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Assessment of Habitat Suitability and Potential Corridors for Bengal Tiger (*Panthera tigris tigris*) in Valmiki Tiger Reserve, India, Using MaxEnt Model and Least-Cost Modeling Approach

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Abstract

Tigers have seen significant population losses due to the degradation and fragmentation of their habitat ranges worldwide. Thus, habitat suitability assessment of such predators is essential for restoring their numbers and devising strategies for their protection. This paper aims to assess the habitat suitability and potential corridors for Bengal tiger species (*Panthera tigris tigris*) in the Valmiki Tiger Reserve (VTR) located in the West Champaran district of Bihar, India. Nine suitability conditioning factors (tree cover, prey richness, drainage density, vegetation types, elevation, slope, aspect, temperature, and rainfall) and seven threatening factors (forest fragmentation, land use land cover, distance from roads, railway tracks, settlement, range offices, and forest fire points) were selected for emphasizing species-environment association in VTR. The spatial layers of all the factors and presence location data of tigers were integrated into the MaxEnt model to prepare a habitat suitability map. The model was validated utilizing the receiver operating characteristic (ROC) curve (0.822), which was found in good agreement. The least-cost corridor modeling based on surface resistance was utilized to identify the cost-effective pathways and prioritize dispersal routes and potential corridors for this species. The findings revealed that the largest area of the Reserve was found to be moderately suitable (41.92%), followed by low suitable (22.98%), highly suitable (19.34%), and unsuitable areas (15.76%). The potential causes for low suitability and unsuitable habitats included human-induced disturbances, especially in the buffer zone of VTR. The core habitats and their connectivity, particularly in the eastern and central parts of the Reserve, facilitated the dispersal of the Bengal tiger population. This study offers significant insights for identifying crucial habitats and establishing corridors between them. The study calls for suitable measures for restricting human encroachment and increasing predator movements from the adjacent corridors of the protected reserves of Nepal and Uttar Pradesh. The findings may help forest managers and stakeholders for suggesting suitable conservation and restoration practices as well as regulating strategies for the self-sustenance of reintroduced tigers in the Reserve.

Keywords Bengal Tiger (*Panthera tigris tigris*) · Habitat suitability · Maximum entropy modeling · Potential corridors · Least-cost path modeling · Protected area

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1 Introduction

Biodiversity conservation is highly challenging due to the increasing human population and resulting consequences on wildlife [1]. Climate change has significantly affected species distribution, their inherent characteristics, and forest ecosystem health. Land use/land cover changes, fragmentation of forests, and habitat destruction have been the prime drivers for causing the extinction of species globally [2–4]. Since the 1970s, anthropogenic activities have substantially influenced climate change, resulting in higher surface temperature and changing precipitation patterns worldwide [5]. The natural environment and wildlife continue to face significant challenges due to industrialization, urbanization, infrastructural development, wildlife trade, and deforestation [6]. Habitat loss and its fragmentation are the foremost reasons for present biodiversity crises. The International Union for Conservation of Nature (IUCN) recognized habitat loss as a significant threat to nearly 85% of all species on the planet earth [7]. During the last two centuries, the accelerated pace of human development, land use change, and environmental degradation have resulted in a loss in terrestrial wildlife habitat quality, particularly for large terrestrial carnivore species [8]. Today, tigers are at continual risk of extinction and are placed in the critically endangered category by the IUCN and the Convention on International Trade in Endangered Species of Wild Fauna and Flora [9]. Tigers face a plethora of threats like habitat loss, habitat destruction, fragmentation, degradation, depletion of prey, poaching, and conflict with humans.

Tigers are cryptic top predators crucial in regulating and maintaining ecological processes [10]. These magnificent creatures have demonstrated remarkable adaptability to diverse environments, including variations in altitude, rainfall patterns, and temperature regimes. Despite their ability to thrive in different habitat types, tigers remain under constant threat of extinction. The main habitats of the tigers include high mountains, dry and deciduous forests, evergreen forests, mangrove swamps, and tall grasslands. Tiger conservation holds immense importance in the Indian subcontinent as it serves as an umbrella species for numerous eco-regions [11]. There are ten recognized subspecies of tigers; four are considered extinct now. Sumatran, Bengal, South China, Indo-Chinese, and Malayan tigers are still struggling to survive in suitable habitats. The Bengal tiger (*Panthera tigris tigris*) is an indigenous species of the Indian subcontinent distributed across Bhutan, Bangladesh, Nepal, and India [12]. This tiger species is widely distributed from the forests in the Himalayan foothills in the north to the Western Ghats in the south, including the forests in the floodplains of the Ganga and Brahmaputra rivers systems. The species is also found in the Central Highlands, Eastern Ghats, and Sundarbans mangrove forests of West Bengal. The ideal conditions for its habitation include tropical and subtropical rainforests, alluvial grasslands, deciduous forests, scrub forests, and mangroves. India had only 2967 Bengal tigers, accounting for about 70% of the global wild tiger population as per the last tiger count held in 2018 [13]. These sub-species are on the verge of extinction due to cumulative consequences of habitat degradation, human intervention, forest fragmentation, and global climate change [2, 14]. Safeguarding the protection of this apex predator assures the well-being of the forested ecosystems and biodiversity [15]. Despite their substantial role in sustaining ecosystem health, tigers are at significant risk due to the shrinkage of their habitats [16]. India's declining tiger population faces substantial threats from large-scale habitat degradation and the decimation of the prey population. Despite the presence of essential habitats in certain areas, the expansion of agriculture and forest clearing, particularly for road networks and hydropower projects, is pushing tigers into small and isolated pockets of remaining habitat [17].

Bengal tigers can best be sustained in disturbed free forest landscapes with ideal conditions for food requirements, access to water, and cover for stalking [18]. Such landscapes will also help in achieving long-term genetic viability. A large contiguous landscape spreading over 3000 and 15,000 km^2 area is an ideal habitat for the Bengal tiger for long-term survival. Habitat evaluation is an initial step in effective wildlife conservation efforts. It involves assessing the quantity and quality of available habitats for specific species. Habitat suitability modeling is a valuable tool in conservation planning as it helps in identifying potential habitats for the targeted species across the landscape. Since the metapopulation is subjected to individual species dispersal between the landscapes and habitat patches, their effective conservation strategies will determine their future existence in areas other than protected parks [19]. Thus, large landscapes are to be identified as having a good network of habitats, ideal conditions for their survival and reproduction, dispersal, and colonization as permanent sites for maintaining their population and persistence.

Mapping and predicting suitable habitats for endangered species are vital for managing their declining population in their native distribution areas. Analyzing the habitat characteristics of tigers is necessary for devising conservation strategies, significantly when the population is increasing in protected areas. GIS-based predictive models such as habitat suitability models, niche models, and species distribution models that assign suitability values to geographic regions to spatially anticipate a species' presence/absence have grown in popularity over the last two decades. As a result of these models, viable areas for protecting priority species in rapidly changing landscapes are identified. To enhance the effective conservation of tigers, numerous modeling approaches are gradually being encouraged for future studies. Numerous robust statistical models are available to examine the distribution of species in relation to habitat parameters. Random forests, maximum entropy modeling (MaxEnt), classification and regression trees (CART), and other machine learning algorithms have lately been shown to outperform traditional regression-based approaches [20–22]. However, the accuracy of these models relies on factors such as the quality and quantity of input data, sampling methods for species occurrence, and the availability of presence-absence records. Earlier studies have used geospatial approaches for mapping suitable habitats for tiger distribution [3, 23–26]. Several studies have employed the MaxEnt modeling approach to study climate change scenarios and their impact on species distribution [27–30]. Although MaxEnt is a conventional SDM, it has received more attention than other SDMs in distribution modeling studies of various wildlife species [31–33]. The advantages of MaxEnt may include easy programming features, avoiding predictions in no analogous environments, and providing species-specific situations. It uses presence-only data and does not require absence records to estimate the species' niche and future geographic distribution. Thus, these characteristics have recognized MaxEnt as the best model for assessing habitat suitability. Moreover, the model avoids biased assumptions about unknown conditions, resulting in highly accurate predictions with minimal deviations, since the size of the protected areas is relatively small compared to the requirements of large, wide-ranging species such as tigers. Tigers disperse to preserve genetic diversity within their species [34, 35]. They rely on a landscape that successfully allows them to move to other areas with an ample prey base and breeding sites. Therefore, connectivity mapping offers a comprehensive understanding of the significant areas for the movement of tigers at various scales. Several scholars have assessed the adequacy of protected area networks and potential corridors' efficacies to protect wildlife species and their connectivity for restoration and conservation [36–43]. Previous research has identified habitat connectivity for various wildlife species across different spatial scales using different analytical approaches, including least-cost path analysis, factorial least-cost path analysis, circuit theory, and resistant kernel approaches [44–46].

To ensure the survival of large carnivores like tigers amidst the growing land demand, novel land use planning methods are necessary to maintain connectivity among the tiger population within a metapopulation framework. In India, the conservation of tiger habitats is achieved through the establishment of protected areas, which play a vital role in global biodiversity preservation and the maintenance of robust ecological systems [8]. The Terai Arc Landscape (TAL), located in the foothills of the Himalayas, is renowned for its rich variety of vulnerable and endangered plant and animal species. It is considered one of the world's 200 most essential eco-regions for wildlife conservation [47]. The TAL serves as a crucial habitat for tigers and encompasses diverse environments such as humid evergreen forests, dry open forests, and swampy grasslands [48]. Valmiki Tiger Reserve (VTR) is an important tiger reserve located in the easternmost corner of the Terai Arc Landscape. The Reserve offers an ideal environment for sustaining the Bengal tiger population due to the presence of dense forests, grasslands, and adequate water sources, ensuring an abundant prey base for these species. However, uncontrolled human encroachment, forest fragmentation, and current land use practices are posing a significant threat to VTR and its conservation goals. Human-tiger conflicts are also emerging within the Reserve due to the interests and well-being of both humans and tigers that are adversely impacted by their interactions within the shared environment. Thus, it is imperative to prioritize the management of the Reserve and take immediate action to restore their connectivity within the Reserve. Despite the potential of VTR to habitat tiger population, information on habitat suitability for Bengal tigers is still found scant in the Reserve. Since habitat suitability analysis plays a vital role in policy-making and enhancing the potentiality of the Reserve to a great extent, therefore, the present study attempts to predict the potential habitat suitability for Bengal tigers in VTR. Additionally, it emphasized the importance of investigating the relationship between species distribution and environmental factors. Hence, the main objectives of this study are as follows: (1) to assess the potential habitat suitability for Bengal tigers in VTR using the MaxEnt modeling approach, (2) to identify core habitats and potential corridors in VTR utilizing the least-cost path approach, and (3) to assess the adequacy of the Reserve based on conditioning and threatening factors for better management and conservation. We argue that the methodology employed in the study may be utilized in other protected areas for the conservation of wildlife species.

2 Materials and Methods

2.1 Study Area

VTR is located in the West Champaran district of Bihar, India (Fig. 1). The Reserve covers a total area of 901.13 km^2 and lies between 27° 10′ and 27° 30′ North latitudes and 83° 50′ and 84° 10′ East longitudes. The Reserve spans an elevation ranging from 140 to 874 m above mean sea level. The western part of the Reserve is characterized by rugged terrain and steeper slopes [49]. The Reserve is drained by multiple rivers and streams. VTR experiences three distinct seasons, namely, winter, summer, and monsoon, with temperature ranging from over 43 °C to as low as 5 °C. The annual precipitation is 1106 mm, primarily received during the southwest monsoon [50].

VTR is divided into two forest divisions and eight ranges, subdivided into 36 beats. Division 1 encompasses three ranges, namely Manguraha (4 beats), Raghia (7 beats), and Gobardhana (5 beats). Division 2 of the Reserve comprises five ranges, namely Ganauli (4 beats), Chiutaha (3 beats), Madanpur (3 beats), Harnatand (7 beats), and Valmiki Nagar (3 beats) [51]. VTR exhibits a distinctive combination of *terai-bhabar* fauna and flora. The landscape of VTR is characterized by moderately dense forests covering 61% of the total area, followed by very dense forests (30%), open forests (8%), and scrubs (1%) [52].

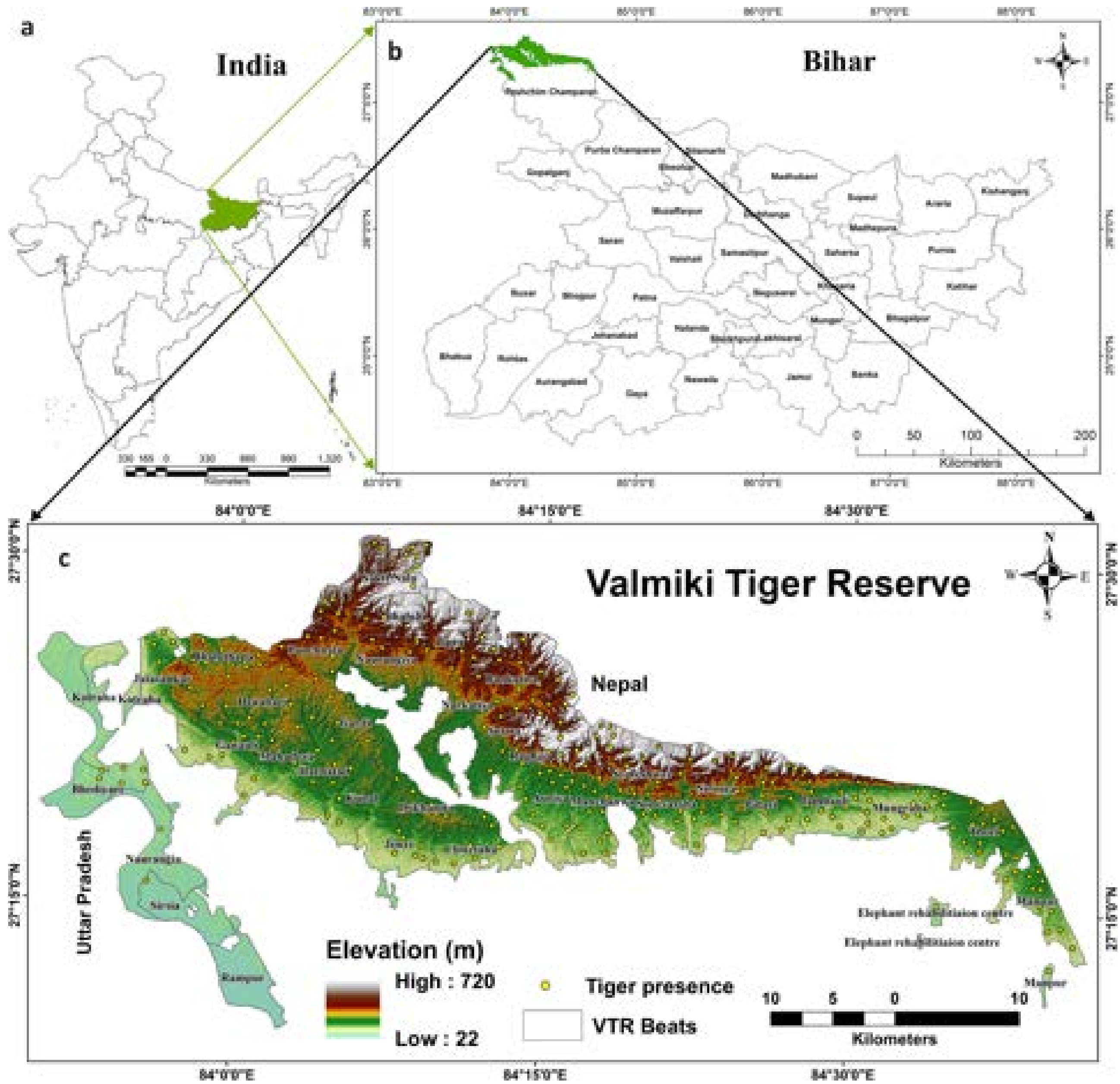

Fig. 1 Location of the study area: **a** India, **b** Bihar, and **c** Valmiki Tiger Reserve

The Reserve is home to a diverse range of faunal species supporting both indigenous and globally endangered species, including Bengal tigers. According to the NTCA report [53], the total population of Bengal tigers in VTR is 40. Spotted deer, sambar, hog deer, nilgai, wild pig, and gaur are among the Reserve's significant herbivores. However, the southern peripheral area of VTR is characterized by human settlement and agricultural fields. VTR has been under growing pressure recently due to population growth and large-scale forest conversion. The indigenous communities residing in and around the Reserve have traditionally relied on biodiversity resources for their livelihoods. They have also been involved in illicit activities such as fuelwood harvesting, poaching, and hunting. This growing dependency on such practices has had detrimental consequences, contributing to the degradation of both forest and wildlife habitats.

2.2 Data Sources

The presence location data of the Bengal tiger was collected from the Environment and Forest Department, Bettiah (West Champaran). The dataset consisted total 224 presence locations of Bengal tigers (2020–2021) was used to predict the potential habitat suitability for these species. We utilized nine location conditioning factors (tree cover, prey richness, drainage density, vegetation types, elevation, slope, aspect, temperature, and rainfall) and seven threats (forest fragmentation, land use land cover, distance from roads, railway tracks, settlement, range offices, and forest fire points). Figures 2 and 3 present all the thematic layers used for assessing habitat suitability. The tree cover map was obtained from Global Forest Watch in 2019 [54]. Prey richness data was collected from the Environment and Forest Department. Vegetation type data was prepared using the data obtained from the Biodiversity Information System of the Indian Institute of Remote Sensing (IIRS) following Roy et al. [55]. A 30-m resolution ASTER DEM was acquired from USGS Earth Explorer to prepare a drainage density map of VTR, while a 10-m resolution ALOS PALSAR DEM

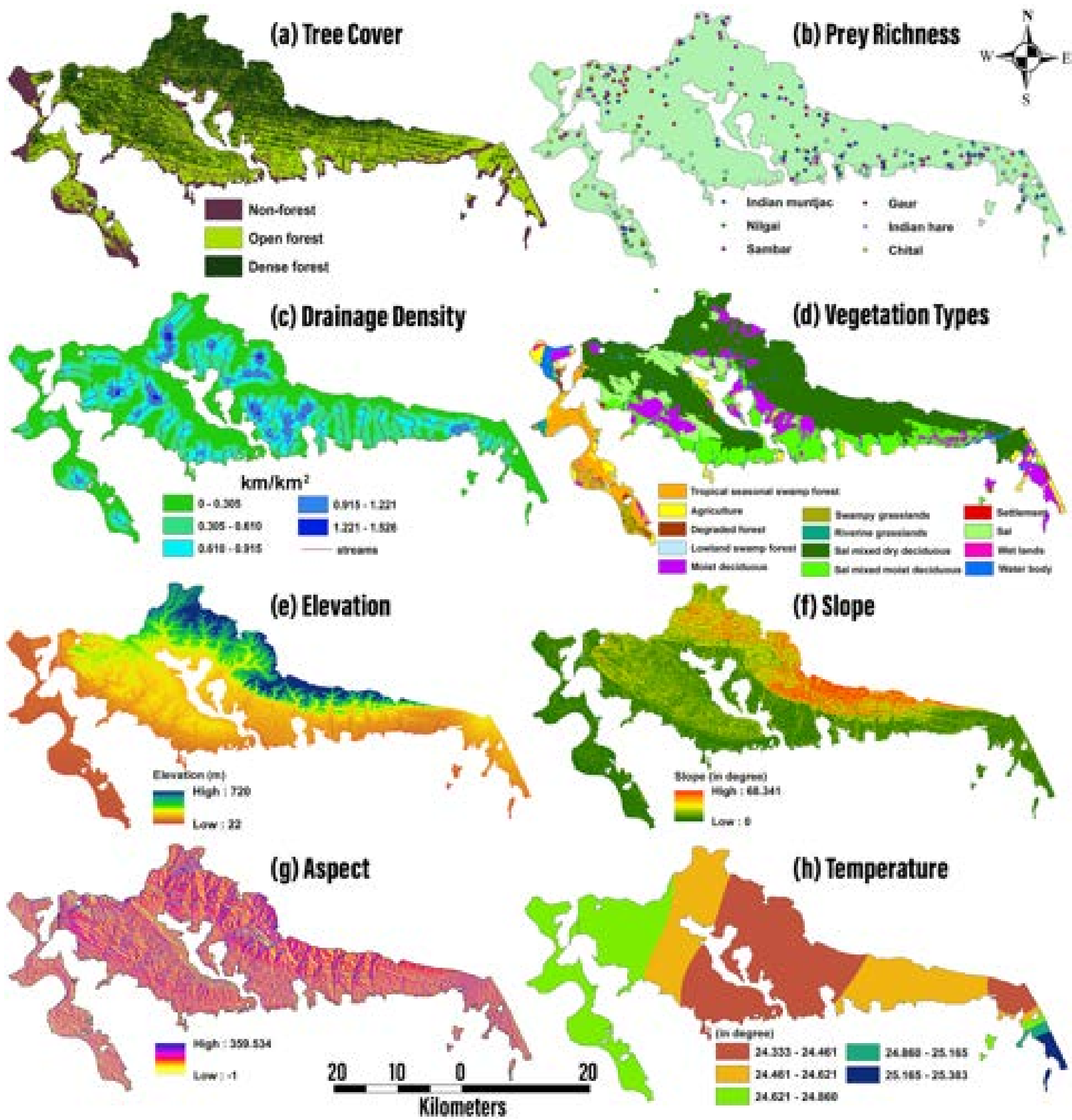

Fig. 2 Conditioning factors for Bengal tiger habitat suitability mapping: **a** tree cover, **b** prey richness, **c** drainage density, **d** vegetation types, **e** elevation, **f** slope, **g** aspect, and **h** temperature

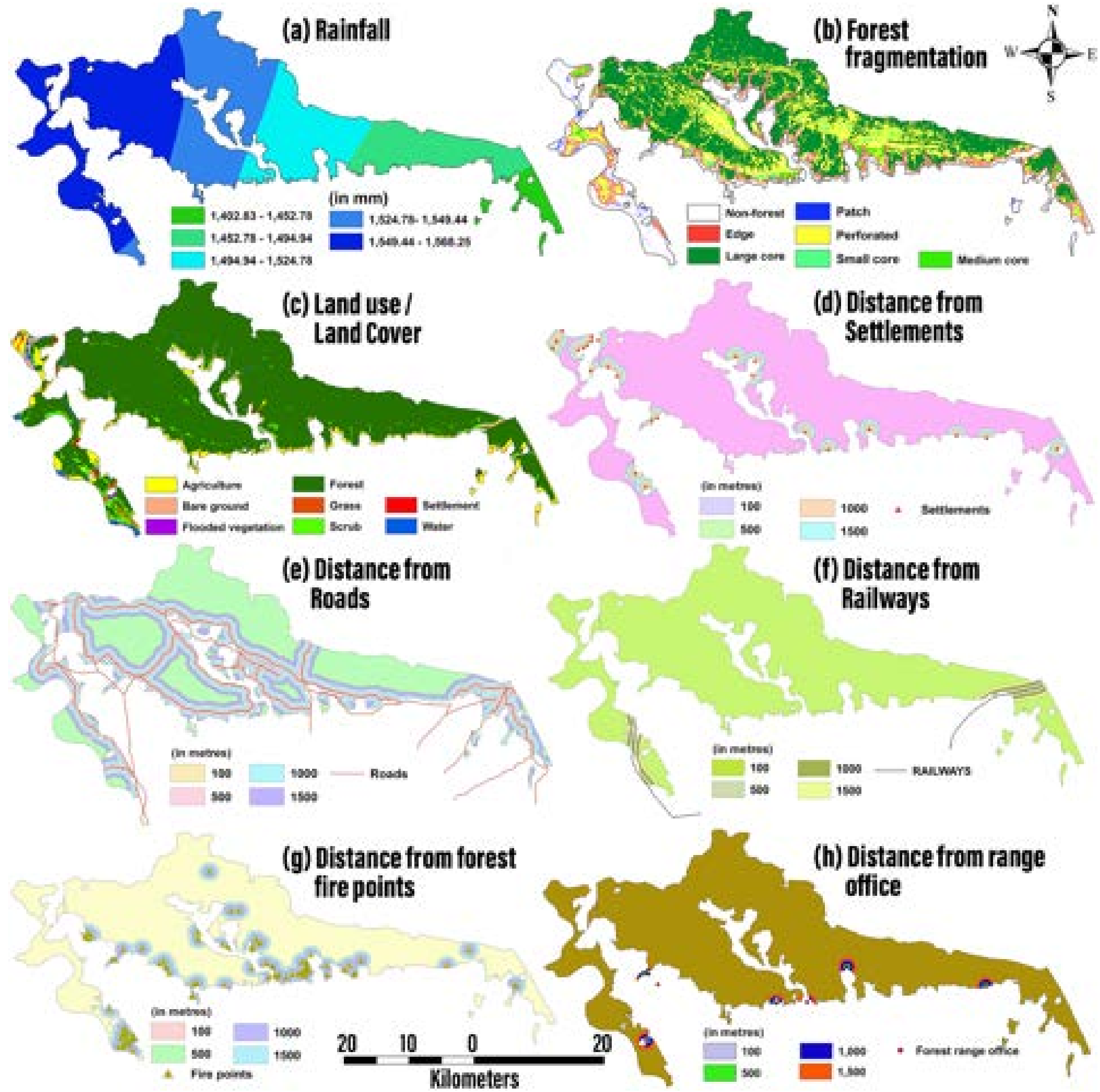

Fig. 3 Conditioning factor for Bengal tiger habitat suitability mapping: **a** rainfall; threatening factors for Bengal tiger habitat suitability mapping: **b** forest fragmentation, **c** land use land cover, **d** distance from settlement, **e** distance from roads, **f** distance from railways, **g** distance from forest fire points, and **h** distance from range office

was obtained from Alaska Satellite Facility (ASF) to prepare the aspect, elevation, and slope of the study area. The climatic data from 2011 to 2020 was collected from NASA POWER, and inverse distance weighting (IDW) was employed to interpolate the selected points for analysis. A forest fragmentation map was prepared using Sentinel-2A satellite data for the year 2020 employing the Landscape Fragmentation Tool. The land use/land cover map was acquired from the ESRI global land cover map for 2020 [56]. Forest fire point data were obtained from the Forest Survey of India (2017–2022). Distance from roads, railway tracks, settlements, and range offices were extracted from Google Earth Pro. Further, multiple buffer rings were created to determine their effect on tiger habitats. Table 1 presents the selected parameters, description, and data sources. Data pre-processing of acquired data was carried out in ERDAS IMAGINE 2014 and ArcGIS 10.7.1 software.

Table 1 Parameters used for assessing habitat suitability in VTR

Category	Factors	Rationale	Description	Data source
Conditioning factors	Tree cover	Tigers prefer dense forest cover for themselves to fetch their prey [57]	Percentage cover of dense, open, and non-forest	Global Forest Watch [58]
	Prey richness	Tigers thrive in where adequate prey is available [39]	Availability of different prey	Environment and Forest Department, Bettiah (2020–2021)
	Drainage density	Tigers are found closer to the rivers and streams [57]	Availability of water	SRTM digital elevation model from USGS Earth Explorer
	Vegetation types	The vegetation type is an important factor that explains the variation in Bengal tiger habitat selection [29]	Percentage cover of different vegetation types	Biodiversity Information System (IIRS)
	Elevation	Tigers prefer lower elevation compared to a higher elevation [39]	Mean elevation at multiple scales	ALOS PALSAR digital elevation model from Alaska Satellite Facility (ASF)
	Slope	Tigers prefer gentle to flat slopes for ease of movement [39]	Mean slope at multiple scales	ALOS PALSAR digital elevation model from Alaska Satellite Facility (ASF)
	Aspect	Tigers show a strong unimodal association with the south-facing slopes [4]	Mean aspect at multiple scales	ALOS PALSAR digital elevation model from Alaska Satellite Facility (ASF)
	Temperature	The temperature has a significant effect in determining tiger distribution in an area [29]	Temperature variation of 10 years	NASA POWER (2011–2020)
	Rainfall	Rainfall has a significant effect in determining tiger distribution in an area [29]	Rainfall variation of 10 years	NASA POWER (2011–2020)
Threats	Forest fragmentation	Habitat fragmentation between protected areas may have a detrimental impact on tiger numbers [4]	Percentage cover of various fragmentations such as patch, edge, perforated, and core forest	Landscape Fragmentation Tool (LFT v2.0)
	LULC	Tigers generally avoid areas of persistent human activity and prefer dense forests [39]	Percentage cover of different land use and land cover classes	ESRI [56]
	Distance from road	Tigers tend to avoid regions where there is a lot of human activity [39]	Euclidean distance to forest roads	Google Earth Pro
	Distance from settlement	Tigers tend to avoid regions where there is a lot of human activity [39]	Euclidean distance to nearest villages	Google Earth Pro
	Distance from railway track	Tigers tend to avoid regions where there is a lot of human activity [39]	Euclidean distance to railway tracks	Google Earth Pro
	Distance from forest fire point	Forest fire poses a great threat to wildlife habitats [59]	Euclidean distance to previous forest fire points	Forest Survey of India (2017–2022)
	Distance from range office	Tigers tend to avoid regions where there is a lot of human activity [39]	Euclidean distance to range offices	Environment and Forest Department, Bettiah

2.3 Habitat Suitability Modeling

The raster layers were resampled to the WGS GCS 1984 projection with a 30-m cell size. The layers were converted into the American Standard Code for Information Interchange (ASCII) for further processing. All the layers of conditioning factors, threatening factors, and presence location data of Bengal tigers were integrated into the MaxEnt model to produce a habitat suitability map of VTR. This is a frequently used model for predicting species distributions and has been demonstrated to be one of the most accurate models [40]. The MaxEnt modeling is an advanced approach that can be employed to simulate species distribution using presence-only data, particularly when limited presence records are available for a specific species [29]. The study utilized the presence records of tigers and the MaxEnt model for assessing the habitat suitability of Bengal tigers. This model allowed us to leverage the information with the presence of data while considering the environmental factors that contribute to tiger habitat suitability. Thus, the model helped to ensure accurate prediction and a comprehensive understanding of the habitat suitability of tigers in the study area.

The habitat suitability model for Bengal tiger species was executed in MaxEnt version 3.4.4. In MaxEnt modeling, the output format was configured as logistic, allowing it to generate probability estimates of species presence. The feature selection process included linear, quadratic, and hinge functions with a 1.000 convergence threshold. The setting of 0.050 for the regularization multiplier and 10,377 background and presence points were used. To prevent over/under prediction, 500 iterations were run during the model fitting process. A threshold-independent evaluation approach was employed to evaluate the habitat suitability model. This involved using the area under the receiver operating characteristic curve (AUC). The model was validated using a receiver operating characteristic curve (ROC). The presence data were divided into 70% for training and 30% for testing of the model. Specifically, 382 presence records were utilized for training, while 163 were used for testing the model. The habitat suitability map was further classified into four classes: three suitability (high, moderate, and low) and one unsuitable class. The predicted habitat suitability area for Bengal tigers was determined using zonal geometry in ArcMap 10.7.1. The details of the methodological steps are presented in Fig. 4.

2.4 Connectivity Modeling

The least-cost modeling is a widely employed approach for mapping corridors to facilitate habitat connectivity for various wildlife species. We employed this modeling technique to simulate the connectivity of tiger habitats within the Reserve. The construction of a landscape network, represented by the resistance surface, was a crucial step in establishing the connectivity model. The quantification of resistance to the movement of tigers is challenging due to the unavailability of movement data. Therefore, in the absence of genetic or movement data, habitat suitability is frequently used as an alternative indicator to estimate landscape resistance [35, 46, 60]. We utilized the tiger habitat suitability map to derive the resistance surface, assuming an inverse relationship between movement resistance and habitat suitability. The resistance surface was calculated using the exponential function using Eq. (1):

$$R = 1000^{(-HS)}, \quad (1)$$

where R represents the resistance value and HS signifies the habitat suitability. The HS values fall within a defined interval, such as (0, 1), where values closer to 0 represents unsuitable habitat, 1 represents highly suitable habitat, and values in between indicate varying degrees of suitability.

The equation used the exponential function due to the presence of an exponent, reflecting the exponential growth or decay behavior inherent in the movement patterns of the tiger, which is a highly mobile species. The resistance value assigned to each habitat pixel indicates the level of obstacles tiger may encounter. Lower resistance values indicate no barriers to tiger movement, while higher resistance values signify complete challenges or barriers that impede their movement [61]. The Linkage Mapper software was then employed to map potential corridors and determine the least-cost paths (LCPs) between adjacent core areas. This software facilitated the identification of adjacent core areas, the creation of a network based on adjacency and distance data, the determination of least-cost paths, the calculation of cost-weighted distances, and the consolidation of these paths into a comprehensive map.

3 Result

3.1 Potential Influencing Factors for Habitat Suitability

3.1.1 Factors Suitable for Tiger Habitats

Tree cover is associated with rich biodiversity and provides habitat for various prey species that tigers depend on for their sustenance. In VTR, 43% of the area is under dense forest cover, followed by open forest (38%) and non-forest (19%). The dense forest is mainly located in the Reserve's core area and is suitable for high prey species. High prey richness in an area enhances the availability and accessibility of food, promotes their survival, and supports wildlife diversity. It also helps in balancing the ecosystem, making

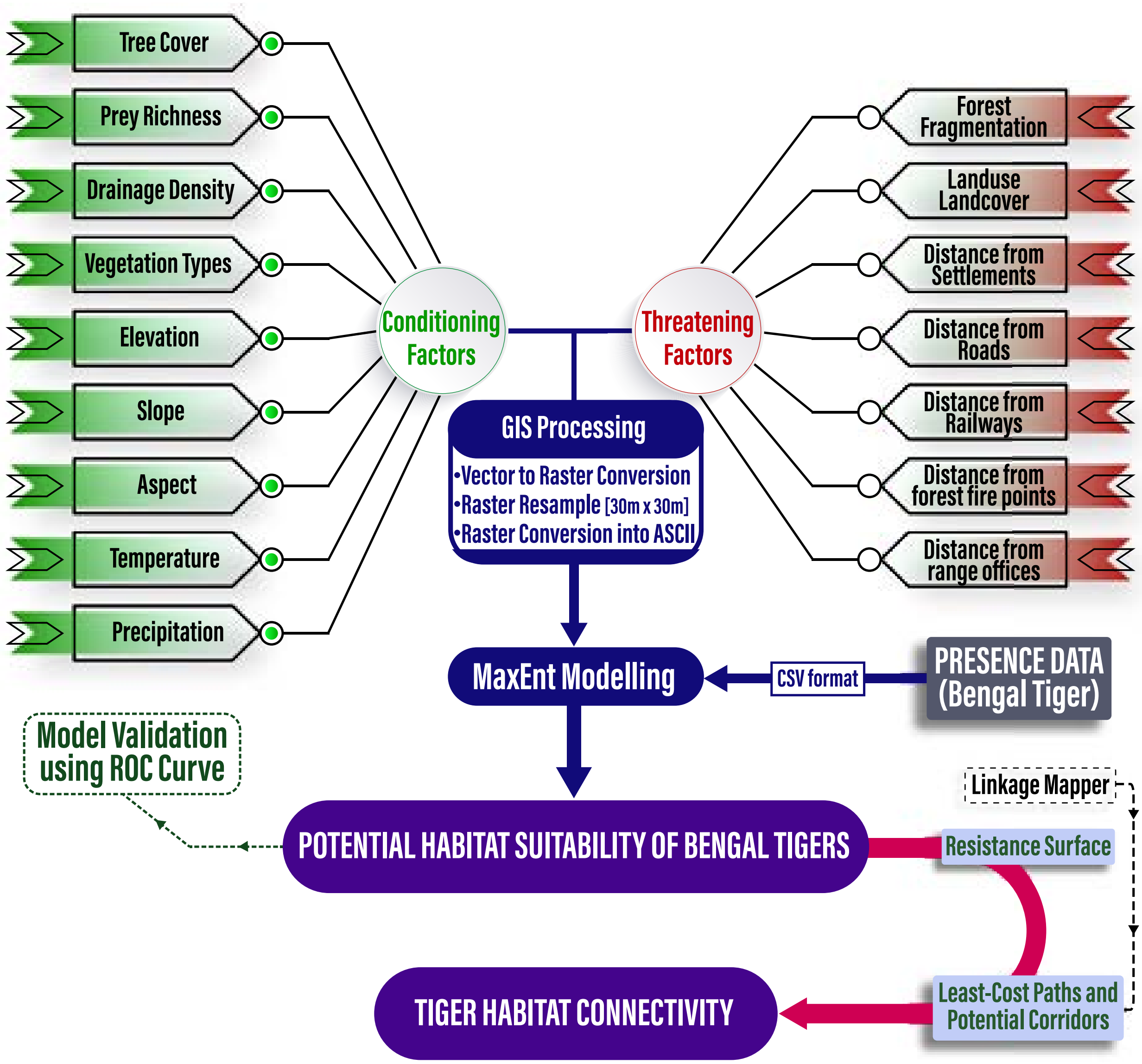

Fig. 4 Methodological framework of the present study

it crucial for maintaining the ecological integrity of tiger habitats and ensuring the long-term conservation of these magnificent predators. The Reserve's diverse ecosystem supports a variety of herbivores such as *chital* (*Axis axis*), wild boar (*Sus scrofa*), *gaur* (*Bos gaurus*), *sambar* (*Cervus unicolor*), *nilgai* (*Boselaphus tragocamelus*), Indian hare (*Lepus nigricollis*), Indian muntjac (*Muntiacus muntjak*), and other smaller mammals. These species were mainly concentrated in the northern and eastern parts of the Reserve. Gandak River and its tributaries flowing through the Reserve play a significant role in shaping its drainage pattern. These water bodies contribute to the overall drainage of the region and provide important habitats for various species, including tigers and other wildlife. The highest drainage density is observed in the central part of the Reserve. Tigers can inhabit a variety of ecosystems, including tropical rainforests, grasslands, mangroves, and mixed deciduous forests. Thus, assessing the suitability of vegetation types for tigers requires understanding the specific requirements. Vegetation types can also serve as corridors that connect different tiger habitats. The forests of VTR have a combination of *bhabar* and *terai* forest tracts. The vegetation types include *sal* (*Shorea robusta*), *sal* mixed dry deciduous, *sal* mixed moist deciduous, riverine grasslands, swampy grasslands, tropical seasonal swamp forests, moist deciduous forests, and lowland swamp forests. The elevation, slope, and aspect of a habitat can collectively contribute to its suitability for tigers. Higher elevations often correspond to steeper slopes, rugged terrain, and mountainous landscapes, which influence tiger behavior and movement patterns. Tigers may prefer habitats with a combination of varied topography that provides a mix of open areas and forested patches. The elevation in the VTR generally ranges between 22 and 720 m above mean sea level. The Reserve covers both low-lying areas (floodplains and river valleys) and relatively higher-elevated areas. The mix of low- and high-elevated regions may benefit prey availability and connectivity. The slope of the terrain influences the movement and territorial patterns of tigers. Aspect can influence sunlight exposure, temperature, and vegetation patterns, thereby determining prey distribution and overall habitat suitability. Though tigers have demonstrated adaptability to a wide range of climatic conditions, however, extreme temperature and rainfall can limit their distribution and survival. Temperature and rainfall are critical climatic factors that influence the tiger's suitability. Suitable temperature conditions are necessary for the survival, reproduction, and overall well-being of tigers. Rainfall patterns influence vegetation growth and water availability, directly impacting the suitability of tigers' habitats.

3.1.2 Factors Threatening the Tiger Habitats

Forest fragmentation poses a significant threat to the habitats of tigers. Fragmented forests result in a reduction of prey population due to the shrinking of their habitats and increased vulnerability to various natural and human disturbances. Most of the area of VTR is under core forest (49%), followed by perforated forest (24%), edge (6%), and patch forest (1%). The edge, patch, and perforated forests are considered unhealthy and have been subjected to various human activities, noticeably altering their natural state. Land use and land cover changes also pose a significant threat to the habitats of tigers. Land use changes result in increasing the likelihood of human-wildlife conflicts. An increase in the area under agriculture is found to be a significant threat in the fringe areas of the Reserve. Severe forest fires can lead to the complete loss of habitat patches, displacing tigers and reducing the availability of suitable habitats. The forest fire occurrences were mainly observed in the buffer zone of the Reserve. Human disturbances, such as settlement, roads, and railways, pose great threats to tiger habitats. Human settlement, unplanned infrastructural development, and transportation networks often require the clearing of forests, leading to the direct loss of habitats. Human disturbances can isolate the tiger population by creating barriers that hinder their movement and gene flow. The Reserve is situated in close proximity to densely populated settlements, which are heavily dependent on forest resources. This has substantially increased biotic pressure in the Reserve and its surrounding buffer zones.

The relative importance of conditioning factors and threatening factors of habitat suitability are presented in Table 2. The analysis revealed that among the conditioning factors for habitat suitability, tree cover (29.4%) was identified as a significant influencing factor, followed by elevation (18.2%), rainfall (16.7%), and vegetation types (3.2%). Among threats, the habitat suitability of Bengal tigers was mainly influenced by the intimidations caused by human activities, namely distance from roads (6.9%), railway track (5.3%), settlement (3.3%), and land use land cover patterns (3.2%). Distance from range offices, temperature, and slope were found to be the least contributing factors.

Table 2 Relative importance of factors in the optimal model

Factors	Percent contribution (%)
Tree cover	29.4
Elevation	18.2
Rainfall	16.7
Distance from roads	6.9
Distance from railways	5.3
Distance from settlements	3.3
LULC	3.2
Vegetation types	3.2
Aspect	3.0
Drainage density	2.8
Forest fragmentation	2.1
Prey richness	1.5
Distance from forest fire points	1.5
Distance from range offices	1.2
Temperature	1.0
Slope	0.5

The jackknife test was performed to identify the most influential factor for suitability (Fig. 5). This test evaluated the significance of variables by calculating the area under the receiver operating characteristic curve (AUC) for models using each variable individually [41]. A higher gain value indicates a variable that provides more informative data when used in isolation. The results showed that the tree cover emerged as the environmental factor with the highest gain when used individually, indicating its significant contribution to modeling Bengal tiger suitability, whereas rainfall exhibited the largest decrease in gain when omitted, suggesting that it possesses unique information not present in the other variables. The variables "distance from range offices" and "forest fire points" obtained the lowest values, indicating a lower level of information relevance for modeling Bengal tiger suitability.

3.2 Potential Habitat Suitability of Bengal Tigers

The predicted habitat suitability index (HSI) generated by MaxEnt varies between 0 (representing unsuitable habitat) and 1 (indicating the most suitable habitat) [41]. We

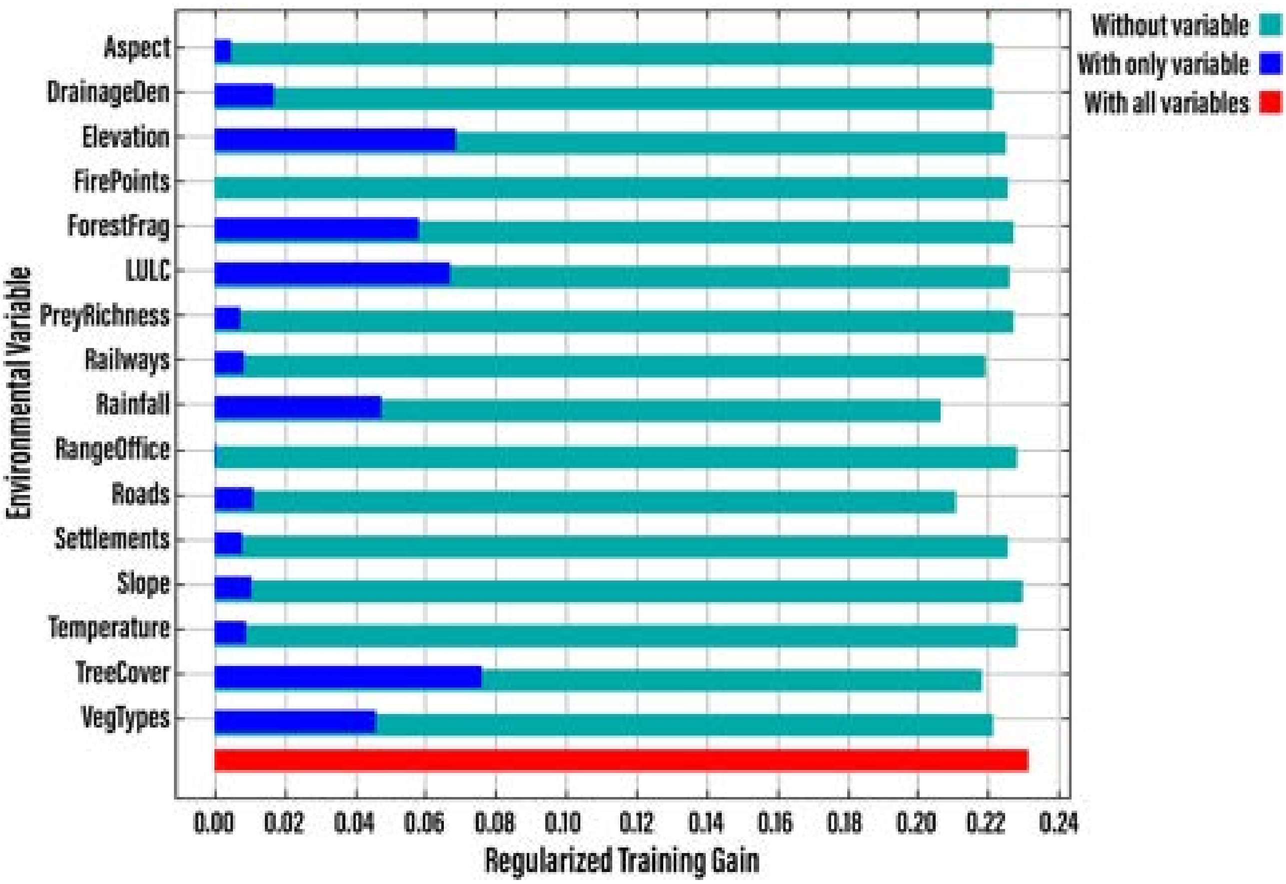

Fig. 5 MaxEnt generated values of jackknife regularized training gain for Bengal tigers

categorized the HSI values into four classes using the natural break classification method: unsuitable (0.0006–0.2435), low suitable (0.2435–0.4826), moderately suitable (0.4826–0.6668), and highly suitable habitat (0.6668–1). Of the total area of the Reserve (923.817 km^2), the largest area was found under moderately suitable habitat (42%), followed by low suitable (23%), highly suitable (19%), and unsuitable habitat (16%) (Fig. 6). Table 3 shows the area distribution under suitable and unsuitable habitats in VTR.

The highest concentration of Bengal tiger was found in the eastern part of the Reserve. Overall, suitable areas for Bengal tigers are found in dense forests and flat to gentle slopes with less human disturbances. The Reserve is divided into 36 beats for effective wildlife conservation. Of the total beats, *Manguraha* (2.11%) was identified as a highly suitable beat supporting this species, followed by *Jamhauli* (2.09%), *Manchanwa* (1.91%), *Pidari* (1.76%), *Thori* (1.60%), and *Sirisiya* (1.55%). *Rampur*, *Kotraha*, Elephant Rehabilitation Centre, *Pipra*, and *Naurangiya* beats were found to be unsuitable habitats. Areas of high suitability were concentrated in the eastern part of the Reserve with dense forest cover with high prey density and minimal human disturbances. Moderate suitability was observed in the central part of the Reserve, attributed to low elevation, perforated forest, and the presence of roads. Developmental activities and settlement were found to be responsible for low habitat suitability in the buffer area of the Reserve. The unsuitable habitats were located at the fringe areas with massive human encroachment and concentration of settlements, roads, railways, and agricultural fields.

3.3 Validation

The AUC values are categorized as excellent (greater than 0.9), good (0.8–0.9), fair (0.7–0.8), and poor (0.6–0.7) [62]. The habitat suitability map generated through MaxEnt for Bengal tigers in VTR was validated using the ROC curve, which indicated a good model performance with an AUC value of 0.822 (Fig. 7).

3.4 Potential Corridors

Corridor mapping is essential for safeguarding core habitat areas and maintaining connectivity networks at landscape scale to ensure the long-term survival of tigers [44]. The linkage pathways tool from linkage mapper was utilized to

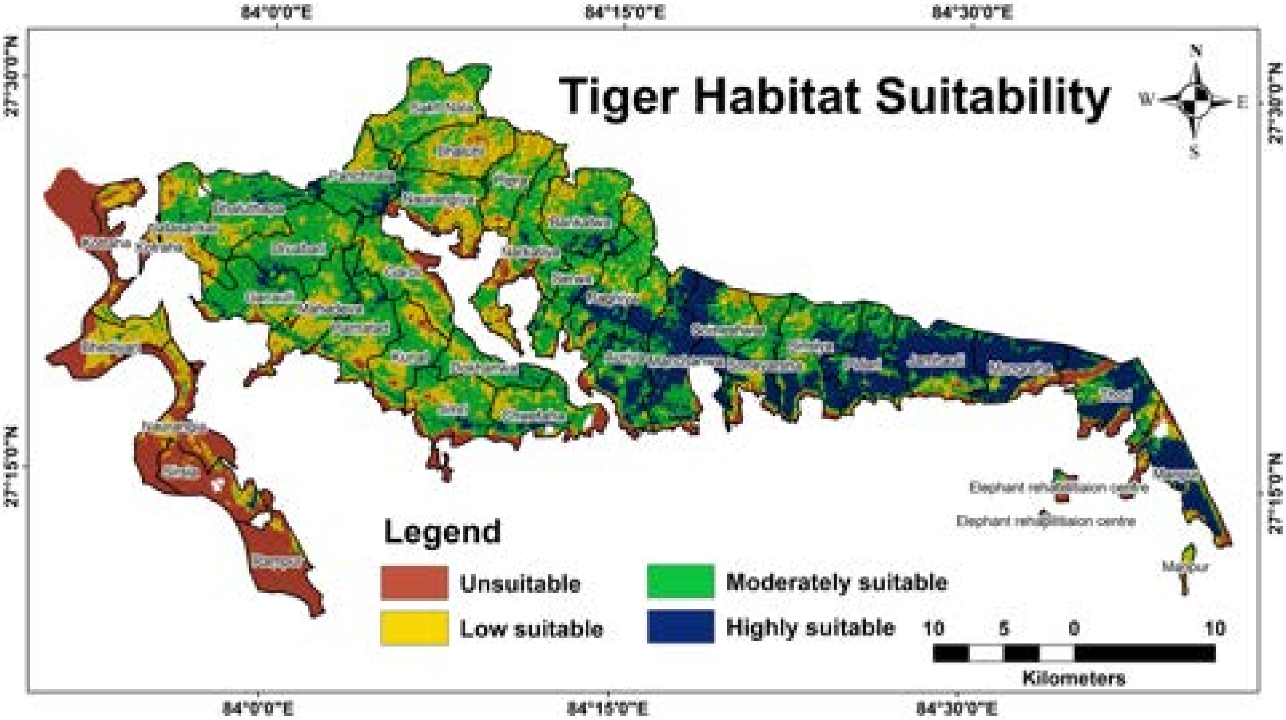

Fig. 6 Habitat suitability map for Bengal tigers in Valmiki Tiger Reserve

identify tiger corridors based on a resistance surface (Fig. 8A). The software identified 73 potential tiger corridors in 39 core habitat areas within the Reserve. These corridors span an average length of 2.8 km^2. Figure 8B represents the least-cost pathways connecting the core habitats and adjacent core areas in VTR. The LCPs play a crucial role in facilitating tiger dispersal. The findings revealed that potential corridors within the Reserve are unevenly distributed. However, the northern and central parts were found to have fairly good ecological environments and landscape connectivity. The connectivity analysis showed that tigers may primarily prefer to utilize forested corridors that exhibit low elevation and gentle slopes for their movement. The identified corridors may play a crucial role in connecting around 60% of the Reserve area and may serve as an effective ecological conservation network. These potential corridors are characterized by dense and continuous forests, which may serve as crucial connectors supporting an optimal tiger population within the Reserve. The analysis demonstrated a higher density of corridors in the northern and central parts of the Reserve, primarily due to the smaller size of the core areas. Despite the limited number of habitat patches in these areas, they hold substantial value as crucial tiger dispersal corridors. The western part of the Reserve, comprising the *Madanpur* and *Valmiki Nagar* ranges, lacks pathways and corridors for tigers. These ranges have been suitable habitats for herbivores in the past. This part of the Reserve is now fragmented due to land encroachment for linear development, agriculture, and human settlement and is under severe threat for the movement of tigers. Few corridors were identified in the buffer zone of the Reserve. These corridors are not suitable for the movement of tigers due to developmental activities.

Table 3 Area under suitable and unsuitable habitats in VTR

Tiger habitat	Area	
Class	(sq. km)	(Percentage)
Unsuitable	145.633074	15.76
Low suitable	212.295251	22.98
Moderately suitable	387.296096	41.92
Highly suitable	178.593196	19.34
Total area	923.817617	100

Source: Authors' own calculation

4 Discussion

Geospatial modeling is significant for identifying optimal habitats for wildlife, enabling a comprehensive understanding of distribution patterns and essential ecological parameters with a high level of detail. Habitat suitability analysis for tigers provides the basis for effective conservation efforts. MaxEnt modeling proved to be quite effective in predicting

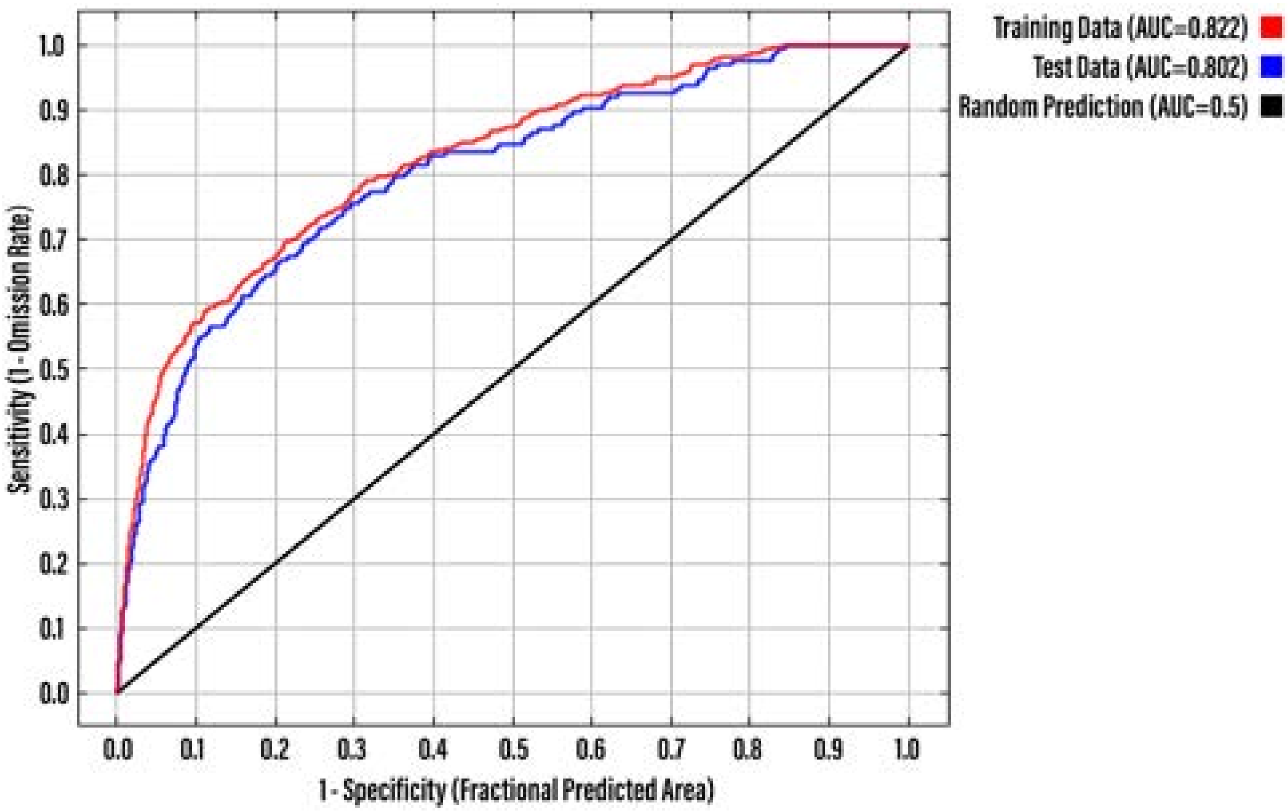

Fig. 7 MaxEnt generated values for ROCs indicating AUC for Bengal tigers

habitat suitability for Bengal tigers in VTR. Many scholars have also proved the effectiveness of MaxEnt in predicting habitat suitability for various species [63–69]. The model simulation result showed that around 41% and 19% of the total area of the Reserve was found under moderately and highly suitable habitats for Bengal tigers. These habitats support an abundance of prey, water availability, and tree cover, mainly *sal* forest, which are efficient for Bengal tiger sustenance. Similar findings were reported by Imam et al. [70], Thinley et al. [39], and Kc et al. [16], emphasizing that tigers exhibit a strong preference for densely forested areas with abundant prey. Low suitability and unsuitable habitats were confined to the peripheral areas of the Reserve where human encroachment seems more prevalent. Anthropogenic threats are inducing habitat deterioration and fragmentation in VTR. The synergistic consequences of habitat loss and overexploitation will exacerbate future climate change impacts. Therefore, identifying and mapping critical tiger habitats will aid in the efficiency of severe conservation efforts to mitigate the effects of climate change and other human disturbances [30].

Due to the extensive human influences on ecosystems and the inadequate political and economic capabilities to implement large-scale conservation programs, it is critical to optimize conservation measures to maximize conservation benefits. The expansion and readjustment in the boundaries of the protected areas may help in the easy movement of tigers in connecting corridors. Previous research highlights the significance of identifying and delineating tiger corridors as a crucial measure for ensuring the long-term viability of the metapopulation dynamics of tigers [71, 72]. The present study identified the least-cost pathways and potential corridors that connect the core habitat patches within the Reserve using a Linkage Mapper. Several researchers have proved the effectiveness of least-cost modeling utilizing Linkage Mapper software [46, 73, 74]. The findings revealed that the eastern and central parts of the Reserve exhibit robust corridors for tiger dispersal, while the corridors situated in the buffer zone face a higher risk of human-induced disturbances within the Reserve. Significant interruptions are identified in these corridors due to the presence of settlements, roads, railways, and canals. In the western part of the Reserve, specifically, *Rampur*, *Sirsia*, *Naurangiya*, *Bhediyari*, and *Kotraha* beats lack tiger corridors, which is attributed to significant biotic pressure and degraded forest ecosystem. Tigers are also susceptible to vehicle collisions, and the presence of numerous roads and railways poses a considerable threat to their habitats and dispersal routes within the Reserve. Therefore, efforts should be concentrated on enhancing degraded habitats and restoring the potential corridors for easy movement of the Bengal tigers.

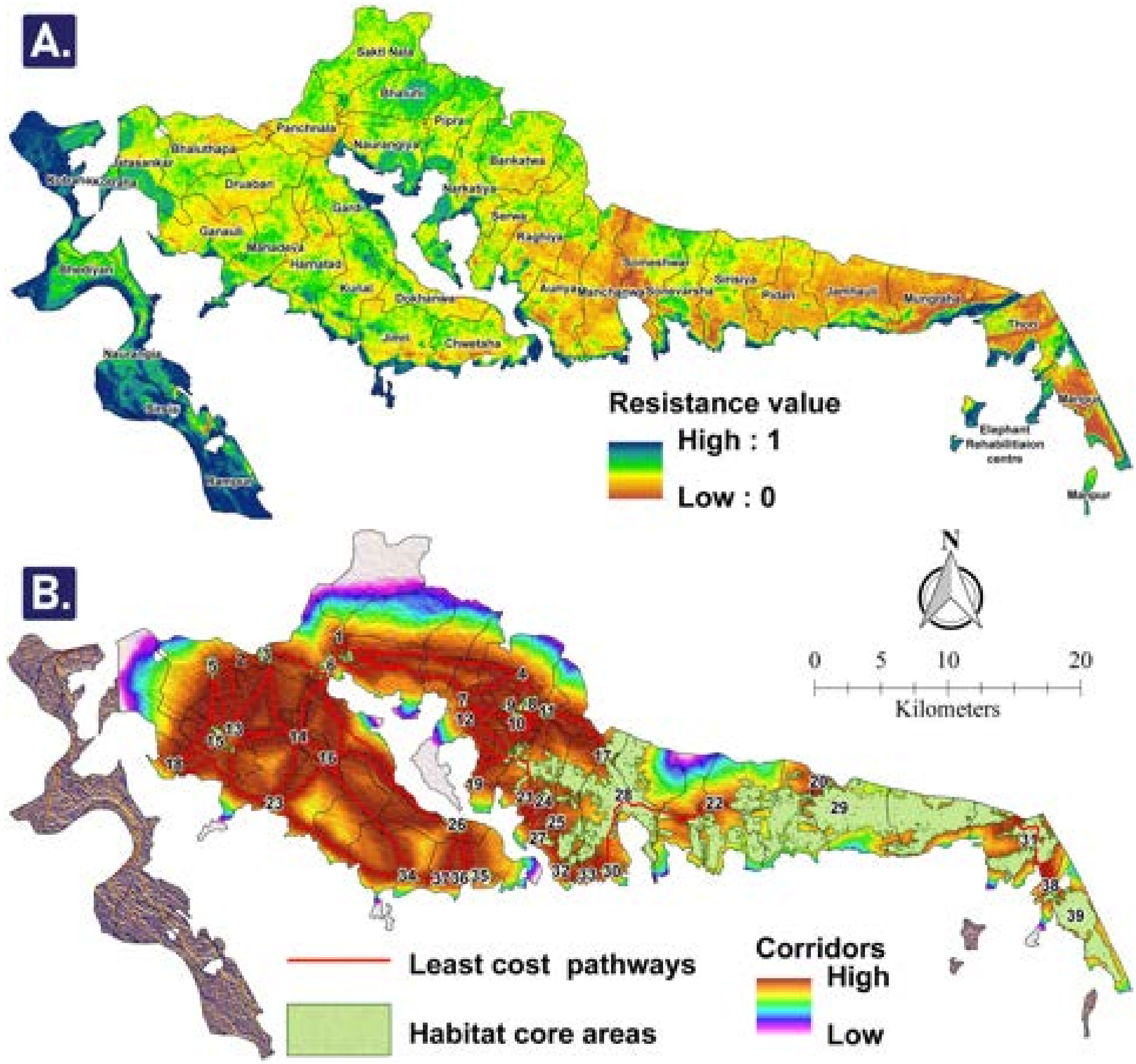

Fig. 8 Habitat connectivity for Bengal tigers in VTR: **A** resistance surface, **B** least-cost paths and corridors between the core habitats

Protected area networks throughout the world will serve as the only protection for endangered species in the near future and cause significant shifts in species distributions [29]. VTR was declared the 18th tiger Reserve in 1994 under "Project Tiger," which acts as an enduring nationwide effort launched in 1972 to protect the magnificent tiger species [51]. However, protected areas have their own limitations due to their relatively small size, and the majority of wildlife habitats are now located beyond their boundaries [75]. Therefore, extending tiger conservation efforts beyond protected areas is crucial to ensure their widespread impact. The size of VTR is limited, which anticipates tigers to disperse in the buffer zone as an alternate habitat, further leading to human-tiger conflicts. Human-tiger conflicts have increased in the VTR over recent years, which can be attributed to several factors, including illegal encroachment, forest fragmentation, and linear intrusion in the corridor. The minimum size of the intact area for a viable tiger population is supposed to be 800 to 1000 km^2, whereas the size of the core of VTR is barely sufficient, being 589 km^2. However, the northern boundary of the Reserve shares contiguity with Chitwan National Park and Parsa National Park. These areas remain stable and free from major human settlements, making it highly promising for the establishment of trans-corridors to enable the movement of tigers and other wildlife [53, 76]. The government needs to prioritize preserving and enhancing existing tiger habitats, both within protected areas and in the buffer zone. Emphasis should be laid on improving the habitat management for tigers and their prey to restore their habitat connectivity.

The villages within a few kilometers of the Reserve create intense pressure on the forests. The forest in the buffer zone is under constant threat due to increased anthropogenic activities. Besides, developmental activities further increased pressure on the forest of the fringe areas. The forest landscape in the *Pandai-Dohram* zone at the eastern end of the Reserve is adversely affected by habitat fragmentation due to the continuation of the *Narkatiaganj-Bhikhna Thori* railway section. *Naurangia Done* includes 26 revenue villages located almost in the center of VTR, threatening to disintegrate the tiger landscape in the central part [11]. In addition, the traditional practice of poaching by the local community is still a threat. Village density at a large scale has a negative effect on tiger distribution; thus, relocation of the villages might be beneficial for the Reserve as well as avoiding human-tiger conflicts. Continuous and long-term monitoring of the tiger population is vital. Additionally, research should prioritize understanding tiger behavior, habitat needs, and landscape connectivity to improve management approaches. In addition to habitat protection and management, government and conservation groups recognized the necessity of tiger movement across landscapes, safeguarding connectivity, which would entail community participation as a crucial component.

5 Conclusion

The paper assessed habitat suitability for Bengal tigers in VTR using the MaxEnt modeling approach. We selected location-specific factors (conditioning and threatening) and tiger presence location data. The thematic layers of all these factors were prepared in a GIS environment and integrated with the MaxEnt model to produce a habitat suitability map. We validated the model with an ROC curve using AUC values (0.822), which indicated the high predictive performance of the model. Least-cost pathways and potential corridors connecting the core habitats of the tiger were also analyzed using Linkage Mapper. The findings revealed that most of the area of the Reserve (61%) is moderately and highly suitable for Bengal tigers. These habitats covered the central and eastern parts of the Reserve. *Sal* forest cover, prey richness, adequate drainage density, and sufficient rainfall were the conditioning factors responsible for the high suitability of the habitat in the Reserve. Nearly 39% of the area of the Reserve was found as low suitable and unsuitable classes for tiger habitats. These habitats were mainly confined in the buffer areas of the Reserve with extensive human encroachment. The least-cost pathways analysis revealed the possibility of robust tiger dispersal corridors in the eastern and central parts of the Reserve, whereas the western part of the Reserve is found not suitable for creating such corridors due to degraded forests and biotic pressure. The Bengal tigers avoid human settlement and prefer to stay at a distance from roads, railways, and forest fire points. In VTR, human interference was shown to have a considerable impact on the suitability of tiger habitats and potential corridors. The habitat degradation in the buffer areas of the Reserve must be prioritized for lessening its effects on tiger habitats. The government should prioritize tiger conservation by enhancing the connectivity of corridors for transboundary tiger mobility. Strict surveillance and law enforcement to restrict illegal anthropogenic activities and create public awareness to counter human-tiger conflicts should be encouraged in the Reserve and peripheral areas. The findings of the study will lay the base for future research and can be used to guide the management of Bengal tiger distribution in VTR, ensuring the species' long-term existence.

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Declarations

Ethics Approval This is an observational study. The Research Ethics Committee has confirmed that no ethical approval is required.

Consent to Participate Not applicable.

Consent for Publication Not applicable.

Competing Interests The authors declare no competing interests.

References

1. WWF. (2020). Enhancing the understanding, establishment and operation of transboundary conservation landscapes. *WWF Tigers Alive, WWF Belgium, Wildteam UK*. Retrieved December 23, 2021, from https://wwfeu.awsassets.panda.org/downloads/transboundary_conservation_report_web.pdf

2. Deb, J. C., Phinn, S., Butt, N., & McAlpine, C. A. (2019). Adaptive management and planning for the conservation of four threatened large Asian mammals in a changing climate. *Mitigation and Adaptation Strategies for Global Change, 24*(2), 259–280. https://doi.org/10.1007/s11027-018-9810-3
3. Tang, T., Li, J., Sun, H., & Deng, C. (2021). Priority areas identified through spatial habitat suitability index and network analysis: Wild boar populations as proxies for tigers in and around the Hupingshan and Houhe National Nature Reserves. *Science of the Total Environment, 774*, 145067. https://doi.org/10.1016/j.scitotenv.2021.145067
4. Rather, T. A., Kumar, S., & Khan, J. A. (2020). Multi-scale habitat modelling and predicting change in the distribution of tiger and leopard using random forest algorithm. *Scientific Reports, 10*(1), 1–19. https://doi.org/10.1038/s41598-020-68167-z
5. Tian, Y., Wu, J., Wang, T., & Ge, J. (2014). Climate change and landscape fragmentation jeopardize the population viability of the Siberian tiger (Panthera tigris altaica). *Landscape Ecology, 29*(4), 621–637. https://doi.org/10.1007/s10980-014-0009-z
6. WII. (2016). Eco-friendly measures to mitigate impacts of linear infrastructure on wildlife. *Wildlife Institute of India, Dehradun, India*. https://moef.gov.in/wp-content/uploads/2019/07/eco_friendly_measures_mitigate_impacts_linear_infra_wildlife_compressed.pdf
7. WWF-USA. (2020). Doubling Wild Tigers - Annual Report. *WWF Tigers Alive, WWF-USA*. https://www.wwf.de/fileadmin/fm-wwf/Publikationen-PDF/Asien/WWF-Report-Doubling-Tigers-2020.pdf
8. Global Tiger Forum. (2019). Status of tiger habitats in high altitude ecosystems of Bhutan, India and Nepal (situation analysis). *Global Tiger Forum*. https://globaltigerforum.org/wp-content/uploads/2019/09/Final-HAT-VERSION-28-AUGUST-20191.pdf
9. IUCN. (2022). The future of Panthera tigris in Thailand and globally. *International Union for Conservation of Nature*. Retrieved May 26, 2023, from https://www.iucn.org/story/202208/future-panthera-tigris-thailand-and-globally
10. Jhala, Y. V., Qureshi, Q., & Nayak, A. K. (2019). *Status of tigers, co-predators and prey in India- 2018. Summary report*. National Tiger Conservation Authority, Government of India, New Delhi & Wildlife Institute of India, Dehradun. TR No./2019/05. Retrieved December 12, 2021, from https://docslib.org/doc/1348499/status-oftigers-in-india-2018
11. Qureshi, Q., Saini, S., Basu, P., Gopal, R., Raza, R., & Jhala, Y. (2014). Connecting tiger populations for long-term conservation. National Tiger Conservation Authority and Wildlife Institute of India, Dehradun. TR2014–TR2002. Retrieved December 23, 2021, from https://wii.gov.in/images/images/documents/conn_tiger_preface_toc.pdf
12. IUCN. (2021). Impact results from projects implemented between 2015 and 2021, Integrated Tiger Habitat conservation programme. Retrieved January 4, 2022, from https://iucnsos.org/wp-content/uploads/2021/07/ITHCP-Phase-I-Impact-Report.pdf
13. World Atlas. (2022). Where do tigers live?. Retrieved January 4, 2022, from https://www.worldatlas.com/articles/where-do-tigers-live.html
14. Long, Z., Gu, J., Jiang, G., Holyoak, M., Wang, G., Bao, H., Liu, P., Zhang, M., & Ma, J. (2021). Spatial conservation prioritization for the Amur tiger in Northeast China. *Ecosphere, 12*(9), e03758. https://doi.org/10.1002/ecs2.3758
15. Chanchani, P., Lamichhane, B. R., Malla, S., Maurya, K., Bista, A., Warrier, R., Nair, S., Almeida, M., Ravi, R., Sharma, R., Dhakal, M., Yadav, S. P., Thapa, M., Jnawali, S. R., Pradhan, N. M. B., Subedi, N., Thapa, G. J., Yadav, H., Jhala, Y. V., et al. (2014). *Tigers of the Transboundary Terai Arc Landscape: Status, distribution and movement in the Terai of India and Nepal*. National Tiger Conservation Authority, Government of India, and Department of National Park and Wildlife Conservation, Government of Nepal. Global Tiger Forum. https://doi.org/10.13140/2.1.2737.2808
16. Kc, K., Bhumpakhpan, N., Trisurat, Y., Mainmit, N., Ghimire, K., & Subedi, M. (2020). Analysis of potential distribution of tiger habitat using MaxEnt in Chitwan National Park. *Nepal. Journal of Remote Sensing and GIS Association of Thailand, 21*(3), 1–15.
17. WWF-Washington. (2022). Facts. Retrieved February 6, 2022, from https://www.worldwildlife.org/species/tiger
18. Kywe, T. Z. (2012). Habitat suitability modeling for tiger (Panthera tigris) in the Hukaung Valley Tiger Reserve, Northern Myanmar. *Doctoral dissertation, Niedersächsische Staats-und Universitätsbibliothek Göttingen*. https://d-nb.info/1042263000/34
19. WWF Tigers Alive. (2020). Landscape connectivity science and practice: Ways forward for large ranging species and their landscapes. *Workshop Report, WWF International*. https://www.wwf.pl/sites/default/files/202211/2020_Landscape_Connectivity_Science_and_Practice_Ways_Forward_for_Large_Ranging_Species_and_Their_Landscapes_Lauren_Simmonds.pdf
20. Rather, T. A., Kumar, S., & Khan, J. A. (2021). Using machine learning to predict habitat suitability of sloth bears at multiple spatial scales. *Ecological Processes, 10*(1). https://doi.org/10.1186/s13717-021-00323-3
21. Bajaj, S., & Geraldine Bessie Amali, D. (2019). Species environmental niche distribution modeling for Panthera Tigris Tigris 'royal Bengal tiger'using machine learning. In: *Advances in Intelligent Systems and Computing, Springer, Singapore,* pp. 251–263. https://doi.org/10.1007/978-981-13-5953-8_22
22. Singh, A., & Kushwaha, S. P. S. (2011). Refining logistic regression models for wildlife habitat suitability modeling-A case study with muntjak and goral in the Central Himalayas. *India. Ecological Modelling, 222*(8), 1354–1366. https://doi.org/10.1016/j.ecolmodel.2011.02.012
23. Kumar, A. A., Sivakumar, R., & Ramesh, K. (2013). Assessing habitat suitability for tiger (Panthera tigris) in Panna Tiger Reserve, Madhya Pradesh, India: A geospatial approach. *Scientific Transactions in Enviornment and Technovation, 7*(2), 77–81. https://doi.org/10.20894/STET.116.007.002.003
24. Gehlot, H. S., & Joshi, P. (2019). Geospatial modelling of potential habitat of tiger (Panthera tigris tigris) in Corbett-Kosi river corridor of Uttrakhand, India. *Journal of Environment and Biosciences, 33*(2), 211–219.
25. Sarkar, M. S., Krishnamurthy, R., Johnson, J. A., Sen, S., & Saha, G. K. (2017). Assessment of fine-scale resource selection and spatially explicit habitat suitability modelling for a re-introduced tiger (Panthera tigris) population in Central India. *PeerJ, 5*, e3920. https://doi.org/10.7717/peerj.3920
26. Jain, P., Ahmed, R., Sajjad, H., Sahana, M., Jaafari, A., Dou, J., & Hong, H. (2021). Habitat suitability mapping of sloth bear (Melursus ursinus) in the Sariska Tiger Reserve (India) using a GIS-based fuzzy analytical hierarchy process. In *Remote Sensing and GIScience* (pp. 205–227). Springer, Cham. https://doi.org/10.1007/978-3-030-55092-9_12
27. Lim, C. H., Yoo, S., Choi, Y., Jeon, S. W., Son, Y., & Lee, W. K. (2018). Assessing climate change impact on forest habitat suitability and diversity in the Korean Peninsula. *Forests, 9*(5), 259. https://doi.org/10.3390/f9050259
28. Khan, R. U., Ali, N., Rahman, I. U., & Rahman, S. U. (2021). Predicting the impacts of climate change on the potential distribution pattern of endangered Himalayan natives (Ulmus wallichiana and U. villosa) in Pakistan. *Arabian Journal of Geosciences, 14*(23), 1–11. https://doi.org/10.1007/s12517-021-08969-1
29. Mukul, S. A., Alamgir, M., Sohel, M. S. I., Pert, P. L., Herbohn, J., Turton, S. M., Khan, M. S. I., Munim, S. A., Reza, A. H. M. A., & Laurance, W. F. (2019). Combined effects of climate change and sea-level rise project dramatic habitat loss of the globally endangered Bengal tiger in the Bangladesh Sundarbans. *Science of*

The Total Environment, 663, 830–840. https://doi.org/10.1016/J.SCITOTENV.2019.01.383

30. Ngo, H. N., Nguyen, H. Q., Phan, T. Q., Nguyen, T. Q., Gewiss, L. R., Rödder, D., & Ziegler, T. (2022). Modeling the environmental refugia of the endangered Lichtenfelder's Tiger Gecko (Goniurosaurus lichtenfelderi) towards implementation of transboundary conservation. *Frontiers of Biogeography, 13*(4), e51167. https://doi.org/10.21425/f5fbg51167
31. Kimsing, A. T., Ngukir, J., Biju, T., & Mize, D. (2022). White-rumped vulture's habitat suitability prediction using MaxEnt in Arunachal Pradesh. *Asian Journal of Biology, 15*(1), 18–30. https://doi.org/10.9734/AJOB/2022/v15i130229
32. Wang, M., Hu, Z., Wang, Y., & Zhao, W. (2023). Spatial distribution characteristics of suitable planting areas for Pyrus species under climate change in China. *Plants, 12*(7), 1559. https://doi.org/10.3390/plants12071559
33. Sharifian, S., Mortazavi, M. S., & Mohebbi Nozar, S. L. (2023). The ecological response of commercial fishes and shrimps to climate change: Predicting global distributional shifts under future scenarios. *Regional Environmental Change, 23*(2), 64. https://doi.org/10.1007/s10113-023-02052-z
34. Dutta, T., Sharma, S., McRae, B. H., Roy, P. S., & DeFries, R. (2016). Connecting the dots: Mapping habitat connectivity for tigers in Central India. *Regional Environmental Change, 16*(S1), 53–67. https://doi.org/10.1007/s10113-015-0877-z
35. Mahmoodi, S., Shadloo, S., Rezaei, S., & Shabani, A. A. (2023). Prediction of habitat suitability, connectivity, and corridors in the future to conserve roe deer (Capreolus capreolus) as a locally endangered species in northern Iran. *Journal for Nature Conservation, 71*, 126313. https://doi.org/10.1016/j.jnc.2022.126313
36. Hameed, S., ud Din, J., Ali, H., Kabir, M., Younas, M., Ur Rehman, E., Bari, F., Hao, W., Bischof, R., & Nawaz, M. A. (2020). Identifying priority landscapes for conservation of snow leopards in Pakistan. *PLoS ONE 15*(11), e0228832. https://doi.org/10.1371/journal.pone.0228832
37. Jiang, F., Li, G., Qin, W., Zhang, J., Lin, G., Cai, Z., Gao, H., & Zhang, T. (2019). Setting priority conservation areas of wild Tibetan gazelle (Procapra picticaudata) in China's first national park. *Global Ecology and Conservation, 20*, e00725. https://doi.org/10.1016/j.gecco.2019.e00725
38. Gardener, B. (2020). Habitat modelling of the Amur leopard and Siberian tiger for future reintroduction using conservation priority setting, ecological corridors and carrying capacities. *Master dissertation, Bangor University*. https://www.proquest.com/openview/916c691bebef565174871581f704311f/1?pqorigsite=gscholar&cbl=18750&diss=y
39. Thinley, P., Rajaratnam, R., Morreale, S. J., & Lassoie, J. P. (2021). Assessing the adequacy of a protected area network in conserving a wide-ranging apex predator: The case for tiger (Panthera tigris) conservation in Bhutan. *Conservation Science and Practice, 3*(2), e318. https://doi.org/10.1111/CSP2.318
40. Sun, X., Long, Z., & Jia, J. (2021). A multi-scale MaxEnt approach to model habitat suitability for the giant pandas in the Qionglai Mountain. *China. Global Ecology and Conservation, 30*, e01766. https://doi.org/10.1016/j.gecco.2021.e01766
41. Dong, X., Zhang, J., Gu, X., Wang, Y., Bai, W., & Huang, Q. (2021). Evaluating habitat suitability and potential dispersal corridors across the distribution landscape of the Chinese red panda (Ailurus styani) in Sichuan. *China. Global Ecology and Conservation, 28*, e01705. https://doi.org/10.1016/j.gecco.2021.e01705
42. Jin, Y., Kong, W., Yan, H., Bao, G., Liu, T., Ma, Q., Li, X., Zou, H., & Zhang, M. (2021). Multi-scale spatial prediction of wild boar damage risk in Hunchun: A key tiger range in China. *Animals, 11*(4), 1012. https://doi.org/10.3390/ani11041012
43. Matyukhina, D. S., Miquelle, D. G., Murzin, A. A., Pikunov, D. G., Fomenko, P. V., Aramilev, V. V., Litvinov, M. N., Salkina, G. P., Seryodkin, I. V., Nikolaev, I. G., Kostyria, A. V., Gaponov, V. V., Yudin, V. G., Dunishenko, Y. M., Smirnov, E. N., Korkishko, V. G., & Marino, J. (2014). Assessing the influence of environmental parameters on Amur tiger distribution in the Russian Far East using a MaxEnt modeling approach. *Achievements in the Life Sciences, 8*(2), 95–100. https://doi.org/10.1016/j.als.2015.01.002
44. Sun, X., Long, Z., & Jia, J. (2022). Identifying core habitats and corridors for giant pandas by combining multiscale random forest and connectivity analysis. *Ecology and Evolution, 12*(2), e8628. https://doi.org/10.1002/ece3.8628
45. Torretta, E., Dondina, O., Delfoco, C., Riboldi, L., Orioli, V., Lapini, L., & Alberto, M. (2020). First assessment of habitat suitability and connectivity for the golden jackal in north-eastern Italy. *Mammalian Biology, 100*(6), 631–643. https://doi.org/10.1007/s42991-020-00069-z
46. Huang, C., Li, X., Khanal, L., & Jiang, X. (2019). Habitat suitability and connectivity inform a co-management policy of protected area network for Asian elephants in China. *PeerJ, 7*, e6791. https://doi.org/10.7717/peerj.6791
47. Harsh, S., Jena, J. & Dave, C. (2015). Connecting habitat corridors for tigers in Panna Landscape - A rapid assessment of forests around Panna Tiger Reserve. *WWF India, New Delhi, India*. https://wwfin.awsassets.panda.org/downloads/panna_report_web.pdf
48. Kanagaraj, R., Wiegand, T., Kramer-Schadt, S., Anwar, M., & Goyal, S. P. (2011). Assessing habitat suitability for tiger in the fragmented Terai Arc Landscape of India and Nepal. *Ecography, 34*(6), 970–981. https://doi.org/10.1111/j.1600-0587.2010.06482.x
49. Maurya, K. K., & Borah, J. (2013). *Status of tigers in Valmiki Tiger Reserve, Terai Arc Landscape, Bihar*. WWF-India. https://www.researchgate.net/publication/262525815_Status_of_tigers_in_Valmiki_Tiger_ReserveTerai_Arc_Landscape_Bihar_India_WWF-India
50. Kumar, R. and Sinha, S. (2016). Planning and implementation of ecotourism in Valmiki Tiger Reserve. *Lambert Academic Publishing*. https://www.researchgate.net/publication/311985959_Planning_and_implementation_of_ecotourism_in_Valmiki_Tiger_Reserve
51. Bihar Government. (2018). Official website: Valmiki Tiger Reserve. Retrieved February 6, 2022, from https://www.valmikitigerreserve.com/landscape.php
52. ISFR. (2021). India state of forest report. Forest Survey of India, Ministry of Environment Forest and Climate Change, Dehradun. https://fsi.nic.in/forest-report-2021
53. NTCA. (2020). Project Tiger Report on Valmiki Tiger Reserve. *National Tiger Conservation Authority, India*. https://ntca.gov.in/assets/uploads/briefnote/valmiki.pdf
54. Global Forest Watch. (2019). Tree cover. Retrieved December 6, 2021, from https://www.arcgis.com/home/item.html?id=3d39084cc55d433ca1a51254f167cdc5
55. Roy, P. S., Behera, M. D., Murthy, M. S. R., Roy, A., Singh, S., Kushwaha, S. P. S., Jha, C. S., Sudhakar, S., Joshi, P. K., Reddy, C. S., Gupta, S., Pujar, G., Dutt, C. B. S., Srivastava, V. K., Porwal, M. C., Tripathi, P., Singh, J. S., Chitale, V., Skidmore, A. K., et al. (2015). New vegetation type map of India prepared using satellite remote sensing: Comparison with global vegetation maps and utilities. *International Journal of Applied Earth Observation and Geoinformation, 39*, 142–159. https://doi.org/10.1016/j.jag.2015.03.003
56. ESRI Land cover. (2020). Global land use/land cover with Sentinel-2 and deep learning. Retrieved November 6, 2021, from https://www.arcgis.com/home/item.html?id=8214141a576848f69f440c793144f6ce
57. Mishra, A., Sarup, J., & Gupta, D. C. (2021). Geo spatial approach for tiger habitat suitability mapping: A case study of Bandhavgarh National Park, Madhya Pradesh, India. *International Journal of*

Geography, Geology and Environment, 3(2), 1–7. https://doi.org/10.22271/27067483.2021.v3.i2a.53
58. Hansen, M. C., Potapov, P. V., Moore, R., Hancher, M., Turubanova, S. A., Tyukavina, A., Thau, D., Stehman, S. V., Goetz, S. J., Loveland, T. R., Kommareddy, A., Egorov, A., Chini, L., Justice, C. O., & Townshend, J. R. G. (2013). High-resolution global maps of 21st-century forest cover change. *Science, 342*, 850–853. https://earthenginepartners.appspot.com/science-2013-global-forest
59. Ahmed, M. R., Rahaman, K. R., & Hassan, Q. K. (2018). Remote sensing of wildland fire-induced risk assessment at the community level. *Sensors, 18*(5), 1570. https://doi.org/10.3390/s18051570
60. Kaboodvandpour, S., Almasieh, K., & Zamani, N. (2021). Habitat suitability and connectivity implications for the conservation of the Persian leopard along the Iran-Iraq border. *Ecology and Evolution, 11*(19), 13464–13474. https://doi.org/10.1002/ece3.8069
61. Zhang, J., Jiang, F., Cai, Z., Dai, Y., Liu, D., Song, P., Hou, Y., Gao, H., & Zhang, T. (2021). Resistance-based connectivity model to construct corridors of the Przewalski's gazelle (Procapra Przewalskii) in fragmented landscape. *Sustainability, 13*(4), 1656. https://doi.org/10.3390/su13041656
62. Zhang, J., Jiang, F., Li, G., Qin, W., Li, S., Gao, H., Cai, Z., Lin, G., & Zhang, T. (2019). MaxEnt modeling for predicting the spatial distribution of three raptors in the Sanjiangyuan National Park. *China. Ecology and Evolution, 9*(11), 6643–6654. https://doi.org/10.1002/ece3.5243
63. Lham, D., Cozzi, G., Sommer, S., Thinley, P., Wangchuk, N., Wangchuk, S., & Ozgul, A. (2021). Modeling distribution and habitat suitability for the snow leopard in Bhutan. *Frontiers in Conservation Science, 2*, 87. https://doi.org/10.3389/fcosc.2021.781085
64. Yan, H., Feng, L., Zhao, Y., Feng, L., Wu, D., & Zhu, C. (2020). Prediction of the spatial distribution of Alternanthera philoxeroides in China based on ArcGIS and MaxEnt. *Global Ecology and Conservation, 21*, e00856. https://doi.org/10.1016/j.gecco.2019.e00856
65. Su, H., Bista, M., & Li, M. (2021). Mapping habitat suitability for Asiatic black bear and red panda in Makalu Barun National Park of Nepal from MaxEnt and GARP models. *Scientific Reports, 11*(1), 1–14. https://doi.org/10.1038/s41598-021-93540-x
66. Wang, G., Wang, C., Guo, Z., Dai, L., Wu, Y., Liu, H., Li, Y., Chen, H., Zhang, Y., Zhao, Y., Cheng, H., Ma, T., & Xue, F. (2020). Integrating MaxEnt model and landscape ecology theory for studying spatiotemporal dynamics of habitat: Suggestions for conservation of endangered red-crowned crane. *Ecological Indicators, 116*, 106472. https://doi.org/10.1016/j.ecolind.2020.106472
67. Bleyhl, B., Sipko, T., Trepet, S., Bragina, E., Leitão, P. J., Radeloff, V. C., & Kuemmerle, T. (2015). Mapping seasonal European bison habitat in the Caucasus Mountains to identify potential reintroduction sites. *Biological Conservation, 191*, 83–92. https://doi.org/10.1016/j.biocon.2015.06.011
68. Ash, E., Macdonald, D. W., Cushman, S. A., Noochdumrong, A., Redford, T., & Kaszta, Ż. (2021). Correction to: Optimization of spatial scale, but not functional shape, affects the performance of habitat suitability models: A case study of tigers (Panthera tigris) in Thailand. *Landscape Ecology, 36*(6), 1837. https://doi.org/10.1007/s10980-020-01105-6
69. Alamgir, M., Mukul, S. A., & Turton, S. M. (2015). Modelling spatial distribution of critically endangered Asian elephant and Hoolock gibbon in Bangladesh forest ecosystems under a changing climate. *Applied Geography, 60*, 10–19. https://doi.org/10.1016/j.apgeog.2015.03.001
70. Imam, E., Kushwaha, S. P. S., & Singh, A. (2009). Evaluation of suitable tiger habitat in Chandoli National Park, India, using spatial modelling of environmental variables. *Ecological Modelling, 220*(24), 3621–3629. https://doi.org/10.1016/j.ecolmodel.2009.06.044
71. Neelakantan, A., DeFries, R., & Krishnamurthy, R. (2019). Resettlement and landscape-level conservation: Corridors, human-wildlife conflict, and forest use in Central India. *Biological Conservation, 232*, 142–151. https://doi.org/10.1016/j.biocon.2019.01.033
72. Sharma, S., Dutta, T., Maldonado, J. E., Wood, T. C., Panwar, H. S., & Seidensticker, J. (2013). Forest corridors maintain historical gene flow in a tiger metapopulation in the highlands of Central India. *Proceedings of the Royal Society B: Biological Sciences, 280*(1767), 20131506. https://doi.org/10.1098/rspb.2013.1506
73. Cao, Y., Yang, R., & Carver, S. (2020). Linking wilderness mapping and connectivity modelling: A methodological framework for wildland network planning. *Biological Conservation, 251*, 108679. https://doi.org/10.1016/j.biocon.2020.108679
74. Liu, C., Newell, G., White, M., & Bennett, A. F. (2018). Identifying wildlife corridors for the restoration of regional habitat connectivity: A multispecies approach and comparison of resistance surfaces. *PLoS ONE, 13*(11), e0206071. https://doi.org/10.1371/journal.pone.0206071
75. Roshani., Sajjad, H., Rahaman, M. H. Rehman, S., Masroor, M., & Ahmed, R. (2022). Assessing forest health using remote sensing-based indicators and fuzzy analytic hierarchy process in Valmiki Tiger Reserve, India. *International Journal of Environmental Science and Technology, 20*, 8579–8598. https://doi.org/10.1007/s13762-022-04512-1
76. Roshani, Sajjad, H., Rahaman, M. H., Masroor, M., Sharma, Y., Sharma, A., & Saha, T. K. (2024). Vulnerability assessment of forest ecosystem based on exposure, sensitivity and adaptive capacity in the Valmiki Tiger Reserve, India: A geospatial analysis. *Ecological Informatics*, *80,* 102494. https://doi.org/10.1016/j.ecoinf.2024.102494

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