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Current and Future Habitat Suitability for Tigers (*Panthera tigris*) in Valmiki Tiger Reserve, Bihar, India

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ABSTRACT

This study assesses the current and projected future habitat suitability for tigers in Valmiki Tiger Reserve (VTR), Bihar, using camera trap data (2019–2021) and Maximum Entropy (MaxEnt) modelling. The spatial distribution of tigers in VTR was analyzed using two years of camera trap records and MaxEnt habitat modelling. Results reveal a strong concentration of tiger occurrences in the Someshwar range, with habitat suitability determined mainly by temperature stability, precipitation, and terrain ruggedness. Western ranges, such as Valmiki nagar and Madanpur, showed low suitability due to habitat fragmentation and human interference. Habitat suitability was primarily influenced by annual mean temperature (40.40%), annual precipitation (12.70%), slope (11.40%), and land use/cover (10.50%). Future projections for 2070 under the RCP 8.5 scenario indicate a severe reduction in suitable habitats, leaving only small pockets in Chiutaha and northern Harnatand. The results highlight the urgent need for climate-resilient conservation planning to ensure long-term tiger survival in VTR.

Keywords Tiger conservation, MaxEnt modelling, Habitat suitability, Climate change, RCP 8.5, Valmiki tiger reserve.

INTRODUCTION

The tiger is an important endangered species for conservation across the Asian continent (Kanagaraj *et al.* 2011). The fascinating behavior of the tiger has been used by the Indian government to promote wildlife conservation. The first systematic estimation of the tiger population in India revealed that merely 1872 tigers existed in 1972. To save the tigers from extinction 'Project Tiger' was launched by the government in 1973 to protect and conserve the tiger population. Implementation of strict conservation rules and habitat restorative measures adopted based on an ecosystem approach has protected the tigers from extinction due to increasing human-wildlife conflict for available space and resources (Aryal *et al.* 2014).

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Tiger reserves provide a safe habitat place for these large mammals where grazing, human settlements, and resource utilization are strictly prohibited. The majority of the tiger population is restricted to core areas of reserve forests (Bargali and Ahmed 2018). The core area is surrounded by buffer zones that act like shock observers for the main habitat zones of the tiger. It has been revealed in the Status of Tigers report published by the government of India every four years that the tiger population in India has improved gradually over the past few years (Rather *et al.* 2020). But still, several tiger reserves in India are situated in isolated human-dominated landscapes and are at constant threat due to habitat fragmentation and increasing human-wildlife conflict (Aryal *et al.* 2014). Tigers are large carnivore animals and require wide-ranging habitat for their survival. Therefore, the conservation of tigers has become more challenging due to its growing population. Land resources are limited and constantly growing anthropogenic pressure leaves less space for the expansion of tiger reserves area (Bayani *et al.* 2016).

Another major problem that has the potential to worsen the present situation is climate change. The Inter-Governmental Panel for Climate change (IPCC) in its fifth assessment report revealed that global surface temperature is going to be 1.5 degrees Celsius higher than the 1890-1990, at the end of the twenty-first century (Rather *et al.* 2020). The report also predicts the large-scale extinction of flora and fauna around the globe due to changes in ecosystems.

Habitat suitability of any species can be predicted by analyzing various variables that control its survival. Different statistical models have been developed to study the species distribution with its habitat variables (Aryal *et al.* 2014). Multi-scale species distribution models like – Maximum Entropy Modelling (MaxEnt) have predicted the habitat and species distribution with higher accuracy in comparison to other traditional regression-based models (Alexander *et al.* 2016). The MaxEnt is the most popular and widely used species distribution model for examining the habitat suitability of any species based on location and environmental datasets (Phillips and Dudík 2008, Jennings *et al.* 2013).

MATERIALS AND METHODS

Max-Ent was used to predict the habitat suitability of tigers in the Valmiki Tiger Reserve (VTR). VTR is the only tiger reserve of Bihar located in the North-Western corner of Champaran district.

It is part of Terai Arc Landscape (TAL) which has been globally identified as a priority wildlife conservation landscape. VTR shares its boundary with Chitwan National Park and Parsa National Park in Nepal (Fig. 1). Collectively, this wildlife zone is known as the Chitwan-Parsa-Valmiki wildlife complex having 3669 sq km of total area (Pattekar *et al.* 2021). VTR is also partially connected with the Sohagibarwa wildlife sanctuary in Uttar Pradesh. It has several threatened and endangered species of flora and fauna and is globally known for its Terai - Bhabar vegetation.

Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER) DEM data were obtained from the USGS website for producing elevation, aspect, and slope maps of VTR (Fig. 2). Elevation, slope, and aspect map for the MaxEnt model were prepared using ASTER DEM data in ArcGIS 10.5 software using the spatial analysis tool. Landsat 8 / Operational Land Imager (OLI) with 30 m of spatial resolution was obtained from the earth-explorer web portal. The land use land cover map of VTR was prepared from Landsat 8 data using the supervised classification method in ArcGIS 10.5 software. For classification training area the following land use land cover class was prepared- deciduous broadleaf forest, agricultural land, barren land, settlements, water body, and wetland. Using these training data sets the classified image classification of the study area was performed. The land use land cover map for the VTR was prepared using supervised maximum likelihood classification of Landsat 8 satellite imagery for the period 2021 (Fig. 2). The producers' and users' accuracy value was around 92% . A high value of Kappa statistics (0.96) and overall accuracy shows a high accuracy level of classification.

Bioclimatic data for the past three decades was obtained from the Worldclim web portal (Fick and Hijmans 2017). Bioclimatic variables have been de-

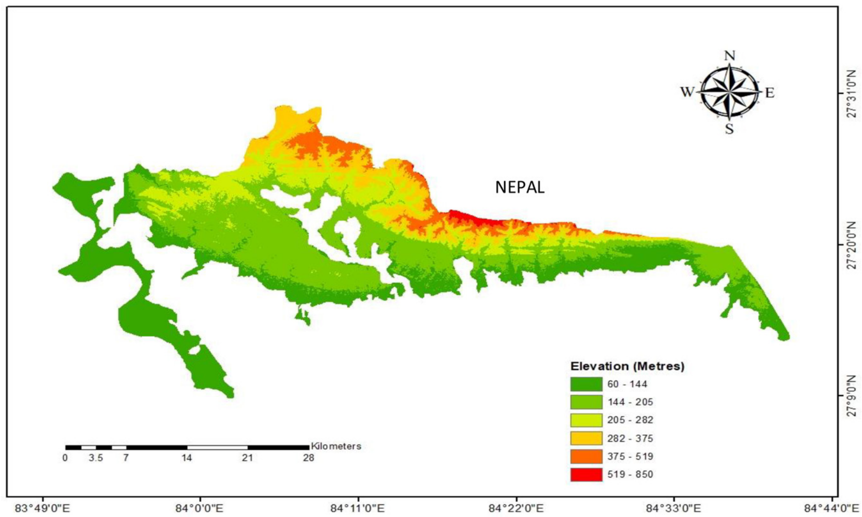

Fig. 1. Location map of study area.

rived from monthly temperature and rainfall values for the past thirty years. These climatic variables have been extensively used for species distribution models and ecological studies (Jennings *et al.* 2013). Bioclimatic data consists of 19 different climatic variables (Table 1) which are biologically meaningful and essential for the survival of life (Logan 2010). The downloaded bioclimatic data and future bioclimatic data (2060-2080) have 1 km of spatial resolution. To examine the impact of climate change on the potential spatial distribution of tigers the Representative Concentration Pathway Scenarios (RCP 8.5) estimated by the Japanese research community called Model for Inter-disciplinary Research on Climate change (MIROC5) for the tome period 2061 to 2080 was used (Mukul *et al*. 2019). The RCP 8.5 is assumed

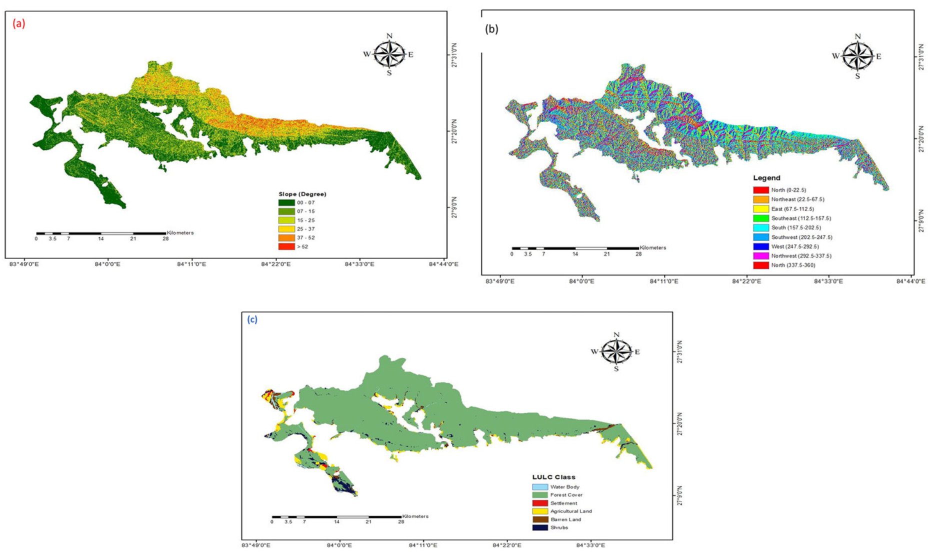

Fig. 2. Slope (a), Aspect (b) and land-use land-cover map (c) of VTR.

Table 1. Bioclimatic layers (Source: www.worldclim.org).

BIO1	Annual mean temperature
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
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

to be the worst climatic scenario due to the rise in greenhouse gases concentration in the atmosphere (Rogelj *et al*. 2012).

Datasets for running the MaxEnt model were prepared using Microsoft Excel and ArcGIS 10.5 software. The geographical coordinates of the tiger were arranged in an excel sheet with column headings naming: Species, longitude, and latitude. Later, it was converted into a comma-separated value (csv) file for use as input samples in MaxEnt. The spatial extent (cell size, extent, and geographic projection system) of different environmental layers should be the same for MaxEnt (Alexander *et al.* 2016). All the environmental layers were converted into ASCII raster grid format of the same cell size, extent, and geographic projection system (WGS84) for running MaxEnt (Athreya *et al.* 2013). The study area shape file was used to clip the environmental layers with the same spatial extent.

The presence of highly correlated variables may lead to an over-fit of the model and can introduce bias in the analysis. To avoid the misinterpretation of the

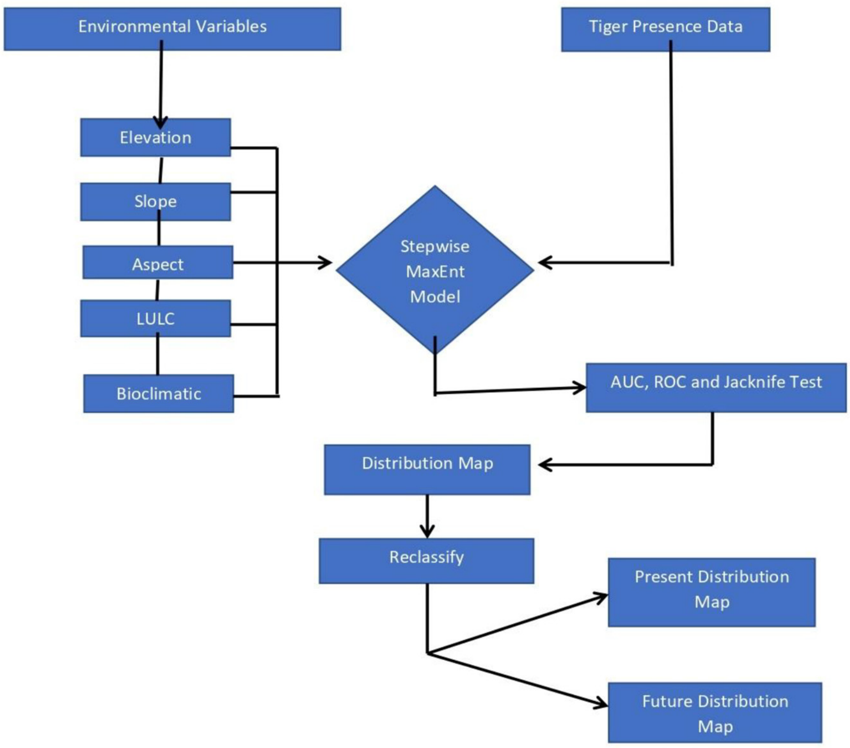

Fig. 3. Flow chart of max-ent model.

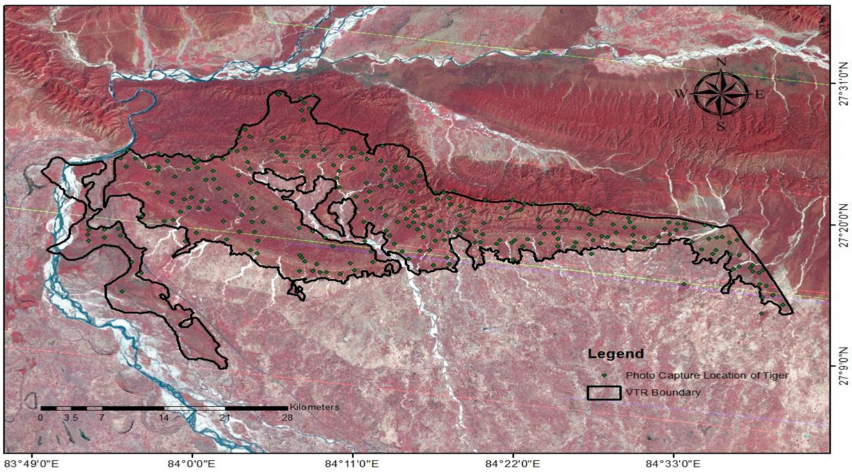

Fig. 4. Photo-capture location of tigers in VTR (2020-21).

outcome the Pearson correlation coefficient test was employed to test the independence of variables. Environmental variables having more than 0.5 Pearson correlation coefficient value was excluded from the model (Cooper 2016). The general linear model was used to examine the relationship between continuous and categorical variables (Fig. 3). To examine the contribution of each variable in the model a Jacknife test was employed (Phillips *et al.* 2006).

RESULTS AND DISCUSSION

The presence and distribution of tigers in Valmiki Tiger Reserve (VTR) were analyzed using camera trap data from 2019–2021 obtained from the report Status of Tigers and Prey in Valmiki Tiger Reserve, Terai Arc Landscape, Bihar, India (2021).

The camera traps were strategically placed across the reserve in a two sq km grid system, ensuring comprehensive monitoring of tiger movement. Each pair of cameras was positioned 15 feet apart and regularly checked for proper functionality. The analysis revealed that tiger sightings were most frequent in the Eastern and central regions of VTR, while the Western part recorded significantly fewer tiger occurrences (Pattekar *et al.* 2021).

In 2019–2020, a total of 248 tiger locations were recorded, while in 2020–2021, this number increased to 264 (Fig. 4). The highest density of tiger presence points was concentrated in the Manguraha, Gobardhana, Gonauli, Harnatand, and Raghia ranges, which form part of the Someshwar range. These areas are characterized by rugged and undulating terrain with thick deciduous forest cover, making them highly suitable for tiger habitation. In contrast, the Valmikinagar and Madanpur ranges in the Western part of VTR recorded the least number of tiger occurrences. This region faces high anthropogenic pressure due to dense human settlements, extensive agricultural activities, and infrastructure development.

A habitat suitability probability map was developed using MaxEnt (Maximum Entropy) modeling to identify key environmental variables influencing tiger distribution. The analysis revealed that annual mean temperature (40.40%) was the most critical factor, as tigers prefer regions with stable temperature conditions, while extreme variations negatively affect their movement and prey availability. Annual precipitation (12.70%) was also significant, with consistent water availability being crucial for sustaining prey populations. Slope (11.40%) played an important role, as steeper terrains provide natural cover and seclusion essential for hunting and avoiding human disturbances. Land use and land cover (10.50%) influenced suitability by offering dense forested areas with better shelter, prey availability, and reduced human interference. Precipitation of the

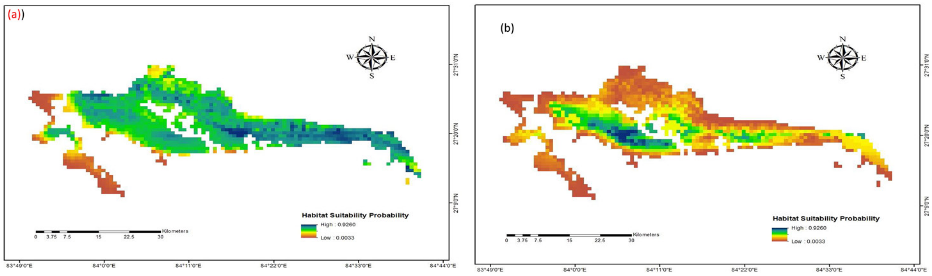

Fig. 5. Habitat suitability probability map of tiger in VTR (a), Future (2070) habitat suitability probability of tiger in VTR (b).

warmest quarter (5.30%) was linked to water source stability and prey migration patterns during hot periods, whereas temperature annual range (3.80%) indicated that extreme seasonal fluctuations could disrupt predator-prey dynamics. Precipitation of the coldest quarter (3.70%) ensured water availability during dry seasons, and mean temperature of the coldest quarter (3.20%) highlighted the influence of cold stress on prey behavior and abundance.The area under the curve (AUC) value for the present habitat prediction was 0.83, while for future predictions (2070), it was 0.78, indicating high model accuracy. The overall classification accuracy for Minimum Training Presence (MTP) and Maximum Training Sensitivity Plus Specificity (MTRSS) was 86% and 91%, respectively, confirming the reliability of the model in predicting tiger habitats (Cooper *et al.* 2016).

The eastern and central parts of VTR, specifically the Manguraha, Gobardhana, and Raghia ranges, were identified as having the highest probability of habitat suitability for tigers (Maurya and Borah 2013). These regions are characterized by steep cliffs, rugged topography, and moderately dense forest cover, making them ideal habitats for tigers. The northern and central portions of VTR, including the Chiutaha, Harnatand, and Gonauli ranges, showed moderate habitat suitability. These areas belong to the Dun range, which has less steep and undulating terrain compared to the Someshwar range, but still provides adequate forest cover. The western part of VTR, including the Valmiki nagar and Madanpur ranges, showed the lowest habitat suitability probability.

The future habitat suitability for tigers in 2070 was assessed using climate projection models, replacing current bioclimatic variables with future climate projections under the RCP 8.5 scenario (worst-case greenhouse gas emissions). The results indicated a drastic reduction in suitable tiger habitats across the Valmiki Tiger Reserve (VTR), with most of the reserve projected to become unsuitable by 2070 due to rising temperatures and altered precipitation patterns. Key ranges currently supporting tiger populations—Manguraha, Gobardhana, Raghia, Harnatand, and Gonauli—are expected to become uninhabitable, leaving only a small portion of VTR, including Chiutaha and the northern part of Harnatand, as viable habitats, thereby confining the species to a highly restricted area. Similar climate-driven habitat losses are anticipated in Chitwan National Park, Nepal, where approximately 28% of suitable tiger habitat is projected to shift by 2050 (Kina *et al.* 2020).

The spatial and temporal analysis of tiger habitat suitability in Valmiki Tiger Reserve (VTR) provides essential insights for long-term conservation planning and adaptive management strategies. Using the MaxEnt model, which has been widely recognized for its high accuracy in species distribution modeling (Jennings *et al.* 2013), this study effectively predicted both current and future habitat suitability for tigers in VTR. The high AUC values (0.83 for present and 0.78 for future predictions) indicate a reliable predictive performance, making the model an effective tool for habitat conservation planning and species management efforts.

The results highlight key environmental variables that significantly influence tiger habitat selection in VTR. Among them, annual mean temperature, annual precipitation, slope, land use and land cover (LULC), and precipitation during the warmest quarter were the most dominant predictors (Ghosal *et al.* 2015). The eastern and central regions of VTR, particularly the Someshwar and Dun ranges, emerged as the most suitable tiger habitats due to their rugged topography, steep slopes, and dense vegetation cover, which offer seclusion, prey availability, and optimal microclimatic conditions for tiger survival (Fig. 5).

The future projections (2070) based on climate change scenarios reveal a significant decline in tiger habitat suitability within VTR. If greenhouse gas emissions continue to rise, the model predicts that a major portion of VTR will become unsuitable for tigers, with only small parts of the Chiutaha and Harnatand ranges remaining viable as suitable habitats (Fig. 5). This is consistent with studies on climate change-induced habitat loss in other tiger reserves. Mukul *et al.* (2019) demonstrated that all suitable tiger habitats in the Sundarbans (Bangladesh) would disappear by 2070 under the RCP 8.5 scenario, primarily due to climate change and sea-level rise. Similarly, Rather *et al.* (2020) projected a 23% reduction in tiger habitat in Bandhavgarh Tiger Reserve, India, by 2070 under the same worst-case climate scenario.

CONCLUSION

The habitat suitability probability map for tigers in Valmiki Tiger Reserve (VTR) was developed using the MaxEnt model, incorporating various environmental layers and tiger presence data. The results indicate that the eastern and central parts of VTR provide the most suitable habitat, characterized by rugged terrain, dense forest cover, and minimal human disturbances. In contrast, the western region of VTR exhibits the lowest habitat suitability, primarily due to high anthropogenic pressure, fragmented vegetation, and infrastructure development. Key environmental factors influencing tiger habitat suitability include annual mean temperature, annual precipitation, slope, land use and land cover (LULC), and precipitation during the warmest quarter. Future climate change projections (2070) suggest that a major portion of VTR will become unsuitable for tigers, emphasizing the need for proactive conservation strategies. With an increasing tiger population and breeding tigresses, the reserve will require higher prey density and expanded habitat availability to sustain a healthy population. Efficient conservation planning must focus on habitat restoration, conflict mitigation, and transboundary conservation efforts.

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