RESEARCH

Geospatial analysis of elephant habitat suitability and movement for mapping the elephant corridor in Dalma Wildlife Sanctuary (India)

Satendra Kumar Chaudhary · Arvind Chandra Pandey · Bikash Ranjan Parida

Abstract   Wildlife and natural resources constitute an integral part of the ecosystem, whereas human interventions dismantled the living conditions of the wildlife. This is testified in the Dalma Wildlife Sanctuary (DWS) where the habitats of Asian elephants have changed due to human intervention and deforestation over the decades. The present study aimed to assess the elephant habitat suitability in the DWS of Jharkhand state (India) using the geospatial parameters such as forest density, degree of slope, proximity to water bodies, land use land cover, proximity to agricultural land, built-up density, and road density. The analytical hierarchical process technique was utilized to determine habitat preference and selection of relevant factors to categorize criteria. The study revealed that about 6.7% (26.74 km^2) of the area is very highly suitable for elephant habitat, while 52.26% (208.49 km^2) of the forest area was found highly suitable. The most suitable habitat was identified in the core parts of the forest, while the least suitable areas were found in the southern part, where the presence of roads, built-up, and agricultural land was prominent. It was also observed that most human–elephant conflicts were exhibited in the low and very low suitable areas, while 90% of the elephant movement was witnessed in the high and very high suitable areas. Among the four identified corridors, three are inactive, and their location corresponds with low to very low suitable habitats. The study identified the migratory corridor routes inside the sanctuary where effective management is required for the conservation of elephant habitats and minimizing conflicts.

Keywords   Habitat suitability · Conflicts · Corridors · Geospatial modeling · Analytical hierarchical process

S. K. Chaudhary · A. C. Pandey (✉) · B. R. Parida
Department of Geoinformatics, School of Natural Resource Management, Central University of Jharkhand, Ranchi 835222, Jharkhand, India
e-mail: arvindchandrap@yahoo.com

S. K. Chaudhary
e-mail: satendra.chaudhary@cuj.ac.in

B. R. Parida
e-mail: bikash.parida@cuj.ac.in

Introduction

Historically, elephants are primarily found across many parts of the world (e.g., Asian, African, European, and American continents) although due to possible climatic variations, their dominance is restricted to Asia and Sub-Saharan Africa. In the Indian subcontinent, the major population of elephants lies in the foothills of the Eastern Himalayas and adjoining part of India (Chase et al., 2016; Talukdar & Choudhury, 2017; Thouless et al., 2016). Typically, the forest resource provides basic life needs for the shelter and habitat of herbivorous mammals, such as elephants and other wild animals (Ahrestani et al.,

2012; Naughton-Treves et al., 1998). Both external and internal factors influence habitat suitability for wildlife conservation. External factors are space use between human and wild animals, feed availability, competition, predation danger, refuge locations, mates, breeding sites, and environmental conditions (e.g., temperature, precipitation and humidity). Internal factors include reproductive status, which may cause individuals to actively seek reproductive partners or females to guard their cubs, age, and other behaviors like hunger, satiation, and relaxation (Nathan et al., 2008). The water distribution and rainfall patterns also influence habitat suitability (Birkett et al., 2012; Marshal et al., 2011).

The main cause of the destruction of wildlife habitat is encroachment and anthropogenic activities in the forest area (e.g., agricultural practices, human settlement, logging, and forest fires, among others) that result in losses of wildlife habitat as well as forest resources (Bar et al., 2020; Mekonen, 2020). In particular, the loss of forage and reduced movement connectivity have created increased human–elephant conflicts (HECs) worldwide (Mekonen, 2020). Moreover, when human settlements expand, they frequently encounter HECs, and consequently, both the frequency and intensity of HECs increase (Mekonen, 2020). In elephant range regions, HEC is a significant issue, and its management is typically expensive. Rani et al. (2024) reported that ~ 20% of the areas of the Rajaji-Corbett landscape in Uttarakhand, India, are at high risk for HECs, particularly in flat farmland where the majority of people live. In Northeast India, more than 1150 humans and 370 elephants died during 1980–2003 (Choudhury, 2004). Around the Nagarahole National Park in south India, 1955 incidences of crop losses have been documented, with 79 villages damaged and 8 persons died between 2006 and 2009. Conflict frequency was the highest from August to November when rainfall was low, and essential crops were at ripening stage (Gubbi, 2012). In West Bengal, Majumder (2022) reported 726 human deaths, 1233 human injuries, 51,542 ha of crop loss, 34,446 hut damages, and 136 elephant deaths as a result of direct HEC. Electrocution was the most common cause of elephant deaths, followed by rail accidents and poaching.

Corridors are isolated strips that are usually connected with patches and natural vegetation (Hale et al., 2001). Forest corridors are intended to improve landscape connection by allowing species to move freely to fulfill their dietary requirements (Doak & Mills, 1994). Forests are rapidly decreasing and shrinking and become abandoned by various anthropogenic and climate-induced interventions (Pal et al., 2023). Agricultural and scrubland changes have impacted the forest range and connectivity loss of elephant habitat in Bangladesh (Dewan et al., 2012; Tishi & Islam, 2019). In recent decades, elephants' habitats have shrunk, compelled them into closer contact with humans. As a result, there was frequent conflict for space and resources, with repercussions ranging from crop-raiding to human death (Liu et al., 2016; Western et al., 2009; White & Ward, 2010). Therefore, studying elephant movement and its corridors for any reserve forest is important to understand HECs.

Geographic information system (GIS) is widely used to monitor the movement of elephants with the help of GPS (Douglas-Hamilton et al., 2005). The GPS monitoring technique is used to identify existing paths of migration between protected areas (PAs) (Cook et al., 2015) and investigate elephant migrations in changing landscapes (Bohrer et al., 2014; Graham et al., 2010). The rapid growth of the human population and urban expansion have been influencing the corridors of Asian elephants. The disturbance in forest and elephant corridors often causes conflict between elephants and humans (Vidya & Sukumar, 2005). Therefore, habitat suitability mapping provides scope for reducing human conflict, loss of agriculture, and planning for wildlife protection and management (Liu et al., 2016; Sengupta et al., 2020). Elephant suitability mapping considers distinct parameters, such as forest density which plays an important role in habitat suitability for hiding and foraging (Epaphras et al., 2008; Follett & Delgado, 2002).

Remote sensing–based data-driven modeling and spatial analysis of habitat suitability are widely used for large-scale habitat suitability mapping. Various studies have integrated multi-source satellite data with climatic variables for assessing wildlife habitats, especially over the PAs like National Parks and Wildlife Sanctuaries (Mandal and Das Chatterjee, 2021; He et al., 2023). Geospatial components of the landscape, comprising land use land cover (LULC), road networks, forest cover, and forest fragmentation-related variables (core, edge), were also employed for assessing elephant habitat (Mandal and Das Chatterjee, 2021; Talukdar et al., 2020b). It investigates

intricate relationships between components by feeding the parameters into the analytic hierarchy process (AHP) for decision-making and forest management. Several habitat models (AHP and MaxEnt) have been applied since the emergence of geospatial technologies (Hazarika & Saikia, 2013; He et al., 2023). The distribution of elephants was further predicted by satellite-derived variables (i.e., Leaf Area Index, Normalized Difference Vegetation Index) and topographical features (i.e., slope, aspect, elevation, and water accessibility) (Ashiagbor & Danquah, 2017). These variables are also used to develop machine-learning algorithms for animal habitat modeling (Anjali & Subramani, 2021). Mostly, Asian elephants prefer lower elevated forest areas, gentle slopes, and along rivers (He et al., 2023). The areas close to the road with less vegetation and a steeper slope were deemed inappropriate for the elephant habitat. Notably, many of these habitat parameters can be derived directly from satellite data and hence, remote sensing and GIS played a crucial role in habitat suitability mapping.

Presently, the Dalma Wildlife Sanctuary (DWS) which is located near the Jamshedpur township in the state of Jharkhand is witnessing rapid anthropogenic activities (e.g., land use change, collections of forest products, tourism, unsustainable management practices, fragmentation, and forest fires). Consequently, it creates disturbances in the elephant corridors. Therefore, the current study is crucial to safeguard the Asian elephant population and their habitat in the DWS. As such, no study is available for DWS related to habitat suitability mapping for elephants and their movements. Therefore, the major objective of this study is to deduce the habitat suitability, demarcate movements, locate conflicts, and delineate elephant corridors in DWS using satellite data and geospatial modeling.

Study area

The state of Jharkhand is enriched by substantial natural resources, unique biological diversity, and wildlife. Dhalbhum Forest Division is the home range for Asian elephants which lie between 21° 51′ and 23° 56′ N latitude and 85° 33′ and 86° 11′ E longitude (Fig. 1). The geographic coordinates of the location are placed at an altitude of 915 m above the mean sea level (Chaudhary et al., 2022a). The total forest covers of Dalma and Saraikela comprised an area of 398.93 km² and 607

km², respectively. The study area is mostly dominated by the presence of tropical dry deciduous forests that constitute a significant natural resource and a necessary ecosystem service to wildlife (Pandey et al., 2023). Most of the tribals and local villagers still rely on forest resources for their livelihood.

Elephants of the DWS in the Jharkhand State of India are noted for their habitat and abundance. DWS is known for its elephant home (MOEFCC, 2017), which has rich biodiversity and diverse forest resources. The flora is dominated by *Sal, Terminalia* spp., *Tamarindus indica*, *Emblica officinalis, Bauhinia* spp., *Albizia* spp., and other species of herbs and shrubs. The major fauna consists of elephants, leopards, jackals, deers, foxes, sloth bears, macaques, languors, mongooses, and local birds. It is surrounded by West Bengal state between Sharikela Forest Division and Jamshedpur Forest Division. These regions fulfill the needs of food, water, and shelter for the survival of Asian elephants (Vidya & Sukumar, 2005). It has been observed that elephant movements in the DWS are connected with the West Bengal and Dalbhum Forest Division. In Jharkhand, there are eleven elephant corridors for Asian elephants (MoEFCC, 2017), and in the DWS, three elephant corridors are recognized namely Dalma-Chandil Corridor, Dalma-Rugai Corridor, and Dalma-Asanbai Corridor (Roy & Sukumar, 2017; Roy, 2024).

The climate in the region largely remains hot and humid, with summer temperatures fluctuating from 37 to 42 °C. The mean annual rainfall is 1447 mm and the monsoon season (June–September) contributes to 75% of total annual rainfall (Chatterjee, 2016). The Sanctuary has gently undulated to steep slopes and abundance of different flora, making it one of the best habitats for the elephants. Recurrent droughts, water scarcity, and forest fires forced the elephants of the Dalma region to travel between forested areas in two neighboring states of Jharkhand namely West Bengal, and Odisha) (Chaudhary et al., 2022b).

Material and methods

Satellite and climate data used

The present study has employed Sentinel-2A imagery for image classification. ASTER-derived DEM was used to demarcate the terrain slope. Settlements and roads were extracted from the Google Earth Imagery

Fig. 1 Location map of Dalma Wildlife Sanctuary as seen in False Color Composite (FCC: NIR, red, and green) of image of Sentinel-2A satellite. The bands used in FCC are NIR, red, and green
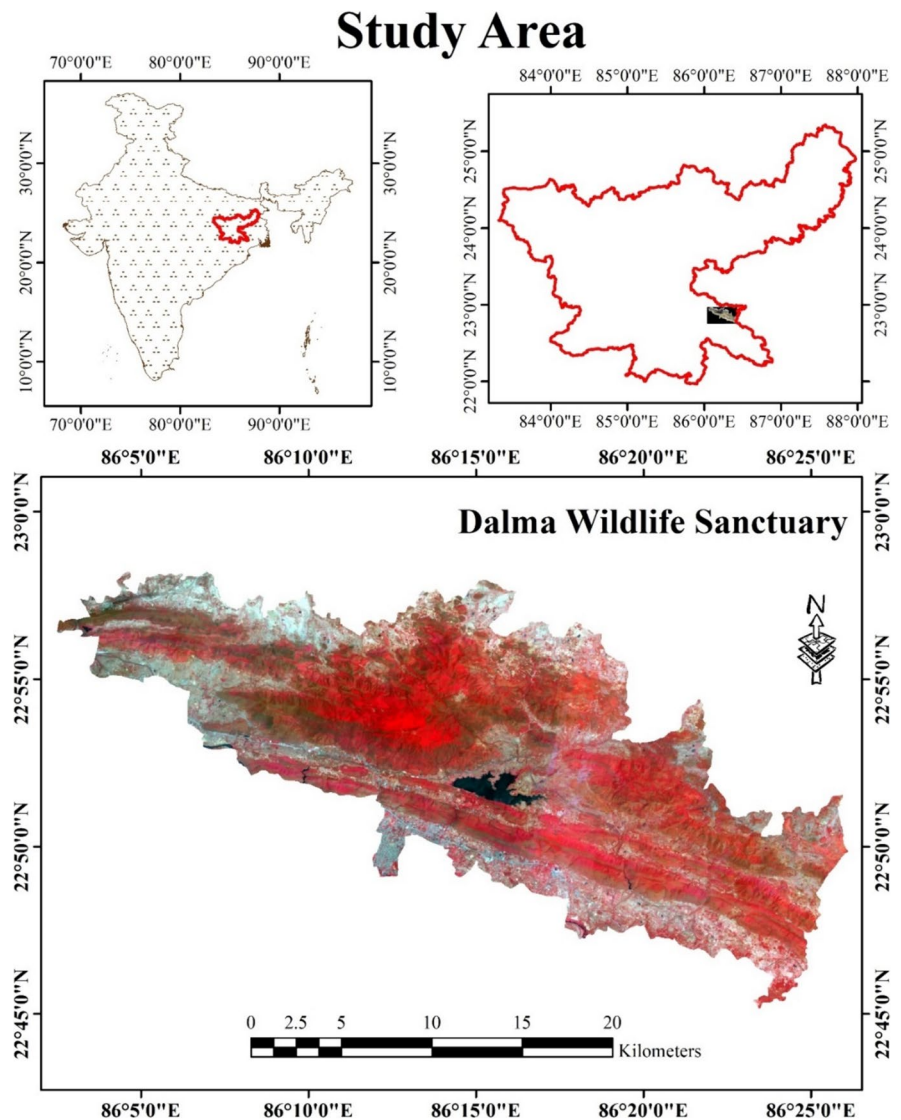
Pro. Specifications and characteristics of the dataset are presented in Table 1. Elephant movement and conflict data were obtained from the Department of Forest, Environment & Climate Change (Government of Jharkhand: https://forest.jharkhand.gov.in/en) which provides coordinate information collected through GPS. The coordinates were recorded along with the spotted date, time, forest range, forest beat and sub-beat, number of elephants, number of causalities, injury, house damage, and crop damage. The precipitation and temperature (Tmax) data were downloaded at a monthly scale from TerraClimate (Abatzoglou et al., 2018) over the span of 1991–2020 to estimate climatic trends using Sen's slope.

Methodology

The study utilized seven geospatial parameters, viz, forest density, slope, LULC, agricultural land, water bodies, road networks, and built-up for assessing the suitability of the elephant habitat. All the parameters were classified into five classes representing very high, high, moderate, low, and very low categories based on the characteristics that are suitable for elephant movement. Pairwise matrix was used for weightage analysis to perform the AHP method (Belton & Gear, 1983). All the parameters were used to perform an overlay analysis for habitat suitability mapping, and the results were validated

Table 1 Satellite data was used in the study and their acquisition dates

| Dataset	Data Acquisition	Spatial resolution (m)	Purpose
Sentinel-2A	January 16, 2020	10 m	Forest density, land use, agriculture, water body
ASTER-DEM	August 5, 2019	30 m	Slope
Google Earth Pro images of Landsat	2020	~5 m	Settlement, road
Precipitation and temperature	1991–2020	~4 km	Trend maps
Elephant's movement and conflict	2019–2020	–	Identifying corridors and places of conflict

with elephant movement data. The variables and the classifications used for the Elephant Habitat Suitability Index (EHSI) are described in the following sections. The flowchart of the methodology is given in Fig. 2.

Forest density

Forest density is the proportion of a ground area covered by a canopy of trees represented as a percentage of the total area (Troy et al., 2012). The forest classification is performed using the NDVI values. Low NDVI levels suggest moisture-stressed vegetation, whereas high values imply a dense cover of green vegetation. Forest density is classified into five classes viz., very dense (>0.55), moderately dense (0.4–0.54), dense (0.25–0.39), open forest (0.1–0.24), and non-forest (<0.1). Very dense forests are classified as very high suitability, whereas the non–forest is classified as very low suitability. The intermediate forests are categorized with appropriate suitability classes as given in Table 2.

Fig. 2 Flowchart shows the adopted methodology for deriving the Elephant Habitat Suitability Index (EHSI) and elephant corridors
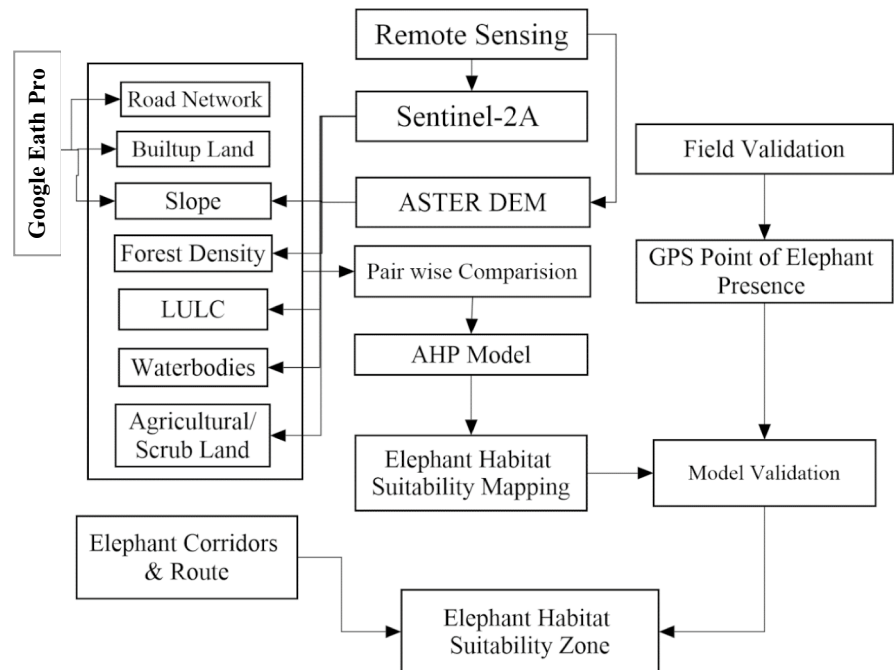
Slope

Slope is one of the major variables as it controls and restricts the elephant's movements. The study has analyzed the degree of steepness using ASTER-based DEM with 30 m spatial resolution. Typically, the gentle slope helps in easy movement in the forest area, while the wall and cliff structures restrict elephant movement. In this scenario, the topographic variation in the area is classified into five different classes with a degree of steepness. A very high suitable area is categorized as having a degree of steepness of less than 10, while between 10–30 is categorized as high, 30–45 moderate, 45–55 low, and above 55 is very low (Table 2).

Land use and land cover (LULC)

LULC map of 2020 was prepared based on the Sentinel-2 satellite images. The satellite data were processed and classified using the Google Earth Engine (GEE) cloud platform. The random forest classification technique is employed for image classification. With respect to the elephant habitat suitability, the satellite image is classified into six classes, namely forest (very high), grassland (high), water body (moderate), wasteland (moderate), agriculture (low), and built-up (very low) (Table 2). For image classification, 700 sample points were collected during field data collection using Garmin GPS and were used for generating training signatures. Among them, 70% of the sample points were used for the model processing and 30% were used for the validation. Accuracy assessment of the LULC map was undertaken with the help of the contingency matrix and kappa coefficient.

Proximity to water bodies

The availability of water resources is an integral variable in elephant habitat suitability because elephant requires nearly 100 L of water for their daily needs. Therefore, the proximity to the water body is considered the most suitable for the elephant habitat, and similarly, the farther distance to the water body is considered the least suitable. Water bodies are extracted from the satellite imagery based on image classification and converted into vector layers. Then, the proximity classes were then prepared using the buffering tool of ArcGIS (Table 2).

Proximity to agriculture

Agricultural lands are considered a pull factor because elephants travel towards the agricultural land in search of food (Majumder, 2022). However, from the human perspective, it is considered a conflict. Hence, the proximity of the agricultural field is considered the least suitable (Rendana et al., 2023), while the farther distance from the agricultural field is deemed most suitable (Table 2). Habitat suitability increases with distance from agriculture and the optimal distance for habitat from agriculture fields was at least > 1 km (Rendana et al., 2023).

Road density

Infrastructure in the forest premises always poses a threat to wild animals, especially elephants, as they move from one location to another. The road network in the DWS is digitalized using Google Earth Pro imagery (Landsat), and the features are used for

Table 2 Physical and socio-economic parameters were considered for assessing the habitat suitability for elephants

Variables	Very high (5)	High (4)	Moderate (3)	Low (2)	Very low (1)
Forest density	≥0.55	0.4–0.54	0.25–0.39	0.1–0.24	<0.1
Slope (degree)	≤10	11–20	21–35	36–50	>50
LULC	Forest	Grassland	Water body, wasteland	Agriculture	Built-up
Proximity to water bodies (m)	≤100	101–250	251–500	501–1000	>1000
Proximity to agriculture (m)	≤100	101–250	251–1000	1001–2000	>2000
Road density (km/km^2)	0	1–60	61 -160	161–230	>230
Settlement density (unit/km^2)	0	1–2	3–6	7–20	>20

the kennel density analysis. Kennel density computes the magnitude-per-unit area from point or polyline characteristics by fitting a smoothly tapered surface to each point or polyline with a kernel function (Tishi & Islam, 2019). The present study calculated road density using the road layer presented in the DWS. Road networks in the forest vicinity may cause accidents or conflicts. The higher road density will be the most dangerous for elephant movement. Therefore, the higher density of road network is considered as least suitable, while the lesser density/no-road network is deemed as most suitable (Table 2).

Settlement density

Settlement density refers to the presence of human settlements. Point data corresponding to the settlements was collected from Google Earth Pro, and then, the point was used for density analysis. The output provides the number of settlements per square kilometer area. The area with more than 20 settlements per km^2 is considered to have a very high density and is classified as very low suitable for elephant movement, while the areas with no settlements are considered as most suitable. The intermediate classes were categorized as 1–2 settlements per km^2 and are considered as highly suitable, 3–6 as moderate, and 7–20 as low suitable (Table 2).

Elephant corridors and route

Elephant corridors and routes are determined based on elephant movement data obtained from the Wildlife Trust of India (WTI) for the years 2005 and 2017 (Majumder, 2022; Vattamthanam, 2020). The published corridor maps of WTI were georeferenced using ArcGIS, and then, the corridors were digitized. Those corridors were analyzed using the real-time GPS points collected during the years 2019 and 2020.

Multi-criteria decision support system for EHSI

Weighted overlay analysis was used to model the suitability of elephants. Higher values generally indicate more suitable, while lower values indicate less suitable. The present study analyzed all geospatial parameters for assigned ranking and its weightage following the guidelines of the AHP approach

(Saaty, 1999). The set of choices for selecting the best in a set of alternatives is the main advantage of the AHP technique used for rating. The eigenvector corresponding to the matrix's eigenvalue is the primary duty of calculation in the AHP method. Each eigenvector member represents the relative priority of the relevant factor. If one element is preferred, its eigenvector component is typically greater than the other (Thouless et al., 2016). AHP's final weights are utilized to generate elephant habitat suitability maps.

The parameters were processed through a pairwise comparison matrix according to expert judgments and allotting them priority weight (Table 3). These values are categorized into distinct classes to help visualize the distribution of different levels of habitat appropriateness and assist in the understanding process. The allocations of each variable are shown in Table 4 where weights are assigned as per the literature values found in similar geographic settings.

The reciprocal matrix was obtained in this study to generate a matrix comparison. This matrix was then used to generate a normalized matrix, which was then used to provide a priority ranking for each habitat characteristic. Finally, the CR was computed to reflect the likelihood that the matrix judgments were created at random. The CR is calculated by using Eq. 1.

$$CR = \frac{CI}{RI} \tag{1}$$

In this study, the RI value is taken as 1.32 (Saaty 1987). The CI is calculated by using Eq. 2.

$$CI = \frac{\lambda_{\max-n}}{n-1} \tag{2}$$

Table 3 AHP pairwise comparison scale

Intensity of importance	Judgment score
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very Strong importance
9	Extreme importance
2, 4, 6, 8	Intermediate value between the two adjacent judgments
1/2, 1/3, 1/4, 1/5, 1/6, 1/7, 1/8, 1/9	Reciprocal values of the previous appreciation

Table 4 Pairwise comparison matrix of parameters

Variables	Forest density	Slope	LULC	Proximity to water bodies	Proximity to agriculture	Road density	Settlement density
Forest density	1	2	4	8	5	8	8
Slope	0.5	1	5	7	7	5	9
LULC	0.25	0.2	1	0.5	5	3	6
Proximity to water bodies	0.13	0.14	2	1	1	1	5
Proximity to agriculture	0.2	0.14	0.2	1	1	1	3
Road density	0.13	0.2	0.33	1	1	1	2
Settlement density	0.13	0.11	0.17	0.20	0.33	0.5	1
	2.33	**3.80**	**12.70**	**18.70**	**20.33**	**19.5**	**34**

where $\lambda_{\max}$ is the principal eigenvalue of the matrix and n indicates the order of the matrix. *CI* value less than 0.1 indicates an error judgment. Therefore, the judgments need to be revised. However, the present study has applied the *CI* value of 0.09 (Table 5), so the judgment for the variables with respect to the elephant habitat suitability is significant. The final weight was derived from the AHP process and then assigned to the EHSI (Eq. 3).

$$\text{EHSI} = \sum_{i-1}^{n} W_i \int i \qquad (3)$$

where EHSI is the habitat suitability index, W_i is the weight of factor *i*, and *i* is the rating factor of *i*. The

overlay tool in ArcGIS was used to join each reclassified vector layer corresponding to the criteria used to construct the spatial distribution map of EHSI.

Elephant movements and conflicts

The elephant conflict data comprises geographic coordinates that were collected during the period 2019–2020 (Government of Jharkhand). The elephant groups with reference to their sexual determination and age were identified and then analyzed for their movement pattern. Conflict and corridor were demarcated using the elephant movement data and WTI-based route, respectively.

Table 5 Consistency index (*CI*) value for all parameters

Variables	Forest density	Slope	LULC	Prox. to water bodies	Prox. to agriculture	Road density	Settlement density	Total	Average	CM
Forest density	0.43	0.53	0.31	0.43	0.25	0.41	0.24	2.59	0.37	7.98
Slope	0.22	0.26	0.39	0.37	0.34	0.26	0.26	2.11	0.30	8.27
LULC	0.11	0.05	0.08	0.03	0.25	0.15	0.18	0.84	0.12	7.37
Proximity to water bodies	0.05	0.04	0.16	0.05	0.05	0.05	0.15	0.55	0.08	8.14
Proximity to agriculture	0.09	0.04	0.02	0.05	0.05	0.05	0.09	0.38	0.05	7.34
Road density	0.05	0.05	0.03	0.05	0.05	0.05	0.06	0.35	0.05	7.70
Settlement density	0.05	0.03	0.01	0.01	0.02	0.03	0.03	0.18	0.03	7.22
Total	1	1	1	1	1	1	1	7.00	1.00	
									CI	0.12
									CR	1.32
									RI	0.09

Results

LULC map of DWS and parameters of elephant habitat suitability

According to the LULC map of 2020, the majority of the area was covered by forest (247 km^2) followed by agricultural land (114.8 km^2). The forest classes are mainly distributed across the DWS, while the agricultural land is found all around the border of the DWS (Fig. 3). As per the area statistics shown in Table 6, very dense forest, dense forest, and open forest classes have accounted for almost 61.9% of the study area. The agriculture and built-up areas accounted for 28.77 and 3.23% of the area, respectively. The overall accuracy of the LULC map was 91% with a kappa coefficient of 0.89.

In addition to the LULC of an area, other parameters, namely forest density, slope, proximity to water bodies and agriculture, road density, and settlement density, influence elephant habitat suitability. The elephant suitability classes and their area statistics are shown in Table 7. Forest density is one measure

Table 6 Area statistics of LULC classes and their corresponding percentage

LULC classes	Area in km^2	Area in %
Very dense forest	27.7	6.94
Dense forest	95.3	23.89
Open forest	124	31.08
Agriculture	114.8	28.77
Barrenland	18.93	4.74
Water bodies	5.3	1.32
Built-up	12.9	3.23
Total area	398.93	

that directly affects the habitat of elephants (Fig. 4a). The higher density of the forest makes it most suitable for the elephant habitat. It was identified that around 53% (231.39 km^2) of the forest area was under very high suitability (Table 7). Similarly, about 22% of the area in DWS exhibited high suitability, while 16% of the area showed moderately suitable for the elephant habitat. Only 3% and 1% of the DWS area were found under low and very low suitable class for
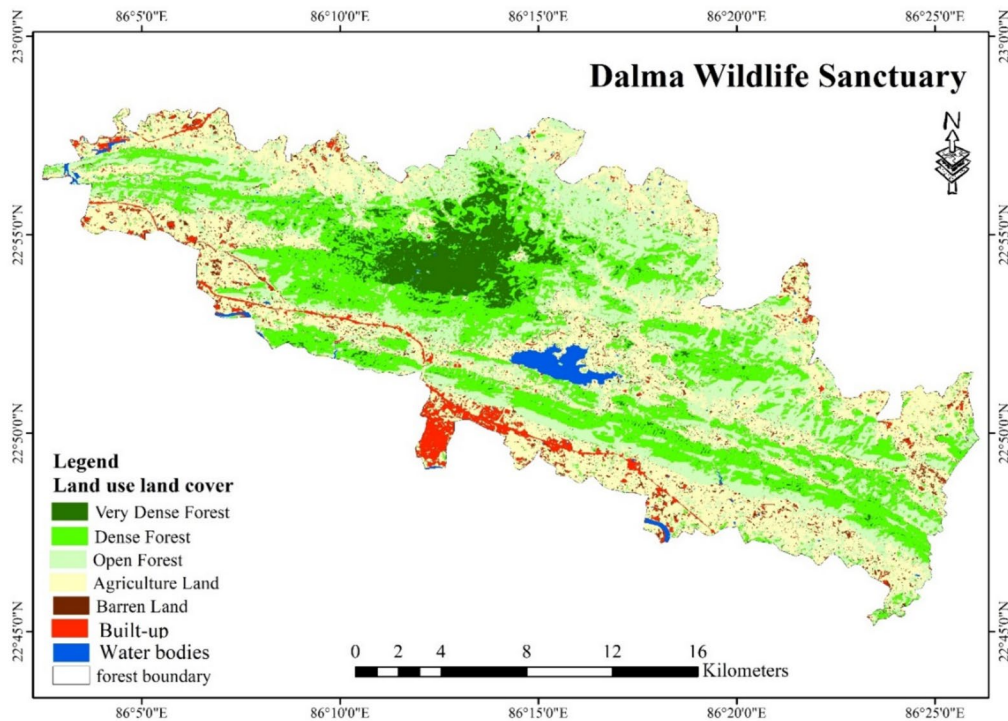

Fig. 3 LULC map of 2020 in DWS as derived from supervised classification

Table 7 Area statistics (km^2) of the EHSI parameters

Class	Forest density	Slope	LULC	Prox. to water body	Prox. to agri	Road density	Settlement density
Very high	231.39	254.23	141.31	23.59	125.13	153.76	103.56
High	87.02	89.06	54.27	44.73	74.82	69.19	34.21
Moderate	64.79	44.15	147.59	89.3	148.37	57.92	85.26
Low	12.36	11.09	22.09	134.12	49.11	54.8	157.4
Very low	3.37	0.4	33.67	107.19	1.5	63.26	18.5
Total	398.93	398.93	398.93	398.93	398.93	398.93	398.93

elephant habitat, respectively (Table 7). The higher density of forest classes was observed in the central part of DWS, especially in the notified forest boundary, while the low density was observed in the southern aspect of DWS (Fig. 4a).

Habitat suitability in terms of the degree of steepness indicates that about 63% (254 km^2) and 22% (89 km^2) of area (DWS) were highly suitable for elephant habitat. However, only 1% of the area in DWS was moderately suitable for the elephant habitat. Altogether, low and very low suitable classes for elephant habitat exhibited only 2.87% (Table 7). The steepest slope reflects the least suitable, whereas the gentle slope areas were very high suitable for elephant habitat. Therefore, most of the area exhibits high suitability for elephant movements inside DWS. However, some pockets were observed under low suitability, especially in the central parts where higher elevation and hilly terrains are present (Fig. 4b). The southern aspect and some small pockets can be seen as very low suitable, while the majority area was found most suitable for elephant habitat.

Typically, the LULC classes played a critical role in determining the elephant habitat suitability. With reference to the elephant habitat suitability, about 35.42% of the area of LULC was found under very high suitability that mainly corresponds to forest classes, whereas 13% of the area of LULC was found under high suitable for elephant habitat (Fig. 4c). Water bodies and wastelands contributed to the moderate class, with around 37% of LULC areas demonstrating moderate suitability for elephant habitat. Around 14% of LULC area has exhibited low and very low suitability for elephant habitat (Table 7), whereas built-up and agricultural lands are considered as very low and low suitability for elephant habitat.

Proximity to water bodies and agricultural land typically favors the movement of elephants but it also creates HECs. Water bodies are major requirements for elephant habitat suitability as elephants require more water to sustain their life. The close proximity to the water body is considered the most suitable. Figure 4 d shows the proximity of water bodies based on the accessibility to water spots. About 6% and 11% of the area exhibited very high and high suitability for elephant habitat, respectively. Around 22% and 34% of the area exhibited moderate and low suitability, respectively, while 26% area was found very low suitability (Table 7).

Proximity to agricultural land is also one of the important factors as major elephant and human conflicts were seen near to agriculture. Hence, the close proximity to the agricultural land has been considered as least suitable. Around 31% of the area was found very high suitability for the elephant habitat, while 19% was found high suitability. Nearly, 37% of the area was found moderately suitable. Low and very low classes accounted for nearly 12% and 1% of the area, respectively (Table 7). Many pockets of agricultural land are found in the inside notified forest boundary (NFB) (Fig. 4e). Therefore, easy movement and accessibility are restricted in such areas which leads to HECs. Thereby, such areas are considered the least suitable for elephant movement and habitat.

Road networks are highly influential in the moving pattern of elephants as they obstruct their easy movement and force them to change their annual movement pattern. Figure 4 f shows the spatial distribution of road density with respect to the different suitability classes. The southern part is considered as the least suitable for elephant habitat, while the central part is most suitable for elephant habitat in terms of road
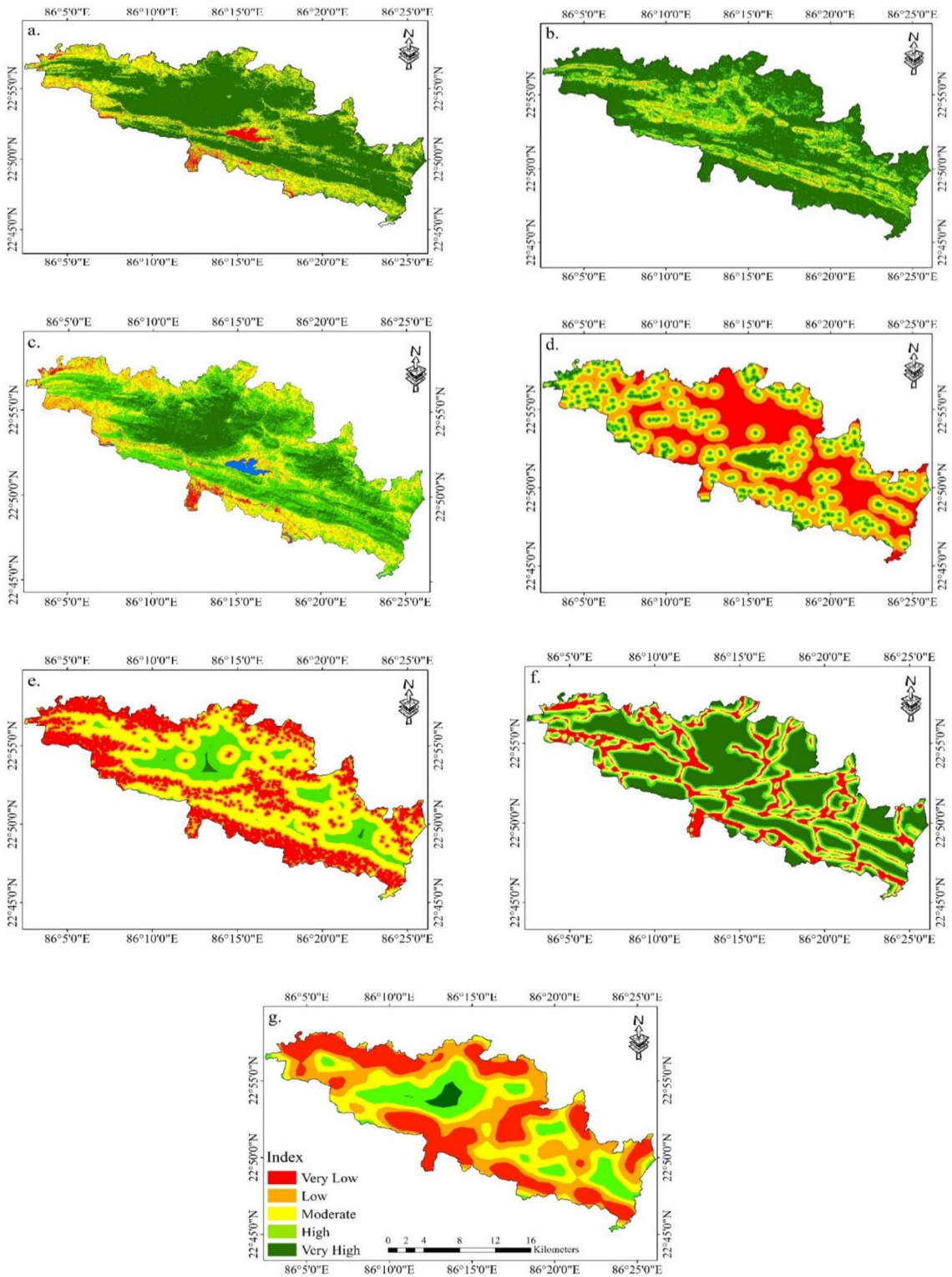
Fig. 4 Map showing parameters of elephant habitat suitability. Forest density (**a**), slope (**b**), LULC (**c**), water body (**d**), agriculture (**e**), road (**f**), and settlement (**g**) were shown where the legend is common for all these maps

density. The road density contributed for ~39% and 17% of the area towards very high and high suitability for elephant habitat, respectively. Moderate suitability represents 14%, whereas 16% was found low suitability for elephant habitat (Table 7).

Settlement density

Settlements generally increase the HECs and act as an obstruction to the elephant corridor. Nearly 51% of the area was found as the most suitable for elephant habitat. About 11% of the area showed high suitability, while 13% of the area was moderately suitable for elephant habitat. Around 23% of the area was found as the least suitable as the higher rate of settlement density was present in those areas (Table 7; Fig. 4g).

Elephant habitat suitability index (EHSI)

Based on the weighted overly analysis using the AHP multi-criteria decision support system, EHSI is calculated and shown in Fig. 6. The results showed that 26.74 km^2 (6.7%) area was found very high suitability for elephant habitat. The majority of the areas were found high suitability comprising 208.49 km^2 (52.26%). Under the moderate suitability category, nearly 142.34 km^2 (35.68%) area was found. Low and very low suitable categories showed only 6.92 km^2 (1.73%) and 14.44 km^2 (3.62%) of area, respectively, indicating non-favorable areas for elephant movement (Table 8).

The higher habitat suitability area was observed mostly along the eastern and central parts of DWS, whereas lower suitability areas were seen in the southern parts where human settlement, agriculture and urban encroachment are prevalent (Fig. 5). Based on the elephant movement and presence of elephants, it indicated that the presence of elephants has mostly occurred in high and moderate suitable locations.

Elephant movement

Elephant movement helps to identify the elephant herd's movement within DWS. Four groups (herd) during all seasons were identified, and their corresponding herd's numbers were 47, 34, 09, and 32. It has been observed that elephant enters the sanctuary

Table 8 Area statistics of EHSI in square kilometers and the corresponding percentage of area in five different suitability categories

Classes	AHP Threshold Range	Area (km^2)	Area (%)
Very low	1.91–2.80	14.44	3.62
Low	2.80–3.23	6.92	1.73
Moderate	3.23–3.45	142.34	35.68
High	3.45–3.88	208.49	52.26
Very high	3.88–4.78	26.74	6.70
Total area		398.93	100.00

in different numbers. Furthermore, the herds get separated into small groups. The different migrated elephant herd's spent different durations within DWS from January 7 to 24, 2019; April 30 to September 15, 2019; October 4 to 12, 2019; and January 11 to 26, 2020. Based on the habitat suitability analysis, it was concluded that an established migratory route (where elephants move throughout their migration) and a connected corridor (a path that connects forest patches to create travel flexibility) would allow free movement without interrupting the human population in the region (Fig. 6). Therefore, an important aspect in maintaining wildlife corridors can be water bodies, especially between 0 and 30° slopes because it can sustain large no of elephant herds throughout the year.

Elephant corridors

Based on the movements of elephants, four elephant corridors, namely the Jhunjhaka-Banduan, Dalma-Rugai, Dalma-Chandil, and Dalma-Asanbani corridors, were identified (Fig. 7). The Jhunjhaka-Banduan corridor has shown active elephant corridors from where the Asian elephant entered into the DWS. Skuklara-Kunchai corridor is situated and shared along with the boundaries of West Bengal that connected with a large strip of forest, Chandil Dalma Elephant Reserve. It was observed that the presence of elephants was higher in the Skuklara-Kunchai regions where high suitability was observed in the EHSI (Fig. 5). Frequently, an elephant herd uses these corridors and then migrates from these corridors. Apart from them, the elephant corridor of Dalma-Chandil lies at NH-33, NH-32, Railway track, and Irrigation canal which showed frequent HECs. Dalma-Rugai corridor passes
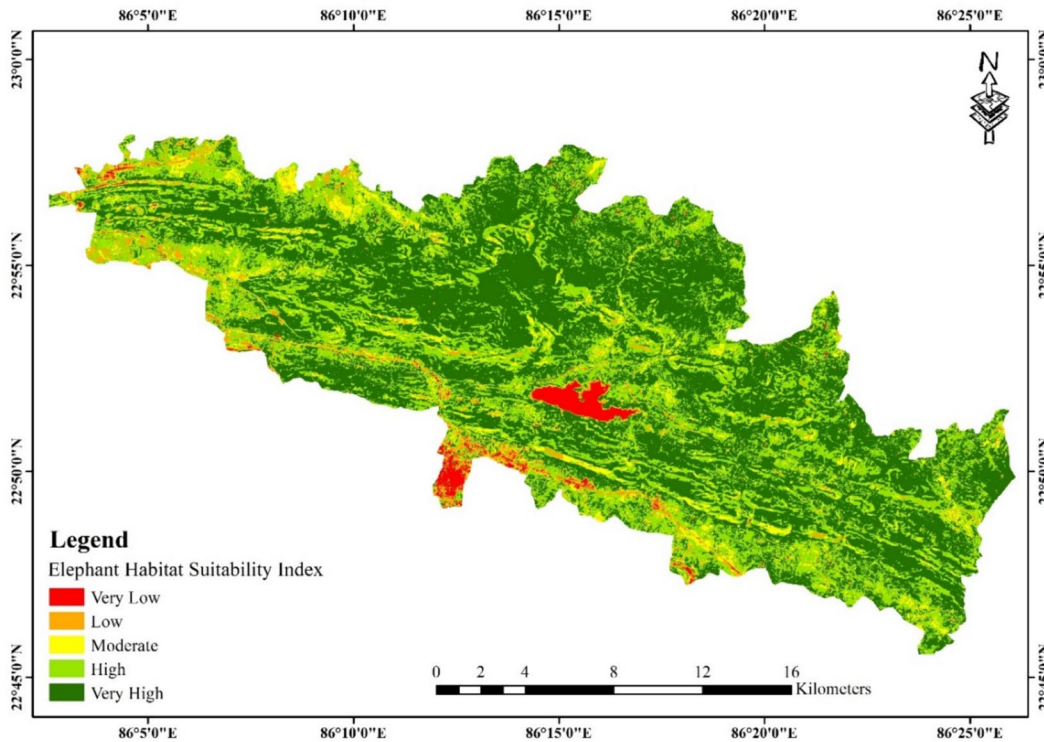
Fig. 5 Elephant habitat suitability index in Dalma Wildlife Sanctuary

through NH-33 which has been proposed for the expansion of four lane road and irrigation canals. In the case of the Dalma-Asanbani corridor, which has been passed by NH-32, similar issues were observed.

Figure 8 unveils the pattern of appearance of elephants at different months and seasons with variations at different time scales. The movement pattern of elephants was seen in January and December because of the winter season (Rabi) crop. During March and April months, moderate number of elephants were seen because of their movement followed by the scarcity of water and food including forest fires. During September and October, the minimum number of elephants was observed as they migrated from DWS to adjoining areas of West Bengal.

It was found that most elephants were move between 6:00 PM and 12:00 AM in DWS (Fig. 9). The availability of fodder and weather also play a critical role in the movement of elephants. In January, the elephants are attracted towards Rabi crops (winter season crops) (i.e., potato, maize, wheat, cauliflower, cabbage) and, hence, elephants were seen during this month, and particularly during night time (Fig. 9). By contrast, in August to October (post-monsoon), the elephants of DWS migrate towards forests of West Bengal state, resulting in a minimal appearance in DWS during these months.

Trends of climate variables and elephant habitat

The climate variation as estimated using Sen's slope in DWS is presented in Fig. 10. In months like January, April and May, elephants were sighted more often (Fig. 8). In January, the precipitation trends exhibited decreasing rate (-0.34 to -0.1625 mm/year) (Fig. 10a). In April, precipitation was increasing pattern across DWS (0.33–0.62 mm/year) (Fig. 10b). In May, the precipitation pattern was increasing at the rate of 0.61 to 0.94 mm/year (Fig. 10c). In January, the temperature trends showed decreasing rate (-0.12 to -0.07 °C/decade) (Fig. 10d). In April, the temperature trends also exhibited a decreasing rate (-0.26 to -0.19 °C/decade) (Fig. 10f). In May,
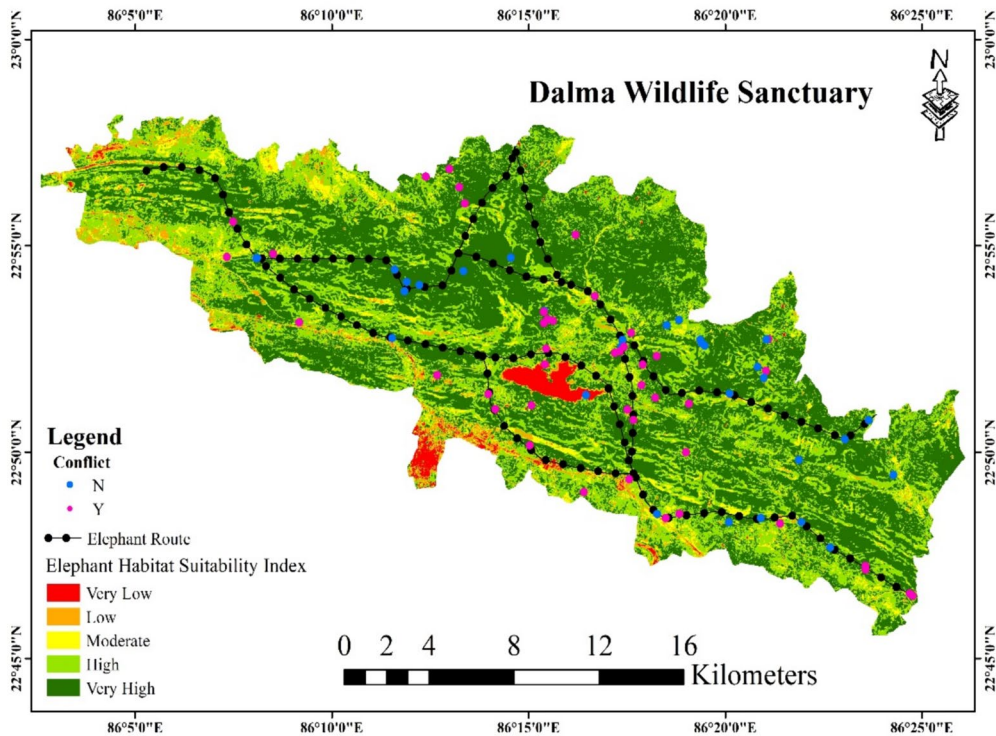
Fig. 6 Map showing elephant habitat suitability with its route and conflict presence in DWS

the temperature trends also exhibited a decreasing rate (−0.16 C/decade) (Fig. 10f), whereas it showed increasing outside the DWS (up to 0.09 °C/decade) due to the presence of human settlements. As temperature trends were decreasing pattern (i.e., indicative of cooling trends) and precipitation trends were mostly increasing rate over the DWS, climate factors may not be influencing the elephant suitability at present.

Discussion

Typically, elephants travel long distance in search of food within protected areas (PAs). They also venture outside of PAs to find food, but connecting passages are within human-dominated landscapes. Anthropogenic activities, namely forest resource collection, grazing, and human mobility, are regularly observed in these places, which has made a significant contribution to the loss of elephant corridors and the increase in confrontations between humans and

elephants. The present study has developed a geospatial modeling framework using the AHP method to assess the elephant habitat suitability with respect to the geospatial variables (e.g., forest density, degree of slope, proximity to water bodies, land use, proximity to agricultural land, built-up density, and road density). The study also performed the spatial analysis of elephant movement in the DWS, namely HECs and elephant corridors.

The key findings exhibited that 235.25 km^2 of area (~59%) was suitable for elephant habitat in DWS, which is mostly at the forest's core parts. On the other hand, the expansion of human settlements and agricultural fields has resulted in loss of habitat suitability because of increasing HECs and reduced landscape connectivity. According to Chaudhary et al. (2022b), anthropogenic activities inside the DWS have caused forest fragmentation, potentially disrupting elephant habitat. Anthropogenic disturbances and pressure on forest resources also forced the elephants to migrate from the forest area into agricultural areas. We identified socioeconomic activity, especially rising human
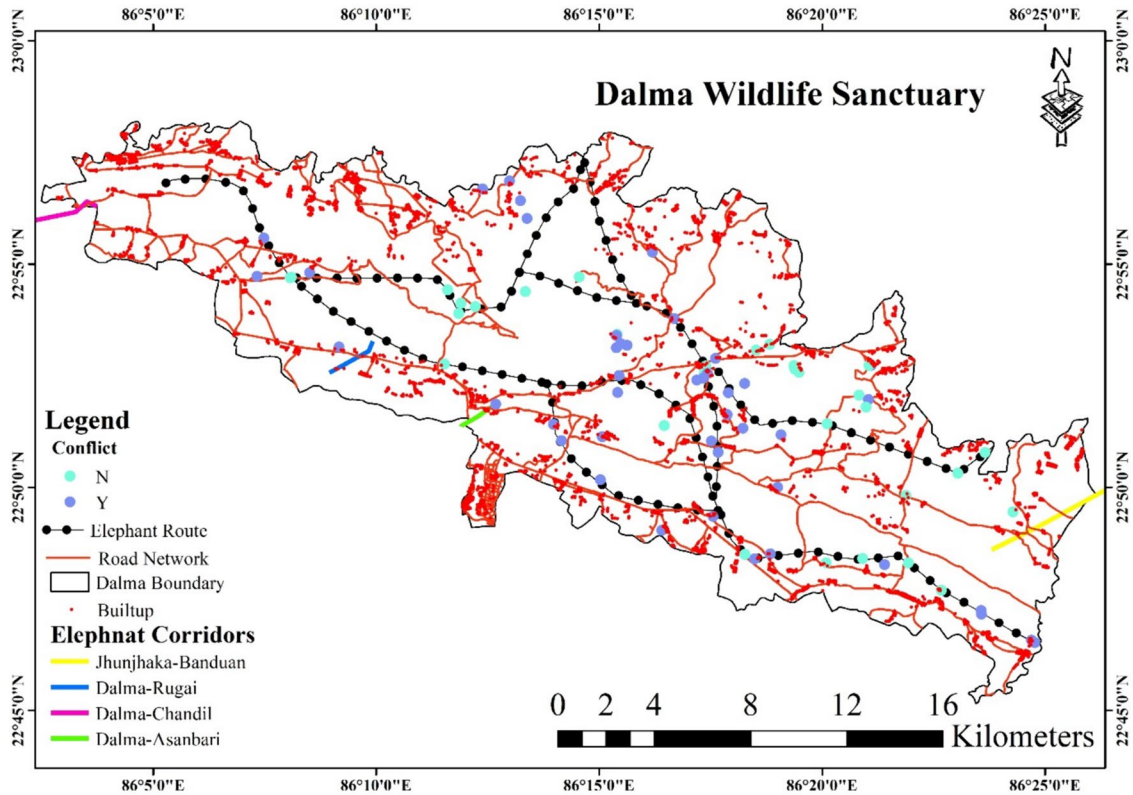
Fig. 7 The elephant route, conflict, and corridors. N and Y represent without conflict and with conflict, respectively
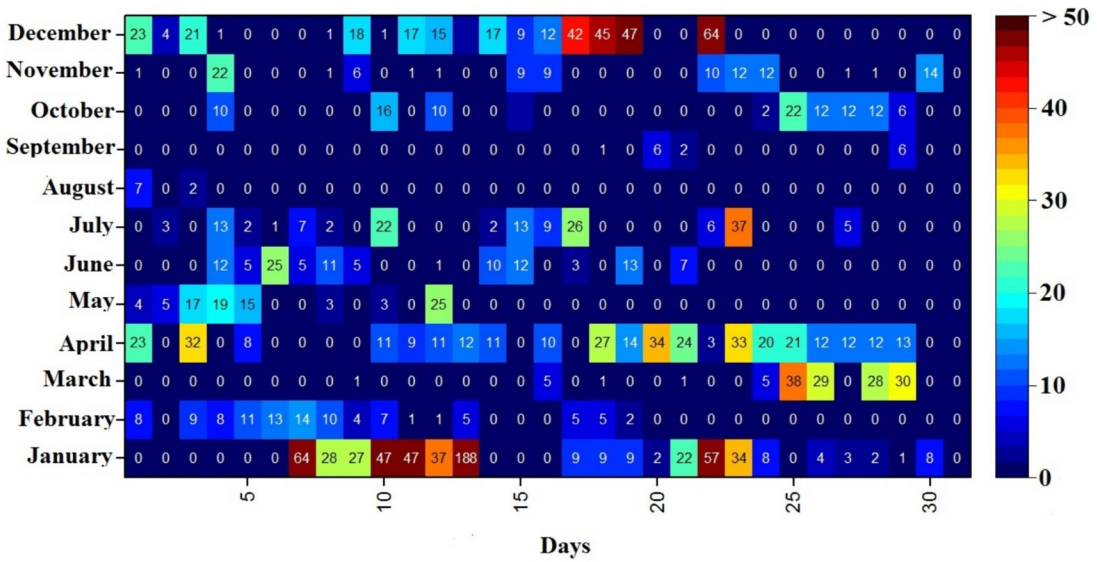

Fig. 8 Daily calendar chart showing the number of elephants sighted in 2020 and their pattern of movement

Fig. 9 Movement pattern of elephant with the seasonal time frame in 2020. The number in *x*-axis indicates the number of elephants sighted at different time intervals
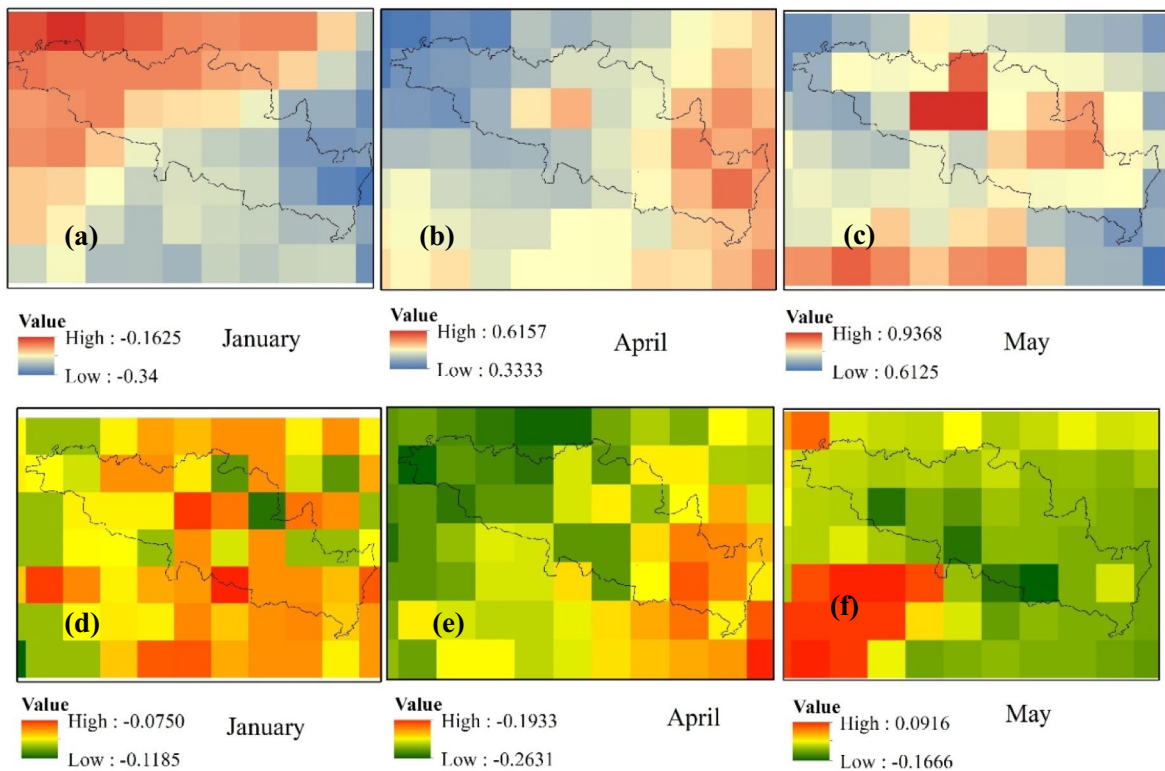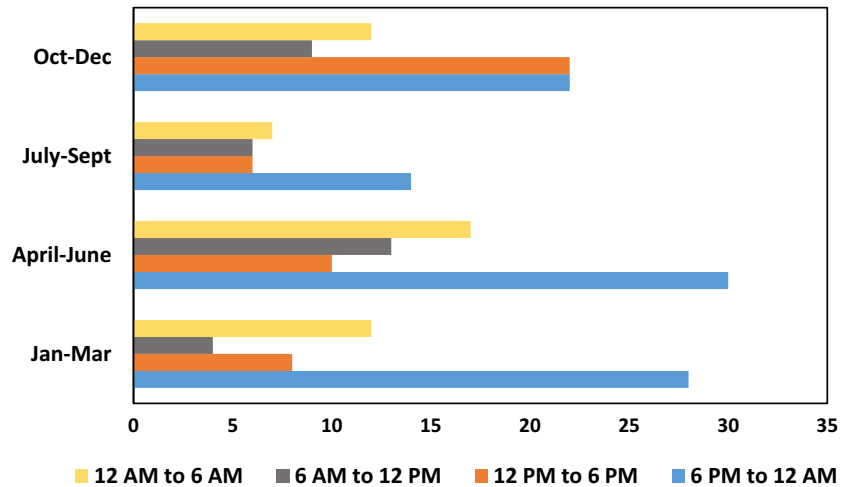

Fig. 10 Precipitation (**a**–**c** in mm per year) and temperature (**d**–**f** in °C/decade) trends as estimated using Sen's slope by using time series data over the span of 1991 to 2020

settlements, farming activities in the forest vicinity, and road connectivity through the forest, as driving forces for LULC changes in the DWS, resulting in increased conflict. Agriculture land was often located adjacent to forest land or between two forest patches in the study area. Hence, elephants were witnessed moving over agricultural regions to access forest areas which caused even more HECs. Elephant

movement patterns revealed that when the elephant came out of the forest, their presence was observed in the agricultural land, indicating the connectivity of the forest patch. Most studies have demonstrated elephant habitats are linked to the availability of water sources (Chamaillé-Jammes et al., 2007; De Beer & Van Aarde, 2008), whereas conflicts are attributed to movement around agricultural land (Talukdar et al., 2020a).

It was reported that elephants take risks with their resource availability by plundering agricultural fields for food owing to feeding opportunities during the crop growing seasons (Huang et al., 2019). However, other environmental variables and infrastructure development also influence the elephant movement. Elephants prefer the soft wood and fastest growing vegetation and the availability of such environments is typically found in outside PAs and agricultural lands (Tore et al., 2022). Hence, the elephant rides across the agricultural lands located in the vicinity of the forest, which leads to HECs. The pattern of elephant movement and HECs in DWS is also influenced by the presence of high nutritional food crops during the Kharif season. It was observed that crop depredation peaks between August and December, when the majority of the rice crop reaches maturity (Ranjan & Parida, 2021). These findings accorded with others who indicated that elephants most often approach toward agricultural field (Tripathy et al., 2022). The increase in crop damage was higher between October and November as elephants target stored crops. Rice is the principal source of income for the majority of rural communities in DWS, and crop destruction by elephants is among the leading causes of HECs in India (Naha et al., 2020). It indicates that the socio-economic development of people is negatively associated with elephant habitat suitability.

Furthermore, infrastructure development like roads, rails, canals, and human settlements either disturb or block the elephant corridor which creates conflicts. This study found that approximately 60% of the elephants frequently move outside the protected areas of DWS. The study area has rich biota of *Shorea robusta* (Sal), which contributes to approximately 70% of the protected forest area. Asian elephants do not prefer to stay inside high density forest cover (de la Torre et al., 2021) which also forces them to move out from the core

area. As a result, confrontations between humans and elephants over water, food, and space become more common. Crop raiding grows with increasing urbanization and agriculture (Hoare & Du Toit, 1999). Furthermore, the existence of distinct crop-raiding zones could streamline mitigation methods (Saiteja, 2020). Several studies have revealed that conflict with elephants becomes more intense as one gets closer to the forest (Nad et al., 2023). Hence, effective strategic planning is required which should attempt to foster the mutual well-being of humans and elephants focusing on coexistence rather than confrontation.

Studies have shown that the changes in precipitation and temperature patterns in regions like reserve forests and wildlife sanctuaries can have severe impacts on the biodiversity and ecological balance of the area. Talukdar and Choudhury (2017) found that the changes in precipitation patterns have led to changes in vegetation cover, which in turn has affected the distribution and population of various animal species in the area. The present study found that the changes in precipitation and temperature patterns may not be influencing the elephant habitat in DWS. However, bio-climatic factors mainly solar radiation, soil moisture, and nutrient availability, need to be tested to understand the potential impacts of climate on local ecosystems, elephant habitat and their corridors. Therefore, it is important for conservation and management efforts to take into account the potential impacts of climate change on local ecosystems.

Habitat suitability modeling methods such as Maxent, generalized regression, machine learning, and deep neural network have been developed during the past decades (Jathanna et al., 2015; Neupane et al., 2020; Sharma et al., 2020; Yang et al., 2022). The present study employed the AHP-based method in which many of the habitat landscape parameters were derived from remote sensing satellite data. Hence, there is a future scope to assess various models for determining the optimal potential habitat for elephants along with the various climatic variables. Also, the elephant suitability map provides base information on DWS, which was quite well corroborated with the geolocation data on elephant presence. Maintaining the elephant corridors and connectivity between the forest patches requires elephant habitat suitability modeling, which can alleviate HECs in the DWS.

Furthermore, to secure the elephant corridors, temporary fencing or relocation of nearby villages is recommended within DWS. Constructing artificial water storage tanks at the location of river confluence and the requisite elevation can meet the water requirements of the elephants. Elephant hotspots near the forest patch and adjacent to village have also been suggested for the intended elephant route. This strategy could help control the number of HECs cases if the corridors are notified and well-maintained (using elephant proof fencing in crucial areas). To do this, a team effort is required on the part of the local communities to reduce the amount of biomass being extracted from elephant habitats and elephant paths. The role of habitat modeling helps in management and prevention to conserve the habitat suitability for elephants and to improve and minimize HECs. The conflicts can be combated by applying conventional approaches along with the use of contemporary technological means, namely satellite tracking of elephants and the monitoring of their habitats.

Conclusions

This is a comprehensive study on elephant habitat, its movement, HECs, and corridors that provide various critical information which are required for a management strategy plan for elephant conservation in DWS. About 59% (235 km^2) of the area was highly suitable for elephant habitat where 90% of the elephant movement was seen. The most suitable places for elephant habitat were identified in the forest's core parts. The elephant corridors are mapped which indicates that only one active corridor (Jhunjhaka-Banduan) is for elephant movement, while other inactive corridors lead to HECs. Most conflicts are observed in the low suitable areas. The limitation of the study includes the traditional approach of AHP along with weights which can be replaced by other advanced models (e.g., Maxent and machine learning). Nevertheless, this study provided elephant habitat suitability regions and migratory corridor routes within the sanctuary, allowing wildlife managers to effectively plan elephant conservation strategies that focus on HECs in the region.

Author contribution   Satendra Kumar Chaudhary: Investigation, Methodology, Software, Data Analysis, Visualization, writing– original draft, review and editing.   Arvind Chandra Pandey: Conceptualization, Investigation, Methodology, Software, Data Analysis, Visualization, writing– original draft, review and editing.   Bikash Ranjan Parida: Conceptualization, Investigation, Methodology, Software, Data Analysis, Visualization, writing– original draft, review and editing.   All authors have read and agreed to the published version of the article.

Arvind Chandra Pandey: Conceptualization, Investigation, Supervision, Methodology, Software, Data Analysis, Visualization, writing– original draft, review and editing.

Bikash Ranjan Parida: Conceptualization, Investigation, Supervision, Methodology, Software, Data Analysis, Visualization, writing– original draft, review and editing.

All authors have read and agreed to the published version of the article.

Declarations   Ethical responsibilities of authors: All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors and are aware that with minor exceptions, no changes can be made to authorship once the paper is submitted.

Ethics approval and consent to participate   Not applicable.

Conflict of interest   The authors declare no competing interests.

References

Abatzoglou, J. T., Dobrowskim, S. Z., Parksm, S. A., & Hegewischm, K. C. (2018). TerraClimate, a high-resolution global dataset of monthly climate and climatic water balance from 1958–2015. *Sci Data, 5*, 170191.

Ahrestani, F. S., Heitkönig, I. M., & Prins, H. H. (2012). Diet and habitat-niche relationships within an assemblage of large herbivores in a seasonal tropical forest. *Journal of Tropical Ecology, 28*, 385–394.

Anjali, P., Subramani, D.N., (2021). Inter and intra-annual spatio-temporal variability of habitat suitability for Asian elephants in India: A random forest model-based analysis, in: 2021 IEEE International India Geoscience and Remote Sensing Symposium (InGARSS). IEEE, pp. 467–470. https://doi.org/10.1109/InGARSS51564.2021.9792132

Ashiagbor, G., & Danquah, E. (2017). Seasonal habitat use by elephants (Loxodonta africana) in the Mole National Park of Ghana. *Ecology and Evolution, 7*, 3784–3795.

Bar, S., Parida, B. R., & Pandey, A. C. (2020). Landsat-8 and Sentinel-2 based Forest fire burn area mapping using machine learning algorithms on GEE cloud platform over Uttarakhand, Western Himalaya. *Remote Sensing Applications: Society and Environment, 18*, 100324.

Belton, V., & Gear, T. (1983). On a short-coming of Saaty's method of analytic hierarchies. *Omega, 11*, 228–230.

Birkett, P. J., Vanak, A. T., Muggeo, V. M., Ferreira, S. M., & Slotow, R. (2012). Animal perception of seasonal thresholds: Changes in elephant movement in relation to rainfall patterns. *PLoS ONE, 7*, e38363.

Bohrer, G., Beck, P. S., Ngene, S. M., Skidmore, A. K., & Douglas-Hamilton, I. (2014). Elephant movement closely tracks precipitation-driven vegetation dynamics in a Kenyan forest-savanna landscape. *Movement Ecology, 2*, 1–12.

Chamaillé-Jammes, S., Valeix, M., & Fritz, H. (2007). Managing heterogeneity in elephant distribution: Interactions between elephant population density and surface-water availability. *Journal of Applied Ecology, 44*, 625–633.

Chase, M. J., Schlossberg, S., Griffin, C. R., Bouché, P. J., Djene, S. W., Elkan, P. W., Ferreira, S., Grossman, F., Kohi, E. M., & Landen, K. (2016). Continent-wide survey reveals massive decline in African savannah elephants. *PeerJ, 4*, e2354.

Chatterjee ND (2016) Man-elephant conflict: A case study from forests in West Bengal in "A case study from forests in West Bengal, India". Springer Cham, India. ISBN: 978-3-319-31162- https://doi.org/10.1007/978-3-319-31162-3

Chaudhary, S. K., Pandey, A. C., & Parida, B. R. (2022a). Forest fire characterization using Landsat-8 satellite data in Dalma Wildlife Sanctuary. *Remote Sens Earth Syst Sci, 5*, 230–245.

Chaudhary, S. K., Pandey, A. C., Parida, B. R., & Gupta, S. K. (2022b). Using geoinformatics to link forest fire severity and fragmentation in India's Dalma Wildlife Sanctuary. *Tropical Ecology, 63*, 453–462.

Choudhury, A. (2004). Human–elephant conflicts in northeast India. *Human Dimensions of Wildlife, 9*(4), 261–270. https://doi.org/10.1080/10871200490505693

Cook, R.M., Parrini, F., Henley, M.D., (2015). Elephant movement patterns in relation to human inhabitants in and around the Great Limpopo Transfrontier Park. Koedoe: African Protected Area Conservation and Science 57, 1–7. https://doi.org/10.4102/koedoe.v57i1.1298

De Beer, Y., & Van Aarde, R. J. (2008). Do landscape heterogeneity and water distribution explain aspects of elephant home range in southern Africa's arid savannas? *Journal of Arid Environments, 72*, 2017–2025.

de la Torre, J. A., Wong, E. P., Lechner, A. M., Zulaikha, N., Zawawi, A., Abdul-Patah, P., Saaban, S., Goossens, B., & Campos-Arceiz, A. (2021). There will be conflict–agricultural landscapes are prime, rather than marginal, habitats for Asian elephants. *Animal Conservation, 24*, 720–732.

Dewan, A. M., Yamaguchi, Y., & Rahman, Z. (2012). Dynamics of land use/cover changes and the analysis of landscape fragmentation in Dhaka Metropolitan, Bangladesh. *GeoJournal, 77*, 315–330.

Doak, D. F., & Mills, L. S. (1994). A useful role for theory in conservation. *Ecology, 75*, 615–626.

Douglas-Hamilton, I., Krink, T., & Vollrath, F. (2005). Movements and corridors of African elephants in relation to protected areas. *Naturwissenschaften, 92*, 158–163.

Epaphras, A.M., Gereta, E., Lejora, I.A., Ole Meing'ataki, G.E., Ng'umbi, G., Kiwango, Y., Mwangomo, E., Semanini, F., Vitalis, L., Balozi, J., (2008). Wildlife water utilization and importance of artificial waterholes during dry season at Ruaha National Park, Tanzania. Wetlands ecology and management 16, 183–188.

Follett, R. F., & Delgado, J. A. (2002). Nitrogen fate and transport in agricultural systems. *Journal of Soil and Water Conservation, 57*, 402–408.

Graham, M. D., Notter, B., Adams, W. M., Lee, P. C., & Ochieng, T. N. (2010). Patterns of crop-raiding by elephants, Loxodonta africana, in Laikipia, Kenya, and the management of human–elephant conflict. *Systematics and Biodiversity, 8*, 435–445.

Gubbi, S. (2012). Patterns and correlates of human–elephant conflict around a south Indian reserve. *Biological Conservation, 148*(1), 88–95. https://doi.org/10.1016/j.biocon.2012.01.046

Hale, M. L., Lurz, P. W. W., Shirley, M. D. F., Rushton, S., Fuller, R. M., & Wolff, K. (2001). Impact of landscape management on the genetic structure of red squirrel populations. *Science, 293*(5538), 2246–2248. https://doi.org/10.1126/science.1062574

Hazarika, R., & Saikia, A. (2013). The pachyderm and the pixel: An assessment of elephant habitat suitability in Sonitpur, India. *International Journal of Remote Sensing, 34*, 5317–5330.

He, K., Fan, C., Zhong, M., Cao, F., Wang, G., & Cao, L. (2023). Evaluation of habitat suitability for asian elephants in Sipsongpanna under climate change by coupling multi-source remote sensing products with MaxEnt model. *Remote Sensing, 15*, 1047.

Hoare, R. E., & Du Toit, J. T. (1999). Coexistence between people and elephants in African savannas. *Conservation Biology, 13*, 633–639.

Jathanna, D., Karanth, K. U., Kumar, N. S., Karanth, K. K., & Goswami, V. R. (2015). Patterns and determinants of habitat occupancy by the Asian elephant in the Western Ghats of Karnataka. *India. Plos One, 10*, e0133233.

Liu, P., Wen, H., Lin, L., Liu, J., & Zhang, L. (2016). Habitat evaluation for Asian elephants (Elephas maximus) in Lincang: Conservation planning for an extremely small population of elephants in China. *Biological Conservation, 198*, 113–121.

Majumder, R. (2022). Human-elephant conflict in West Bengal, India: Present status and mitigation measures. *European Journal of Wildlife Research, 68*, 33.

Mandal, M., Das Chatterjee, N., (2021). Geospatial approach-based delineation of elephant habitat suitability zones and its consequence in Mayurjharna Elephant Reserve, India. Environment, Development and Sustainability 1–22. https://doi.org/10.1007/s10668-021-01412-1

Marshal, J. P., Rajah, A., Parrini, F., Henley, M., Henley, S. R., & Erasmus, B. F. (2011). Scale-dependent selection of greenness by African elephants in the Kruger-private

reserve transboundary region, South Africa. *European Journal of Wildlife Research, 57*, 537–548.

Mekonen, S. (2020). Coexistence between human and wildlife: The nature, causes and mitigations of human wildlife conflict around Bale Mountains National Park, Southeast Ethiopia. *BMC Ecology, 20*, 1–9.

MoEFCC (2017). Ministry of Environment, Forest and Climate Change (MoEFCC). Synchronized elephant population estimation. Project Elephant, MoEFCC, New Delhi, India.

Nad, C., Roy, R., & Roy, T. B. (2022). Human elephant conflict in changing land-use land-cover scenario in and adjoining region of Buxa Tiger Reserve. *India. Environmental Challenges, 7*, 100384. https://doi.org/10.1016/j.envc.2021.100384

Nathan, R., Getz, W. M., Revilla, E., Holyoak, M., Kadmon, R., Saltz, D., & Smouse, P. E. (2008). A movement ecology paradigm for unifying organismal movement research. *Proceedings of the National Academy of Sciences, 105*, 19052–19059.

Naughton-Treves, L., Treves, A., Chapman, C., & Wrangham, R. (1998). Temporal patterns of crop-raiding by primates: Linking food availability in croplands and adjacent forest. *Journal of Applied Ecology, 35*, 596–606.

Neupane, D., Kwon, Y., Risch, T. S., & Johnson, R. L. (2020). Changes in habitat suitability over a two decade period before and after Asian elephant recolonization. *Global Ecology and Conservation, 22*, e01023.

Pal, S. C., Chatterjee, U., Chakrabortty, R., Roy, P., Chowdhuri, I., Saha, A., et al. (2023). Anthropogenic drivers induced desertification under changing climate: Issues, policy interventions, and the way forward. *Progress in Disaster Science, 20*, 100303. https://doi.org/10.1016/j.pdisas.2023.100303

Pandey, A. C., Kumari, N., Ahmad, S., Kumar, A., Saikia, P., Parida, B., Chaudhary, S. K., & Lele, N. (2023). Evaluating biochemical and biophysical characteristics of tropical deciduous forests of eastern India using remote sensing and in-situ parameter estimation. *Remote Sensing Applications: Society and Environment, 29*, 100909.

Rani, M., Panda, D., Allen, M. L., Pandey, P., Singh, R., & Kumar Singh, S. (2024). Assessment and prediction of human-elephant conflict hotspots in the human-dominated area of Rajaji-Corbett landscape, Uttarakhand. *India. Journal for Nature Conservation, 79*, 126601. https://doi.org/10.1016/j.jnc.2024.126601

Ranjan, A. K., & Parida, B. R. (2021). Predicting paddy yield at spatial scale using optical and synthetic aperture radar (SAR) based satellite data in conjunction with field-based crop cutting experiment (CCE) data. *International Journal of Remote Sensing, 42*, 2046–2071.

Rendana, M., Razi Idris, W. M., Abdul Rahim, S., Ghassan-Abdo, H., Almohamad, H., Dughairi, A. A., & A. (2023). Habitat suitability analysis in a natural peat swamp forest on Sumatran elephants using remote sensing and GIS. *Forest Science and Technology, 19*(3), 221–231. https://doi.org/10.1080/21580103.2023.2234463

Roy, M., Sukumar, R., (2017). Railways and wildlife: A case study of train-elephant collisions in Northern West Bengal, India, in: Borda-de-Água, L., Barrientos, R., Beja, P., Pereira, H.M. (Eds.), Railway ecology. Springer International Publishing, Cham, pp. 157–177. https://doi.org/10.1007/978-3-319-57496-7_10

Roy, S.B. (2024).Aster Plan Iteration 01, Jharkhand, Ministry of Tourism, Government of India. Available online: https://sd2.tourism.gov.in/DocumentRepoFiles/MasterPlan/MPa64a2b9c-4f39-4ea8-a0c7-74e368804a1f.pdf. Accessed on: 13 July 2024

Saaty, T.L., (1999). Fundamental of the analytic hierarchy process. Presented at the International Symposium on the Analytic Hierarchy Process. https://doi.org/10.13033/isahp.y1999.038

Saiteja, P., (2020). Documenting and analysing the human-wildlife conflict and its mitigation (species and region wise) of India on the basis of secondary data available.

Sengupta, A., Binoy, V. V., & Radhakrishna, S. (2020). Human-elephant conflict in Kerala, India: A rapid appraisal using compensation records. *Human Ecology, 48*, 101–109. https://doi.org/10.1007/s10745-020-00128-6

Sharma, P., Panthi, S., Yadav, S. K., Bhatta, M., Karki, A., Duncan, T., Poudel, M., & Acharya, K. P. (2020). Suitable habitat of wild Asian elephant in Western Terai of Nepal. *Ecology and Evolution, 10*, 6112–6119.

Talukdar, N. R., & Choudhury, P. (2017). Conserving wildlife wealth of Patharia Hills Reserve Forest, Assam, India: A critical analysis. *Global Ecology and Conservation, 10*, 126–138. https://doi.org/10.1016/j.gecco.2017.02.002

Talukdar, N. R., Choudhury, P., Ahmad, F., Ahmed, R., & Al-Razi, H. (2020a). Habitat suitability of the Asiatic elephant in the trans-boundary Patharia Hills Reserve Forest, northeast India. *Modeling Earth Systems and Environment, 6*, 1951–1961.

Talukdar, N. R., Choudhury, P., Ahmad, F., Al-Razi, H., & Ahmed, R. (2020b). Mapping and assessing the trans-boundary elephant corridor in the Patharia Hills Reserve Forest of Assam, India. *Rangeland Ecology & Management, 73*, 694–702.

Thouless, C., Dublin, H.T., Blanc, J., Skinner, D.P., Daniel, T.E., Taylor, R., Maisels, F., Frederick, H., Bouché, P., (2016). African elephant status report 2016. Occasional paper series of the IUCN Species Survival Commission 60.

Tishi, T. R., & Islam, I. (2019). Urban fire occurrences in the Dhaka Metropolitan Area. *GeoJournal, 84*, 1417–1427. https://doi.org/10.1007/s10708-018-9923-y

Tripathy, B. R., Liu, X., & Ranga, V. (2022). Demographic circumstances and people's sentiments towards elephants in the human–elephant conflict hotspot villages of Keonjhar Forest Division in Eastern India. *Diversity, 14*(5), 311. https://doi.org/10.3390/d14050311

Troy, A., Morgan Grove, J., & O'Neil-Dunne, J. (2012). The relationship between tree canopy and crime rates across an urban–rural gradient in the greater Baltimore region. *Landscape and Urban Planning, 106*, 262–270. https://doi.org/10.1016/j.landurbplan.2012.03.010

Vattamthanam, S., (2020). Planning for conservation of elephant corridors: Case of Ankua-Ambia West Sighbhum, Jharkhand (PhD Thesis). SPA Bhopal.

Vidya, T. N. C., & Sukumar, R. (2005). Social and reproductive behaviour in elephants. *Animal Behaviour, 89*, 8.

Western, D., Russell, S., & Cuthill, I. (2009). The status of wildlife in protected areas compared to non-protected

areas of Kenya. *PLoS ONE, 4*, e6140. https://doi.org/10.1371/journal.pone.0006140

White, P. C. L., & Ward, A. I. (2010). Interdisciplinary approaches for the management of existing and emerging human - wildlife conflicts. *Wildlife Research, 37*, 623. https://doi.org/10.1071/WR10191

Yang, W., Ma, Y., Jing, L., Wang, S., Sun, Z., Tang, Y., & Li, H. (2022). Differential impacts of climatic and land use changes on habitat suitability and protected area adequacy across the Asian elephant's range. *Sustainability, 14*, 4933.