ORIGINAL ARTICLE

Understanding the impact of climate change on the habitat of the rufous-necked hornbill (*Aceros nipalensis*) (Hodgson, 1829) using MaxEnt modeling in Bhutan

Damudar Dahal[1] · Arjun Nepal[2] · Chandra Man Rai[3] · Sunil Sapkota[4]

Abstract

Climate change and anthropogenic activities such as deforestation, forest fires, and land use change are serious threats to faunal and avian species including their habitat and population. Using maximum entropy (MaxEnt) modeling, this study assessed the current and future suitable habitats of the rufous-necked hornbill (*Aceros nipalensis*) under SSP1-2.6 and SSP3-7 climate scenarios for 2021–2040 and 2061–2080 in Bhutan. The impact of climate change on species's habitat was evaluated using 158 occurrence points collected as presence-only data and the environmental covariates obtained from www.worldclim.org. ENM-evaluate was conducted in R to obtain MaxEnt settings and bias files. A total of 10,000 background points with a regularization multiplier of 1 and linear and quadratic features were selected to build a model in MaxEnt software. A large area of Bhutan is predicted as an unsuitable habitat, accounting for 70.61% (27,100 km^2), and only 29.39% (11,284.7 km^2) is predicted as a suitable habitat area, with 9197.19 km^2 outside of the protected area. The annual mean temperature has a significant influence (54.1%) on the model, followed by elevation (13.1%) and the least by slope (1.5%). The suitable area is expected to decline from 3.3% (1278.32 km^2) under SSP1-2.6 to 1.42% (549.54 km^2) under SSP3-7 in 2021–2040 and 2061–2080, respectively. The study also found that the present suitable habitat will shift towards the southeast in the future. The results of the study call for the relevant agencies to implement projects in suitable areas to protect the habitats of the rufous-necked hornbill and conserve the species. The inclusion of variables such as distance from the settlement, road, and river is recommended for future studies.

Keywords Climate change · MaxEnt · Rufous-necked hornbill · SSP · Vulnerable

Introduction

Climate change and land-use change alter the spatial and temporal habitats of the species, making them unsuitable to inhabit. Avian species exhibit high sensitivity to natural and anthropogenic changes, causing shifts in species distribution ranges (Jose and Nameer 2020; Mudereri et al. 2021). Ecological niche modeling of target species has been useful in identifying potential habitats, suggesting a valuable approach in efforts to conserve birds (Mudereri et al. 2021). Among several ecological models, the MaxEnt model uses presence-only points and environmental variables to predict the distribution of species in a user-defined landscape. The model estimates the probability of the habitat of species from the unknown background location. The MaxEnt model works with minimal occurrence points and does not require absence data yet provides high predictive accuracy (Phillips et al. 2017). The algorithm assumes that the niche of the species is constant over space and time and evaluates the relative significance of each environmental variable in determining habitat suitability (Coban et al. 2020). The results from the MaxEnt model are useful in order to make informed decision planning and management of the species (Merow et al. 2013; Trisurat et al. 2013).

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✉ Arjun Nepal
nepaalarjun1994@gmail.com

[1] Gifu University, Gifu City, Japan

[2] Centre for Research On Bhutanese Society, Thimphu, Bhutan

[3] College of Natural Resources, Royal University of Bhutan, Punakha, Bhutan

[4] Raise Hands Nepal, Adarsha Tole, Bharatpur-15, Chitwan, Nepal

Out of 54 species of hornbill found worldwide, 32 species are found in South Asia (Birdlife International 2016; Ugyen Wangchuck Institute for Conservation and Environmental Research 2017). The rufous-necked hornbill (*Aceros nipalensis* – Hodgson, 1829) is a member of the Bucerotidae family and it is distributed across Bhutan, northeast India, Myanmar, southern Yunnan, and southeast Tibet, China, Thailand, Laos, and Vietnam. The bird is assessed as a "Vulnerable" species in the Threatened Species Red List of the International Union for Conservation of Nature (Birdlife International 2016) and listed under Appendices I and II of the Convention on International Trade in Endangered Species (CITIES) because of its declining population.

There are four species of hornbills found in Bhutan: rufous-necked hornbill (*Aceros nipalensis*), great hornbill (*Buceros bicornis*), wreathed hornbill (*Rhyticeros undulates*), and oriental pied hornbill (*Anthracoceros albirostris*), among which the rufous-necked hornbill is endangered, and is protected under the Forest and Nature Conservation Act 1995 (FNCA) and Forest and Nature Conservation Rules and Regulations (FNCR) (Ugyen Wangchuck Institute for Conservation and Environmental Research 2017) of Bhutan. Rufous-necked hornbill in Bhutan is sighted in Zhemgang, Trongsa, Mongar, Lhuentse, Trashigang, Samdrup Jongkhar, Tsirang, Sarpang, Dagana, Samtse, and Chhukha districts of Bhutan (Sherub and Singh 2020). The habitat of this bird species in Bhutan is encroached by road construction, power transmission line installation, forest timber logging, cardamom plantation, and agricultural activities demanding higher conservation priority (Ugyen Wangchuck Institute for Conservation and Environmental Research 2017; Sherub and Tshering 2019; Nepal 2020; Sherub and Singh 2020).

There is no study carried out to assess the impact of climate change on habitat suitability and distribution of hornbills in Bhutan. Thus, in this study, the MaxEnt approach was used to model the rufous-necked hornbill's vulnerability to climate change. The objectives of the study were to (i) model the current suitable habitat of the rufous-necked hornbill; and (ii) predict future suitable habitat of the rufous-necked hornbill under SSP1-2.6 and SSP3-7 climate scenarios for 2021–2040 and 2061–2080.

Material and methods

Study area

Located in the eastern Himalayas, Bhutan covers an area of 38,394 km^2 (National Statistics Bureau, [NSB] 2018) with altitudes ranging from 100 masl (meters above sea level) to 7500 masl (Thinley et al. 2019). The country has three eco-floristic zones: alpine (4000 masl and above), temperate (2000–4000 masl), and sub-tropical zone (Ohsawa 1991). The current forest cover of 70.77% exceeds the constitutional mandate of 60% for perpetuity. About 51.44% of the country is designated as protected areas: five national parks, four wildlife sanctuaries, one nature reserve, and eight biological corridors (Forest Resource Management Division 2016). This pristine nature offers diverse ecosystems to harbor 11,248 species of flora and fauna, including 4978 species of plants, 129 species of mammals, and 736 species of birds (National Biodiversity Centre, NBC 2017). The conservation of threatened species is further protected by the Forest and Nature Conservation Act 1995 and the Nature Conservation Rules and Regulations 2017 (National Environment Commission, NEC 2021). Bhutan has a mean annual maximum temperature of 22 °C and a mean annual rainfall of 2076.7 mm (National Center for Hydrology and Metrology (NCHM) 2020). Figure 1 shows the presence-only occurrence points of the rufous-necked hornbill in Bhutan.

Target species

The rufous-necked hornbill is 117 cm long and has a distinctive rufous head and underparts (ventral region) (Birdlife International 2016). The global population of this bird is estimated to be 1500–7000 mature individuals (Ugyen Wangchuck Institute for Conservation and Environmental Research 2017). Among the four species of hornbill in Bhutan, the rufous-necked hornbill is still widespread and fairly common between 900 and 1800 m above sea level (a maximum altitude of 2200 m), but it is also found at a lower altitude of 150 m (Nepal 2020). It inhabits mature broad-leaved, evergreen forests and the edges of forest clearings, where it breeds in March through June in tall, wide-girthed trees. The rufous-necked hornbill also makes seasonal movements between forested areas in response to variations in the abundance of fruit trees (Birdlife International 2016).

The rufous-necked hornbill is a flagship species for conservation because of its striking appearance and intriguing nesting behavior of females for 5–6 months (Jinamoy et al. 2014) (Fig. 2). They are bio-indicators of healthy forests as they require large tracts of primary forest with large trees for nesting and foraging. Hornbills are known as the "farmers of the forest" for their role in seed dispersal and predation of forest insects and pests, which are essential for the sustainability of the forest (Ugyen Wangchuck Institute for Conservation and Environmental Research 2017).
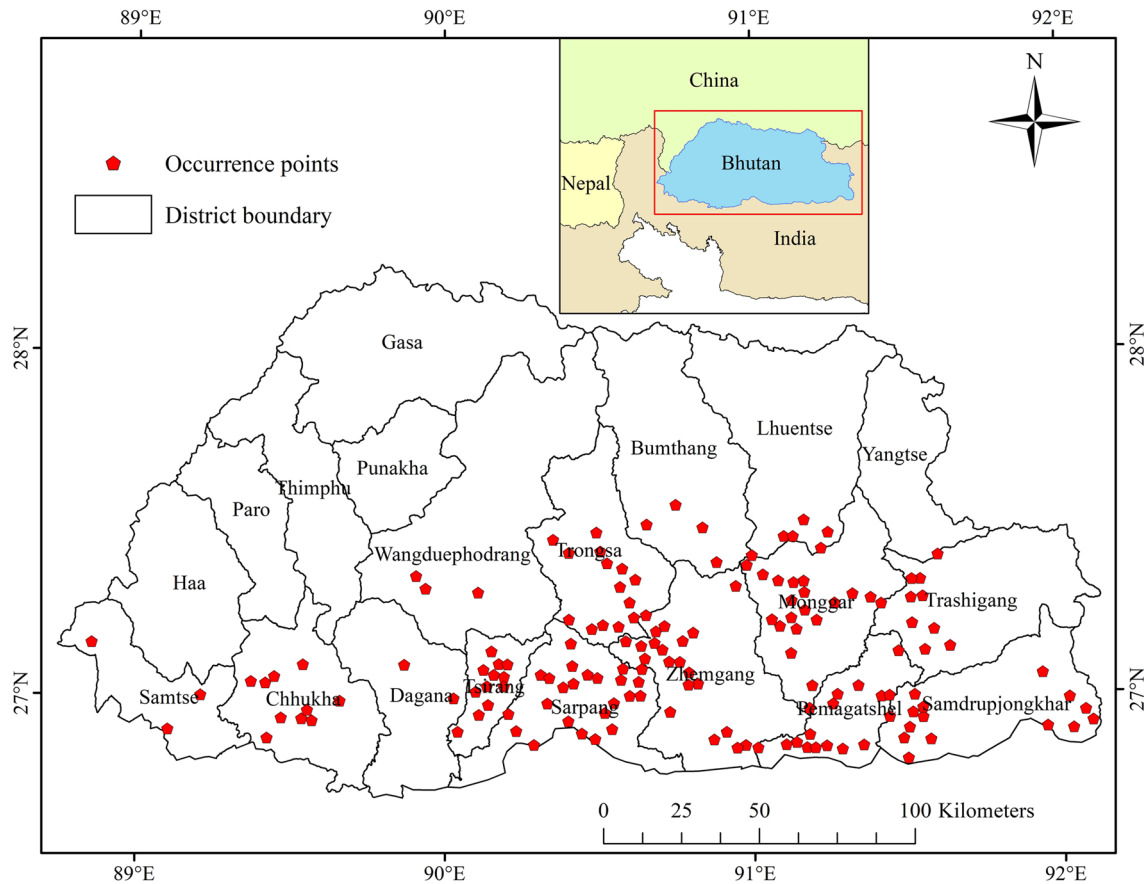
Fig. 1 Presence-only coordinates of rufous-necked hornbill in Bhutan

Fig. 2 Rufous-necked hornbill male and female (photo courtesy: Thinley Wangchuk)

Data collection

A total of 140 occurrence points were collected from the field survey, and 481 points were obtained from the Global Biodiversity Information Facility (GBIF) (Fig. 1). The GBIF (https://www.gbif.org) is an online access point database providing species occurrence data from records obtained through field observations (GBIF 2021). Spatial autocorrelation (Moran's *I*) was performed to remove correlated points using the "spatially rarefy occurrence data tool" in the Species Distribution Modeling (SDM) toolbox at 3-km resolution (Brown 2014). Following correction, a total of 158 presence-only (PO) data points were used, meeting the adequate sample size requirement of Stockwell and Peterson (2002), which is at least 50 presence-only data points. The data was converted into comma-separated values (.csv file) to feed it into MaxEnt. A total of 19 bioclimatic variables (raster layers) were obtained from www.worldclim.org.

Preprocessing of environmental layers

Predictor variables having a direct relationship predict biologically informative and generalizable information from the model (Sapkota et al. 2021; Nepal et al. 2022). A multicollinearity test among 19 bioclimatic variables

Table 1 Pearson's (R) correlation for the six standardized bioclim variables used in species distribution modeling (SDM) for the rufous-necked hornbill

	Bio1	Bio2	Bio3	Bio13	Bio14	Bio15
Bio1	1	−0.934	0.995	0.743	−0.107	0.803
Bio2	−0.934	1	−0.895	−0.803	0.051	−0.833
Bio3	0.995	−0.895	1	0.710	−0.107	0.786
Bio13	0.743	−0.803	0.710	1	−0.013	0.764
Bio14	−0.107	0.051	−0.107	−0.013	1	0.268
Bio15	0.803	−0.833	0.786	0.764	0.268	1

Table 2 Selected variables used in model development used in species distribution modeling (SDM) for the rufous-necked hornbill

Climatic variables	Unit	Resolution	Source
Annual mean temperature (BIO1)	℃	~ 1 km^2 (30 s)	Worldclim.org
Mean diurnal range (BIO2)	℃	~ 1 km^2 (30 s)	Worldclim.org
Isothermality (BIO2/BIO7) (*100) (BIO3)	℃	~ 1 km^2 (30 s)	Worldclim.org
Precipitation of wettest month (BIO13)	mm	~ 1 km^2 (30 s)	Worldclim.org
Precipitation of driest month (BIO14)	mm	~ 1 km^2 (30 s)	Worldclim.org
Precipitation seasonality (BIO15)	mm	~ 1 km^2 (30 s)	Worldclim.org
Slope	Degree	~ 30 m (1 s)	earthdata.nasa.gov
Aspect	Degree	~ 30 m (1 s)	earthdata.nasa.gov
Elevation	Meter	~ 30 m (1 s)	earthdata.nasa.gov
Land use land cover	Categorical	-	National Land Commission of Bhutan

(Table 1) was conducted to avoid overfitting or poor model development and misinterpretation, using the SDM toolbox in ArcGIS (Merow et al. 2013; Brown 2014; Brown et al. 2017). A total of six bioclimatic variables having $r \leq 0.8$ were selected for model simulation, along with the topographic variables, shown in Table 2: Bio1, annual mean temperature; Bio2, mean diurnal range; Bio3, isothermality; Bio13, precipitation of wettest month; Bio14, precipitation of driest month; and Bio15, precipitation seasonality.

Maximum entropy (MaxEnt) and model setting

The MaxEnt model is used to predict habitat suitability using geographic coordinates (presence-only data) and environmental variables of target species (Phillips et al. 2006, 2017). MaxEnt accepts presence-only data (PO) and performs the model with the minimum number of occurrence data. The model handles continuous and categorical variables using regularization parameters and produces habitat suitability models (Phillips et al. 2017, 2020). For future projections, data was obtained from the Model for Interdisciplinary Research on Climate (MIROC6) (Fig. 3). The MIROC6 is used for seasonal to decadal climate predictions and future climate projections. This model was chosen based on its improvement in simulating atmospheric and oceanic

circulation, and the snow cover fraction in the northern hemisphere. The model also best describes the climate mean and natural climate variability in the mid-latitudes, as well as the tropical climate system and mid-latitude atmospheric circulation (Tatebe et al. 2019).

Ecological Niche Model Evaluation was performed in R using the package ENMevaluate version 0.3.1 to optimize the model set (Nepal et al. 2022). The model with the lowest Delta AICc (Akaike Information Criterion) value was selected which showed that linear and quadratic (LQ) features were suitable features to develop the model. A total of 10,000 background points, a regularization multiplier of 1, and 5000 iterations were selected for model development. The cross-validation technique with 10 replications was used to obtain a realistic model average, which uses data efficiently while optimizing the model set. The binary map was produced using the maximum sensitivity plus specificity threshold. The conservative cutoff value of the "equal training sensitivity and specificity threshold" value of 0.248 was used to classify the continuous probability into a binary prediction (0–1) of presence or absence. The predicted suitable area for the probability of rufous-necked hornbill occurrence was calculated using threshold values ≥ 0.248, while the unsuitable area was regarded as having a value < 0.248. The total number of pixels for each predicted class was used to estimate the total coverage of the predicted suitable area against the unsuitable area.

Fig. 3 Conceptual framework for the distribution of rufous-necked hornbill in Bhutan
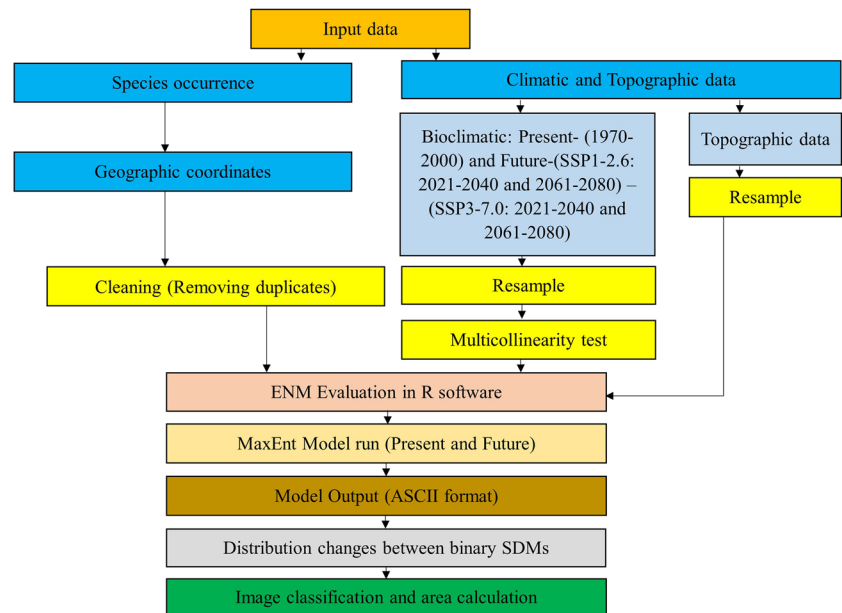
Model evaluation

The accuracy of the model was evaluated by the area under curve (AUC) of the receiver operating characteristic (ROC) plot (Phillips et al. 2017). AUC describes the relationship between the proportion of correctly predicted presences and the proportion of absences of incorrectly predicted species in the model (Chhogyel et al. 2020). The AUC measures the model's performance, and its value ranges between 0 and 1. AUC values of > 0.9 indicate high accuracy, values of 0.7 to 0.9 indicate good accuracy, and values below 0.7 indicate low accuracy

(Phillips et al. 2006, 2017; Merow et al. 2013). The variable importance of the model was estimated through the jackknife test.

Results and discussion

Evaluation of the model and its importance to variables under current climatic conditions

The simulated model predicted good accuracy for the overall model with an AUC mean of 0.844 and SD = ± 1

Fig. 4 The receiver operating characteristic (ROC) curve. The values shown are the averages of the ten replicate runs. The red-colored line shows the model AUC value and the blue line indicates the standard deviation of ± 1
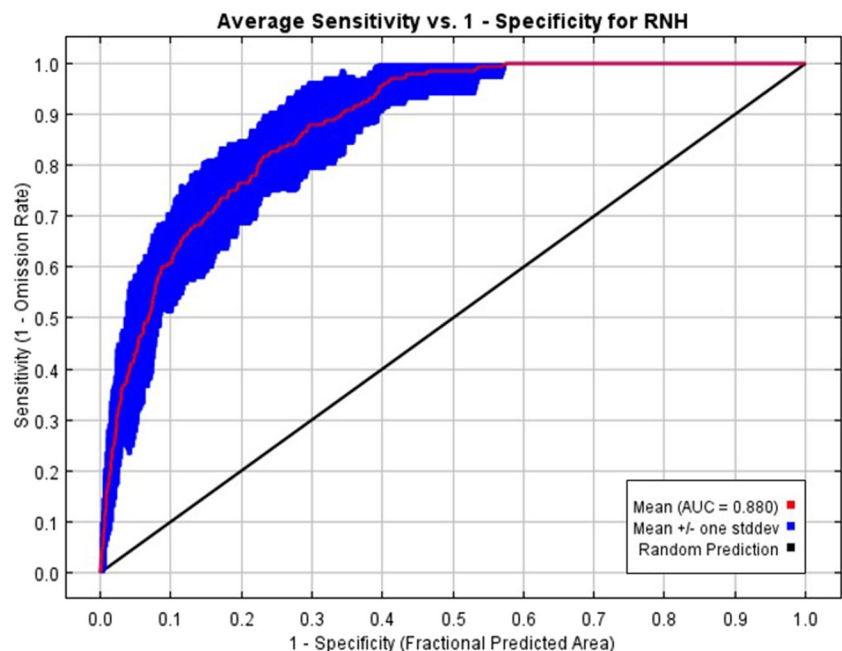
(Fig. 4). The model predicted the annual mean temperature (Bio 1) to have the most useful information and resulted in the highest permutation importance value of 57.4%. The relative importance of individual predictors was assessed using a jackknife test, which indicated the distribution of rufous-necked hornbills was mainly influenced by the annual mean temperature, accounting for 54.1%, followed by elevation, contributing to 13.1%, and least by the slope. In consideration of the permutation importance, the annual mean temperature (Bio 1) had the highest impact, contributing 57.4%, followed by the precipitation of the wettest month (Bio13) contributing 12.4% to the model. Precipitation seasonality, isothermality, and slope have small contributions, with less than 2% each for the distribution of the rufous-necked hornbill (Table 3).

Response of the rufous-necked hornbill to environmental variables

Figure 4 shows the overall accuracy of the model which is measured by AUC having value of 0.88. The red lines show the rufous-necked hornbill's mean responses, while the x-axis represents the values of the environmental variables, and the y-axis reflects the probability of occurrences. The rufous-necked hornbill is predicted to inhabit an altitude between 600 and 2600 masl. This finding is consistent with the distribution of the rufous-necked hornbill in the Tsirang district, where it is found mostly at altitudes between 150 and 2600 masl in Bhutan (Ugyen Wangchuck Institute for Conservation and Environmental Research 2017). According to Jinamoy et al. (2014), elevation is a key eco-factor for rufous-necked hornbill distribution. The model predicts a suitable slope for rufous-necked hornbills is lower than 35° and prefers a north-east facing aspect of 0–50° (Fig. 5a, c).

Table 3 Variable contributions and permutation importance of the predictor variable used in simulating the model used in species distribution modeling (SDM) for the rufous-necked hornbill

Variables	Percentage contribution (%)	Permutation importance
Annual mean temperature	54.1	57.4
Elevation	13.1	2.3
Mean diurnal range temperature	9	4.9
Precipitation of wettest month	7.8	12.4
Precipitation of driest month	5	9.5
Land use land cover	3.4	1.7
Aspect	2.7	2.1
Isothermality	1.8	6.6
Precipitation seasonality	1.7	1.4
Slope	1.5	1.8

Furthermore, the model indicates that the rufous-necked hornbill prefers an annual mean temperature of 15–20℃ and precipitation of the wettest month of 200–1200 mm. This indicates that the rufous-necked hornbill normally lives in the tropical and sub-tropical forests of southern Bhutan. This agrees with the findings of the rufous-necked hornbill habitat in the Western Forest Complex, Thailand, and Phrumshingla National Park, Bhutan (Jinamoy et al. 2014; Ugyen Wangchuck Institute for Conservation and Environmental Research 2017). The precipitation seasonality (bio15) represents the variability of precipitation and showed a good probability of hornbill presence between 60 and 120 mm. It was found that the rufous-necked hornbill prefers habitats with a mean diurnal range temperature of 7–14℃, isothermality of 35–55℃, and an annual mean temperature of 5–25℃ (Fig. 5e, f, h).

The broadleaf forest is the major habitat preferred by the rufous-necked hornbill, followed by the conifer-broadleaf and fir forests (Fig. 5d). The model also depicts agricultural land as a suitable habitat for the rufous-necked hornbill. A few studies on hornbills' habitat preferences have observed that marginal agricultural land is suitable for food and nesting (Nepal 2020; Sherub and Singh 2020; Mudereri et al. 2021). The response of the rufous-necked hornbill to land use and land cover was similar to that of its counterpart in Thailand, as revealed by a study carried out using MaxEnt modeling (Jinamoy et al. 2014). However, a study reveals that habitat in blue-pine and mixed conifer forests is less preferred by the rufous-necked hornbill.

Spatial analysis of the current and future potential geographic distribution

The current distribution of the rufous-necked hornbill

The current predicted distribution areas for the rufous-necked hornbill in Bhutan reveal that 11,284.7 km² (29.39%) are suitable and 27,100 km² (70.58%) are unsuitable. About 1454.36 km² of protected areas (national parks and wildlife sanctuaries) and 633.15 km² of biological corridors are suitable areas for the bird. Among the protected areas, Jigme Singye Wangchuck National Park (656.96 km²) and Royal Manas National Park (656.96 km²) are the potential areas for the rufous-necked hornbill. The model predicted a biological corridor connecting Phibsoo Wildlife Sanctuary, Jigme Singye Wangchuck National Park, and Royal Manas National Park (BC3) (351.75 km²) as the suitable habitat for this bird (Fig. 6).

The remaining 9197.19 km² of the potential habitat is outside the protected areas (Fig. 7), which are found in Sarpang, Dagana, Tsirang, Zhemgang, Chukha, Pemagatshel, and Mongar districts. Non-protected areas and settlements

Fig. 5 Response curves of 10 environmental variables: aspect (**a**), elevation (**b**), slope (**c**), land use land cover (**d**), annual mean temperature (**e**), mean diurnal range (**f**), precipitation of wettest month (**g**), isothermality (**h**), precipitation of driest month (**i**), and precipitation seasonality (**j**) of rufous-necked hornbill
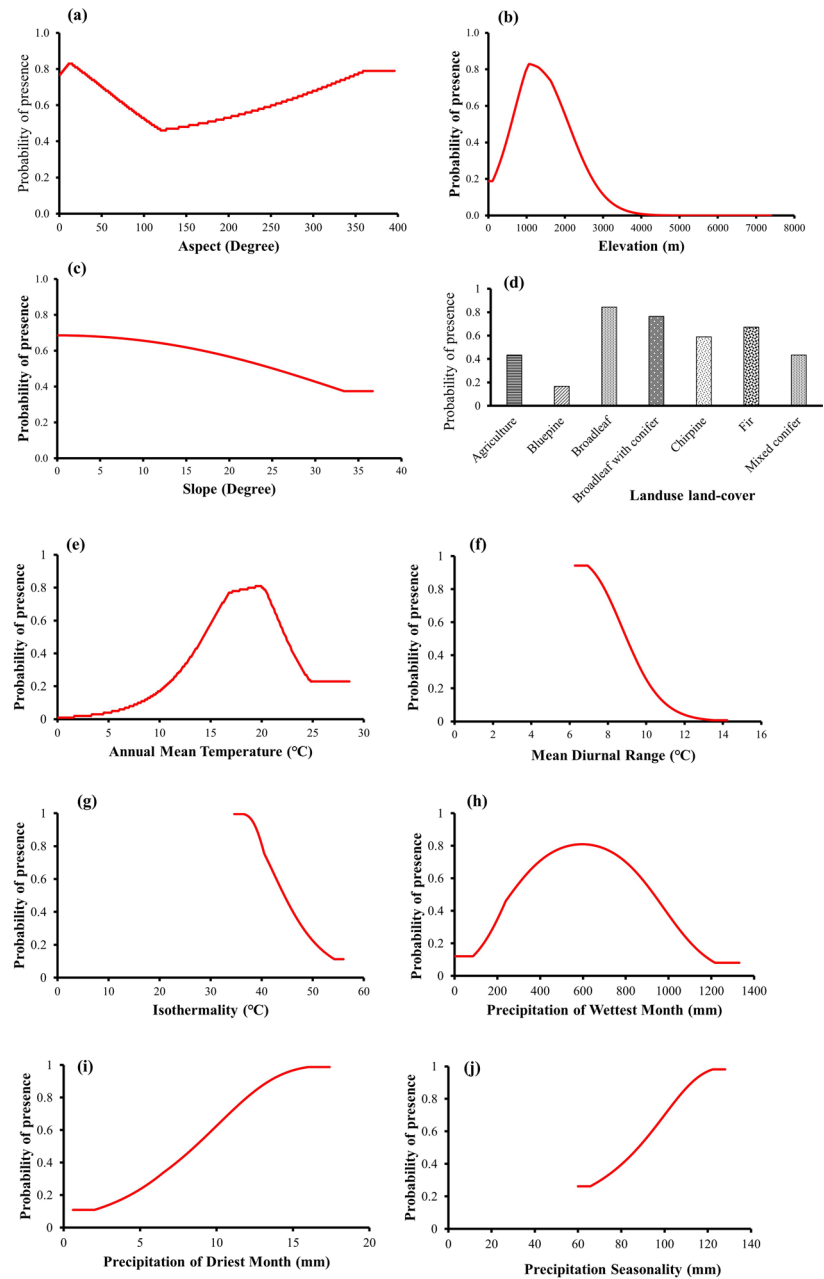
characterized by extensive cattle grazing and the periphery of agricultural land are the key habitats for the rufous-necked hornbill. The least suitable districts in northern Bhutan include Bumthang, Trashi Yangtse, Thimphu, Gasa, Paro, and Haa because of unfavorable climatic conditions, as shown in Fig. 7. The finding suggests that the rufous-necked hornbill prefers biological corridors and forest patches. Previous studies (Ugyen Wangchuck Institute for Conservation and Environmental Research 2017; Sherub and Singh 2020) also demonstrate that the rufous-necked hornbill is found mostly in large and small patches of forest and biological corridors in Bhutan. Similarly, this research aligns with the finding of rufous-necked hornbill distribution in the western

forest complex in Thailand, where hornbills are found in patches in the forest depending on fruit and nesting tree species (Trisurat et al. 2013; Jinamoy et al. 2014).

Predicted future suitable habitat of the rufous-necked hornbill in Bhutan

The habitat suitability changes of the rufous-necked hornbill within Bhutan under the current and future climate scenarios—SSP1-2.6 and SSP3-7.0—for the periods 2021–2040 and 2061–2080 are shown in Fig. 8. Although the study shows (Table 4) a slight shift in climate suitability, birds thrive to acclimatize to the new environment
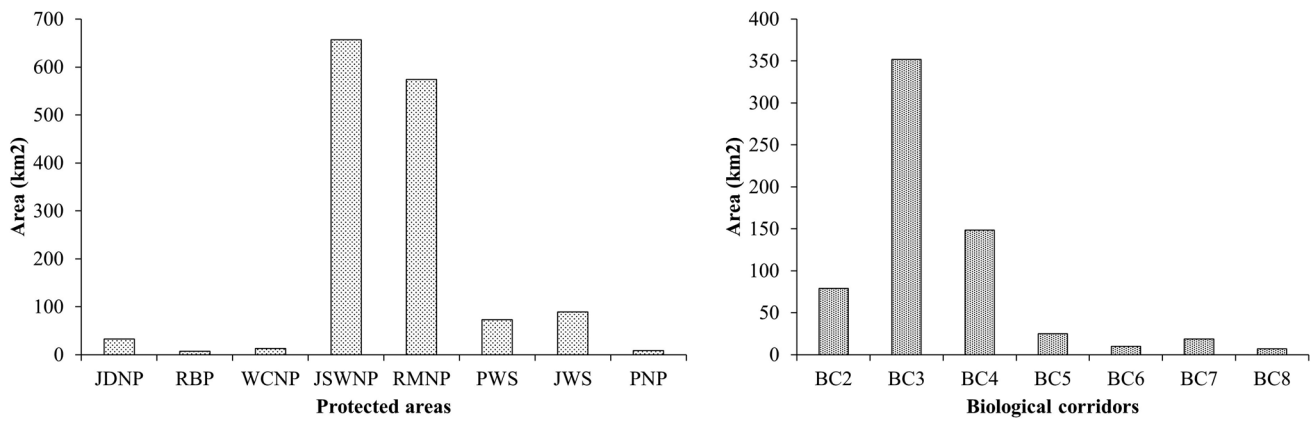
Fig. 6 Suitable habitat of rufous-necked hornbill in protected areas of Bhutan
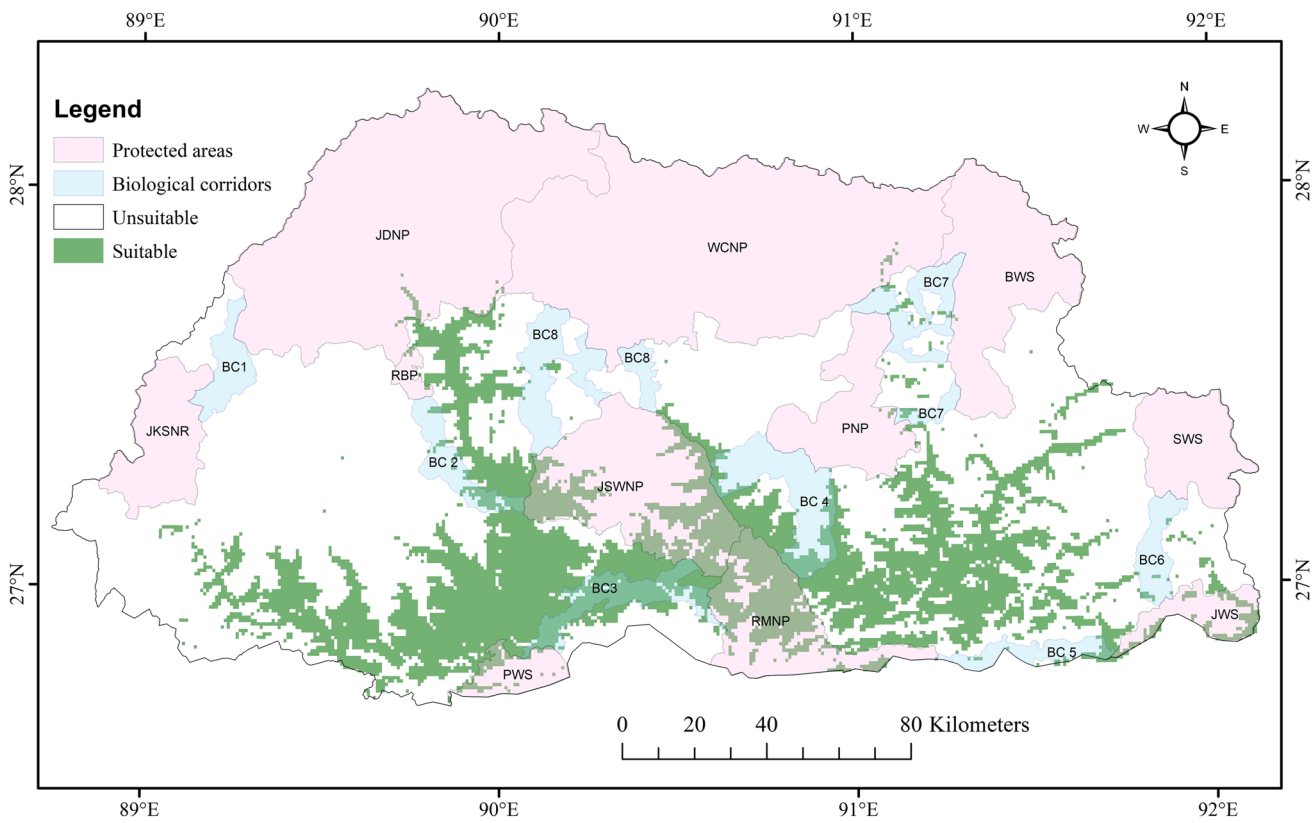

Fig. 7 Current distribution (2022) of rufous-necked hornbill in Bhutan

under changing climatic conditions (Jose and Nameer 2020; Sreekumar and Nameer 2022). Hornbills are sensitive to climate change, leading to stress and the risk of disappearing from the natural environment (Mudereri et al. 2021). The bird responds to varying distributional range shifts under different SSP scenarios with the constriction of potential areas in northern districts and expansion in the southeastern parts of Bhutan. This implies that

Fig. 8 Predicted rufous-necked hornbill distribution model for Bhutan under four different emission scenarios: SSP1-2.6 (2021–2040 and 2061–2080) and SSP3-7.0 (2021–2040 and 2061–2080)
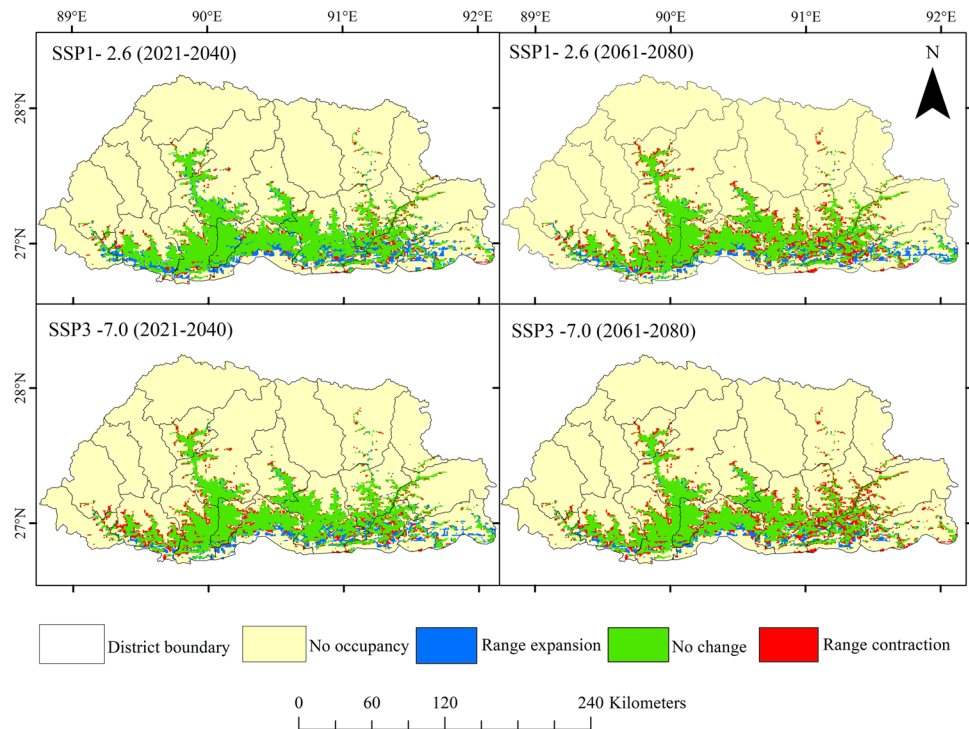
the habitats are subject to shift, mostly fragmenting them. The model shows a decline of 3.3% of the suitable area under SSP1-2.6 to 1.42% under SSP3-7.0.

The model predicts range contraction in the eastern part of Bhutan under SSP3-7.0 (2061–2080), which contradicts the general assumption that rufous-necked hornbills tend to move upwards in elevation due to habitat degradation, fragmentation, and climate change (Ugyen Wangchuck Institute for Conservation and Environmental Research 2017). The range shift will cause modifications to functional structures and the diversity of communities in the thriving habitat. As a result, conservation measures and project implementation should be prioritized in new habitats for the conservation of the rufous-necked hornbill in Bhutan.

Conclusion

A maximum entropy model was used to simulate the current and future habitat suitability of rufous-necked hornbills in Bhutan. The study is limited to climatic variables and topographic and land-use land-cover variables. The model predicts the decrease and fragmentation of the present suitable habitat of hornbills under different climatic scenarios. The finding shows the annual mean temperature and elevation as the most important variables for the distribution of the rufous-necked hornbill. The present suitable habitat shifts toward the southeast in the future. The projected spatial range shifts will be a useful reference for conservation measures of the rufous-necked hornbill in Bhutan.

Table 4 Predicted suitable areas for rufous-necked hornbill in Bhutan under future climatic conditions

	SSP1-2.6				SSP3-7.0			
Suitability	2021–2040 (area km²)	2021–2040 (% change)	2061–2080 (area km²)	2061–2080 (% change)	2021–2040 (area km²)	2021–2040 (% change)	2061–2080 (area km²)	2061–2080 (% change)
Range expansion	1278.32	3.3	907.19	2.35	886.16	2.29	549.54	1.42
No occupancy	29,863.46	77.26	30,153.80	78.02	30,174.84	78.07	30,511.46	78.94
No change	6639.87	17.18	5879.95	15.21	6171.13	15.96	5534.07	14.41
Range contraction	866.80	2.24	1609.89	4.16	1318.72	3.41	1955.77	5.06

The study suggests the protection of habitat along the biological corridors and non-protected areas for the conservation of the rufous-necked hornbill. Prediction of the presence of rufous-necked hornbills in agricultural land suggests making farmers aware of their presence in their localities. We recommend further studies and collaborations among researchers on rufous-necked hornbill distribution with the inclusion of factors such as distance from the road, river, and human settlement.

Declarations

Conflict of interest The authors declare no competing interests.

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