Environment and Ecology 44 (3A) : 717—729, July—September 2026
Article DOI: https://doi.org/10.60151/envec/NOQH9062
ISSN: 0970-0420 (Print), ISSN: 3049-3625 (Online)

Predicting Potential Habitats of Nilgiri Tahr (*Nilgiritragus hylocrius*) in Periyar Tiger Reserve under Current Landscape Conditions Using MSTrIPES and GIS

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Received 10 March 2026, Accepted 5 August 2026, Published on 2 September 2026

ABSTRACT

The Nilgiri Tahr (*Nilgiritragus hylocrius*), an endangered mountain ungulate endemic to the Western Ghats of India, is a flagship species of the montane ecosystems, yet its habitat preferences and spatial ecology remain insufficiently explored. This study employed Species Distribution Modelling (SDM) using the Maximum Entropy (MaxEnt) algorithm integrated with Geographic Information System (GIS) to predict the potential distribution of Nilgiri Tahr in the Periyar Tiger Reserve (PTR), Kerala. Presence data were obtained from MSTrIPES field surveys (April 2024 to September 2025) and correlated with 24 environmental variables, including elevation, slope, aspect, NDVI, rainfall, temperature, land cover, and distance to water sources. Model performance was evaluated using the Area Under the Receiver Operating Characteristic Curve (training AUC = 0.923, test AUC = 0.922) and jackknife tests to determine the relative contribution of predictor variables. Habitat suitability was classified into three probability categories: Unsuitable, moderately Suitable and Highly Suitable. The model revealed that highly suitable habitats covered approximately 134.97 km², moderately suitable habitats spanned 249.52 km², and unsuitable areas accounted for 540.51 km². The most suitable habitats were concentrated along Ponnambalamedu, Mangaladevi, Palkachimala, Medhakanam, Pachamudi, Kumarikulam, Vaikolpadappu, and Manamuttymala, extending towards Circle Road, Uppupara, Zero Point, Venkalapara, Ottamaram, and Churulipara. These zones are characterized by steep grassland-Shola mosaics and rugged high elevation cliffs, providing ideal foraging, resting, and breeding environments for the species. Conservation management should emphasize the maintenance of high-altitude grassland connectivity, protection of Shola grassland ecotones, and integration of Nilgiri Tahr habitats into PTR's conservation and monitoring framework to ensure long-term population persistence under changing climatic conditions.

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Keywords Species distribution modelling, MaxEnt, GIS, Nilgiri Tahr, Habitat suitability, Western ghats, Periyar Tiger Reserve, Conservation planning.

INTRODUCTION

The Nilgiri Tahr is an endangered mountain ungulate endemic to the high-altitude landscapes of the Southern Western Ghats, India. It is widely recognized as a critical flagship species for montane ecosystem conservation in the region. Serving as a key biotic component of the sensitive shola–grassland ecosystem, this species contributes significantly to vital local ecological processes. These roles include the mediation of grazing dynamics, seed dispersal, nutrient cycling and the structural maintenance of grassland vegetation patterns (Karanth *et al*. 2010).

Nilgiri Tahr populations are characteristically restricted to steep rocky escarpments, montane grasslands, and sheer cliff habitats occurring at elevations typically between 1200 and 2600 meters. These high-altitude zones form a complex landscape mosaic with Shola forests, providing essential resources for foraging, shelter, breeding, and predator avoidance.

The Western Ghats is internationally recognized as one of the world's major biodiversity hotspots, supporting exceptional levels of species richness, endemism, and ecosystem diversity. Despite the presence of extensive protected areas, the region continues to face significant ecological challenges that threaten its long-term environmental integrity (Western Ghats Ecology Expert Panel 2011). Among the species affected, the Nilgiri Tahr experiences substantial pressures on habitat quality and landscape connectivity. Its populations are increasingly vulnerable to range contraction and isolation resulting from habitat degradation and fragmentation, the encroachment of invasive plant species, and various anthropogenic disturbances such as infrastructure development, recurrent fires, livestock grazing, and unregulated tourism activities. In addition, climate change poses an emerging threat through alterations in vegetation composition, habitat structure, and environmental conditions, which may further reduce the availability and suitability of montane habitats required by the species (Chen *et al.* 2022).

Understanding the exact relationships between species occurrences and environmental variables is fundamental to biodiversity conservation and wildlife management. Species Distribution Models (SDMs) have emerged as powerful quantitative tools for assessing habitat suitability and predicting geographic distributions across heterogeneous landscapes (Elith and Leathwick 2009; Franklin 2020; Zurell *et al.* 2020). By integrating species occurrence records with environmental predictors, SDMs provide valuable, data-driven insights into core ecological requirements and potential distribution patterns. Consequently, these models are increasingly utilized for conservation prioritization, protected area planning, habitat restoration, and climate change adaptation studies.

Among the available predictive frameworks, the Maximum Entropy (MaxEnt) machine-learning algorithm remains one of the most robust and widely applied methods for presence-only occurrence data (Phillips *et al.* 2017; Phillips *et al.* 2006). MaxEnt is uniquely suited for rare, threatened, or elusive wildlife because it can generate reliable, statistically sound predictions even when occurrence records are geographically restricted. The algorithm calculates habitat suitability by estimating the probability distribution of maximum entropy, constrained by environmental parameters associated with known species locations. Recent wildlife studies have continually demonstrated the effectiveness of MaxEnt in improving predictive accuracy and ecological interpretation for conservation planning.

Over the past decade, advances in Geographic Information Systems (GIS), remote sensing technologies, and environmental monitoring have significantly enhanced the resolution and power of habitat models. High-resolution environmental datasets derived from satellite observations allow researchers to integrate diverse climatic, topographic, hydrological, and vegetation-related variables into modern SDM frameworks (Boyd and Foody 2011; Sillero and Tarroso 2010). For mountain ungulates, parameters such as elevation, slope, aspect, rainfall, temperature, distance to water sources, and vegetation indices—such as the Normalized Difference Vegetation Index (NDVI) are recognized as primary environmental determinants of distribution.

The Periyar Tiger Reserve (PTR), situated in the Southern Western Ghats of Kerala, stands as one of India's most ecologically significant protected areas due to its exceptional biodiversity, varied topography, and habitat heterogeneity. The reserve provides a crucial ecological corridor connecting the Southern Anamalai and Cardamom Hill landscapes, thereby sustaining regional landscape connectivity.

Historically, foundational research on the Nilgiri Tahr has concentrated primarily on population estimations, behavior, and basic ecology within targeted strongholds like Eravikulam National Park and Mukurthi National Park. While several broad studies have evaluated distribution patterns for large mammals across the wider Western Ghats, spatially explicit, fine-scale habitat suitability modelling for the Nilgiri Tahr within the complex microclimates of PTR remains virtually non-existent. Identifying highly suitable habitats and uncovering the environmental variables driving Tahr occurrence inside the reserve are vital steps required to design effective local conservation and evidence-based management strategies.

The Monitoring System for Tigers – Intensive Protection and Ecological Status (MSTrIPES) program provides a robust, standardized platform for the systematic field collection of geo-referenced wildlife occurrence records. Integrating these standardized MSTrIPES patrol records with GIS-derived environmental layers presents a unique opportunity to build scientifically robust habitat models.

This study utilizes a GIS-based MaxEnt framework to execute a comprehensive habitat suitability and potential distribution analysis for the Nilgiri Tahr within the Periyar Tiger Reserve. The model integrates field-verified MSTrIPES occurrence data collected between April 2024 and September 2025 alongside a comprehensive suite of 24 environmental variables representing regional climatic, topographic, hydrological, and vegetation characteristics.

The specific objectives of this research are:

To identify the key environmental variables influencing Nilgiri Tahr habitat suitability in the Periyar Tiger Reserve;

To generate spatially explicit habitat suitability and potential distribution maps using the MaxEnt algorithm, and

To provide baseline scientific information for conservation planning, habitat management, and long-term monitoring of Nilgiri Tahr populations within the broader Western Ghats landscape.

MATERIALS AND METHODS

Study area

The study was conducted in the Periyar Tiger Reserve (PTR), situated within the Western Ghats biodiversity hotspot of peninsular India, extending approximately between 8°N and 12°N latitudes. The Nilgiri Tahr (*Nilgiritragus hylocrius*) primarily inhabits the montane grasslands and shola ecosystems of the Southern Western Ghats, generally occurring above an elevation of 1200 meters (Fig. 1). The existing and potential habitats of the Nilgiri Tahr within PTR were identified through a combination of field-based surveys and MSTrIPES (Monitoring System for Tigers – Intensive Protection and Ecological Status) datasets collected between April 2024 and September 2025, in consultation with forest officials, wildlife biologists, and species experts who have previously studied the species' ecology and distribution in the region. Field verification was carried out in representative high-altitude zones such as Ponnambalamedu, Mangaladevi, Palkachimala, Medhakanam, Pachamudi, Kumarikulam, Vaikolpadappu, and Manamuttymala, where each locality was visited and systematically surveyed for direct sightings and indirect evidence (pellets, tracks, or grazing signs). The geographic coordinates of Tahr presence were recorded using handheld GPS units at or near the point of first detection. Supplementary data were extracted from previous research publications and PTR monitoring records to strengthen the occurrence dataset. A total 14 of MSTrIPES derived occurrence points were compiled and processed after spatial filtering to reduce sampling bias and ensure representative spatial distribution across the study area. The study area was gridded into map pixels of 1 km^2 spatial resolution, collectively encompassing the

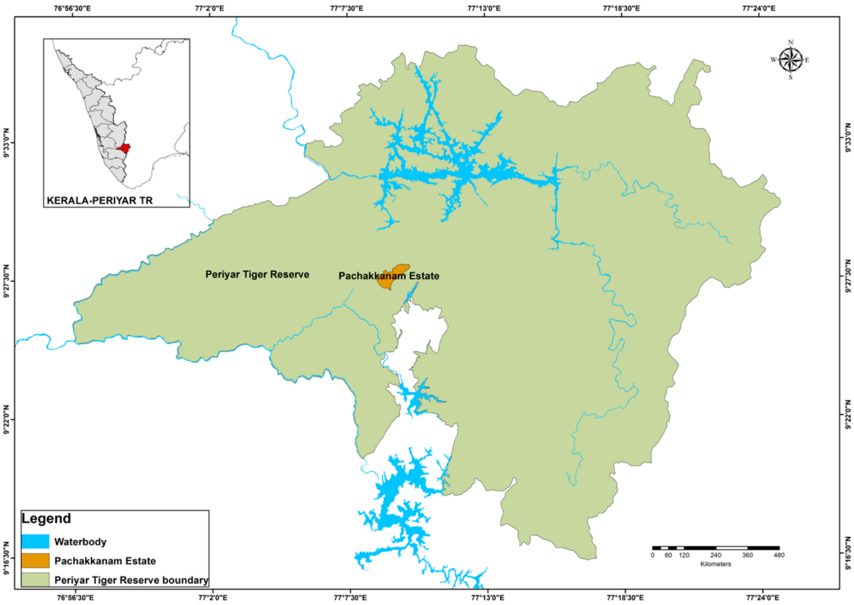

Fig. 1. Location of Periyar Tiger Reserve.

known elevation range and habitat types of the Nilgiri Tahr within the Periyar landscape. These occurrence data served as input for Ecological Niche Modelling (ENM) using the MaxEnt algorithm (Phillips *et al.* 2006) to predict potential habitat suitability under current environmental conditions.

Environmental variables and model setup

A total of 24 environmental predictor variables representing topographic, climatic, vegetation, and anthropogenic factors were used to model the potential habitat suitability of the Nilgiri Tahr (*Nilgiritragus hylocrius*) in the Periyar Tiger Reserve (PTR). These predictors were selected based on their known ecological relevance to mountain ungulate distribution and accessibility of reliable datasets from multiple open and institutional sources.

Topographic variables, including elevation, slope, aspect, flow accumulation, terrain ruggedness index (TRI), plan and profile curvature, topographic position index (TPI), topographic wetness index (TWI), stream power index (SPI), and LS factor, were derived from the ALOS PALSAR DEM (12.5 m) obtained from the Alaska Satellite Facility (ASF Vertex). Vegetation indices were generated from Sentinel-2 (10 m) imagery accessed through the USGS Earth Explorer, and the Normalized Difference Vegetation Index (NDVI) was computed to represent vegetation productivity and canopy density. Climatic layers annual temperature and annual precipitation were obtained from the Kerala Forest Department.

Land cover and edaphic factors such as forest cover Forest Survey of India. (2019), soil suborder (FAO–UNESCO 2003), and lithology (Geological Survey of India) were included to capture habitat heterogeneity and substrate conditions. Anthropogenic disturbance variables, including distance from water bodies, settlements, roads, trek paths, power lines, faults, and streams, were generated using Survey of India (SOI) toposheets. Additionally, livestock density (11 km grid) was derived from the Geo-Wiki Livestock Database (Geo-Wiki 2024), representing grazing pressure and potential competition zones within PTR. forest cover data obtained from the Forest Survey of India (Forest Survey of India 2019).

All spatial layers were resampled to a common 10 m spatial resolution, projected to WGS 84 UTM Zone

Table 1. Predictor variables used for species distribution modelling of Nilgiri Tahr in PTR.

Sl. No.	Data Description	Type	Source	Derived Layers
1.	Sentinel2 10 m	Raster	USGS Earth Explorer	NDVI
2.	ALOS PALSARDEM12.5 m	Raster	Alaska Satellite Facility Vertax	Elevation, Slope, Aspect, Accumulation TRI, Plan curvature, profile Curvature, TPI, TWI, SPI, LS factor
3.	Annual Temperature	Raster	Kerala Forest Department	
4.	Annual Precipitation	Raster	Kerala Forest Department	
5.	Forest Cover	Raster	(Forest Survey of India 2019)	Sentinel2
6.	Soil Suborder	Raster	FAO-UNESCO 2003	
7.	Lithology	Raster	GSI, India	
8.	Water body	Raster	SOI TOPOSHEET	Distance from Water Source
9.	Settlements	Raster	SOI TOPOSHEET	Distance from Settlements,
10.	Linear networks	Raster	SOI TOPOSHEET	Distance from Roads, Trek path, Power lines
11.	Faults	Raster	SOI TOPOSHEET	Distance from faults
12.	Streams	Raster	SOI TOPOSHEET	Distance from Streams
13.	Livestock	Raster	https://livestock.geo-wiki.org	11 km Grid

43N, and converted to ASCII format for integration into MaxEnt (Phillips *et al.* 2006). Multicollinearity among predictors was tested using Pearson's correlation coefficient ($|r| < 0.70$) and Variance Inflation Factor (VIF) analysis in R (package usdm, Naimi *et al.* 2014). Variables with VIF > 5 were excluded to minimize redundancy and improve model performance (Veloz 2009). The final set of 24 predictor layers was used for model fitting, treating all variables as continuous in the MaxEnt framework.

The list of datasets employed, their sources, and derived layers are summarized in Table 1.

Maximum entropy implementation

The potential habitat distribution of the Nilgiri Tahr (*Nilgiritragus hylocrius*) within the Periyar Tiger Reserve (PTR) was modelled using the Maximum Entropy (MaxEnt) algorithm implemented in MaxEnt version 3.3.3e (Phillips *et al.* 2006). MaxEnt applies a machine learning approach to estimate the most uniform probability distribution of species presence across a landscape, constrained by known environmental conditions at observed locations. By integrating presence only records with continuous environmental predictor variables, the model identifies areas that share ecological characteristics similar to known occurrence points, thereby generating a spatially explicit habitat suitability surface.

All environmental predictors were converted into ASCII grid format with consistent spatial resolution, projection, and geographic extent to ensure compatibility across layers. To accurately represent the Tahr's microhabitat preferences within complex montane terrain, a 30-meter spatial resolution was adopted, which provides sufficient detail for fine scale ecological inference. Spatial preprocessing and standardization of predictor variables were conducted using the Spatial Distribution Modelling (SDM) Toolbox in ArcGIS 10.8 (ESRI 2020) prior to model input.

Model performance was evaluated using the Receiver Operating Characteristic (ROC) curve, which plots Sensitivity against 1-Specificity across all classification thresholds (Fig. 2). The Area Under the Curve (AUC) was calculated for both training and test datasets to measure predictive accuracy. A training AUC of 0.923 and a test AUC of 0.922 indicated high predictive performance, signifying a strong ability of the model to capture the realized environmental niche of the Nilgiri Tahr within PTR. Following the criteria proposed by Hosmer *et al.* (2013), AUC scores above 0.9 are considered excellent.

To enhance robustness and minimize sampling bias, the MaxEnt algorithm was executed 1,000 times under the subsample replication method, which partitions occurrence data into training and testing subsets

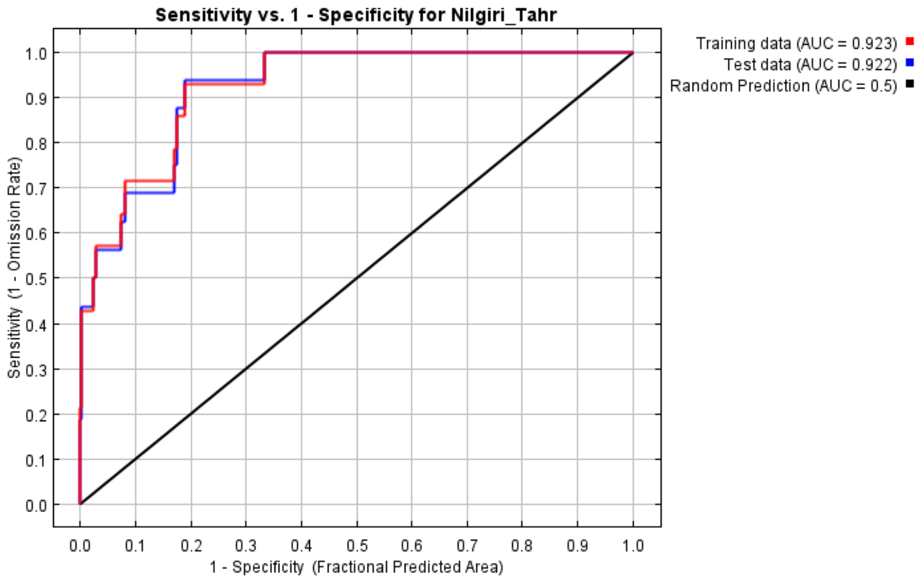

Fig. 2. Receiver Operating Characteristics (Sensitivity Vs. 1-Specificity).

for cross validation. The final habitat suitability map was derived by averaging the outputs from all iterations, ensuring a stable representation of predicted suitable zones. The resulting probability maps were classified into Unsuitable, moderately Suitable, and Highly Suitable categories based on natural break thresholds, facilitating interpretation for conservation planning.

MSTrIPES and species data collection

The Monitoring System for Tigers – Intensive Protection and Ecological Status (MSTrIPES) is a geospatially integrated patrolling and monitoring framework developed by the National Tiger Conservation Authority (NTCA) in collaboration with the Wildlife Institute of India (WII). This system assists forest managers and field personnel in recording real time field observations through GPS enabled mobile applications, capturing details on wildlife sightings, tracks, habitat attributes, threats, and patrol routes. Each observation automatically logs spatial coordinates, date, and time, enabling the creation of spatial databases for species occurrence and patrol effort across protected areas.

For this study, field based presence data of the Nilgiri Tahr were collected between April 2024 and September 2025 using the MSTrIPES mobile application across major montane grassland and rocky escarpment habitats of PTR. Each record was verified by trained forest staff and researchers to ensure taxonomic accuracy and spatial precision. To enhance dataset reliability:

1. Only confirmed direct visual sightings were retained for analysis.

2. Records with positional errors exceeding 50m were excluded.

3. Duplicate observations within a 100m buffer radius were filtered to reduce spatial autocorrelation.

4. The final dataset comprised validated presence only points, which served as the input layer for MaxEnt habitat suitability modelling.

The processed occurrence data, when integrated with the set of 24 environmental predictors, enabled the generation of a high-resolution spatial model identifying potential strongholds for Nilgiri Tahr within PTR, including key zones around Ponnambalamedu, Mangaladevi, Palkachimala, Medhakanam, Pachamudi, Kumarikulam, Vaikolpadappu, Manamuttymala, and surrounding ridges.

RESULTS AND DISCUSSION

Habitate suitability modelling for Nilgiri Tahr

The Maximum Entropy (MaxEnt) model was employed to predict the potential distribution of the Nilgiri Tahr (*Nilgiritragus hylocrius*) within the Periyar Tiger Reserve (PTR). Field occurrence data were collected between April 2024 and September 2025 using direct sightings recorded in the MSTrIPES mobile application. A total of 24 raster based environmental predictors including elevation, slope, rainfall, temperature, forest cover, NDVI, lithology, distance to streams, roads, and settlements were used to develop the model.

The model achieved high AUC values of 0.923 for training data and 0.922 for test data (Fig. 2), indicating strong predictive performance and demonstrating that MaxEnt effectively captures the ecological niche of this mountain ungulate.The strong ecological relevance of the model further supports its utility for conservation planning.

Model reliability was further assessed using omission curves, which illustrate the relationship between omission rate and predicted area across cumulative threshold values (Fig. 3). The low omission rates observed at key thresholds indicate stable model behavior and reinforce the ecological relevance of the predicted habitat suitability outputs. Collectively, these results confirm the suitability of the MaxEnt model for conservation planning and habitat management of the Nilgiri Tahr within the PTR landscape.

Ecological interpretation of the most influential variables

Forest cover (53.4%) – dominant driver of habitat suitability

Forest cover emerged as the most influential predictor of Nilgiri Tahr habitat suitability (Table 2, Fig. 4). The Nilgiri Tahr relies heavily on the shola–grassland mosaic ecosystem, which consists of steep montane grasslands interspersed with stunted shola forests. Although commonly associated with open grasslands, Tahrs utilize forest patches for thermal refuge during periods of high temperature, movement between foraging zones, and shelter during lambing seasons. These ecological functions enhance habitat suitability and support the survival of populations

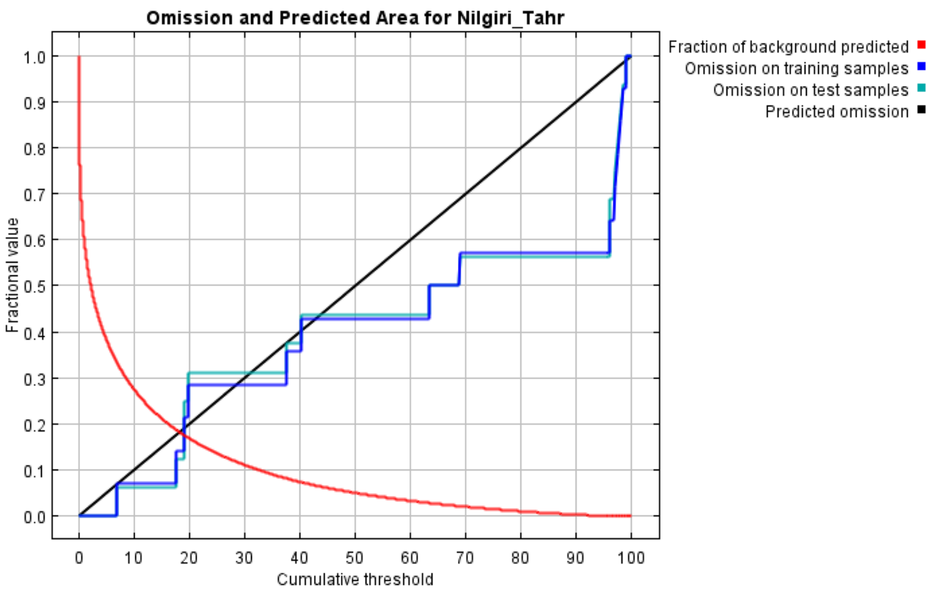

Fig. 3. Omission Curves of MaxEnt Output: Omission rate and predicted area by using cumulative threshold.

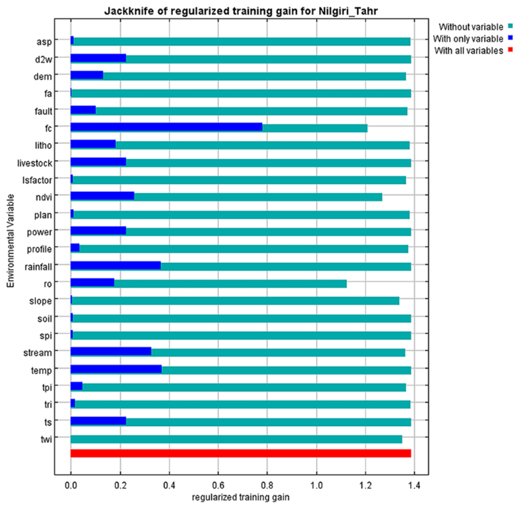

Fig.4. (A)

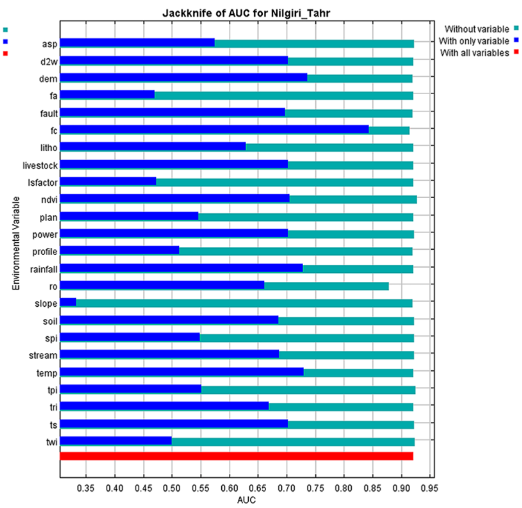

Fig.4. (B)

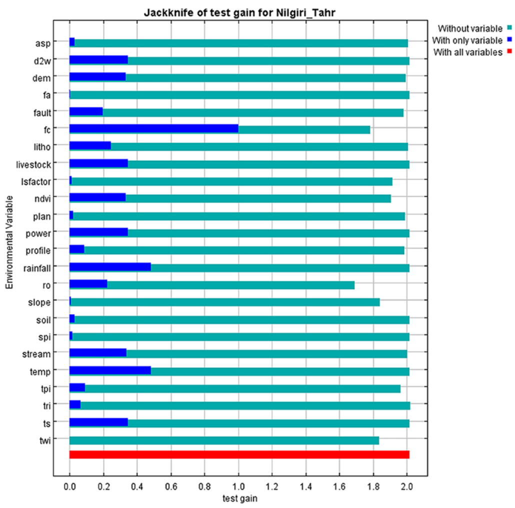

Fig.4. (C)

Fig. 4. Jackknife test of Max Ent model output showing variable importance for Nilgiri Tahr habitat suitability in Periyar Tiger Reserve: (A) Jackknife results for regularized training gain. (B) Jackknife results for AUC. (C) Jackknife results for test gain.

in rugged mountain landscapes. The complex shola–grassland landscape of the Periyar Tiger Reserve (PTR) therefore represents an ecologically optimal habitat for the species.

Distance from roads (18.2%) – indicator of disturbance avoidance

A strong negative relationship was observed between habitat suitability and proximity to roads (Table 2, Fig. 4). Roads disrupt ridge connectivity, increase human presence, generate noise disturbances, and facilitate habitat fragmentation. Such anthropogenic disturbances can alter movement patterns and reduce habitat use by mountain ungulates. Within PTR, tourism routes and pilgrimage pathways near Gavi, Ponnambalamedu, and Mangaladevi may act as disturbance hotspots, reducing the suitability of otherwise favorable habitats.

NDVI (12.4%) – Forage productivity and nutritional ecology

NDVI, which represents vegetation greenness and biomass productivity, was the third most influential variable affecting habitat suitability (Table 2, Fig. 4). Higher NDVI values correspond to productive montane grasslands that provide fresh grass shoots, protein-rich herbaceous vegetation, and abundant post-monsoon regrowth. These conditions improve forage availability and nutritional quality for Nilgiri Tahr populations. Seasonal aggregation of Tahr herds in highly productive grassland habitats indicates the importance of vegetation productivity in determining habitat selection and distribution patterns.

Lithology (2.8%) and TPI (2.7%) – microhabitat structure and anti-predator behavior

Lithology and Topographic Position Index (TPI) indicate the species' preference for rocky escarpments, ridge crests, and rugged cliff environments (Fig. 4). These microhabitats provide escape terrain from predators, elevated vantage points for herd vigilance, secure lambing refuges, and opportunities for thermal regulation on exposed mountain slopes.

Elevation, slope and TRI – combined topographic influence

Although the individual contributions of elevation, slope, and Terrain Ruggedness Index (TRI) were relatively low, their combined influence is ecologically significant. Nilgiri Tahr populations are generally restricted to elevations between 1200 and 2600 m above sea level and exhibit a strong preference for steep slopes and rugged terrain. These topographic conditions provide suitable climatic environments, reduce accessibility to predators and human disturbances, and support the ecological requirements of the species.

Spatial distribution patterns

The habitat suitability map (Fig. 5) classified the Periyar Tiger Reserve into three suitability zones:

1. Highly Suitable: 134.97 km²
2. Moderately Suitable: 249.52 km²
3. Unsuitable: 540.51 km².

Table 2. Variable contribution analysis.

Sl.No.	Variable	Code	Percent contribution	Permutation Importance
1	Forest Cover	fc	53.4	29.1
2	Distance to road	ro	18.2	32.3
3	NDVI	ndvi	12.4	3.7
4	Lithology	litho	2.8	9.7
5	TPI	tpi	2.7	0.4
6	Elevation	dem	2.1	3.2
7	Distance to stream	stream	1.9	0
8	TWI	twi	1.3	12.9
9	Distance to fault	fault	1.1	4.5
10	Precipitation	rainfall	1	0
11	Profile curvature	profile	0.9	0.5
12	TRI	tri	0.8	0.4
13	Slope	slope	0.6	2.6
14	Plan curvature	plan	0.5	0.4
15	LS factor	lsfactor	0.3	0
16	Temparature	temp	0.2	0
17	Aspect	asp	0.1	0.2
18	Distance to Waterbody	d2w	0	0
19	livestock	livestock	0	0
20	Soil	soil	0	0
21	Flow Accumulation	fa	0	0
22	Tribal Settlements	ts	0	0
23	SPI	spi	0	0
24	Distance to powerline	power	0	0

High suitability clusters

The most suitable habitats were concentrated in the following areas:

1. Ponnambalamedu–Palkachimala Range
2. Mangaladevi–Medhakanam Ridge
3. Pachamudi–Kumarikulam Complex
4. Mullayar-Vallakkadavu Region
5. Vaikolpadappu–Manamuttymala Region
6. Uppupara, Zero Point, Venkalapara, Ottamaram, and Churulipara

These areas share several common ecological characteristics:

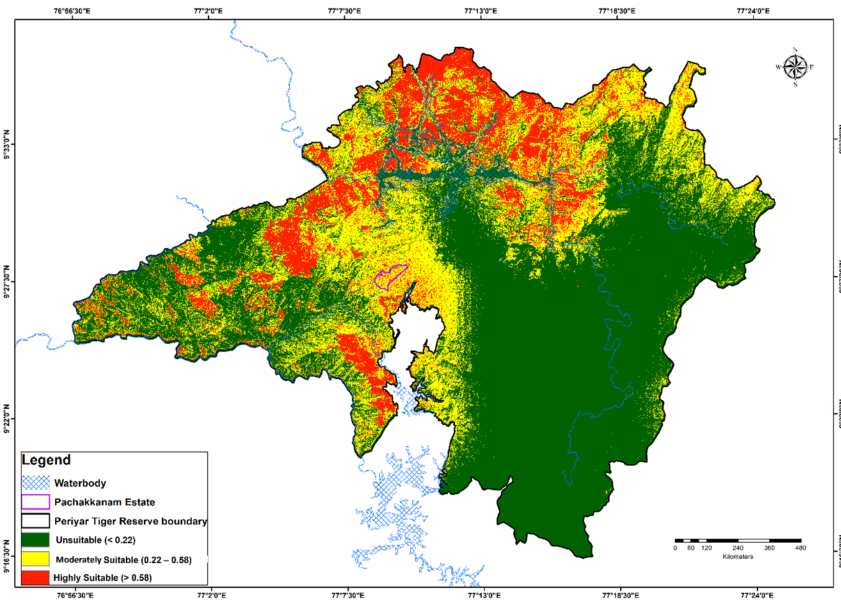

Fig. 5. Habitat suitability map of Nilgiri Tahr in Periyar Tiger Reserve generated using the MaxEnt model, showing highly suitable, moderately suitable, and unsuitable habitat zones.

1. Rugged terrain providing escape cover.

2. Shola–grassland mosaics supporting year-round forage availability.

3. Lower levels of anthropogenic disturbance.

4. Availability of seasonal water resources.

5. Wind-exposed slopes that help reduce thermal stress.

Collectively, these landscape attributes create highly favorable habitat conditions for Nilgiri Tahr populations and are consistent with habitat characteristics reported from the High Range landscapes of the Southern Western Ghats.

Fragmentation and connectivity concerns

Despite the presence of approximately 135 km² of highly suitable habitat, these areas occur as fragmented ridge-top patches separated by valleys, plantations, roads, human settlements, and steep landscape discontinuities. Habitat fragmentation can increase the risks of genetic bottlenecks, reduced dispersal opportunities during extreme climatic conditions, localized population declines resulting from fires or landslides, and increased vulnerability to future climate change impacts.

Maintaining and enhancing connectivity among the major habitat complexes of Ponnambalamedu, Mangaladevi, Mullayar, Vaikolpadappu, and Manamuttymala is therefore essential for ensuring metapopulation stability and long-term conservation of Nilgiri Tahr populations within PTR.

Climate change vulnerability

Climate-induced upward shifts of forest vegetation into montane grassland ecosystems represent a significant threat to alpine specialists such as the Nilgiri Tahr. Potential impacts include loss of open grassland habitats, upward displacement into progressively shrinking high-altitude zones, nutritional stress resulting from changes in vegetation composition, and increased exposure to elevated temperatures.

The high-elevation landscapes of PTR may serve as important climate refugia for the species in the future. Consequently, proactive conservation measures aimed at protecting montane grasslands and maintaining habitat connectivity will be critical for enhancing the resilience of Nilgiri Tahr populations under changing climatic conditions.

Summary of variable contributions

The variable contribution analysis (Table 2) revealed that forest cover (53.4%), distance from roads (18.2%), and NDVI (12.4%) were the most influential variables determining habitat suitability, followed by lithology (2.8%) and Topographic Position Index (TPI) (2.7%). These results highlight the species' preference for structurally complex shola–grassland mosaics, productive vegetation communities, low-disturbance environments, and rugged mountain terrain. The Jackknife test of variable importance further supported these findings, indicating that forest cover produced the highest model gain when used independently. Together, these variables provide important insights into the ecological requirements and spatial distribution patterns of Nilgiri Tahr within the Periyar Tiger Reserve.

Management recommendations

1. Safeguard montane grassland ecosystems:

Strengthen protection and management of high elevation montane grasslands and rocky escarpments within PTR, particularly around Ponnambalamedu, Palkachimala, Medhakanam, Kumarikulam, and Manamuttymala, which were identified as high suitability zones for Nilgiri Tahr. These habitats provide critical forage and breeding grounds that support long-term population persistence.

2. Enhance habitat connectivity:

Develop ecological linkages between isolated Tahr populations through targeted restoration of corridor zones connecting fragmented grassland patches, especially across Vaikolpadappu, Mangaladevi, and the Mullayar ridge complex. Maintaining landscape permeability will facilitate gene flow and seasonal movement across elevation gradients.

3. Implement sustainable tourism practices:

Regulate visitor access and ecotourism infrastructure in high-altitude grassland areas to prevent habitat degradation, vegetation trampling, and disturbance to Tahr herds. Establish designated viewing trails and enforce carrying capacity limits to ensure minimal ecological impact.

4. Mitigate human–wildlife interface pressures:

Conduct awareness programs and participatory conservation initiatives among local communities, trekkers, and pilgrimage groups frequenting PTR's highland areas. Reducing livestock grazing, unregulated trekking, and waste dumping will alleviate pressure on fragile Tahr habitats.

5. Restore degraded slopes and grassland margins:

Implement habitat restoration programs in degraded montane slopes using native grass and shrub species such as Chrysopogon zeylanicus and Ischaemum indicum. These species improve soil stability, enhance forage availability, and support microhabitat regeneration.

6. Integrate fire management strategies:

Incorporate grassland fire control and early detection systems into PTR's management plan. Fire management should focus on creating low intensity-controlled burns and maintaining natural firebreaks to preserve vegetation structure vital for Tahr survival.

7. Control invasive plant species:

Actively monitor and remove invasive flora such as Lantana camara, Eupatorium odoratum, and Acacia mearnsii from montane zones, as these species reduce native forage quality and impede Tahr movement along grassland ridges.

8. Long term population monitoring:

Establish a systematic monitoring framework combining MSTrIPES data, dronebased surveillance, and automated camera traps to track population dynamics, herd structure, and habitat changes over time. This will enable adaptive management and early detection of habitat stressors.

9. Integrate findings into PTR management framework:

Incorporate the Nilgiri Tahr habitat suitability maps generated through MaxEnt modelling into Periyar Tiger Reserve's management, eco restoration, and climate resilience strategies. This will ensure that Tahr habitats receive priority in land use zoning, fire prevention, and conservation funding.

10. Collaborate on regional conservation initiatives:

Promote interagency coordination between Kerala and Tamil Nadu Forest Departments to manage the Nilgiri Tahr's transboundary populations. Developing a Western Ghats Tahr Conservation Network will facilitate joint monitoring, research, and habitat connectivity planning.

CONCLUSION

his study presents the first spatially explicit habitat suitability model for the Nilgiri Tahr (*Nilgiritragus hylocrius*) in the Periyar Tiger Reserve (PTR), integrating MSTrIPES population data with remote sensing and GIS-based environmental predictors using the MaxEnt algorithm. The model, which achieved high predictive accuracy (training AUC = 0.923, test AUC = 0.922), identified forest cover distance from roads, and NDVI as the primary environmental variables determining Tahr habitat suitability. Highly suitable habitats are primarily distributed across the Kumarikulam, Vaikolpadappu, Manamuttymala, and Mullayar–Pamba–Vallakkadavu regions, highlighting the critical ecological significance of high-altitude grasslands and adjoining shola forest mosaics. The spatial outputs indicate that anthropogenic pressures such as settlement expansion, road proximity, and land-use alterations—pose significant threats to long-term habitat continuity. Consequently, future conservation efforts should prioritize the protection of high-suitability core patches, the enhancement of corridor connectivity, and the ecological restoration of degraded montane zones within PTR. Integrating these predictive spatial layers into long-term wildlife management, anti-poaching, and fire prevention frameworks will substantially strengthen conservation outcomes. Overall, this study establishes a robust scientific baseline for Nilgiri Tahr conservation planning under shifting climatic and landscape conditions, reinforcing the value of GIS-based species distribution modelling as a vital decision-support tool for managing endangered mountain ungulates in the Southern Western Ghats.

ACKNOWLEDGMENT

The authors would like to express their sincere gratitude to the Field Director (Project Tiger), Periyar Tiger Reserve, for their encouragement and continuous support throughout the study. They also extend their appreciation to the Deputy Directors, Assistant Field Director, Range Officers, and field staff from all sections of Periyar Tiger Reserve for their assistance in data collection and field validation. The authors acknowledge the European Space Agency (ESA) for providing free access to Sentinel 2 satellite imagery through the Copernicus Open Access Hub, and the ALOSPALSAR dataset through the ESA Earth Online portal (https://alospalsards.eo.esa.int). These data sources were invaluable in supporting the spatial analyses conducted in this study.

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