Fine-scale habitat suitability modelling of Northern red muntjac (*Muntiacus vaginalis*) in the Chitwan Annapurna Landscape, Nepal

Jagan Nath Adhikari[1,2,3], Bishnu Prasad Bhattarai[1,3*], Suraj Baral[4,5], Tej Bahadur Thapa[1]

[1]Central Department of Zoology, Institute of Science and Technology, Tribhuvan University, Kirtipur, Kathmandu, Nepal
[2]Department of Zoology, Birendra Multiple Campus, Tribhuvan University, Chitwan, Nepal
[3]Nepal Zoological Society, Kathmandu, Nepal
[4]Section of Herpetology, Leibniz Institute for the Analysis of Biodiversity Change–Museum Koenig Bonn, Bonn, Germany
[5]Biodiversity Research and Conservation Society, Kathmandu, Nepal

Abstract

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Factors associated with the habitat suitability of northern red muntjac (*Muntiacus vaginalis*) especially outside protected areas in the human-dominated landscape are still lacking. Fine-scale environmental variables can influence the habitat suitability of the animals. This study aimed to explore the different eco-geographic fine-scale variables for the distribution of the northern red muntjac; and predict suitable habitats using the maximum entropy (Maxent) model in the Chitwan Annapurna landscape (CHAL). The presence points of the northern red muntjac (n = 265) were collected between 2018 to 2021 using 150 transects of various lengths in four blocks. Density-based occurrence points rarify and performance-based variable selection were applied to improve the output of the model. The model was evaluated based on the area under the curve (AUC) value of operator characteristic (ROC) and analyzed on the basis of the response curve, the relative importance of variables, Jackknife test and suitability map. Results indicated the model was statistically satisfactory (mean AUC > 0.75). The distance to the nearest cropland was the most contributed variable followed by Normalized Difference Built-up Index (NDBI), distance to developed/settlement area and distance to grassland that explained suitability of Northern red muntjac. The species distribution model predicted 6.52% highly suitable and 23.77% suitable area for northern red muntjac. Therefore, this area is important for the muntjac and provides a possible alternative habitat for other wild animals outside the protected areas. Our research suggests that human dominated landscape should be prioritized in management plans for the conservation of muntjac.

Keywords

cervids, conservation, Maxent, protected area, species distribution model, suitability

Introduction

The knowledge of the spatial distribution and status of the species and their habitats are essential for effective conservation. This is useful for the conservationist, researchers and managers so that they can undertake effective conser-

*Corresponding author:
e-mail: bishnu.bhattarai@cdz.tu.edu.np, bhattaraibp@gmail.com

vation planning (Shrestha et al., 2010; Lu et al., 2012). Conservation of wildlife through protected areas (PAs) has been questioned on several fronts, as they can't cover all the suitable habitats and are not able to maintain the viable population of many species (Naughton-Treves et al., 2005). The habitats outside the protected areas also played a crucial role in the conservation of wildlife but these habitats are beyond the conservation priority (Karanth et al., 2010). Hence, in recent years, conservation outside the protected areas are also getting some attention by establishing the landscape-level conservation approaches (MOFSC, 2016). Landscape-level conservation actions are recommended by the World Heritage Convention (WHC) in 1972 (CBD, 1992). Then, the state declares the landscapes for conserving biodiversity. India has 10 biogeographic zones (e.g., Trans-Himalayan Region, Himalayan Zone, Indian Desert Zone, Semi-arid Region, Western Ghats, Deccan Plateau, Gangetic Plain, North East Region, Coastal Region and Islands) that cover 3,287,263 km^2 of the total geographic area (Balasubramanian, 2017; Jamal, 2020). Similarly, 10 top landscapes of China (e.g., Yellow Mountains Range, The Great Wall, West Lake, Hong Village, The Li River – an amazing karst landscape and blue waters, Tibet, Xinjiang – the largest province with various striking landscapes, Wuyuan, Zhangjiajie and Zhangye Danxia National Geological Park) play the vital role for biodiversity conservation (Knapp, 1992; Ge et al., 2020). The Government of Nepal (GoN) implements five landscapes (e.g., the Terai Arc Landscape (TAL), Chitwan Annapurna Landscape (CHAL), Sacred Himalayan Landscape (SHL), Kanchenjunga Landscape (KL), and Kailash Sacred Landscape (KSL)) and proposes two landscapes (e.g., Karnali Conservation Landscape (KCL) and Eastern Chure-Terai Complex (ECTC)) for conservation (MOFSC, 2016).

Northern red muntjac or barking deer (*Muntiacus vaginalis* (Boddaert, 1785)) (Fig. 1) is a shy and small-sized and widely distributed cervid across the South and Southeast Asia (Habiba et al., 2021; Singh et al., 2022). The population of northern red muntjac is decreasing in size, and has become isolated by scattered human settlements, urban areas and developmental activities (Jnawali et al., 2011). They can adapt to multiple habitat types and easily adapt to live in close association with humans (Mishra, 1982). The PA system plays a key role for the conservation of many herbivores but for northern red muntjac, conservation cannot be confirmed only in the PAs (Mishra, 1982). Among the herbivores, this deer is a habitat generalist and relatively abundant and distributed from a lower elevation to middle elevation ranges (up to 3,500 m) (Jnawali et al., 2011).

The middle mountains of Nepal are an intermediate landscape that connects the lowland Terai with the high Himal (WWF, 2013b). This middle mountain landscape has more species diversity than high mountain and high Himal in the country (Paudel and Bhattarai, 2012; Primack et al., 2013). However, the biodiversity of the middle mountain ecosystems is poorly explored, hence, there is limited information about the status and distribution of wildlife in the middle mountain. The middle mountains of Nepal are poorly represented in the protected area network too (Hunter and Yonzon, 1993; Shrestha et al., 2010; Paudel and Heinen, 2015). These mountains are human-dominated and highly fragmented due to human activities such as agriculture activities, livestock grazing, timber, firewood and fodder collections. These activities in the fragmented forest directly or indirectly affect the community structure of the wildlife, mainly the mammals like muntjac (Paudel and Heinen, 2015; Fahrig and McGill, 2019).

Species distribution models were often used by the researchers for evaluating the suitable habitats and possible corridors (Guisan and Zimmermann, 2000; Guisan and Thuiller, 2005; Hirzel and Le Lay, 2008; Paudel and Heinen, 2015; Huang et al., 2018). The species distribution modelling (SDM) is useful in predicting suitable habitats for threatened species (Guisan and Zimmermann, 2000; Guisan and Thuiller, 2005; Penjor et al., 2021). Species distribution modelling examines the environmental conditions in the locations in which records have been generated for the target species. It to extrapolate and predict the suitability across a wide area based on identified local environmental conditions (Elith and Leathwick,

Fig. 1. Studied mammal: Northern red muntjac (*Muntiacus vaginalis* (Boddaert, 1785)).

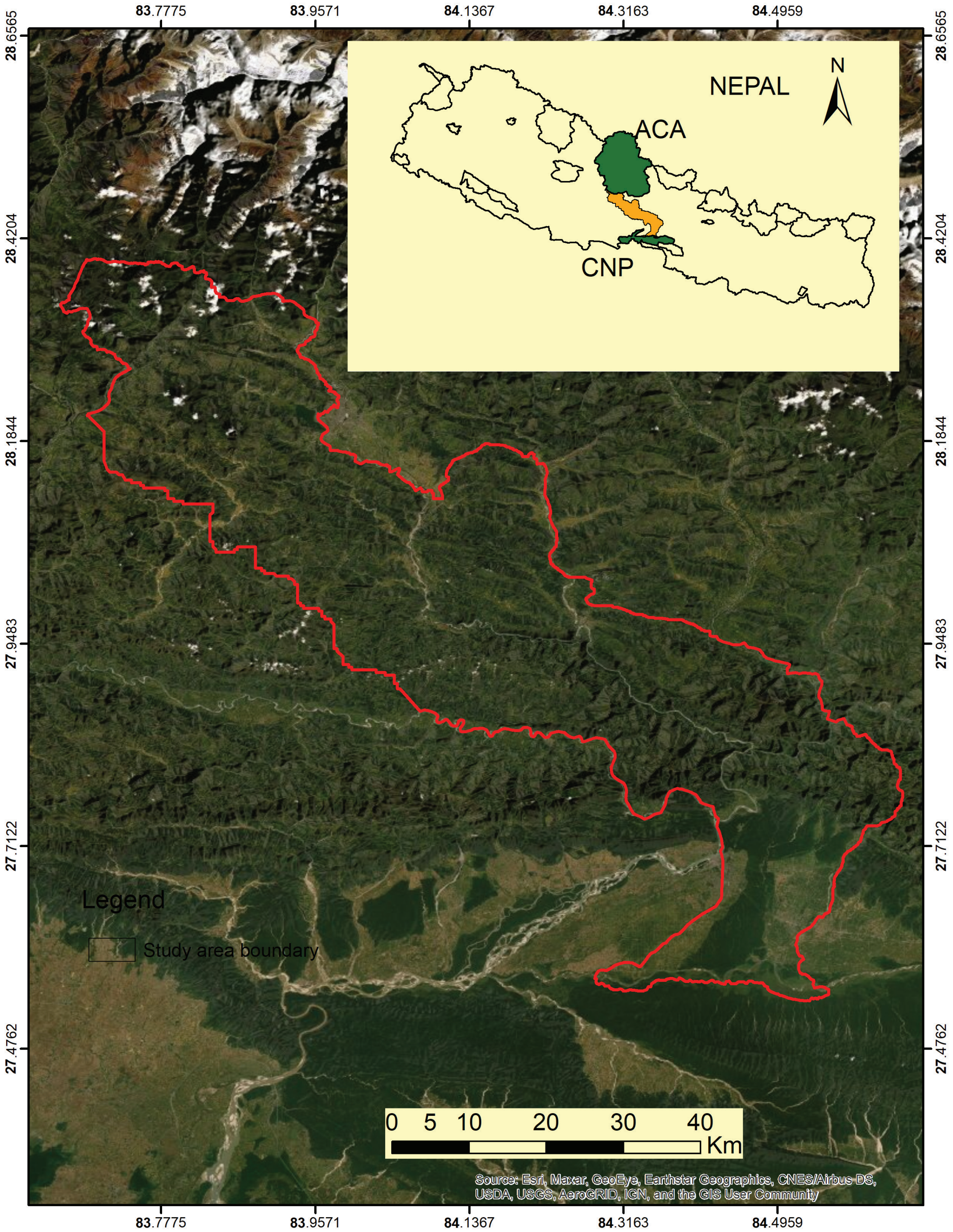

Fig. 2. Map showing the intensive study areas. Source: Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.

2009). For SDM, the Maximum Entropy algorithms (Maxent) has been commonly used (Phillips et al., 2006; Phillips and Dudík, 2008).

Several studies on SDM have been performed by using Maxent, e.g., for leopard (Maharjan et al., 2017; Sarkar et al., 2018), tiger (Kanagaraj et al., 2011; Battle, 2016), Asian elephant (Neupane et al., 2020; Sharma et al., 2020; Pla-ard et al., 2022), rhinoceros (Rimal et al., 2018) and snow leopard (Shrestha and Kindlmann, 2020). Most of these studies were focused on the protected area only. Still there is a lack of study on northern red muntjac outside the protected area in fine scale. Hence, this study focused on central part of Chitwan Annapurna Landscape that connects two biologically significant protected areas Chitwan National Park and Annapurna Conservation Area. We aimed to develop a fine-scale habitat suitability map and identify important environmental covariates for predicting muntjac in the central part of the Chitwan Annapurna Landscape (CHAL).

Materials and methods

Study area

The study area is an example of a biological corridor that connects two biodiversity-rich protected areas: Chitwan National Park (CNP), the world heritage site, in the south, and Annapurna Conservation Area (ACA), the largest protected area, in the north. The major parts of the study area represent middle mountain landscape and are rich in biodiversity, including three Global 846 Ecoregions (Terai–duar Savanna and Grasslands, Himalayan Subtropical Broadleaf Forests, Himalayan Sub-tropical Pine Forest) (Wikramanayake et al., 2002; Dinerstein et al., 2017). The study area ranges from 150 m to 3,300 m and covers 2,748.49 km^2 (Fig. 2). Our study focused on the central part of the CHAL which has given the highest priority corridor for landscape-level connectivity that extends 27.282ºN to 28.405ºN and 84.282ºE to 83.677ºE (WWF, 2013b). The lowland of this region has the tropical and subtropical type of climate, whereas middle mountain has a subtropical and temperate type of climate and the upper mountain region has the temperate and subalpine type of climate. The average annual minimum and maximum temperature reported from 1989 to 2018 were 4.84 °C (reported from Lumle station) and 39.32 °C (reported from Rampur, Chitwan station) respectively (DHM, 2019).

This landscape is highly fragmented and human-dominated, which is the home to many mammalian species including muntjac (WWF, 2013b). This area harbors two Ramsar sites (Beeshazari and associated lakes, Chitwan and Lake Clusters of Pokhara valley, Kaski) (NLCDC, 2020). CHAL is a prime habitat for mammals such as the tiger (*Panthera tigris* (Linnaeus, 1758)), Greater one-horned rhino (*Rhinoceros unicornis* Linnaeus, 1758), leopard (*Panthera pardus* (Linnaeus, 1758)), clouded leopard (*Neofelis nebulosa* (Griffith, 1821)), snow leopard (*Panthera uncia* (Schreber, 1775)), sloth bear (*Melursus ursinus* (Shaw, 1791)), Himalayan black bear (*Ursus thibetanus* G. [Baron] Cuvier, 1823), sambar (*Rusa unicolor* (Kerr, 1792)), chital (*Axis axis* (Erxleben, 1777)), musk deer (*Moschus chrysogaster* (Hodgson, 1839)), hog deer (*Axis porcinus* (Zimmermann, 1780)), Himalayan goral (*Naemorhedus goral* (Hardwicke, 1825)), etc., birds, herpetofauna, fish and many other micros and macroinvertebrates (Bhuju et al., 2007; WWF, 2013a).

Methods

Data collection

The presence data of northern red muntjac were collected from 2018 to 2021 through the sign survey and direct observation methods. The droppings and foot print of the muntjac are the reliable source of their presence. For the intensive study, the study area was divided into four different blocks regarding course of rivers, topography and landscape. These blocks were named as A, B, C and D (Fig. 3). Block A represents the low land of Terai (Barandabhar and associated area of Chitwan), Block B represents the mid-hill along with the part of Seti River of Tanahun district, Block C represents the part of mid-hill along Seti and Madi River basin and Block D represents the high hill along with the part of Annapurna Conservation Area of Nepal.

The size and the length of the transects were different according to the habitat type and size of the forest patches (Silveira et al., 2003). In the middle mountains, the habitats are highly fragmented, with variations in elevations, slopes, and aspects, and, as such, locating transects was more challenging than in the low lands (Paudel et al., 2015). At first, the habitat patches were identified using the base map, topographic map, then transects were designed. The transects were selected based on the dimension of the forest. The habitat patches were numbered and chosen randomly based on the landscape characteristics such as elevation, aspects, slopes, and heterogeneity. The distance between any two transects was more than 500 m. The location of transects was designed with the accessibility for walking. The inaccessible gorges, steep mountains, and swampy areas were avoided.

A total of 150 transects with 10 width (5 m on the either side of the central line) were laid that covered 477.7 km linear distance (average length ± SE = 3.18 ± 0.11 km, range = 1.18 to 7.84 km). Block A had 31 transects with the total linear distance = 138.64 km (average length = 4.47 ± 0.29 km, range = 1.72 to 7.84 km), block B had 35 transects (total length = 103.55 km, average = 2.96 ± 0.18 km, range = 1.18 to 5.6 km), similarly, block C had 38 transects with total linear distance 99.13 km (average = 2.61 ± 0.12 km, range = 1.31 to 4.39 km) and block D had 46 transects with the total linear length of 136.37 km (average = 2.96 ± 0.16 km, range = 1.58 to 6.02 km) (Fig. 3). The signs of the muntjac such as pellets (droppings), footprints were reported during the data collection by two observers for each side of transect. Two observers were walked along the transects for the data collection. The data were collected in one time from January to May and October to December. We avoided the data collection during rainy seasons, as the growing vegetation hides the animals and the rainfall washes away the signs. We also collected presence of northern red muntjac opportunistically from other possible sites of the study area (e.g., croplands). These presence coordinates were recorded by using the Global Positioning System (GPS – Garmin eTrex 10).

We collected 265 presence points which were spatially filtered by 30 m using the Spatially Rarify Occurrence Data tools in the SDMtoolbox 2.0. (Brown et al., 2017). A total of 264 filtered points were available for Maxent modelling.

Environmental variables

To minimize the risk of over-fitting the model and develop the most parsimonious model, the environmental variables were selected on the basis of field knowledge, experts' suggestions and an extensive literature review of northern red muntjac (Watts et al., 2019; Rather et al., 2020). The slope and terrain ruggedness index (TRI) were extracted by using the digital elevation model (DEM) in

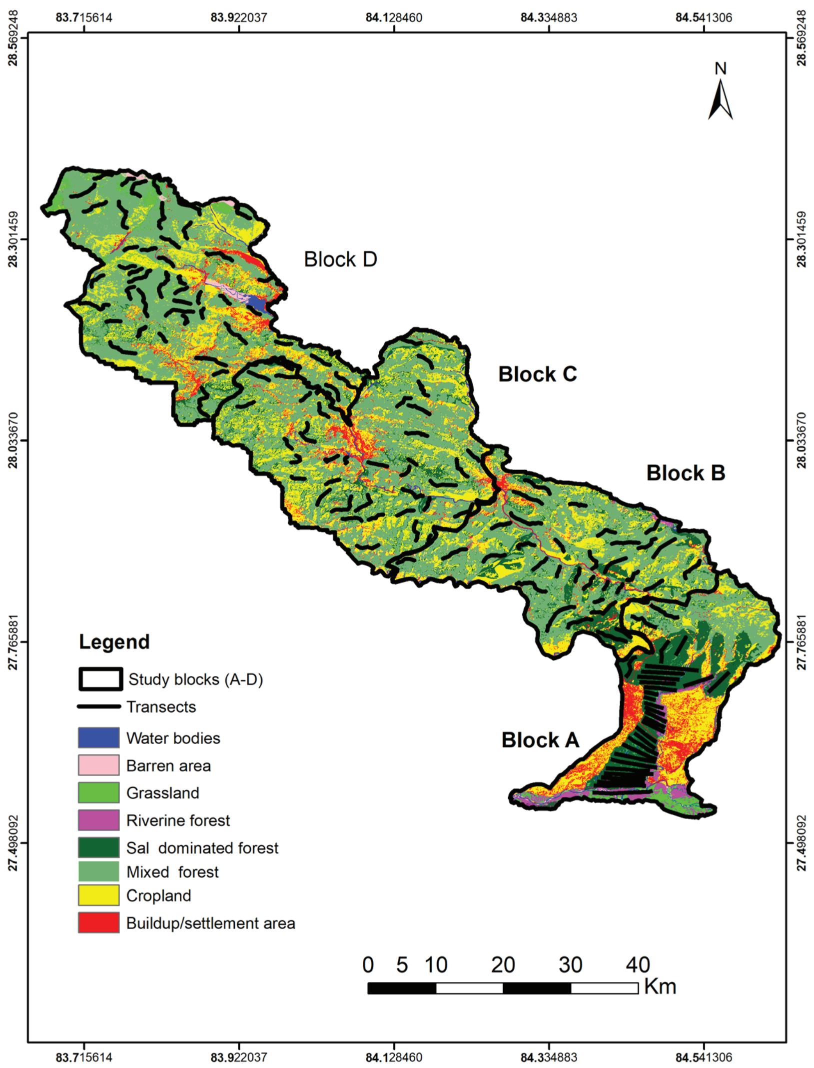

Fig. 3. Map showing the study blocks with transects. The land use and land cover classified in to eight categories: water bodies, barren area, grassland, riverine forest, sal dominated forest, mixed forest, cropland and developed/settlement area.

QGIS 3.20.3 (Team, 2022). The TRI is used to indicate the amount of elevation difference between adjacent cells of a DEM. TRI is calculated using equation 1.

$$TRI = \sqrt{\frac{1}{8}(x_{ij}-x_{00})^2} \,, \qquad (1)$$

where x_{ij} = elevation of each neighborhood cell to the central cell at 0,0, x_{00} = elevation of central cell at 0,0, and TRI = terrain ruggedness index. The classified image from Landsat (acquisition date 2020-03-17) (Landsat 8, Operational Land Imager (OLI)) by Adhikari et al. (2022) was used to find out the Euclidian distances to the nearest forest, grassland, water sources, developed area or human settlements and cropland. We performed supervised classification of the images into eight different classes (water sources, barren area, grassland, riverine forest, sal dominated forest, mixed forest, cropland and developed area) by using the ground-truthing points (Adhikari et al., 2022). Among these eight classes, we merged riverine forest, sal forest and mixed forest as single layer forest. We extracted water sources, grassland, forest, cropland and developed area from the available data and calculated Euclidian distances in ArcGIS Pro to be used as environmental variables for modelling.

The Normalized Difference Vegetation Index (NDVI) is the most popular vegetation index and is used to quantify the greenness of the vegetation, vegetation density and detect the changes in plant health (Pettorelli et al., 2011; Yengoh et al., 2015; USGS, 2022), hence we selected NDVI as one environmental layer for the muntjac. The NDVI was calculated by using red and Near Infrared Red (NIR) bands (Equation 2). The image has 30 m resolution and the width of the study area varies from 12.827 km to 34.47 km. The value of NDVI ranges from –1 to 1. NDVI value –1 to 0 represents the water sources, –0.1 to 0.1 represents barren rocks, sands, gravels or snow, 0.2 to 0.5 indicates the shrubs, grassland or crop land and the value 0.6 to 1 indicates the dense vegetation.

$$MNDWI = \frac{(Green–SWIR)}{(Green+SWIR)} \text{ or } \frac{(Band\ 3–Band\ 6)}{(Band\ 3+Band\ 6)} \qquad (2)$$

The modified Normalized Difference Water Index (MNDWI) is calculated by using the green and Shortwave Infrared (SWIR) bands as it enhances the features of open water (Equation 2). MNDWI also minimizes the features of developed areas which are correlated with open water in other indices (Xu, 2006; Xu and Guo, 2014). The MNDWI value ranges from −1 to +1. If the value of MNDWI is greater than 0, the cover type is water, and if it is less than or equal to zero, it is regarded as non-water bodies.

$$\mathrm{MDBI} = \frac{(\mathrm{SWIR–NIR})}{(\mathrm{SWIR+NIR})} \text{ or } \frac{(\text{Band 6–Band 5})}{(\text{Band 6+Band 5})} \quad (3)$$

The Normalized Difference Built-up Index (NDBI) is a ratio designed to minimize the effects of terrain brightness differences and atmospheric conditions. (Zha et al., 2003). Two spectral bands NIR and SWIR are used to enhance the build-up or developed area, thus differentiating built-up over the natural area. The value of NDBI ranges from –1 to 1 and was calculated using the equation (4). Higher NDBI positive values indicate the built-up area, while the negative values are regarded as non-build up area.

$$\mathrm{NDVI} = \frac{(\mathrm{NIR–R})}{(\mathrm{NIR+R})} \text{ or } \frac{(\text{Band 5–Band 4})}{(\text{Band 5+Band 4})} \quad (2)$$

The values of each environmental variable (n = 12) were extracted at presence locations (Table 1) and multicollinearity analysis of the variables was performed. We removed the variable with high correlation ($|r| \geq 0.7$) to reduce the redundancy in environmental variables (Table S1). The spatial resolution of 30 m and UTM 44N projected coordinate system was used for the modelling.

Running maxent

Maxent develops a model based on series of features (environmental variables) (Phillips et al., 2006). Two types of data are necessary for processing in the Maxent program: occurrence data and environmental layers. The CSV file containing occurrence points for the muntjac was uploaded into the samples section, while all chosen environment variable layers in ASCII format were uploaded into the

Table 1. The environmental variables selected for the modelling

Group	Variables	Predictor code	Description	Units	Original resolution (m)	Source
Habitat types	Distance to forest	Forest	Euclidean distancem to forest	m	30	Supervised classification of Landsat image 8 (OLI) of 2020 using ground truthing points
	Distance to grassland	Grass	Euclidean distance to grassland	m	30	
	Distance to water sources	Water sources	Euclidean distance to water sources	m	30	
	Habitat heterogeneity	Variety	Total number of habitat variables in 3 × 3 moving window	–	30	Classified image of 2020
Vegetation Index	Normalized Difference (NDVI)	ndvi_rv	Near Infrared (NIR) and Red bands used to calculate NDVI	–	30	Downloaded from https://earthexplorer.usgs.gov/
	Normalized Difference Water Index (MNDWI)	Mndwi	Green and SWIR bands used to calculate MNDWI	–	30	
Topographical variables	Elevation	ele	Elevation above sea level	m	30	Digital elevation model
	Slope	Slope	Gradient of slope	°	30	Digital elevation model
	Terrain Ruggedness Index (TRI)	Tri	Topographic heterogeneity	–	30	Digital elevation model
Disturbance variables	Distance to cropland	Crop	Euclidean distance to cropland	M	30	Supervised classification of Landsat image 8 (OLI) of 2020 using ground truthing points
	Developed and settlement area	Dev	Euclidean distance to developed area	M	30	
	Normalized Difference Built-up Index (NDBI)	Ndbi	Two spectral bands NIR and SWIR are used to enhance the build-up or developed area	–	30	Downloaded from https://earthexplorer.usgs.gov/

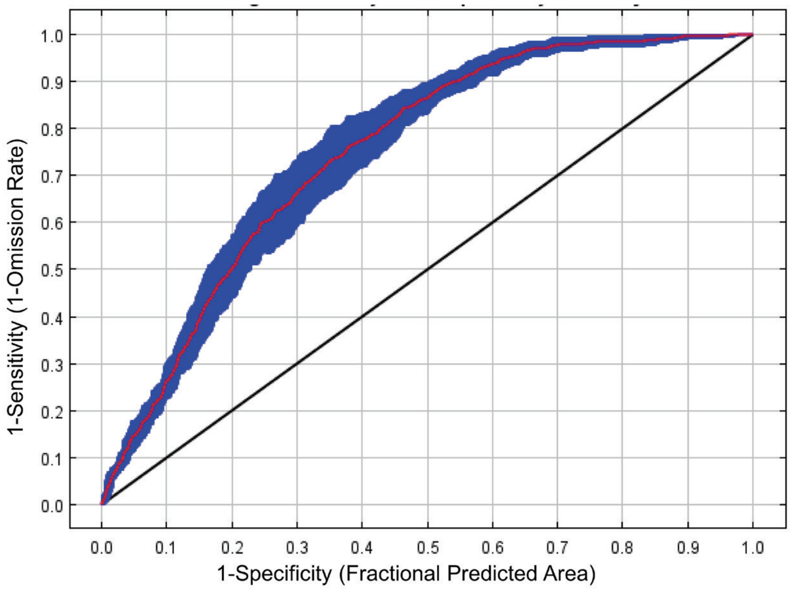

Fig. 4. The average area under curve (AUC) for 25 replicates of Maxent runs, this indicates the Receiver Operating Characteristics (ROC) (average Sensitivity Vs 1 – Specificity for northern red muntjac). Here, the red line is the mean value, blue bar indicates mean ± SD and black line is random prediction.

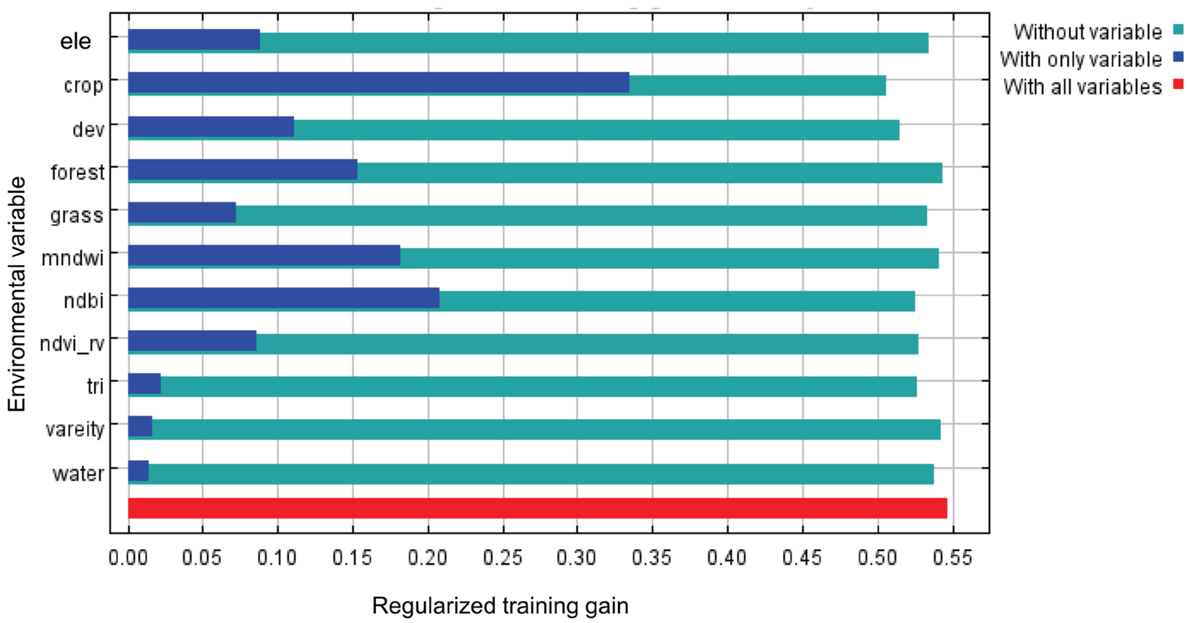

Fig. 5. The internal Jackknife test for evaluating the relative importance of environmental variables for habitat suitability of northern red muntjac.

environmental layer menu. The replicates and replicated run type were set to 25 and subsample, respectively. The Maxent model was run with ten iterations and 1,000 background points, using 70% of the points for training data and 30% for model validation. The model's output was logistic. The performance of the model was evaluated using AUC values from the receiver operating characteristic (ROC) plot analysis (Phillips et al., 2006; Phillips, 2008; Phillips and Dudík, 2008). The AUC values range from 0 to 1 (Fielding and Bell, 1997; Phillips et al., 2006; Qin et al., 2017). The AUC of below 0.5 indicates the model did not perform better than random, 0.5–0.6 indicates no discrimination, 0.6–0.7 indicates the discrimination, 0.7–0.8 indicates acceptable, 0.8–0.9 indicates excellent and 0.9–1.0 indicates outstanding (Phillips et al., 2006). Jackknife and sensitivity analysis were performed on each variable to determine the contribution of the variables and importance to the model. The final habitat suitability maps were prepared by converting average prediction of the 25 replicates. The value of the suitability map ranges from 0 to 1. The logistic probability of suitability was further regrouped as 0–0.2 = unsuitable, 0.2–0.4 = moderately suitable, 0.4–0.6 = suitable and 0.6–1 = highly suitable (Ansari and Ghoddousi, 2018; Kogo et al., 2019). All

Table 2. The environmental variables with their percentage contribution and permutation important in the Maxent model on habitat suitability of northern red muntjac in CHAL Nepal

Variable	Code	Contribution (%)	Permutation importance
Distance to cropland	crop	55.4	28.7
Normalized Difference Built-up Index (NDBI)	ndbi	11.8	16.7
Distance to developed and settlements area	dev	7.5	12.3
Distance to grassland	grass	6.5	4.6
Normalized Difference Vegetation Index (NDVI)	ndvi_rv	5.9	10.4
Terrain Ruggedness Index (TRI)	tri	3.8	8.9
Distance to forest	forest	3.2	3.5
Elevation	alt	3	5.6
Normalized Difference Water Index (MNDWI)	mndwi	1.2	3.3
Distance to water sources	water	1.1	4.7
Index of habitat heterogeneity	vareity	0.7	1.3

the spatial analysis and classification were performed in ArcGIS Pro.

Results

The species distribution modelling of northern red muntjac was predicted from the Maxent model with satisfactory statistical accuracy (mean AUC ± one standard deviation = 0.75 ± 0.03) (Fig. 4). The results of the internal Jackknife test of variable importance showed that the variables with higher importance in predicting habitat suitability were distance to cropland and NDBI (Fig. 5). These two variables had higher contribution than other variables, hence presented the higher gain than other variables (Fig. 5). Likewise, the results obtained from the response of the model to each variable showed similar results with internal Jackknife test of variable importance. Distance to cropland was the most contributing variable that alone positively contributed 55.4% followed by negative contribution of NDBI (16.7%), first positive and then negative contribution of distance to developed and settlements areas (7.5%), negative contribution of distance to grassland (6.5%), and positive contribution of NDVI (5.9%), whereas other environmental variables such as TRI, distance to forest, elevation, MNDWI, distance to water sources and index of habitat heterogeneity contributed less than 4% (Table 2).

The response curves showed the relationship between each environmental variables and occurrence probability of northern red muntjac (Fig. 6). The response curves revealed that the distance to nearest cropland played positive role in the probability of occurrence of northern red muntjac with rapid increase till 250 m and more or less constant afterwards (Fig. 6a) but probability of occurrence sharply decreased on increasing the NDBI (Fig. 6b). Similarly, negative response was seen on increasing the distance from developed/settlement areas (Fig. 6c) and the grasslands was considered as more suitable for muntjac and the probability of occurrence was seen higher nearer the grassland and reduced as the distance from the grassland increased (Fig. 6d). On increasing the value of NDBI, the probability of occurrence of muntjac was also decreasing (Fig. 6e) and TRI (up to 140) was suitable (probability of occurrence > 0.4) (Fig. 6f). The distribution of muntjac was predicted comparatively higher inside the forest and showed negative but constant response on increasing the distance from forest (Fig. 6g). The elevation ranges from 158 m to 3,300 m, but the probability of occurrence was higher in the low elevation (up to 300 m) and mid elevation (2,000 to 2,500 m) (Fig. 6h). Similarly, low MNDWI shows a bell distribution with a maximum in the middle (at –0.1) and sharply drop on either side of the values (Fig. 6i). Last two environmental variables (distance to water sources and habitat heterogeneity) had a minimal effect on the model. Proximity to water sources (Fig. 6j), slightly increasing habitat heterogeneity (Fig. 6k) were suitable for muntjac.

Potential distribution of northern red muntjac

The Maxent model predicted that more than 55% of the total area of CHAL was suitable for northern red muntjac (Fig. 7, Table 3). The Barandabhar Corridor Forest and surrounding area, Panchase Protected Forest and lower part of the Annapurna Conservation Area contained the most suitable habitats for the muntjac.

Discussion

The habitat quality of the northern red muntjac in the central part of CHAL was preliminarily determined using species distribution modelling using Maxent. This modelling was also used by Jianping et al. (2020) to assess the habitat suitability of black muntjac in the Gutianshan National

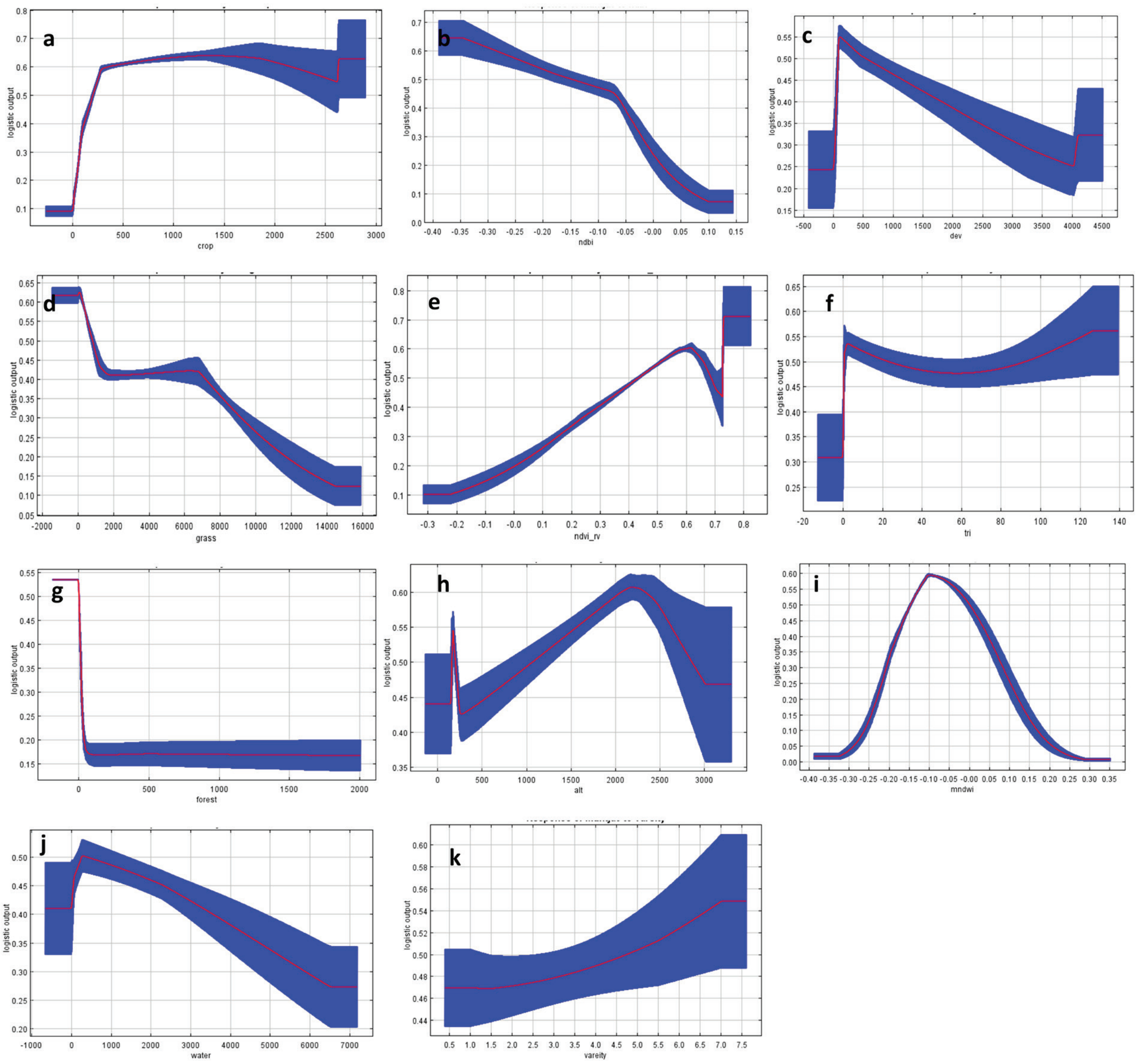

Fig. 6. Relationships between the environmental predictors and the probability of occurrence of northern red muntjac. The response curves were arranged on the basis of percentage of their contribution as shown in Table 2 (x-axis names: for codes see Table 2; y-axis names: logistic output). (a) distance from nearest cropland (m), (b) NDBI – Normalized Difference Built-up Index, (c) distance to developed /settlements area (m), (d) distance to grassland (m), (e) NDVI – Normalized Difference Vegetation Index, (f) TRI – Terrain Ruggedness Index, (g) distance to forest, (h) elevation (m), (i) MNDWI – Modified Normalized Difference Water Index, (j) nearest distance to water sources, (k) Index of Habitat Heterogeneity.

Nature Reserve (GNR) of China. The modelling showed that low, moderate and high specifications with different selected environmental parameters. Interestingly, northern red muntjac was the generalist species which was reported in all types of habitats, elevation and landscape gradients.

This study developed fine-scale habitat suitability maps. Environmental variables at fine-scales provided the clear picture of their effect on the habitat suitability than large-scales analysis (Krishnamurthy et al., 2016; Sarkar et al., 2017). As increasing the scale-size, the exact effects of the environment variables on the distribution of mammals may loss and provide the less information in which they reside or explore (Sarkar et al., 2017). Our study found that northern red muntjac responded to fine-scale environmental variables and the probability of occurrence of the northern red muntjac was best fitted and explained by the functions of different environmental variables. Identification of different environmental variables that determine the probability of suitability for northern red muntjac will help formulate appropriate conservation decisions.

According to this study, the distance to cropland was the most contributing variable followed by NDBI, distance to developed/settlement area and distance to grassland for prediction of northern red muntjac distribution. The occurrence probability was increasing as the distance of developed/settlement area increases up to 500 m and then decreasing. In the mid-hills, the settlement areas and forest

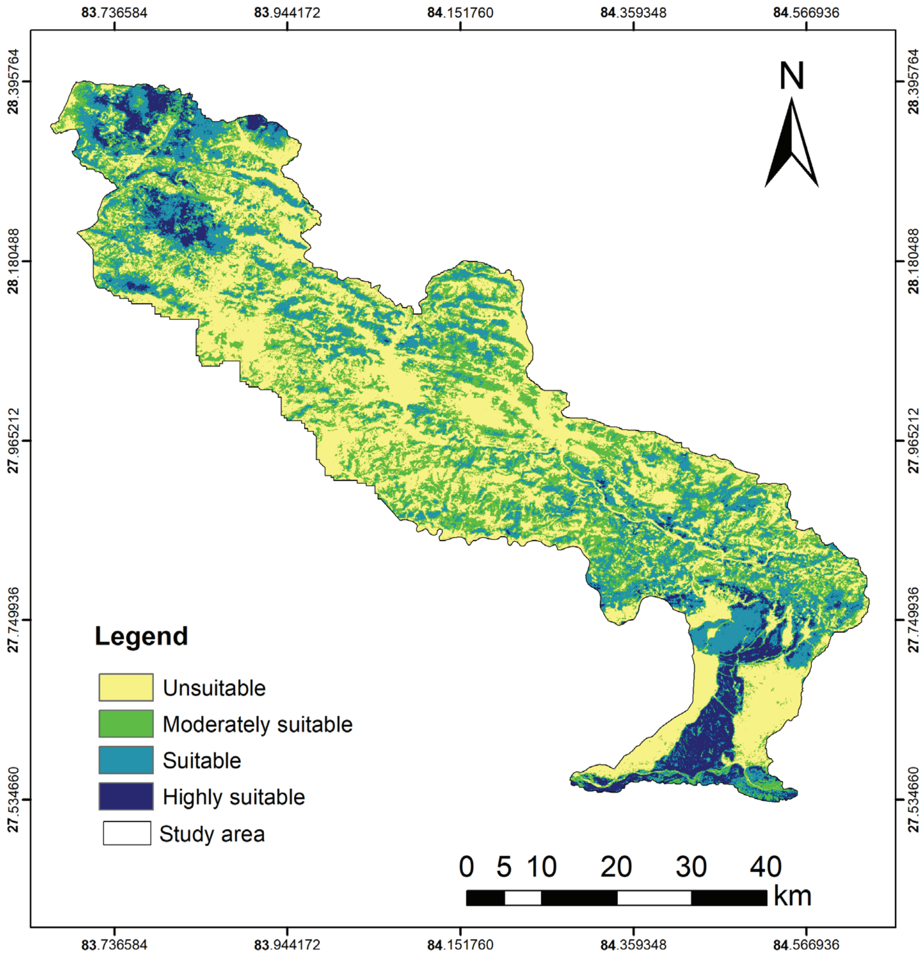

Fig. 7. Predicted potential suitable habitats of northern red muntjac using Maxent modelling divided into categories based on Maxent prediction of suitability, split into four categories, unsuitable, moderately suitable, suitable and highly suitable.

Table 3. Predicted potential suitable habitat area of northern red muntjac in Chitwan Annapurna Landscape, Nepal

SN	Group	Logistic probability of suitability	Area (km²)	Area ratio (%)
1	Unsuitable	0–0.2	1,228.53	44.68
2	Moderately suitable	0.2–0.4	688.24	25.03
3	Suitable	0.4–0.6	653.49	23.77
4	Highly suitable	0.6–1.0	179.22	6.52
Total			2,749.48	100

were very near. The muntjac entered into the settlement areas for grazing. Hence, these were reported in the vicinity of the developed or settlement areas. Sometimes they were reported from the croplands nearer to the settlements as they enter the nearby cropland for grazing purpose as these are less sensitive to human disturbance (Mishra, 1982; Bhattarai and Kindlmann, 2012). The scattered distribution of northern red muntjac was seen in the middle mountain of Tanahun and Kaski as it is a human-dominated landscape and human settlements along with croplands are scattered. The northern red muntjac is a habitat generalist species that is recorded from low elevation to high elevation (up to 3,500 m) in Nepal (Jnawali et al., 2011). In this study, we found that Northern Red Muntjac can adapt in the open and rugged mountain area. Increasing terrain ruggedness index (TRI) up to 140 increased the suitability of the muntjac, but highly steep area limits them to the proximity of the croplands and human settlements nearer to forest (Paudel et al., 2012).

The area of forest of middle mountain landscape is increasing due to the effective implication of community forests in Nepal (Baralet al., 2018). The previous studies pointed about one third of agricultural land in the middle mountains of Nepal has already been abandoned and the people migrate to the urban and semi-urban area on the valley floors (Paudel et al., 2012; Adhikari et al., 2022). This migration process leads to an increase forest cover in rural area with the landscape becoming more suitable for the northern red muntjac. Two protected forests (BCF and Panchase) and protected areas (part of

ACA and CNP) were identified as having habitat with a high level of suitability for the species. In the less protected and human dominated landscape, human settlements and disturbance limit the occurrence of this species and their movements to small patches of the forest (Paudel et al., 2012).

Conclusions

This study highlights the importance of species distribution modelling for the conservation of northern red muntjac. Identification and prediction of the suitable habitats and the variables that affect the distribution can be useful baseline evidence for further researchers and planners. This study recommends: (1) Before managing the landscape-level habitat for muntjac and other sympatric herbivores, a habitat suitability study of these animals is undertaken for all species in the relevant area. It is essential that this is then used for developing conservation planning, strategies to improve the habitat quality and long-term viability of the populations concerned. (2) Landscape-level conservation and local landscape management of large mammals in this landscape like muntjac. (3) Muntjac is the principal prey of leopard, the study recommends the conservation of pointed priority areas of this study for the conservation of muntjac as well as other predators like leopard.

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