictions of air temperature and circulation in the troposphere, particularly during monsoon seasons in India and Eastern Asia (Sun et al., 2021). It has been successfully used for Maximum Entropy Modeling (MaxEnt) in Asia to project potential distribution shifts under changing climates (Cao et al., 2021). To project future climate scenarios, the study employed the Shared Socioeconomic Pathways (SSPs) from CMIP6. These pathways depict various greenhouse gas emission scenarios and provide insights into potential socioeconomic developments and their implications for climate change (Rawat et al., 2022). The selection of SSP5-8.5 for the periods 2041–2060 and 2081–2100 was based on empirical studies demonstrating that SSPs more accurately reflect the interplay between climate scenarios and socioeconomic development than other pathways (Moss et al., 2010; van Vuuren et al., 2011). SSP5-8.5 is considered a high-path scenario characterized by very rapid economic development, rapid technological development, and medium-to-high climate change vulnerability (van Vuuren and Carter, 2014) that is why SSP5-8.5 for the periods 2041–2060 and 2081–2100 was selected for the analysis.

2.4 | Modeling overview

To map the distribution of *O. hannah*, Maximum Entropy Modeling (MaxEnt) software version 3.4.4 was employed (https://www.cs.princeton.edu/schapire/maxent/). Of the initial 32 environmental variables considered, 15 were used to model the distribution of *O. hannah* in Asia. The model configuration was set as follows: output format = logistic, regularization multiplier = 1, maximum iterations = 1, and convergence threshold = 0.00001. A bias file was created to select background points, with a maximum of 10,000 background points set for model development. A linear-quadratic-hinge-product feature (LQHP) combination was used to manage model complexity. To ensure model robustness, a 10-percentile training presence threshold criterion was used. Model validation was performed using 10-fold cross-validation, where occurrence points were divided into 10 smaller subsets. The model's output was categorized into four potential classes: least potential (0–0.2), minimum potential (0.2–0.4), moderate potential (0.4–0.6), and maximum potential (0.6–1). The distribution map was generated using QGIS version 3.28.

3 | RESULTS

The distribution model for *O. hannah* incorporated three bioclimatic and 12 consensus land cover variables. The testing area under the curve value of this model was 0.880 ± 0.030, demonstrating high accuracy. Evergreen Broadleaf Trees emerged as the most influential variable in the distribution of *O. hannah* with a 27.3% contribution, followed by Mean Diurnal Range, Urban/Built-up areas, Barren, Precipitation Seasonality, and Precipitation of Warmest Quarter. Based on the Jackknife test gain, the Mean Diurnal Range is the best fit for the testing data.

After running the final model, the output was transferred to QGIS 3.28, where a detailed final map was prepared to depict the distribution of *O. hannah* in Asia. In the current scenario, approximately 413,268 km^2 of land in Asia is considered to have the most suitable conditions to support this species (Figure 2).

The present study demonstrated that India (134,191 km^2), Myanmar (47,276 km^2), Bangladesh (9231 km^2), Vietnam (35,715 km^2), Malaysia (4850 km^2), Indonesia (32,876 km^2), and Cambodia (13,837 km^2) have significant land areas with suitable conditions to sustain this species.

Under the SSP5-8.5 future climate scenario, the total area of highly suitable habitat for *O. hannah* will shrink to 398,324 km^2 (relative loss = 3.61%) and 406,269 km^2 (relative loss = 1.69%) for the periods 2041–2060 and 2081–2100, respectively (Figures S1 and S2). In India, however, areas that are highly suitable for *O. hannah* will increase by 6.91% (highly suitable habitat = 143,474 km^2) and 2.59% (highly suitable habitat = 137,676 km^2) for the same periods. Conversely, Vietnam and Bangladesh will experience significant reductions in suitable habitats. Vietnam's highly suitable potential habitat for *O. hannah* will decrease by 61.23% (highly suitable habitat = 13,845 km^2) and 57.90% (highly suitable habitat = 15,033 km^2), and Bangladesh's by 30.49% (highly suitable habitat = 6416 km^2) and 44.70% (highly suitable habitat = 5104 km^2) for the periods 2041–2060 and 2081–2100, respectively.

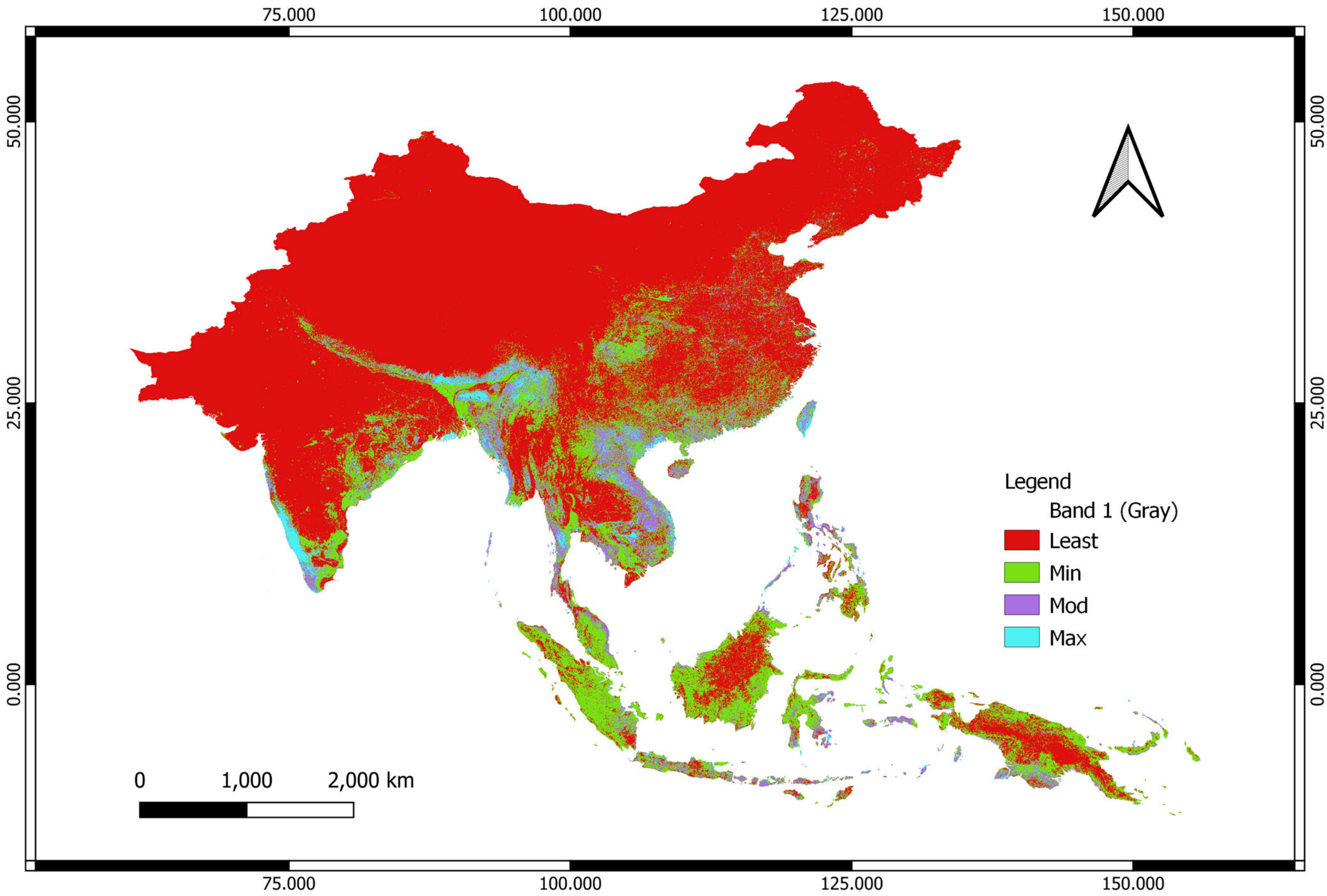

FIGURE 2 Aerial distribution of *Ophiophagus hannah* in Asia under current conditions.

4 | DISCUSSION

In a global context, biodiversity loss is closely linked to various anthropogenic factors (Ehrlich, 1994; Pimm et al., 1995). As demonstrated by Gowri Shankar et al. (2013), mortality patterns among wildlife can be affected by a combination of seasonal factors, life history traits, and behavioral characteristics.

In this study, 15 predictor variables were used to predict the distribution of *O. hannah* across Asia. These predictors underscore the important role that bioclimatic conditions play in the survival of living organisms, especially as they adapt to new conditions.

The current study identifies Evergreen Broadleaf Trees as having a positive effect on the potential distribution of the king cobra, corroborating findings by Rao et al. (2013), who noted that evergreen forests are particularly suitable habitats for *O. hannah*. This suitability is partly due to the high volume of leaf litter, which is essential for the king cobra's nesting habits, with the majority of occurrence points recorded in these forested areas (Rao et al., 2013).

Conversely, It was found that the Mean Diurnal Range has a negative effect on the potential distribution of *O. hannah*. Being ectotherms, reptiles depend on external heat sources to regulate their body temperature. However, empirical studies have demonstrated that global warming poses a significant threat to the survival of most flora and fauna and is considered to be a major cause of biodiversity loss globally (Araújo et al., 2005).

Urban/built-up areas were observed to positively affect the potential distribution of *O. hannah*. Rapid human population growth and urbanization lead to habitat destruction and increased human-wildlife conflicts worldwide (Barve et al., 2013). Barve et al. (2013) also highlighted that human-snake conflicts often arise from human encroachment into snake habitats and the adaptability of snakes to urban environments, which can inadvertently provide favorable conditions for their survival.

Furthermore, two precipitation-related variables, Precipitation Seasonality and Precipitation of the Warmest Quarter, were associated positively with the potential distribution of *O. hannah*. Smith (1943) demonstrated that deciduous, evergreen, and riparian rainforests, characterized by high precipitation levels, are ideal habitats for the species. This is supported by empirical studies showing the king cobra's prevalence in the rainforests of Southeast Asia, Southern China, and India (Gowri Shankar et al., 2013).

The present distribution analysis for *O. hannah* across Asia showed that India, Myanmar, Bangladesh, Vietnam, Cambodia, Indonesia, and

Malaysia contain environmental conditions conducive to sustaining this species.

In future climate change scenarios, for the periods of 2041–2060 and 2081–2100 under SSP5-8.5, it was observed that the areas highly suitable for *O. hannah* initially decrease and then show an increase in the later period. As *O. hannah* is an ectothermic species, the increase in suitable habitats during the period 2081–2100 may be due to a rapid increase in temperatures, which could facilitate great suitability (Jankowsky, 1973). However, global warming remains a significant threat to biodiversity, impacting the survival of most flora and fauna (Sapkota et al., 2021). Empirical studies also demonstrate that reptiles typically lack the capacity to shift their distribution rapidly in response to climate change (Araújo and Pearson, 2005).

Despite the potential expansion of suitable habitats in the SSP5-8.5 (2081–2100) scenario, there is no guarantee that *O. hannah* will thrive under the projected conditions. This is because the study's results are based on presence-only data, necessitating further validation and caution in interpretation. The findings provide insights into the potential shifts in the distribution of *O. hannah* under changing climatic scenarios. Due to the rapid increase in temperature and the destruction of preferred habitats in future climatic scenarios, the distribution of the king cobra across Asia may be threatened. To mitigate these impacts, the relevant authorities should conduct proper environmental monitoring programs. It is imperative to safeguard preferred habitats, such as evergreen forests, from anthropogenic activities. Each country within this geographical range should develop comprehensive conservation policies, which could include forming dedicated snake rescue teams, promoting public awareness about the ecological benefits of snakes, and curbing poaching to reduce mortality due to human-snake conflicts.

5 | CONCLUSION

This study conducted a species distribution analysis of *O. hannah* across Asia using the MaxEnt program, incorporating three bioclimatic and 12 consensus land-cover variables to train the model. Evergreen Broadleaf Trees emerged as the most important determinant influencing the distribution of *O. hannah* under both current and projected future climatic conditions and habitat. The analysis revealed that the most suitable areas for *O. hannah* are expected to decrease in future climatic scenarios when compared to current conditions. The insights gained from this study are instrumental in identifying the areas capable of sustaining this species in current and future climate change scenarios, thereby aiding in the formulation of effective conservation strategies for *O. hannah* throughout Asia.

AUTHOR CONTRIBUTIONS

Subha Shankar Mukherjee collected the basic data, analyzed data, and wrote the initial draft of the manuscript. Debidas Patra contributed to data analysis and manuscript writing. Asif Hossain conceived and designed the study and prepared the final manuscript.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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