Research Article:

FACTORS PREDICTING HABITAT SUITABILITY FOR THE OCCURRENCE OF GAUR USING ENSEMBLE MODELING IN CHITWAN NATIONAL PARK OF NEPAL

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ABSTRACT

Gaur, a large herbivore native to South and Southeast Asia, supports ecosystem health by enhancing soil sustainability, promoting plant growth, and aiding plant succession. In Nepal, their presence is limited to the protected habitats of two lowland (Terai) protected areas: Chitwan National Park (CNP) and Parsa National Park (PNP). However, information on the habitat factors influencing Gaur occurrence is limited, yet is essential for improving the existing habitats of this keystone species and prioritizing conservation efforts within the protected area. To address this gap, our study used an ensemble modelling approach to predict Gaur habitat suitability and identify key factors influencing their occurrence in CNP, Nepal. To gather data on Gaur's presence points, field-based surveys were conducted in April and May 2021, including periodic censuses and annual monitoring. Their presence was verified through direct observations, identification of pellet droppings, and hoofmarks found within the park. Ensemble modeling identified approximately 183.53 km^2 within the CNP as highly suitable habitat for Gaur, representing 2.1% of the buffer zone and 97.9% of the core area. Of the 33 variables used to construct the habitat suitability model, human population density, slope, and livestock density were the most influencing factors. For long-term Gaur conservation, our study recommends prioritizing habitat management by strictly limiting human activities and livestock grazing in the core of CNP.

Keywords: *Bos gaurus*, CNP, habitat, lowland, occurrence

INTRODUCTION

The Gaur (*Bos gaurus*), commonly known as 'Indian Bison' or 'Gauri Gai', is the largest member of the Bovidae family, are mega herbivore and provides significant ecological services, including nutrient cycling, promoting plant growth, dispersal, soil sustainability, facilitating plant successional processes, and maintaining diversity and distribution of plant species (Augustine and McNaughton, 1998; Hobbs, 1996). The species is listed as vulnerable under the IUCN Red List of Threatened Species and listed under Appendix I of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) (Duckworth et al., 2016). In Nepal, Gaur is designated as a protected under the National Park and Wildlife Conservation Act, 1973 (GoN, 1973). It is found in Bhutan, Bangladesh, China, Cambodia, India, Burma, Peninsular Malaysia, Thailand, Nepal, and Vietnam. The global population is estimated at 15,000 to 35,000 individuals (Duckworth et al., 2016).

Gaurs inhabit evergreen, semi-evergreen, and moist deciduous forests, with some occurrence in dry deciduous forests at the edges of their range (McShea et al., 2011). The species prefer to live in contiguous natural habitats that are less influenced by human disturbances and interventions (Ding et al., 2018). They usually graze in the open grasslands during mornings and evenings and spend long hours of daytime inside the forest (Choudhury, 2002). The major vegetation types that Gaur prefers include the Sal (*Shorea robusta*) forest and the grasslands, and they primarily prefer flat terrain rather than steeper slopes (Sankar et al., 2013). They require more habitat space and food than smaller or medium-sized herbivores (Chetri, 2006). In Nepal, they occur mainly in S. robusta forests within the Churia Bhabar area in Parsa National Park (PNP), Chitwan National Park (CNP). The total estimated population is 473 individuals (DNPWC, 2020). In most range countries including Nepal, Gaurs face conservation threats including habitat loss and encroachment, poaching for meat and horns, zoonotic diseases, invasive species, competition with domestic cattle, and human-Gaur conflict (Ashokkumar et al., 2011; Choudhury, 2002; Duckworth et al., 2016). Moreover, limited scientific information on their habitats and the ecology restricts long-term conservation in Nepal (DNPWC, 2020).

The occurrence and distribution of Gaur are influenced by various ecological, anthropogenic, and climatic parameters (Ariffin et al., 2021; Imam and Kushwaha, 2013; Kumar and Karanth, 2020; Paliwal and Mathur, 2012; Prayoon et al., 2024, 2021; Sankar et al., 2013). The ecological parameters affecting Gaur's occurrence and distribution include forest type, forest density, canopy cover, ground cover, land use, elevation, water distance, and slope (Imam and Kushwaha, 2013; Paliwal and Mathur, 2012; Prayoon et al., 2024, 2021). Moreover, the anthropogenic parameters influencing the Gaur's occurrence and distribution include distance from the road, human footpath, and settlements, as well as livestock density, and livestock grazing (Ariffin et al., 2021; Kumar and Karanth, 2020). Bioclimatic variables, including annual mean temperature, temperature seasonality, annual precipitation, and precipitation seasonality, may have affected Gaur habitat suitability in the past, present, and may be in the future as well (Prayoon et al., 2021). Based on the available scientific information on ecological, anthropogenic, and climatic parameters affecting the occurrence and distribution of Gaur across its range countries including, India (Sankar et al., 2013), Bhutan (Zangmo et al., 2018), China (Ding et al., 2018), Thailand (Prayoon et al., 2024, 2021), and Peninsular Malaysia (Ariffin et al., 2021), it is evident that Nepal, despite being one of the Gaur stronghold range countries, lacks such studies to date. Previous studies on Gaur in Nepal were focused only on its food habits and diet analysis (Chetri, 2006, 2003). Recently, a few studies have explored summer habitat use in CNP (Poudel et al., 2024) and habitat and occupancy mapping in Parsa National Park (Bhattarai et al., 2025; Dhakal et al., 2025).

Targeted conservation planning and habitat management efforts need up-to-date information on the important factors affecting species distribution and their predicted habitat suitability (Ashcroft et al., 2011; Klaassen and Broekhuis, 2018). Such information could be more crucial for habitat-specialized mega herbivores with specific ecological niches and a larger ecosystem impact, such as Gaur.

Species distribution models (SDM), or ecological niche modeling, are important tools widely used in ecology, biogeography, and conservation science (Hao et al., 2019). SDM technique uses species presence data and explains the relationships between species distribution and their associated ecological and environmental factors to delineate the suitability of current habitat (Ahmad et al., 2019; Guisan and Zimmermann, 2000). SDM can be employed in the conservation planning process of threatened species by identifying the ecological niche and its potential distribution, as well as for selecting the targeted species habitat for appropriate management interventions (Adhikari et al., 2019; Joshi et al., 2022; Nakao et al., 2013; Sharma et al., 2022). Moreover, Species Distribution Modeling is essential for assessing the historical and future effects of climate change on species, which is essential for achieving conservation objectives and understanding how the species' distribution may change in response to climate impacts (Dormann et al., 2007). Ensemble modeling, also known as ensemble forecasting, has become increasingly popular in SDM in recent years. This approach integrates multiple algorithms to improve projection performance (Hao et al., 2020). This approach combines predictions from individual SDM models to produce more accurate species distribution predictions, known as 'ensemble' predictions (Araújo and New, 2007; Kaky et al., 2020). Furthermore, ensemble modelling techniques systematically evaluate species distribution models and their projected variations under future climate change using the BIOMOD package in R (Thuiller et al., 2009).

This study was carried out to analyze how bio-climatic, bio-physical, anthropogenic, and topographic variables influence the distribution and occurrence of Gaur in CNP using an ensemble modeling approach. This research will aid in identifying suitable future habitats for the Gaur, supporting habitat connectivity and long-term conservation of this globally threatened mega herbivore.

RESEARCH METHODS

Study area

This study was conducted in Chitwan National Park (CNP), Nepal (Latitude: 27°20'19"N to 27°43'16"N; Longitude: 83°44'50"E to 84°45'03"E) as shown in Fig.1. CNP is Nepal's first national park and is listed as a UNESCO World Heritage site. Encompassing a vast area of 952.6 km² in the tropical lowland of Nepal known as Terai, CNP is accompanied by buffer zones spanning an additional 729.37 km² and located in southern Central Nepal, which covers Chitwan, Nawalparasi, Parsa, and Makwanpur Districts. It consists of tropical and subtropical forests dominated by *S. robusta* covering 70%, while grassland covers 20% of the park, and the buffer zone comprises similar forest types and croplands. The park supports significant biodiversity, with 68 mammal species, 576 bird species, 49 herpetofauna species, 120 fish species, and various invertebrates (CNP, 2015). CNP has the largest population of Royal Bengal Tigers among Nepal's national parks, with an estimated 128 individuals (DNPWC, 2023). Furthermore, CNP houses a significant population of the Greater one-horned rhinoceros, ranking second globally after India's Kaziranga National Park (Pant et al., 2020). The combined area of CNP, PNP, and their surrounding forest habitats supports Gaur population (DNPWC, 2020). With an average group size of 4.36 during winter and 5.81 during summer, CNP provides a favourable habitat for Gaur (Bhattarai and Kindlmann, 2018).

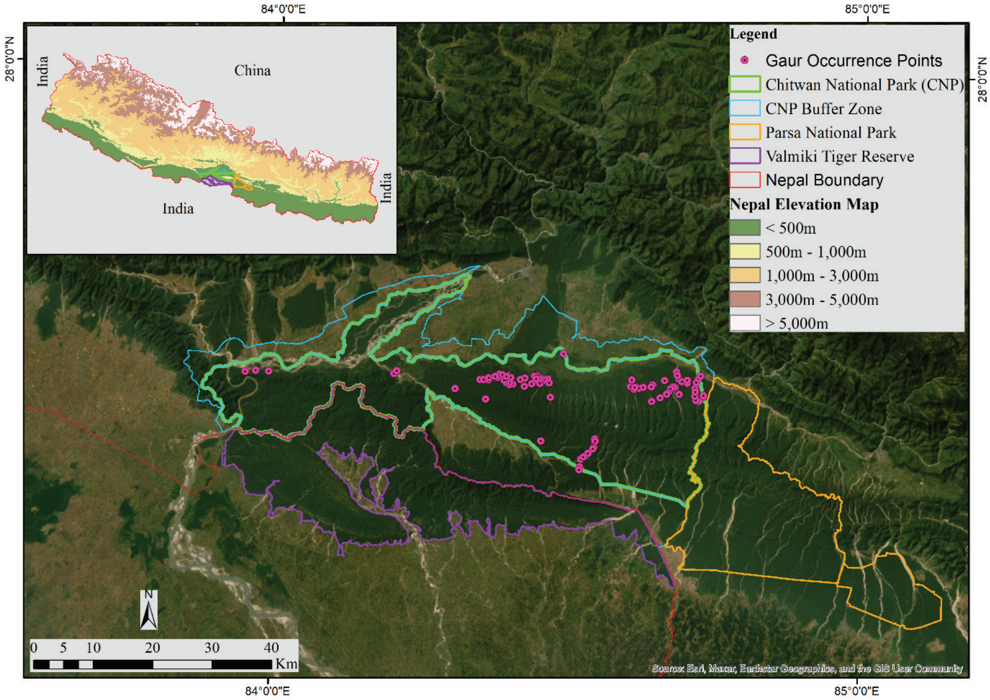

Fig. 1. Study area map showing Chitwan National Park (green outline), its buffer zone (blue outline), adjacent Parsa National Park (orange outline), and Gaur occurrence points before cleaning (pink circles) within the elevation map of Nepal, and Valmiki Tiger Reserve (violet outline) of India.

Data collection

Field survey

The gaur occurrence data used in this study were obtained from the official gaur census conducted in 2021 within Chitwan National Park (CNP, 2021). The census was designed to estimate the population status and spatial distribution of gaur across the park. The survey area was divided into 13 census blocks, each surveyed independently by a dedicated field team. Data collection was conducted over three consecutive days using direct head-count methods, with two trained observers mounted on elephants in each survey team. Observers were equipped with Global Positioning System (GPS) units, binoculars, and standardized data sheets. GPS coordinates were recorded for every gaur sighting, providing spatially explicit occurrence data for subsequent analyses. A total of 98 georeferenced gaur occurrence records were obtained and used as the initial dataset for habitat suitability modeling.

To minimize bias arising from spatial autocorrelation and uneven sampling intensity, spatial filtering was applied using the SpThin package in R (Aiello-Lammens et al., 2015). A minimum thinning distance of 1 km was used, corresponding to the spatial resolution (1 × 1 km) of the environmental predictor variables. After spatial thinning, 58 independent occurrence points were retained for subsequent habitat suitability analyses.

Environmental variables (habitat factors)

Bioclimatic, anthropogenic, topographic, and vegetation variables in the habitat suitability model was combined and only significant predictors were included, as variable selection is essential in species distribution modeling (SDM) (Araújo and Guisan, 2006). 33 variables were compiled for Gaur's habitat suitability modeling as they are considered crucial in determining their preferred habitat (Table 1) (Zeng et al., 2016). Numerous studies have also adopted such variables to predict habitat suitability; for instance, Dhami et al. (2023) mapped the habitat suitability of the Blue Bull. Bioclimatic variables are ecologically important, as they describe annual trends, seasonality, temperature and precipitation extremes so they are widely used in spatial modelling (Hijmans, 2012; Hijmans et al., 2005). Altogether 19 bioclimatic variables were obtained from WorldClim-Global Climate Data (www.worldclim.org/bioclim) in grid format with a spatial resolution of 1×1 km (Fick and Hijmans, 2017).

Our model included six anthropogenic variables: distance to human paths, distance to roads, distance to settlements, human population density, livestock density, and land use or land cover data. Data on paths, roads, and buildings was obtained from Geofabrik's website (GEOFABRIK, 2022). Settlement data were obtained from the Department of Survey, Nepal and a distance raster file was generated using ArcMap10.8.1 (ESRI, 2020). Land use and land cover change, human population density, and livestock density data were obtained from (Thuiller et al. 2020), the ICIMOD Humanitarian Data Exchange Dataset (HDX, 2022), and Open Data Nepal (ODM, 2022), respectively.

Elevation, aspect, and slope data were extracted from a 1 km resolution Digital Elevation Model (DEM) from the US Geological Survey database (USGS, 2022) using ArcMap (ESRI, 2020). Geofabrik's website was used to extract the shapefiles of water sources (GEOFABRIK, 2022) and converted to a distance raster file using ArcMap10.8.1 (ESRI, 2020).

In this study, four vegetation-related variables were used: forest cover, minimum EVI, mean EVI, and maximum EVI. Forest cover data was obtained from the Earth Engine partner Appspot (Hansen et al., 2013), while EVI time-series data was sourced from MODIS (USGS, 2022). The Savitzky-Golay filter was used in the TIMESAT algorithm (Jönsson and Eklundh, 2004) to minimize cloud cover and enhance image visualization. Mean values of all indices were calculated to produce the final EVI index.

Similarly, a multi-collinearity test was carried out on 33 environmental variables, removing those with correlation coefficients above 0.7 and variance inflation factors above 5 to prevent collinearity (Dormann et al., 2013). Finally, 9 predictor variables were then selected for habitat suitability modelling of Gaur (Table 1).

The selection of environmental variables for Gaur is appropriately justified by its ecological requirements. Gaur is known for its remarkable adaptability across various habitats, ranging from sea level to 2,800 meters above sea level, with a strong preference for lowland regions (Choudhury, 2002; Wharton, 1968). This preference is supported by undisturbed forests, rich evergreen, semi-evergreen, and moist deciduous vegetation, as well as an abundance of water sources and forage availability (Schaller, 2009). Temperature and precipitation are crucial for providing prefer habitat in a particular location. Although there is no significant difference in Gaur densities between moist and dry deciduous forests (Karanth and Sunquist, 1992), human disturbances, undulating terrain, and the effectiveness of conservation efforts play a crucial role in shaping Gaur distribution (Kumar, 2011). Gaur's preference for foothill tracts with lower human populations may be attributed to varying human pressures in lowlands and hills (Duckworth et al., 2016; Wharton, 1968). Gaur population densities vary regionally, with higher concentrations observed in lowland areas characterized by a mix of open and closed forest types (Duckworth et al., 1999; Duckworth and Hedges, 1998; Timmins and Rattanak, 2001). Notably, Gaur shows flexibility in adapting to fragmented and disturbed habitats, rugged terrain, and denser forests as long as it has access to sufficient water sources (Hoffmann et al., 2008; Kumar, 2011). Additionally, using previously cultivated land amidst forested areas highlights its ability to thrive in diverse environmental conditions (Bali et al., 2007).

Table 1. A complete list of environmental variables compiled for this study and those used for habitat suitability modelling for Gaur in CNP are presented in italic font.

Category	Variable	Source	Unit
Bioclimatic	BIO1 = Annual Mean Temperature	WorldClim	°C
	BIO2 = Mean Diurnal Range (Mean of monthly (max temp - min temp))		
	BIO3 = Isothermality (BIO2/BIO7) (×100)		
	BIO4 = Temperature Seasonality (standard deviation ×100)		
	BIO5 = Max Temperature of Warmest Month		
	BIO6 = Min Temperature of Coldest Month		
	BIO7 = Temperature Annual Range (BIO5-BIO6)		
	BIO8 = Mean Temperature of Wettest Quarter		
	BIO9 = Mean Temperature of Driest Quarter		
	BIO10 = Mean Temperature of Warmest Quarter		
	BIO11 = Mean Temperature of Coldest Quarter		
	BIO12 = Annual Precipitation		mm
	BIO13 = Precipitation of Wettest Month		
	BIO14 = Precipitation of Driest Month		
	BIO15 = Precipitation Seasonality (Coefficient of Variation)		
	BIO16 = Precipitation of Wettest Quarter		
	BIO17 = Precipitation of Driest Quarter		
	BIO18 = Precipitation of Warmest Quarter		
	BIO19 = Precipitation of Coldest Quarter		
Topographic	Elevation	USGS	km
	Aspect		Degree
	Slope		Degree
	Distance to water	GEOFABRIK	km
Vegetation-related	Mean EVI, Minimum EVI, Maximum EVI (Enhanced Vegetation Index)	Landsat	Dimensionless
	Forest	GFC	Dimensionless
Anthropogenic	*Distance to settlement*	Department of Survey, Nepal	km
	Distance to the motor road	GEOFABRIK	km
	Distance to path		km
	Population density	HUMDATA	Dimension less
	Livestock density	ODM	Dimension less
	Land use land cover (LULC)	ICIMOD	km

Data analysis

Gaur habitat suitability modeling

The overview, data, model, assessment, and prediction approach as described by (Zurell et al. 2020) was applied to develop habitat suitability models for Gaur in CNP. Continuous probability map was classified into high (0.6-1), medium (0.4-0.6), and low (0-0.4) categories of suitable area. Recent SDM practices increasingly employ the integration of multiple models developed with diverse modelling techniques into an ensemble map, as this approach enhances predictive accuracy (Hao et al., 2019; Hao et al., 2020). The habitat suitability models for Gaur was applied using an ensemble modeling approach in R (R. Core Team, 2022) with the BIOMOD2 package (Thuiller et al., 2020). A total of ten algorithms-classification tree analysis (CTA), artificial neural network (ANN), flexible discriminant analysis (FDA), generalized boosting model (GBM), generalized additive model (GAM), generalized linear model (GLM), multiple adaptive regression splines (MARS), maximum entropy (MAXENT), surface range envelope (SRE), and random forest (RF) were applied to create ensemble models. We generated 1,000 random pseudo-absence points, assigned equal weight to presence and pseudo-absence datasets, and repeated the pseudo-absence generation three times to reduce random bias (Barbet-Massin et al., 2012). Among Gaur's presence and pseudo-absence data, 70% were assigned training data, while 30% were assigned testing data sets. Using ten algorithms, three pseudo-absence selection runs, and three evaluation runs, our model produced 90 runs. To assess the accuracy of predictive distribution models, two independent methods were used: Receiver Operating Characteristics (ROC) curve/Area Under the Curve (AUC) and True Skill Statistics (TSS) (Lobo et al., 2008; Thuiller et al., 2009). Although AUC is widely used as a model evaluation metric, it has been criticized for its limitations (Lobo et al., 2008). Hence, we used the TSS evaluation criterion (-1 to +1) to assess our model's predictive performance. TSS value was used in this study as it is a well-established metric in the ecological modelling community and is widely accepted as a reliable measure for assessing model accuracy. Its robustness and versatility make it a preferred choice for model evaluation in many ecological studies.

The model is assumed to be perfect if the TSS value is +1, whereas the value between 0.7 and 0.9 denotes a good model (Allouche et al., 2006; Thuiller et al., 2009). Multiple base models was developed using different algorithms; each base model was trained on the same dataset. Out of 10 algorithms, we used models with a TSS value greater than 0.6 (Marmion et al., 2009). Only three models (GLM, MaxEnt, and RF; TSS value > 0.6) were used to develop the weighted mean ensemble approach. The default weighted mean ensemble approach was used in which each base model's predictions are combined using the arithmetic mean and where each model contributes equally to the final prediction. Moreover, ensemble methods are effective because they combine predictions from multiple models to improve overall performance. Even if individual models within the ensemble are not perfectly optimized, the diversity of models and their combined predictive power can still lead to better results than any single optimized model (Thuiller et al., 2009). For this reason, we applied the default optimization setting in the BIOMOD2 package.

RESULTS

Sighting of Gaur and occurrence points

The Gaur sighting data showed that 307 individuals were sighted, including 66 male, 94 female, 118 unidentified, and 29 calves. The sightings occurred in various locations, with the highest number of sightings in Jarneli to Tamor Tal with 81 individuals, followed by Bhawanipur to Jarneli (63) and Sunachuri to Harda with 43 individuals. The information regarding the Gaur population on each surveyed block is listed in Table 2.

Table 2. Block-wise information of sighted Gaur in the study area

Block	Male	Female	Unidentified	Calf	Total
Bhawanipur to Jarneli	14	33	11	5	63
Chapparchuli to Hattikhet	1	1	5	0	7
Barandabhar and Padampur	2	4	0	0	6
Harda khola to Chapparchuli	0	0	0	0	0
Hattikhet to Bhawanipur	9	5	19	5	38
Jarneli to Tamor Tal	32	38	0	11	81
Kamal Tal to Reu	0	0	0	0	0
Madi	0	0	0	0	0
Riu to Sailimaili	0	0	9	0	9
Sailimaili to Seri	0	0	2	0	2
Seri Tamaspur	2	4	9	2	17
Sunachuri to Harda	6	9	22	6	43
Tamortal to Kamaltal	0	0	41	0	41
Grand Total	66	94	118	29	307

Current suitable habitat and occurrence points of Gaur

A map created using the ensemble modeling approach indicated 183.53 km² of the CNP as highly suitable for Gaur, with 2.1% of this area falling within the buffer zone and 97.9% within the core area. Additionally, 536.78 km² was identified as a moderately suitable habitat for Gaur, with 9.3% within the Buffer zone and 90.7% within the core area (Fig.2, Table 3). Similarly, 965.68 km² was identified as low suitable habitat representing 69.84% within the Buffer zone and 30.16% within the core area. These statistics highlight the diverse distribution and concentration of habitat suitability across the various classes in the study area, underscoring the core area's importance in supporting highly suitable habitats.

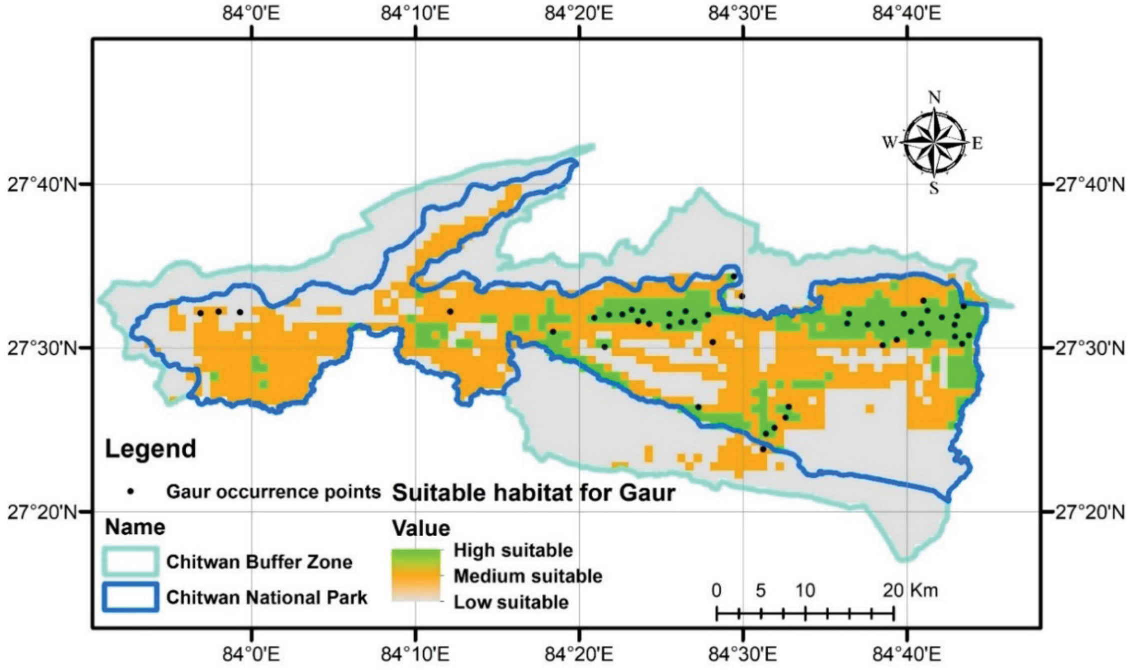

Fig. 2. Current suitable habitat for Gaur within the CNP of Nepal. Light green represents a highly suitable area, while orange represents a moderately suitable area. The black circles are the occurrence point of Gaur.

Table 3. Current suitable habitat area of Gaur

Habitat class	Area (km²)	Within BZ (%)	Within core area (%)
Low suitable	965.68	69.84	30.16
Medium suitable	536.78	9.30	90.7
High suitable	183.53	2.10	97.9

Contribution of the variables in predicting the occurrence of Gaur

Livestock density, human population density, and slope were the most influencing environmental variables in developing the habitat suitability model (see Table 4 for details). Gaur prefers a habitat with a gentle slope (0-5) degrees, livestock density below 100/km², and human population density below 200/km².

Table 4. List of variables that contributed significantly to make the Gaur's habitat suitability model

Variables	Percentage contribution
Livestock density	37%
Human population density	30%
Slope	19%
Distance to settlement	4%
Distance to road	4%
NDVI mean	2%
Distance to path	1%
Distance to water	Less than 1%

The remaining variables, such as annual precipitation, distance to road, distance to path, distance to settlement, distance to water, and NDVI mean, have varying percentage contributions ranging from less than 1% to 4%.

The response curve showed that the suitable habitat of Gaur decreases with increased human population density, slope, and livestock density (Fig.3).

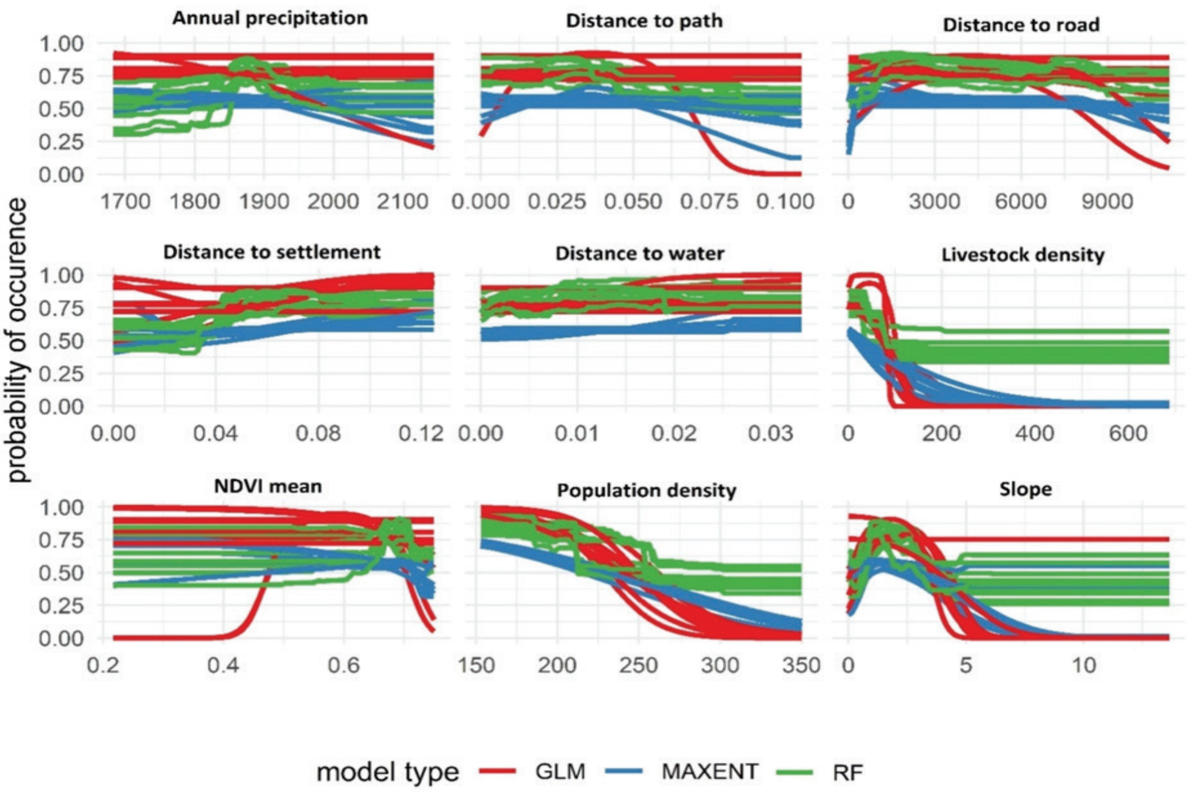

Fig. 3. Response curve showing the effect of different environmental variables on the habitat suitability of the Gaur in CNP. The ensemble model, integrating generalized linear models (GLM), MaxEnt, and random forest (RF), predicts a decline in suitable Gaur habitat with rising human population density, slope inclination, and livestock density, illustrated by the descending red curve line.

Some interesting findings were observed during our analysis on the occurrence probabilities using different models such as GLM, MaxEnt, and RF. The GLM model yielded the highest probability of occurrence (0.9) for annual precipitation of 1700-1950 mm, followed by the RF modeling approach (probability = 0.85 and annual precipitation = 1850 mm). For distance to settlements, the GLM model also highlighted the significance of high distances to settlements, with distances greater than 0.04 km associated with a higher probability of Gaur occurrence, indicating the best suitable from 0.08 km to 0.12 km from the settlement. This indicates that Gaur prefers habitats that are relatively far from human settlements. Similarly, the GLM model demonstrated a strong correlation between Gaur occurrence and livestock density, representing 0-150 livestock/km². This suggests that areas with higher livestock density may be less favourable for Gaur. When considering the terrain's slope, Gaur preferred areas with a slope ranging from 0-5%. The RF model was best compared to GLM and RF. This implies that Gaur inhabits regions with gentle slopes rather than steep or rugged terrains. Furthermore, the GLM model indicated that Gaur habitat suitability decreases with increased values of NDVI (Normalized Difference Vegetation Index) mean of 0.6. This implies that Gaur thrives in areas with abundant grassland and vegetation cover, reflected in higher NDVI values. In terms of proximity to roads, the range of 3000-7000 m appeared to be preferable for Gaur, according to our analysis. This finding was particularly prominent in the GLM model, suggesting that Gaur favors habitats within this distance range from roads. Our analysis using different models provided valuable insights into Gaur's habitat preferences. The GLM model indicated the highest probability of occurrence, followed by RF and MaxEnt. These findings enhance our understanding of Gaur habitat suitability and support targeted conservation efforts.

Ensemble summarized the important variables

The suitability of Gaur habitat is greatly influenced by several factors, primarily the slope of the terrain, livestock density, and human population density. Analysis using three models (GLM, MaxEnt, and RF) showed that certain conditions favour Gaur habitat suitability (Fig. 4). According to the findings, the highest probability of Gaur habitat suitability (0.72) was observed within a slope range of 2 to 5 degrees. Beyond this range, the probability decreases steadily, indicating that steeper slopes are less favourable for Gaur habitats. Similarly, regarding livestock density, an optimal range of 10 to 250 livestock/km² is identified, with a maximum probability of 0.73 for Gaur habitat suitability. Deviating from this range results in a decline in suitability, suggesting that too few or too many livestock negatively impact Gaur habitats. Moreover, the suitability of Gaur habitats is significantly influenced by human population density. The ideal range lies between 150 to 250 individuals/km², with a peak probability of 0.75 observed at a density of 230 individuals/km². Beyond this range, habitat suitability diminishes progressively, indicating that higher human population densities adversely affect Gaur habitats.

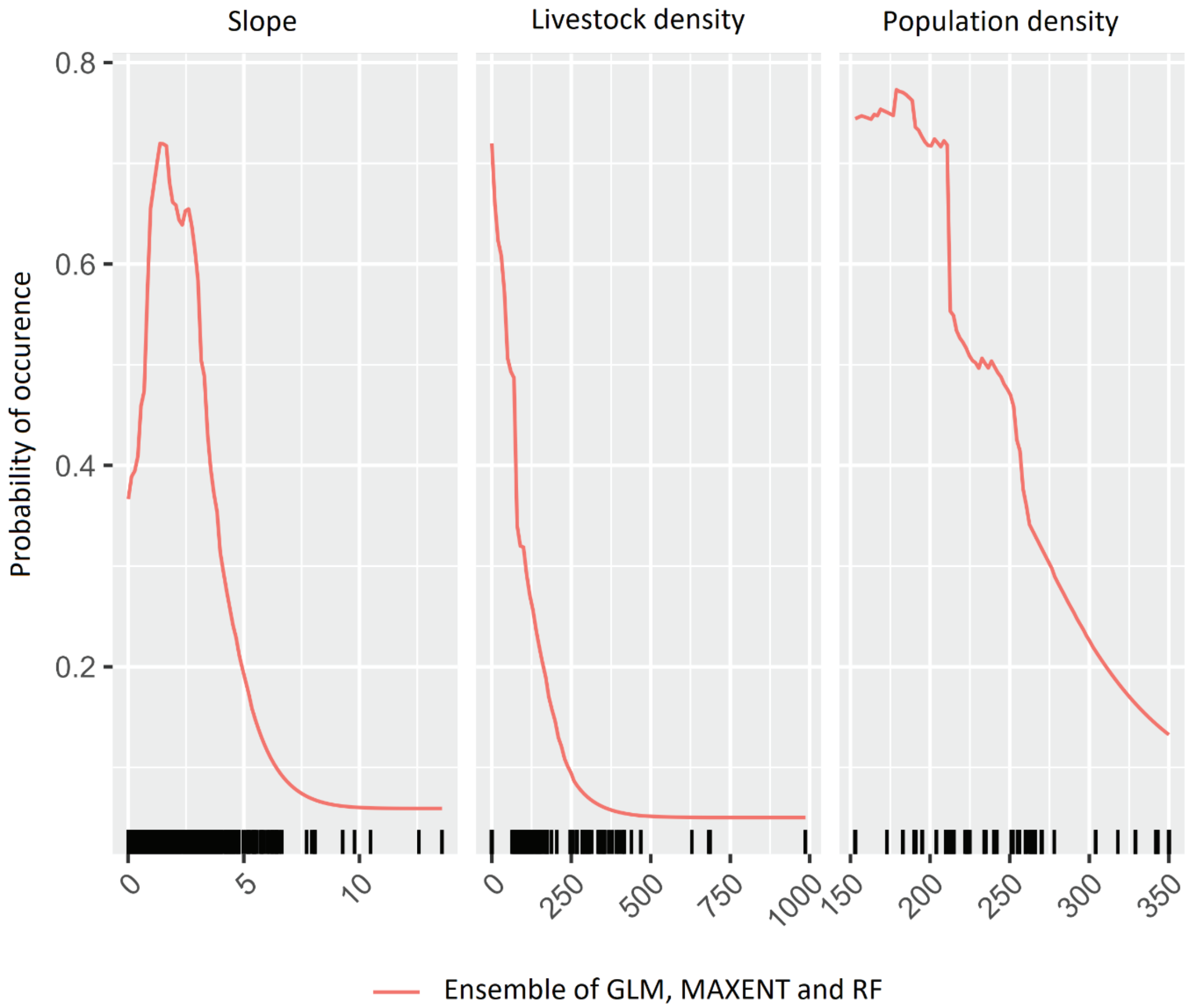

Fig. 4. Ensemble of the most influential variables on GLM, MaxEnt, and RF

Model accuracy in building a suitable habitat for Gaur in CNP

Among the ten modelling approaches used, GLM, MaxEnt, and RF have the highest TSS value, indicating better accuracy in predicting the distribution of Gaur. Analysis of TSS indicates that the ensemble model demonstrated superior predictive performance compared to the single algorithm models (Fig. 5).

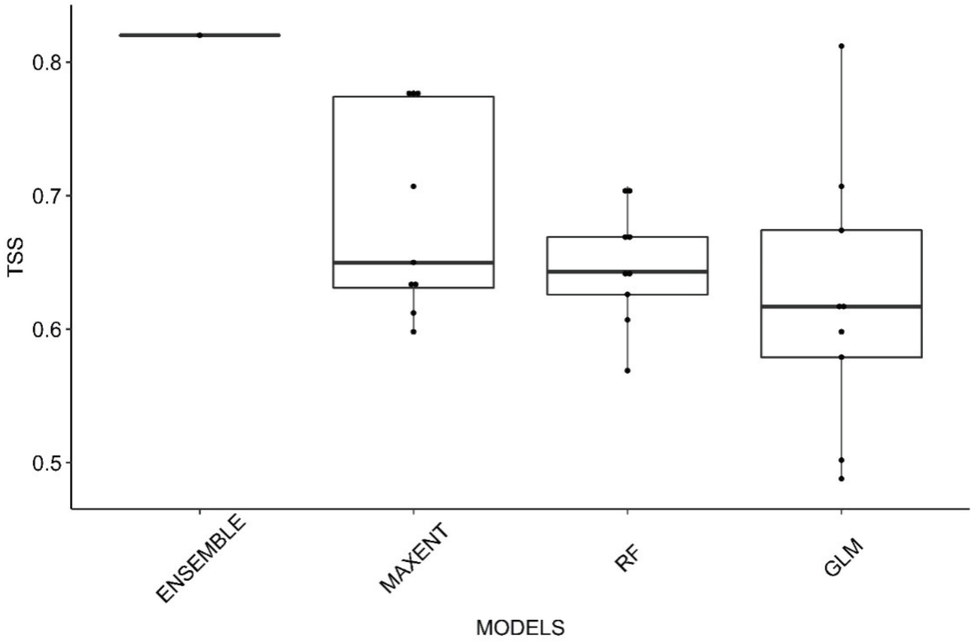

Fig. 5. Predictive performance of various models used to predict Gaur's suitable habitat in CNP. The ensemble model outperformed the single modeling approach based TSS.

DISCUSSION

Predicted suitable habitats of Gaur

In the habitat suitability map, the CNP core area is a more suitable habitat for Gaur than the buffer zones (Fig.2), which is in line with (Prayoon et al., 2021) where they assessed Gaur habitats employing the MaxEnt model across historical, current, and future contexts, revealing that more suitable habitats for Gaur in Thailand exist within protected areas in all scenarios. The likely causes of Gaur extirpation in Thailand include fragmented habitat and significant human activities, as documented in studies by Kanchanasaka et al. (2010) and Trisurat et al. (2015). This might be linked to the influence of various environmental factors on the presence of Gaur (Pla-ard et al., 2022). For instance, the core area may have higher vegetation density, better habitat quality, or lower human disturbance levels than the buffer zone, which could enhance the availability of food and other resources necessary for Gaur survival (Choudhury, 2002; Ding et al., 2018; Paliwal and Mathur, 2012; Trisurat et al., 2010; Walker et al., 1983). Previous studies (Ariffin et al., 2021; Rizal et al., 2020; Sankar et al., 2013) had reported that primary as well as secondary forests and areas close to water bodies were found to be suitable for Gaur, while agricultural lands and urban areas were found to be unsuitable. Some studies report that the buffer zone program prioritizes infrastructure development over wildlife and habitat management, making the area less suitable for Gaur and other species (Lamichhane et al., 2019; Silwal et al., 2013). Nevertheless, this does not necessarily suggest neglecting the buffer zone, as it can play a crucial role as a habitat and corridor for the movement of wildlife species (DNPWC, 2020). Conservation efforts should focus on protecting and managing core and buffer zones to maintain and enhance habitat quality and connectivity for Gaur and other wildlife.

Fine-scale habitat factors predicting the occurrence of Gaur

Livestock, human population density and slope are the environmental variables significantly predicting the occurrence of Gaur (Fig.3 and Table 4). Our study found that areas with gentle slopes, less than 5 degrees, are suitable for the Gaur. This result is consistent with previous research in Malaysia (Ariffin et al., 2021), Thailand (Pla-ard et al., 2022), and Bhutan (Zangmo et al., 2018). These studies indicate that Gaur exhibits a preference for flat terrains as opposed to sloping landscapes. This might be due to easy movement and easier accessibility to food and water sources in flat terrain (Imam, 2005). On the contrary, Gaur resorts to steep slopes during the monsoon, as flat terrain is prone to waterlogging, potentially causing the lush grasses that Gaur feeds on to become submerged (Sankar et al., 2013). Moreover, our study revealed a decrease in the suitable habitat of Gaur with elevated levels of human population density (Prayoon et al., 2021), slope (Ariffin et al., 2021), and livestock density (Madhusudan, 2004). Similarly, the inverse correlation with livestock density suggests that the presence of livestock may lead to competition with Gaur for resources like grazing land, water, and forage, resulting in diminished habitat suitability for Gaur (Madhusudan, 2004). This is particularly pertinent in areas where livestock grazing lacks regulation or surpasses carrying capacity, potentially causing habitat degradation and fragmentation (Reid et al., 2010). Similar habitat suitability and ecological studies in Nepal have highlighted the importance of vegetation composition, species behavior, and anthropogenic pressures in shaping ungulate distributions (Bhattarai et al., 2023; Neupane et al., 2025; Subedi et al., 2023). Intense resource competition between wild herbivores and grazing livestock is notable, especially in regions with limited resources such as grazing lands and water sources (Dahal et al., 2023; Madhusudan, 2004). Likewise, the negative association with human population density indicates that human activities and development can significantly impact Gaur’s habitat suitability. Various human activities, including the construction of road and foot trails as well as noise from nearby settlements, along with urbanization, agricultural expansion, and infrastructure development, lead to habitat loss, fragmentation, and degradation, thereby rendering the environment less suitable for Gaur and other wildlife (Choudhury, 2002; Imam and Kushwaha, 2013; Paliwal and Mathur, 2012). Moreover, the most frequent disturbances in the study area include invasive species (*Mikania micrantha* and *Chromolaena odorata)*, and forest fires, which have impacts on Gaur's habitat (Pun et al., 2022). Further, the spread of invasive species such as *Mikania micrantha* in CNP, Nepal, may increase due to human activities, including illegal fodder collection and grassland burning by local communities (Murphy et al., 2013).

Additionally, Gaur, being inherently shy, tends to avoid contact with anthropogenic activities (Ahrestani, 2018; Paliwal and Mathur, 2012; Sankar et al., 2013). Similarly, Zangmo et al. (2018) found that Gaur steered clear of areas with high human disturbance, such as agricultural fields. While numerous researchers have utilized traditional radio telemetry and GPS collars to investigate habitat use, their primary focus has been on determining mean annual home range, habitat preferences, seasonal distribution, and feeding habits (Dinerstein and Price, 1991; Laurie, 1982; Subedi et al., 2017). The maxent model was effective in detecting the habitat suitability of Gaur, aligning with the finding of (Ariffin et al., 2021) in Malaysia. Consequently, there remains a gap in exploring the impact of edges on the Gaur movement. Studies addressing this aspect could yield crucial insights into the Gaur’s distribution and movement within its suitable habitat, shedding light on how adjacent unsuitable habitats may influence its behavior. This area presents an open field for future research.

CONCLUSION

Our research examines the potential distribution of Gaur and emphasizes the specific habitat factors that influence its distribution. Our combined model indicates that the most suitable Gaur habitats are within the park's core area rather than the buffer zone. Slope, livestock density, and human population density were the primary factors influencing habitat suitability. We recommend that park authorities prioritize habitat management within the CNP's core area to support the long-term survival of the Gaur population. Regular monitoring of habitats in the buffer zone is also essential, as these areas promote connectivity between Parsa National Park in Nepal and Balmiki Tiger Reserve in India, supporting sustained Gaur population growth. Additionally, it is important to reduce anthropogenic disturbances, such as livestock grazing and human activities, within the park core area, which holds the suitable habitat for Gaur. This can be achieved by implementing updated habitat management strategies, including restoring degraded forest habitats, and controlling the invasive alien plant *Mikania micrantha*. Altogether, this study supplemented the habitat suitability information for Guar in CNP, opening an avenue for future investigations.

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AUTHOR CONTRIBUTIONS

KK: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization; **SKY:** Writing – review & editing, Methodology; **NKC:** Writing – original draft; **BD:** Writing – review & editing; **BN:** Investigation, Formal analysis, Writing – review & editing; **RJ:** Writing – original draft, Writing – review & editing; **ST:** Methodology; **BA:** Writing – original draft, Writing – review & editing; **MSM:** Writing – review & editing; **SA:** Writing – review & editing; **DG:** Writing – review & editing; **HA:** Conceptualization, Visualization, Writing – review & editing.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

GENERATIVE AI STATEMENT

During the preparation of this manuscript, the authors utilized ChatGPT (OpenAI) solely to assist with language editing and improving readability. Following its use, the authors thoroughly reviewed and revised the content as necessary and assumed full responsibility for the final published article.

ETHICAL APPROVAL AND PERMITS

Ethical approval for this research was obtained from the Department of National Parks and Wildlife Conservation, and the study was conducted in coordination with Chitwan National Park, Nepal.

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