Geospatial Quantification of Human–Elephant Conflict Hotspots in the Southern Western Ghats

G.M. Pavithra[1*], G.V. Venkataramana[1], S. Vazeed Pasha[2], C. Sudhakar Reddy[3], B. Swarada[2], V.K. Dadhwal[2]
[1]Department of Studies in Environmental Sciences, University of Mysore, Karnataka, India
[2]School of Natural Science and Engineering, National Institute of Advanced Studies (NIAS), Indian Institute of Science (IISC) Campus, Karnataka, India
[3]Forest Biodiversity and Ecology Division, National Remote Sensing Centre, Telangana, India
*Corresponding Author email: pavithrakesari@gmail.com

(Received on 31 December 2025; In final form on 17 August 2026)

DOI: *https://doi.org/10.58825/jog.2026.20.2.312*

Abstract: Human–elephant conflict (HEC) in the Southern Western Ghats has significant socio-economic and ecological impacts, highlighting the need for an integrated mitigation approach. The present study leverages a geo-tagged database of 1,22,986 HEC incidents from 2019 to 2023 sourced from the e-Parihara web portal, Karnataka Forest Department (KFD), to analyse conflict patterns, damage types, and compensation trends across eight districts of Karnataka. Kodagu became the district with the highest number of cases and compensation, highlighting the need for targeted interventions. The study distinguishes between districts within the Western Ghats and those outside, such as Mandya and Ramanagara, to understand the geographical and ecological aspects of HEC dynamics. A significant increase in HEC cases and compensation was observed during the study period, with the number of cases rising from 8,184 in 2019 to 30,912 in 2023, while compensation payments increased from ₹53.7 million to ₹390.4 million over the same period. As a result, a total of ₹1,050.5 million was spent on compensation during the 2019–2023 period. The damage was categorised into six types: plantation damage, crop loss, property damage, human injury and death, livestock kills, and other damages. A total of 1,998 conflict-prone villages were identified and classified into five categories: Very High (26.1%), High (35.4%), New/Emerging Hotspots (9.4%), Sporadic Hotspots (19.2%), and Cold Spots (9.9%). This classification aids in prioritising mitigation efforts, particularly in high and emerging hotspots, to prevent further escalation. The study aligns with the Ministry of Environment, Forest and Climate Change (MoEFCC) 2023 HEC mitigation guidelines, emphasising the implementation of early warning and rapid response systems. The village-level hotspot database serves as a strategic tool for conflict mitigation, supporting targeted habitat management and policy interventions to reduce human–wildlife conflict in the Southern Western Ghats.

Keywords: Elephant, Human–elephant conflict, e-Parihara, Hotspots, Karnataka.

1. Introduction

Human–elephant conflict (HEC) is a major global conservation and socio-economic challenge, particularly in Asia, where interactions between humans and Asian elephants (*Elephas maximus* L.) frequently result in loss of human lives, crop damage, property destruction, and economic hardship for local communities (Sharma, 2022; Gunawansa et al., 2024; Mohd Taher et al., 2021). The identification of HEC hotspots using satellite remote sensing and Geographic Information Systems (GIS) has become an important approach for understanding conflict patterns and supporting mitigation measures (Gunawansa et al., 2024; Pavithra et al., 2025). In India, Karnataka is recognised as a major HEC hotspot because it supports the largest population of Asian elephants and contains extensive areas where human activities overlap with elephant habitats (Wildlife Institute of India, 2025). According to the Ministry of Environment, Forest and Climate Change (MoEFCC), Karnataka supports 6,049 elephants, representing 20.19% of India's elephant population (Government of India, 2024; India WRIS, 2023). The average forest area available per elephant in the state is approximately 6.13 km², indicating considerable pressure on habitat resources (Karnataka Evaluation Authority, 2022; ISFR, 2023). Furthermore, Asian elephants require nearly 300 kg of fodder and 225 litres of water each day, making habitat availability and quality critical for their survival (Thomassen et al., 2011; Fernando, 2020; Dhairykar and Singh, 2020; Dunkin et al., 2013).

Given the ecological and socio-economic significance of HEC, the Government of India has emphasised coordinated management through State-Level Coordination Committees (SLCCs), District-Level Coordination Committees (DLCCs), and inter-departmental collaboration (MoEFCC, 2023; MoEFCC, 2024). Key mitigation strategies include the promotion of alternative crops, rapid response systems, compensation mechanisms, and financial support under Project Elephant and Project Tiger initiatives. In addition, site-specific interventions such as the capture and translocation of conflict-causing elephants are implemented in areas experiencing severe conflict (Sukumar, 2019). The Integrated Development of Wildlife Habitats Scheme further contributes to conflict mitigation by improving habitat quality through water augmentation and the

© Indian Society of Geomatics

planting of native fodder species (MoEFCC, 2023; MoEFCC, 2024).

The Western Ghats landscape of Karnataka, including the districts of Chamarajanagar, Ramanagara, Kodagu, Mysuru, Mandya, Hassan, Dakshina Kannada, and Chikkamagaluru, forms one of the most important elephant habitats in southern India (Ramachandra et al., 2019; Pavithra et al., 2025). However, increasing habitat fragmentation caused by deforestation, agricultural expansion, and infrastructure development has intensified HEC across the region (Hossen and Røskaft, 2023; Sabu et al., 2022). The spread of invasive alien plant species (IAPS) has further degraded native vegetation (Pasha et al., 2014; Pasha et al., 2015) and reduced habitat quality, compelling elephants to move into human-dominated landscapes in search of food and water (MoEFCC, 2023). Consequently, incidents involving crop loss, property damage, livestock depredation, and human casualties have increased. (Gubbi et al., 2014) reported that southern India, including Karnataka, experiences some of the highest levels of HEC in the country.

Forest degradation and habitat loss have further intensified the problem (Padalia et al., 2019; Reddy et al., 2016a; Reddy et al., 2016b; Reddy et al., 2018a, b). Between 1930 and 2013, India lost 21.49% of its forest cover, while elephant habitats experienced a decline of 3.19% between 1975 and 2013 (Padalia et al., 2019). Such habitat changes have contributed to elephant displacement and increasing incidences of human fatalities, crop damage, and property loss (Ravenelle and Nyhus, 2017). Previous studies have emphasised both the ecological and policy dimensions of HEC and highlighted the urgent need for evidence-based mitigation strategies (Sukumar, 2019; Zakaria et al., 2024; Mundoga et al., 2025).

Recent advances in geospatial technologies and Information and Communication Technology (ICT) have significantly improved wildlife conflict monitoring and management (Pavithra et al., 2025). In Karnataka, the Forest Department has developed the Android-based e-Parihara system, a geo-tagged human–wildlife conflict monitoring platform that enables near real-time recording, verification, and monitoring of conflict incidents (Karnataka Forest Department, 2023; Pasha et al., 2024). The system supports transparent compensation processing through Direct Benefit Transfer (DBT) mechanisms and provides valuable spatial information for conflict assessment and management. In addition, geospatial platforms such as Bhuvan-MGNREGA and Survey of India datasets contribute critical location-based information for planning and resource management (National Remote Sensing Centre, 2024; Survey of India, 2024). The availability of geo-tagged conflict data presents an opportunity to identify emerging conflict hotspots and improve evidence-based conservation planning.

Against this background, the present study aims to evaluate the spatial and temporal dynamics of human–elephant conflict in Karnataka using geo-tagged e-Parihara records collected between 2019 and 2023. Specifically, the objectives are to: (i) analyse the distribution and temporal trends of different categories of HEC incidents and associated compensation claims; (ii) identify and classify HEC hotspots across conflict-prone districts using geospatial analysis; and (iii) assess the role of the e-Parihara system in documenting conflict incidents and facilitating compensation delivery. The findings are expected to support informed decision-making, strengthen conflict mitigation strategies, and promote long-term coexistence between humans and elephants in the Western Ghats region of Karnataka.

2. Study Area

Karnataka is geographically located between 11°50′–18°50′ N latitudes and 74°–78°50′ E longitudes, with a total area of 191,791 km² (Karnataka Forest Department, 2024; India WRIS, 2023). Forests cover approximately 38,575 km², accounting for 20.11% of the state's geographical area (ISFR, 2023). This diverse landscape, characterised by a mix of forested regions and human settlements, provides an ideal setting to study the dynamics of human-wildlife interactions and their management.

Karnataka receives an average annual rainfall of 1153 mm (Karnataka State Natural Disaster Monitoring Centre, 2023) and features an elevation range from 1 to 1920 metres above mean sea level, creating a diverse and undulating landscape interspersed with mountains and deep ravines. This topography supports a variety of forest types, including evergreen and semi-evergreen forests, moist and dry deciduous forests, scrub and thorny forests, and grasslands.

The Western Ghats, a biodiversity hotspot in the state, are home to valuable tree species such as teak (*Tectona grandis*), rosewood (*Dalbergia latifolia*), casuarina (*Casuarina equisetifolia*), and eucalyptus (*Eucalyptus* spp.). Other notable species include *Iphigenia mysorensis*, *Derris indica*, *Barringtonia racemosa*, *Cassia fistula*, *Dipterocarpus indicus*, *Caryota urens*, *Dillenia pentagyna*, and *Zizyphus mauritiana*. Common flora species in Karnataka's forests include *Lagerstroemia lanceolata*, *Adina cordifolia*, *Careya arborea*, *Terminalia paniculata*, *Terminalia tomentosa*, and *Vitex altissima* (Karnataka Biodiversity Board, 2024).

Karnataka's fauna is equally diverse, comprising a range of mammals, including leopards (*Panthera pardus*), slender lorises (*Loris tardigradus*), gaurs (*Bos gaurus*), wild pigs (*Sus scrofa*), pangolins (*Manis* spp.), Malabar giant squirrels (*Ratufa indica*), mouse deer (*Tragulus* spp.), bonnet macaques (*Macaca radiata*), and barking deer (*Muntiacus muntjak*). The avifauna is rich as well, featuring species like ruby-throated bulbuls (*Pycnonotus jocosus*), Indian shamas (*Copsychus malabaricus*), Malabar whistling thrushes (*Myophonus horsfieldii*), orange-headed thrushes (*Geokichla citrina*), paradise flycatchers (*Terpsiphone paradisi*), great Indian hornbills (*Buceros bicornis*), cormorants (Phalacrocoracidae), darters (Anhingidae), and white ibises (*Threskiornis melanocephalus*) (Karnataka Biodiversity Board, 2024).

This combination of climatic, topographic, and biological diversity makes Karnataka a critical region for studying human-wildlife interactions and implementing conservation strategies.

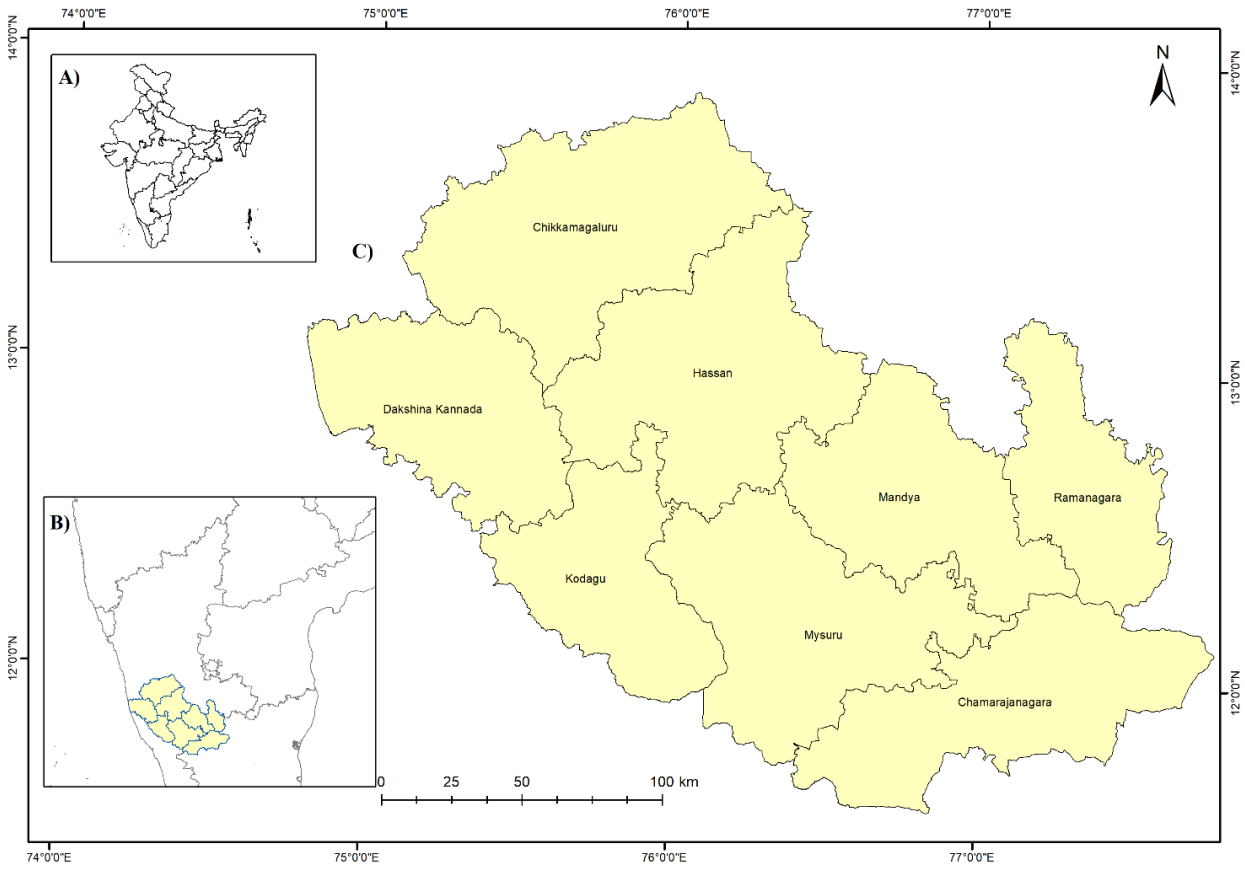


Figure 1: Map showing a) India states, b) Map of Karnataka state, and c) Identified eight districts with the highest HEC.

The study area also supports a wide variety of reptiles, including crocodiles (*Crocodylus* spp.), tortoises (Testudinidae), lizards (Lacertilia), chameleons (Chamaeleonidae), geckos (Gekkonidae), and various species of snakes (Serpentes) (Karnataka Biodiversity Board, 2024). Elephants in Karnataka are primarily distributed across 12 protected areas, including Bandipur, Nagarahole, and Bannerghatta National Parks, along with wildlife sanctuaries such as Biligirirangaswamy Temple (BRT), Bhadra, Cauvery, Brahmagiri, Talacauvery, Pushpagiri, Dandeli, and Nugu. A smaller population of elephants also resides in Kudremukh National Park. Beyond these protected areas, elephants are frequently observed in forest divisions such as Kollegala, Virajpete, Madikeri, Hunsur, Ramnagara, Mandya, Hassan, Mysore, Chikmagalur, Koppa, Bhadravathi, Haliyal, and Yellapura (Gubbi et al., 2014).

These distributions highlight the challenges of managing HEC across a mosaic of protected and non-protected landscapes, necessitating targeted conservation and conflict mitigation strategies (Figure 1).

3. Methodology

The methodology involves integrating elephant conflict occurrence data, type of damages and compensation.

3.1 Detection of HEC village hotspots

To identify HEC incidents at the village scale, this study adheres to the Guidelines for HEC Mitigation set forth by the Ministry of Environment, Forest and Climate Change (MoEFCC, 2023). According to these guidelines, HEC Hotspots are defined as areas where actual or predicted repeated occurrences of HEC incidents, such as plantation damage, crop raids, livestock kills, and human deaths or injuries, are observed over both temporal and spatial scales. These hotspots can be classified as static, where conflicts occur repeatedly in the same location or at the same time, or dynamic, where conflicts shift in space and time over the years.

Furthermore, the magnitude of HEC incidents is assessed through interpolation or extrapolation techniques, which are employed to accurately define the hotspots in both space and time (MoEFCC, 2023). This approach enables a comprehensive understanding of conflict patterns, helping to prioritise areas for mitigation strategies. In this study, we generated both Incident Hotspots using Kernel density and Vulnerability Hotspots to assess HEC patterns at the village scale.

Incident Hotspot refers to the frequency of HEC occurrences over specific past years, such as the previous 5 or 10 years, mapped across the target area. The data include incidents of crop damage, plantation damage, property damage, human injury and death, and livestock kills and attacks. These hotspots provide insights into areas where HEC incidents have been most frequent and impactful. Vulnerability Hotspot is a cumulative index derived by overlaying past incidents, the vulnerability of the local community, and the potential risk of the area. This index identifies areas more prone to conflict due to both historical data and socio-economic conditions (MoEFCC, 2023;

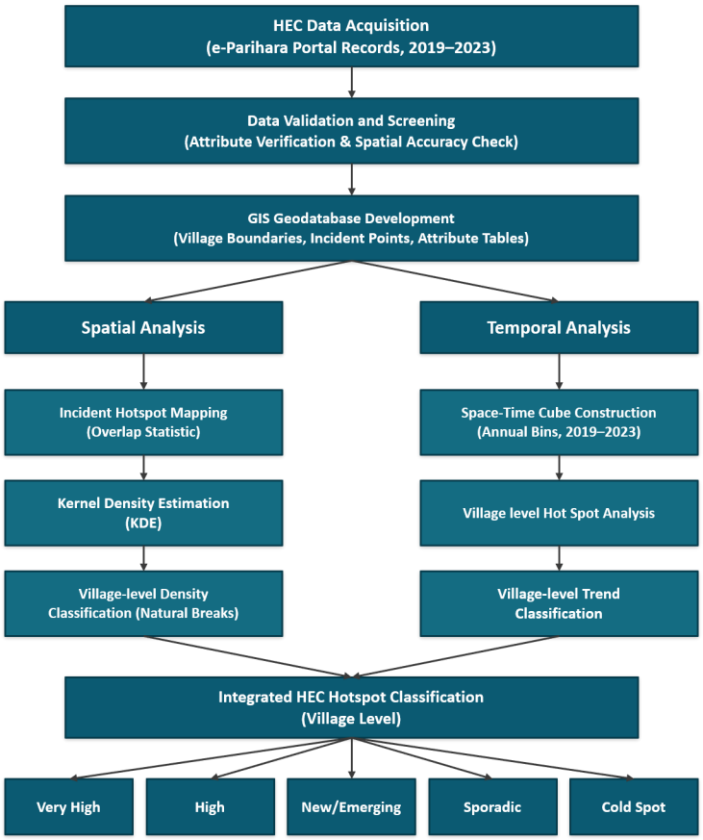


Figure 2: Flow chart depicting the overall Methodology adopted in the study

MoEFCC, 2024). It considers not only the frequency of incidents but also the socio-economic vulnerabilities that could increase the risk of conflict in certain regions. Based on the above criteria, we categorised conflict villages according to the degree of incidents and the total compensation paid, as well as their Vulnerability Hotspot status at the village level, considering spatial repetition and alterations in conflict patterns. This categorisation helps identify areas where mitigation efforts should be prioritised, as well as those that require targeted interventions.

The study followed these steps:

Procurement of HEC data from the KFD for the years 2019-2023 (Karnataka Forest Department, 2023) (Figure 2). Spatial visualisation of data, followed by attribute and spatial evaluation, to select the relevant elephant conflict data from January 2019 to December 2023. This step allowed for the identification of areas most affected by HEC incidents over the past five years. Annual trends analysis of HEC incidents with respect to the number of cases and compensation paid. This analysis provides insights into how HEC has evolved over time and the financial impacts on affected communities. This methodology enables a detailed assessment of spatial and temporal patterns of HEC and supports the development of effective mitigation strategies.

The damage caused by HEC is classified into the following categories: Plantations, Crops, Human Death and Injury, Property Damage, Livestock Kills, and Others. The Plantations category includes all horticultural and commercial plantations, such as Areca Nut-Coconut, Banana, Coffee, etc. Crops refer to agricultural products like Paddy, other vegetable crops, and green leafy vegetables. Human Death and Injury, Property Damage, and Livestock Kills are the other classes, with each class representing specific types of damage caused by elephant interactions. Data for district and village level boundaries were obtained from the Survey of India (www.onlinemaps.surveyofindia.gov.in).

3.2 Village-level incident and vulnerability hotspots

Two types of hotspot maps were generated for this study. The first stage was based on a spatial overlay of conflict villages, showing the repetition and alteration of incidents over time and space. The hotspots were further categorised into i) Very high Hotspot-I (Persistent HEC Incident Overlap): Areas where HEC incidents have consistently occurred over five consecutive years (2019 to 2023). ii) High Hotspot-II (Moderate Conflict Overlap): Areas where HEC incidents have occurred intermittently, spanning 2 to 4 years within the study period. iii) New/Emerging Hotspots: village areas where human–elephant incidents occurred exclusively in the year 2023. iv) Sporadic Hotspots: areas with irregular patterns of conflict. v) Cold Spot Villages: Areas where no incidents occurred in the last 2 to 3 consecutive years. The kernel density map was generated using a kernel density algorithm to visualise the intensity of HEC incidences by calculating the density of events in a defined neighbourhood, using a quadratic kernel function (Silverman, 2018). Kernel density estimate (KDE) is a non-parametric technique that transforms discrete incident points into a continuous density surface (Silverman, 2018). This technique enhances the distribution of HWC points across the landscape and highlights areas with a greater likelihood of conflict.

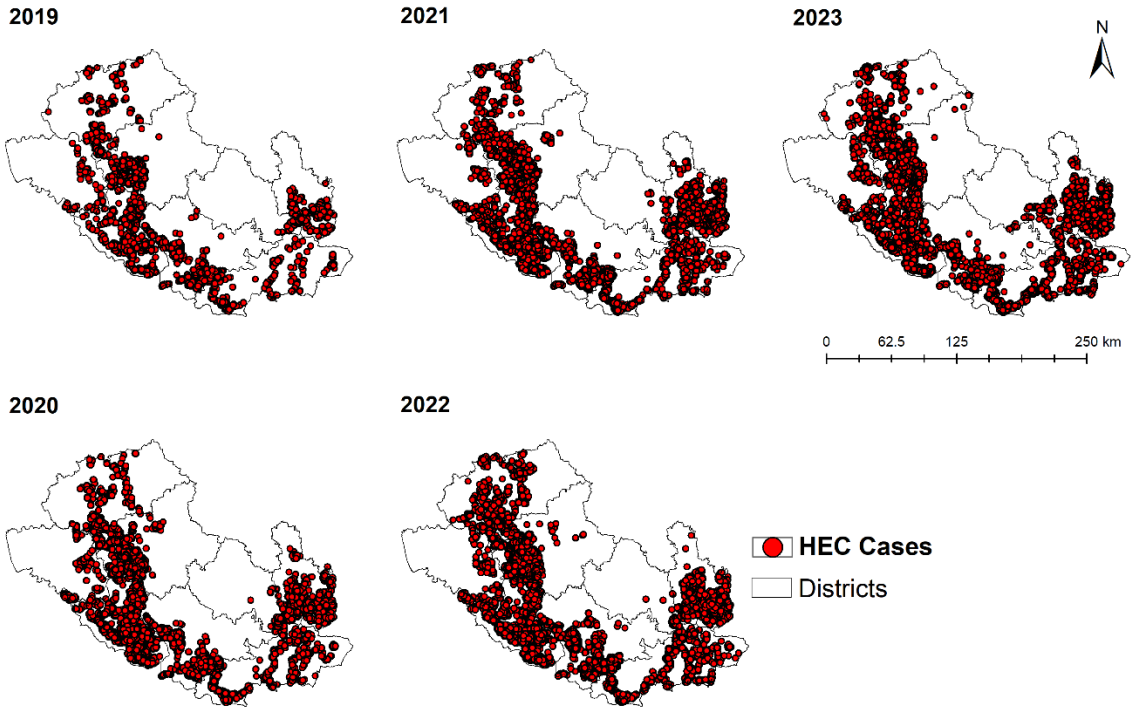


Figure 3: Year-wise number of HEC incidents and compensation amount paid from 2019 to 2023 in southern Karnataka.

The HEC GIS analysis and village-level hotspots were generated using spatial overlay techniques in ArcGIS 10.8 and Q-GIS software.

4. Results and Discussion

The geo-tagged HEC data provided valuable insights into the annual trends of conflict cases and compensation payments in Karnataka for the duration of the 2019 to 2023 period. A total of 1,22,986 HEC incidents were recorded, with a cumulative compensation amount of 1,050.5 million Rs. In 2019, there were relatively few incidents, with 8,184 cases reported. However, 2022 saw the highest number of incidents, with 34,205 incidents, which slightly decreased to 30,912 in 2023.

Despite this decline in incidents from 2022 to 2023, the total compensation paid did not fall correspondingly. The compensation amount increased substantially, from 53.7 million Rs. in 2019 to 390.4 million Rs. in 2023. Year-wise HEC mapping depicted the annual number of conflict cases and corresponding compensation, revealing trends and variations over the study period (Figure 3). This underscores the importance of geo-tagged HEC data in understanding the spatial dynamics of conflicts and to effectively plan and allocate resources for compensation.

4.1 Type of damage by HEC

Among the six categories of damage, Plantations and Agriculture accounted for 91.4% of the total HEC cases and 84% of the total compensation value. The Plantations category contributed 50.8% of the incidents, followed by the Agricultural category, which accounted for 40.6%. Human Death and Injury cases totalled 216, contributing 6.5% to the total compensation. Property Damage also had a notable impact on compensation, accounting for 3.8%.

In the Plantations category, most damage was observed in Areca Nut-Coconut, Banana, Coffee, and other horticultural plantations. The agricultural products impacted by elephant raids included Paddy (rice), Ragi (finger millet), Jowar (sorghum), Corn, Tomato, and Sugarcane between 2019 and 2023. Additionally, there were 4,484 cases categorised as Other Damages, with a compensation value of 61.6 million Rs. (5.4%).

Between 2019 and 2023, Karnataka witnessed a steady rise in the financial burden of HEC, driven largely by agricultural and plantation damage. In 2019, the total financial loss from HEC was 53.7 million Rs., with agricultural crops accounting for most of the damage. Over the next few years, the financial toll grew substantially, reaching 145.6 million Rs. in 2020, 181.7 million Rs. in 2021, 279.2 million Rs. in 2022 and finally peaking at 390.4 million Rs. in 2023. The upward trend in the financial impact is indicative of the increasing intensity and frequency of conflicts between humans and elephants in the state.

Agricultural crops, which bore the brunt of the damage, saw a steady increase in losses, rising from 23.2 million Rs. in 2019 to 90.6 million Rs. in 2023. Similarly, plantations, including crops like tea and coffee, followed a similar trajectory, with damages escalating from 28.2 million Rs. in 2019 to 230.7 million Rs. in 2023. This suggests that the growing conflict is primarily rooted in the destruction of crops, which significantly impacts the livelihoods of farmers in affected areas.

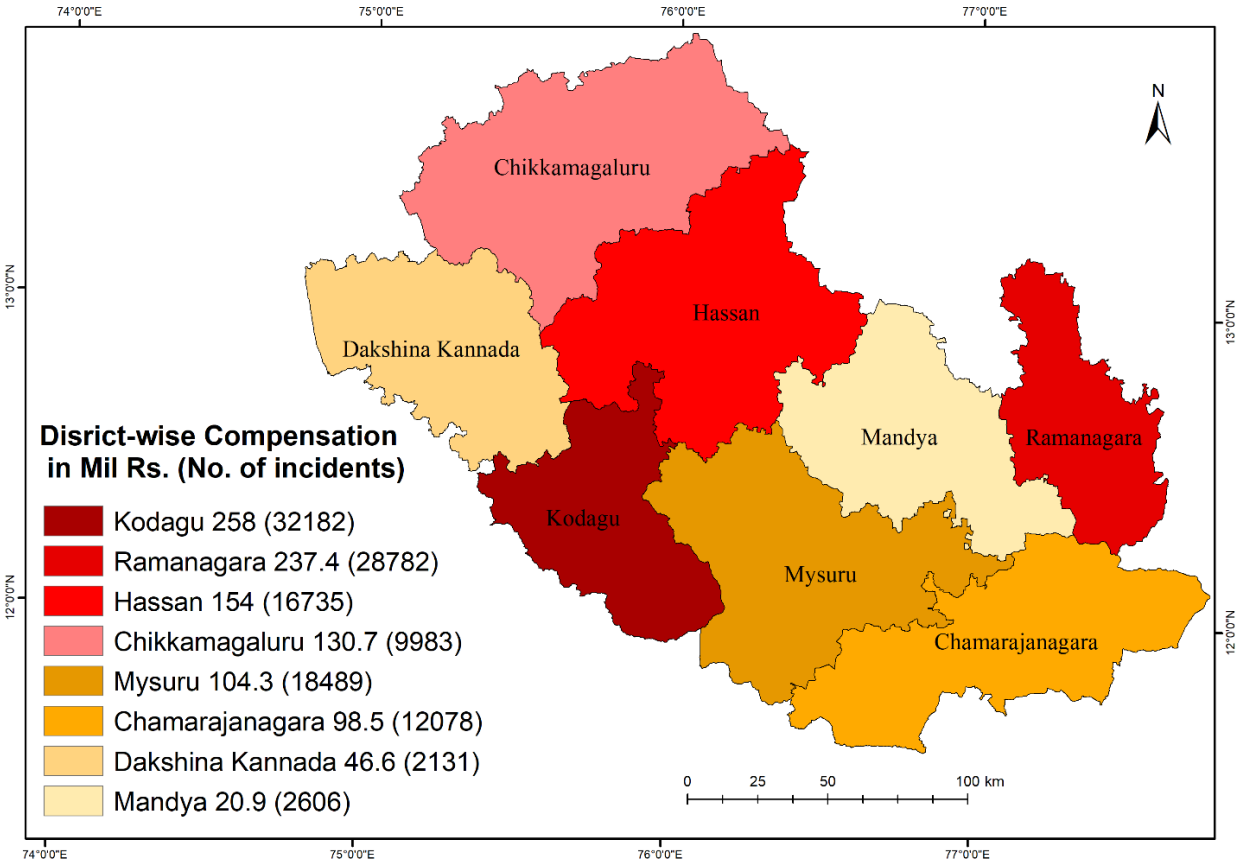


Figure 4: Identification of District level HEC Hotspots (2019-2023) in Southern Western Ghats Karnataka

Human injuries and livestock killings, while important, accounted for a smaller proportion of the total financial losses. Human injuries increased from 0.8 million Rs. in 2019 to 31.5 million Rs. in 2023, reflecting a rise in the severity of encounters between humans and elephants. Livestock killings, though contributing minimally, also showed an increase, with total losses growing from 0.1 million Rs. in 2019 to 0.9 million Rs. in 2023.

District-level analysis of HEC incidents in Karnataka reveals the proportional distribution of cases and compensation across eight districts. Kodagu accounted for 32,182 cases (26.17%) and received 258 million Rs. (24.56%). Ramanagara reported 28,782 cases (23.40%) with 237.4 million Rs. (22.60%) in compensation. Hassan had 16,735 cases (13.61%) and 154 million Rs. (14.66%) in compensation. Chikkamagaluru, despite fewer cases (9,983 or 8.12%), received 130.7 million Rs. (12.44%). Mysuru recorded 18,489 cases (15.03%) and 104.3 million Rs. (9.93%). Chamarajanagara had 12,078 cases (9.82%) and 98.5 million Rs. (9.38%). Dakshina Kannada reported 2,131 cases (1.73%) and 46.6 million Rs. (4.44%), while Mandya had 2,606 cases (2.12%) and 20.9 million Rs. (1.99%). Across all eight districts, a total of 122,986 HEC cases were recorded and 1,050.5 million Rs. was paid in compensation, underscoring the substantial financial and social impact in the study region (Figure 4).

The Kernel density map illustrates spatial clusters of HEC incidents, with intensity represented by a heat scale (red = high, yellow = moderate, blue = low) (Figure 5).

The Persistent HEC Incident Overlap (Hotspot-I): These villages have a total of 522 (26%) of the total. These areas are experiencing ongoing conflict related to HWC incidents from 2019–2023. The highest number of villages 707 (35.4%) fall into the Hotspot-II (Moderate Conflict Village Overlap) category. Around 188 (9.4%) villages are attributed to new/emerging hotspots. These areas experienced conflict in the year 2023. Irregular patterns/ Sporadic Hotspots observed in 384 (19.2%) villages. There are 197 (9.9%) villages identified as Cold Spots indicating no conflict incidents in the last two to three consecutive years (Figure 6).

Kodagu and Ramanagara exhibit the most intense red clusters, indicating high concentrations of HEC incidents, which aligns with their leading positions in both case numbers and compensation amounts. Hassan and Chikkamagaluru exhibit significant red areas, indicating localised hotspots of conflict despite Chikkamagaluru having fewer cases overall. The localised clustering in Chikkamagaluru, despite its lower overall case count, likely reflects a higher compensation per case and more severe types of damage in the affected areas. Mysuru and Chamarajanagara exhibit moderate clusters (yellow to red) indicating widespread but less concentrated conflict compared to Kodagu and Ramanagara. Dakshina Kannada and Mandya show sparse yellow patches with predominantly low areas, confirming their low case counts and compensation figures. These inter-district variations can be attributed to differences in the extent of forest cover and elephant habitat, proximity to protected areas and elephant movement corridors, and the degree of interface

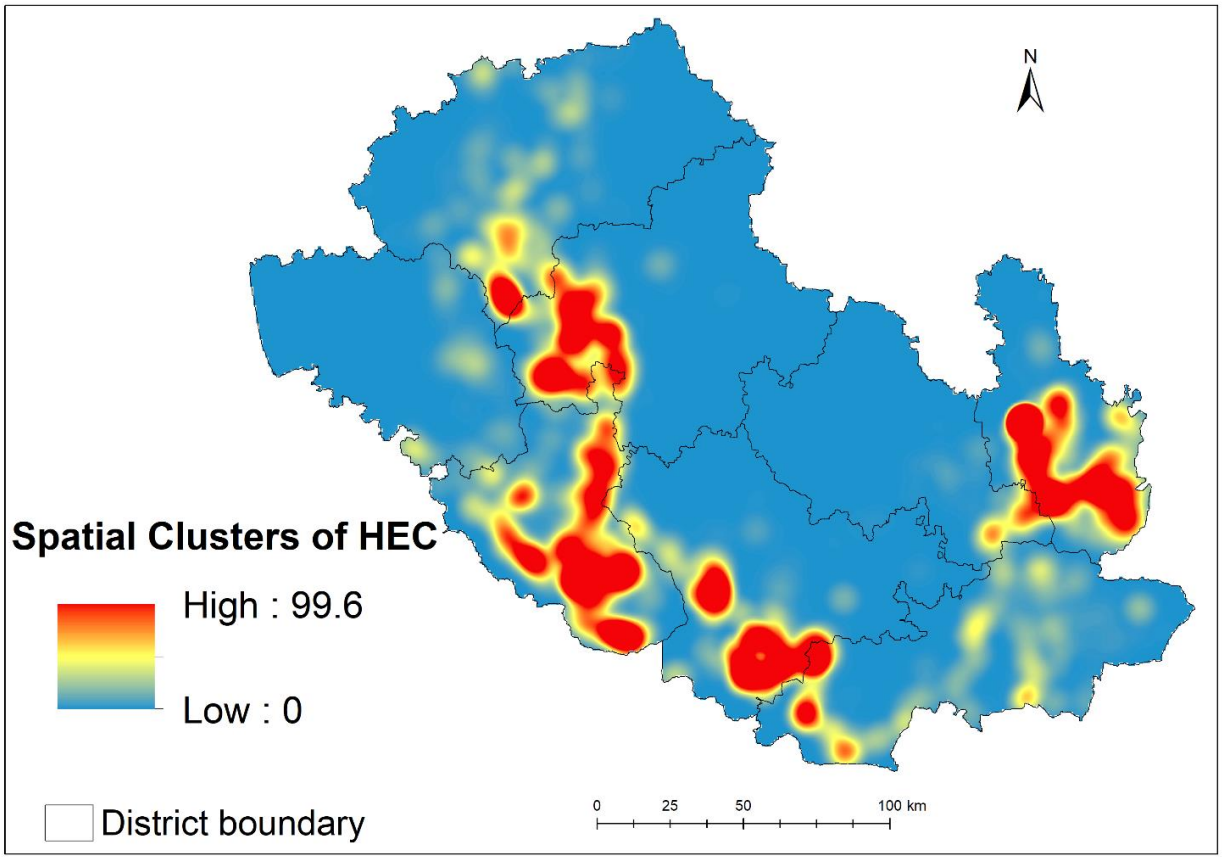


Figure 5: Identification of HEC spatial clusters and varying conflict intensities using the Kernel Density (2019-2023) approach

between forests and cultivated land. Districts such as Kodagu and Ramanagara, where extensive forest–agriculture interfaces and palatable crops adjoin elephant habitats, experience frequent and intense conflict, whereas Dakshina Kannada and Mandya, with limited elephant habitat and predominantly coastal or plains agriculture, record comparatively few incidents. The clustering pattern suggests that HEC is concentrated along forested and hilly regions, particularly in the Western Ghats and adjoining areas, where elephant habitats intersect with agricultural landscapes. Field photographs of damage to crops and horticultural plantations are shown in Figure 7.

This study examined the spatio-temporal dynamics of HEC incidents in the study area. It identifies the annual trends and compares the damage over time and space during 2019-2023. HEC has a significant impact on both human economic activities and the wild elephant's survival in the impacted regions at the local level (Sukumar, 2019). Elephants require large habitats, and dietary requirements lead to HEC and cause severe harm to the socio-economic conditions of humans. Therefore, understanding HEC has become one of the most significant challenges for elephant management and conservation in recent years. However, it has been relatively little investigated using geo-tagged HEC data at the village scale. We identified the HEC hotspots and created a database that is useful for the effective use of early warning and rapid response systems. This study highly aligns with the implementation measures in the latest MoEFCC (2023) guidelines to mitigate HEC. Geospatial technology can be used to identify conflict hotspots using space and time data. A recent study revealed the potential use of geospatial technology for identifying wildlife conflict hotspots (Pasha et al., 2024; Pavithra et al., 2025).

The present study shows that a substantial share of the compensation is concentrated in a few major districts and their respective villages (Figures 3-7). The conflict villages identified in this study exhibit varying levels of conflict intensity, from persistent to sporadic occurrences, and some areas remain conflict-free. Understanding these patterns is crucial for effective conflict management and mitigation strategies. Identified new/emerging village hotspots need special attention; otherwise, these hotspots may transform into high-risk zones. Generated village-level hotspots may be prioritised while drafting actions such as early warning systems and other mitigation measures.

There are three key elements in most HEC scenarios: i) the elephant, ii) humans (i.e. settlements), and iii) the attractant for the elephant (i.e. palatable crops). Figure 7 shows the major food crops raided viz, Paddy, sugarcane, and banana in the study area, the most vulnerable crops, indicating crop preference patterns by elephants causing substantial agricultural losses. The temporal span (2019–2023) shows that HEC is persistent and escalating, suggesting a need for targeted mitigation strategies. This visual evidence supports spatial and temporal HEC analysis, reinforcing hotspot identification and prioritisation for conflict management. Sometimes elimination of one of these elements in the conflict is required to resolve an intractable situation (MoEFCC,

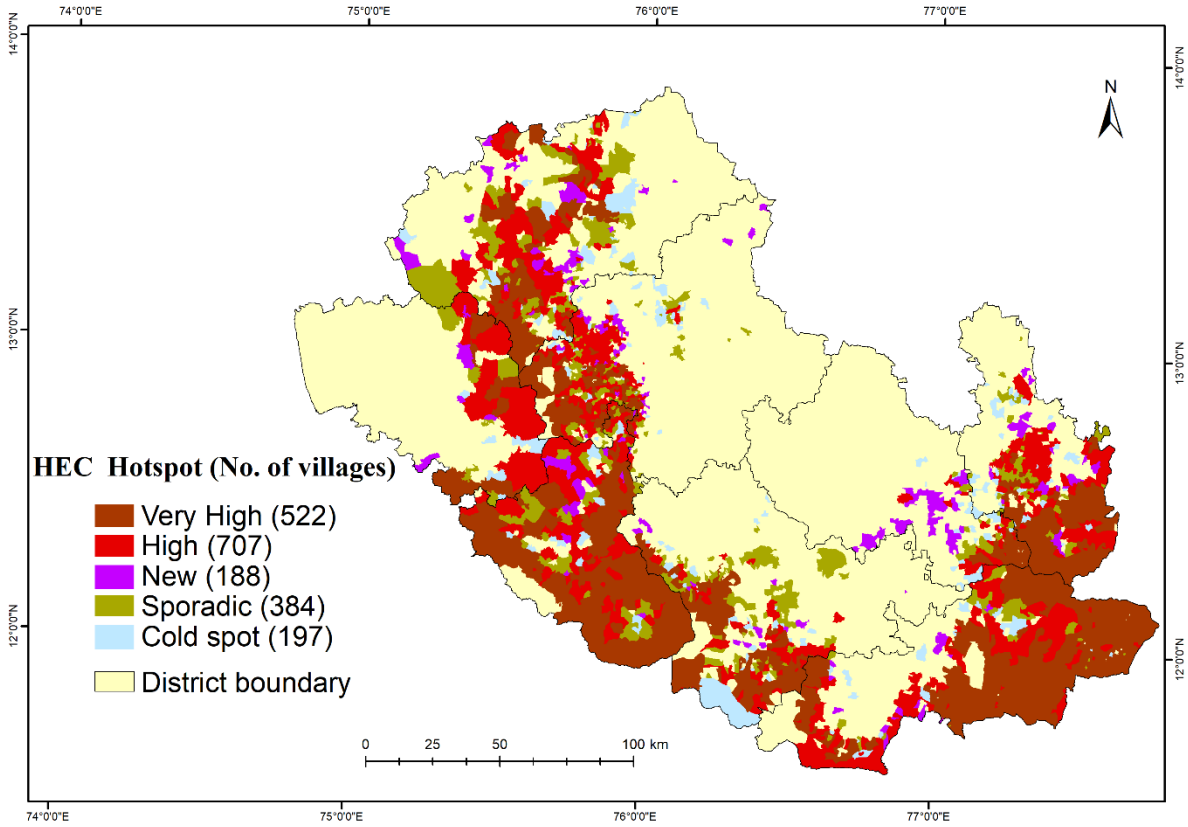


Figure 6: Village-level HEC Hotspots categorised by number of occurrences and compensation value from 2019 to 2023

2023, 2024). There is a clear requirement to have a holistic understanding of HEC, and the threat evaluation of the forest ecosystems is recommended to incorporate remote sensing-derived layers such as deforestation, forest fragmentation, invasive alien plant species, fires, and areas of mono-plantations. Few attempts have been carried out with this approach (Reddy et al., 2014). Sabu et al., (2022) studied satellite-derived forest cover loss and fragmentation in the tiger and elephant ranges of Asia. Most of the wildlife ranges are within biologically rich protected areas (i.e., Wildlife Sanctuaries, National Parks, and Conservation Reserves). Despite its rich biological diversity, there has been an increase in HEC in recent years. There is an urgent need for mapping and monitoring the available natural resources and habitats within protected areas and elephant ranges.

The following approaches will facilitate more suitable habitats for wildlife, including elephants towards HEC mitigation:

Mapping habitat quality and disturbance regimes in the elephant ranges and PAs

a) The elephant ranges in India remain vulnerable to forest loss and habitat fragmentation (Padalia et al., 2019). Mapping habitat quality or integrity and disturbance regimes of the natural forests, mainly in elephant ranges, plays an important role in identifying suitable habitats. Due to large uncertainties over natural forests and managed forests in the country, many studies have recommended using satellite remote sensing technology to discriminate natural forests, mono-plantations, and the extent of IAPS (Reddy et al., 2016a; Pasha et al., 2024; Swarada et al., 2024; Pasha et al., 2014). This study recommends preparing a threat evaluation of forest ecosystems and the net and gross available resources or habitat within the elephant ranges needs to be mapped by integrating geospatial technology and in situ observation for the management of natural habitat integrity in the HEC ranges. b) IAPS have the potential to modify the native species composition and population structure of trees and shrubs, which are critical for elephant habitat and forage. IAPS hotspots within the PAs should be prioritised and monitored using field and Earth observation technologies. Based on the field observations, the most widely colonised invasive alien plant species, mainly *Senna spectabilis, Lantana camara, Chromolaena odorata and Ageratum conyzoides, need to be removed and the sites* restored. Phase-wise eradication of IAPS and restoration with suitable native vegetation will ensure efficient mitigation. c) Space technology should be used in monitoring forest burnt areas in vegetation types and elephant ranges of India. Minimise the dependency of forest fringe communities on forests (e.g., collection of non-timber forest produce (NTFP), cattle grazing, fodder, fuelwood etc.) by participatory forest management. d) Several elephant ranges have large monoculture plantations, which may not be suitable habitats for wildlife (MoEFCC, 2023; Mundoga et al., 2025).

The data strongly suggest that the escalating financial losses due to HEC are primarily a result of increased agricultural and plantation damage, likely driven by the expansion of human settlements into elephant habitats and changes in elephant movement patterns. This increasing trend in damage could be attributed to factors such as



Figure 7: Field photographs showing crop damage by elephants in the study area (2019–2023): (a) *Oryza sativa* (paddy), (b) *Saccharum officinarum* (sugarcane), and (c) *Musa acuminata* (banana) plantations.

habitat fragmentation, reduced food availability for elephants, and increased human activity in conflict zones. Inferences from this trend point to the need for urgent intervention strategies to mitigate the conflict, particularly in agricultural and plantation areas (Mohd Taher et al., 2021). Implementing effective early warning systems, enhancing crop protection measures, and creating wildlife corridors could help reduce the economic impact and improve human–elephant coexistence. As the financial toll of HEC continues to rise, these measures will be crucial for sustainable elephant conservation and the protection of local communities in Karnataka.

A recent study by Swarada et al. (2024) identified 15% of mono-plantations in the Rajiv Gandhi (Nagarhole) Tiger Reserve. This study reveals that these plantations emerged from clearing natural forests during the British colonial period and have not naturalised even after 100 years, compromising the integrity of native forests. Hence, mapping and monitoring mono-plantations, mainly those established before the declaration of protected areas i.e., Teak, Eucalyptus, etc., need to be removed in a phase-wise manner and need to restore native forest integrity. Fine-scale land use land cover (LULC) mapping using high-resolution satellite imagery is recommended for implementing suitable action plans.

e) The conservation status of waterbodies (Wyals or swamps or hadlu) inside PAs needs to be monitored using high-resolution satellite remote sensing datasets to establish their status before, during and after (BDA) treatment. The Geospatial Planning Portal for Geo-MGNREGA (https://bhuvan-app2.nrsc.gov.in) can support the monitoring of these activities, together with elephant movement, corridor mapping and land transformations in and around elephant habitats. f) Abandoned sites, such as plantations, mining sites and houses, need to be restored under suitable action plans. g) Geolocation of the elephant-proof trench (EPT) along with its operational status would help in mitigating measures. h) The KFD initiative (e-Parihara), an Android-based geo-located HEC reporting system, needs to be implemented at the national scale for recording human–wildlife conflicts (HWC), including HEC. The geo-tagged HWC data should be made open source under the National Geospatial Policy (2022) guidelines. This will enhance the wildlife research ecosystem and facilitate advanced mapping, monitoring, and modelling for conflict mitigation measures across the country. i) High-density native tree planting in and around the village hotspots towards HEC mitigation. These activities should be subject to Monitoring, Reporting and Independent Verification (MRV) using multi-temporal and multi-source satellite data.

5. Conclusions

The alarming increase in HEC raises environmental and socio-economic concerns. The precise mapping of HEC high-risk areas or hotspots in the affected areas through geospatial technology is essential for evidence-based conservation strategies. The findings of this research demonstrate a significant increase in HEC cases and associated compensation, highlighting the need for more wildlife space and site-specific management plans. By integrating geo-tagged HEC records with geospatial analysis, this study mapped conflict hotspots at multiple scales, providing an evidence base that in situ records alone cannot offer for monitoring HEC and meeting conservation targets. As geospatial techniques advance, they will enable more accurate, multi-scale detection of HEC and help bridge traditional field monitoring with integrated, data-driven mitigation. The incident and vulnerability Hotspots identified at village scale should be considered when making management decisions. We therefore recommend coupling geospatial hotspot mapping with active community participation to guide

targeted HEC mitigation and to support national conservation goals, the SDGs, and biodiversity targets.

Acknowledgment
The authors are grateful to the Principal Chief Conservator of Forests, Aranya Bhavana, Bengaluru, Karnataka, for providing the e-Parihara data used in this study. We sincerely thank the Department of Studies in Environmental Science, University of Mysore, Manasagangotri, Mysuru, for its support and facilitation of this research. Our gratitude to Prof. Shailesh Nayak, Director, National Institute of Advanced Studies (NIAS), Bengaluru, for his encouragement and support in carrying out the geospatial components of the study. Finally, we extend our heartfelt appreciation to the anonymous reviewers for their constructive comments, valuable suggestions, and insightful feedback, which significantly enhanced the quality, clarity, and scientific rigor of this manuscript. Their time and effort in evaluating our work are deeply appreciated.

References

Dhairykar, M., and K. P. Singh. 2020. "Management of Nutrition in Captive Asian Elephants." *International Journal of Veterinary Science and Animal Husbandry* 5(4):160–163.

Dunkin, R. C., D. Wilson, N. Way, K. Johnson, and T. M. Williams. 2013. "Climate Influences Thermal Balance and Water Use in African and Asian Elephants: Physiology Can Predict Drivers of Elephant Distribution." *Journal of Experimental Biology* 216(15):2939–2952. https://doi.org/10.1242/jeb.080218

Fernando, P. 2020. "Asian Elephants and the Concept of Carrying Capacity." Centre for Conservation and Research, Tissamaharama, Sri Lanka. https://www.ccrsl.org/userobjects/2811_2555_Report-CarryingCapacity.pdf

Government of India. 2024. *Data Portal*. New Delhi: Government of India. https://www.data.gov.in/

Gubbi, S., M. H. Swaminath, H. C. Poornesha, R. Bhat, and R. Raghunath. 2014. "An Elephantine Challenge: Human–Elephant Conflict Distribution in the Largest Asian Elephant Population, Southern India." *Biodiversity and Conservation* 23:633–647. https://doi.org/10.1007/s10531-014-0621-x

Gunawansa, T. D., K. Perera, A. Apan, and N. K. Hettiarachchi. 2024. "Identifying Human Elephant Conflict Hotspots through Satellite Remote Sensing and GIS to Support Conflict Mitigation." *Remote Sensing Applications: Society and Environment* 35:101261. https://doi.org/10.1016/j.rsase.2024.101261

Hossen, A., and E. Røskaft. 2023. "A Case Study on Conflict Intensity between Humans and Elephants in Bangladesh." *Frontiers in Conservation Science* 4:1067045. https://doi.org/10.3389/fcosc.2023.1067045

Forest Survey of India. 2024. *India State of Forest Report 2023, Volume II: Karnataka State Summary*. Dehradun: Ministry of Environment, Forest and Climate Change, Government of India.

India WRIS. 2023. *Karnataka State Profile*. New Delhi: Water Resources Information System, Government of India. https://indiawris.gov.in/wiki/doku.php?id=karnataka

Karnataka Biodiversity Board. 2024. *Flora and Fauna of Karnataka*. Vols. 1–2. Department of Forest, Ecology and Environment, Government of Karnataka. https://kbb.karnataka.gov.in/

Karnataka Evaluation Authority. 2022. *Evaluation Study on Human–Elephant Conflict: Mitigation Methods Employed and Its Impact on Conflict Resolution*. Bengaluru: Government of Karnataka. https://kmea.karnataka.gov.in. Accessed 21 July 2024.

Ministry of Environment, Forest and Climate Change (MoEFCC). 2023. *Guidelines for Human–Elephant Conflict Mitigation (Revised)*. New Delhi: Government of India. https://moef.gov.in/uploads/pdf-uploads/pdf_6808a7bccc3e27.37250543.pdf

Ministry of Environment, Forest and Climate Change. 2024. "Cabinet Approved Continuation of Wildlife Habitat Development Scheme under Integrated Development of Wildlife Habitats." Press Information Bureau, Government of India. https://pib.gov.in/PressReleasePage.aspx?PRID=2057291

Mohd Taher, T., T. Lihan, N. A. Tajul Arifin, N. F. Khodri, M. Ahmad Mustapha, P. Abdul Patah, and S. Mohd Nor. 2021. "Characteristic of Habitat Suitability for the Asian Elephant in the Fragmented Ulu Jelai Forest Reserve, Peninsular Malaysia." *Tropical Ecology* 62(3):347–358. https://doi.org/10.1007/s42965-021-00154-5

Mundoga, T., W. Musakwa, and N. Chanza. 2025. "A Bibliometric Analysis of Wildlife Governance in Relation to African Elephant Conservation and Community Participation." *Environmental Research Communications* 7(2):022001. https://doi.org/10.1088/2515-7620/adb130

National Remote Sensing Centre. 2024. *Bhuvan MGNREGA Grid*. Hyderabad: Indian Space Research Organisation. https://bhuvan-app2.nrsc.gov.in/mgnregagrid/. Accessed 23 July 2024.

Padalia, H., S. Ghosh, C. S. Reddy, S. Nandy, S. Singh, and A. S. Kumar. 2019. "Assessment of Historical Forest Cover Loss and Fragmentation in Asian Elephant Ranges in India." *Environmental Monitoring and Assessment* 191(1):1–13. https://doi.org/10.1007/s10661-019-7696-5

Pasha, S. V., K. V. Satish, C. S. Reddy, and P. V. V. Rao. 2014. "Satellite Image-Based Quantification of Invasion and Patch Dynamics of Mesquite (*Prosopis juliflora*) in Great Rann of Kachchh, Kachchh Biosphere Reserve, Gujarat, India." *Journal of Earth System Science* 123(7):1481–1490. https://doi.org/10.1007/s12040-014-0486-0

Pasha, S. V., K. V. Satish, C. Sudhakar Reddy, and C. S. Jha. 2015. "Massive Invasion of Mesquite (*Prosopis juliflora*) in Wild Ass Wildlife Sanctuary, India." *National Academy Science Letters* 38(3):271–273. https://doi.org/10.1007/s40009-015-0373-2

Pasha, S. V., V. K. Dadhwal, B. Swarada, and G. M. Pavithra. 2024. "Harnessing Geospatial Technology for Human–Elephant Conflict Hotspots: Insights from e-Parihara Data from Karnataka Forest Department." *International Conference on Human Elephant Conflict Management*.

Pavithra, G. M., G. V. Venkataramana, S. V. Pasha, C. S. Reddy, B. Swarada, and V. K. Dadhwal. 2025. "Geospatial Identification of Human–Wildlife Conflict Hotspots in the Southern Western Ghats." *Journal of the Indian Society of Remote Sensing*:1–16. https://doi.org/10.1007/s12524-025-01536-5

Ramachandra, T. V., S. Bharath, and S. Vinay. 2019. "Visualization of Impacts Due to Proposed Developmental Projects in the Ecologically Fragile Regions of Kodagu District, Karnataka." *Progress in Disaster Science* 3:100038. https://doi.org/10.1016/j.pdisas.2019.100038

Ravenelle, J., and P. J. Nyhus. 2017. "Global Patterns and Trends in Human–Wildlife Conflict Compensation." *Conservation Biology* 31(6):1247–1256. https://doi.org/10.1111/cobi.12948

Reddy, C. S., C. S. Jha, P. G. Diwakar, and V. K. Dadhwal. 2014. "Threat Evaluation for Biodiversity Conservation of Forest Ecosystems Using Geospatial Techniques: A Case Study of Odisha, India." *Ecological Engineering* 69:287–303. https://doi.org/10.1016/j.ecoleng.2014.03.014

Reddy, C. S., C. S. Jha, V. K. Dadhwal, and P. G. Diwakar. 2016a. "Assessment and Monitoring of Long-Term Forest Cover Changes (1920–2013) in Western Ghats Biodiversity Hotspot." *Journal of Earth System Science* 125(1):103–114. https://doi.org/10.1007/s12040-015-0645-y

Reddy, C. S., C. S. Jha, V. K. Dadhwal, and P. G. Diwakar. 2016b. "Quantification and Monitoring of Deforestation in India over Eight Decades (1930–2013)." *Biodiversity and Conservation* 25(1):93–116. https://doi.org/10.1007/s10531-015-0983-7

Reddy, C. S., C. S. Jha, and V. K. Dadhwal. 2018a. "Earth Observations Based Conservation Prioritization in Western Ghats, India." *Journal of the Geological Society of India* 92(5):562–567. https://doi.org/10.1007/s12594-018-1068-6

Reddy, C. S., C. S. Jha, and V. K. Dadhwal. 2018b. "Assessment and Monitoring of Deforestation and Forest Fragmentation in South Asia since the 1930s." *Global and Planetary Change* 161:132–148. https://doi.org/10.1016/j.gloplacha.2018.01.003

Sabu, M. M., K. Suresh, K. Ramesh, and K. Vinod. 2022. "The Effectiveness of Tiger Conservation Landscapes in Decreasing Deforestation in South Asia: A Remote Sensing-Based Study." *Spatial Information Research* 29(5):123–135. https://doi.org/10.1007/s41324-021-00404-1

Sharma, A. R., ed. 2022. *Conservation Agriculture in India: A Paradigm Shift for Sustainable Production*. Routledge. https://doi.org/10.4324/9781003292487

Silverman, B. W. 2018. *Density Estimation for Statistics and Data Analysis*. London: Routledge.

Sukumar, R. 2019. "Conflicts between Wildlife and People: An Ecological, Social, and Policy Perspective." *Special Issue on Environment* 167.

Survey of India. 2024. *Online Maps*. Dehradun: Survey of India. https://onlinemaps.surveyofindia.gov.in. Accessed 5 June 2024.

Swarada, B., S. V. Pasha, and V. K. Dadhwal. 2024. "How Natural Are the Forests in Rajiv Gandhi (Nagarhole) Tiger Reserve? A Multi-Source Data Approach." *Environmental Monitoring and Assessment* 196(5):444. https://doi.org/10.1007/s10661-024-10689-2

Thomassen, J., J. Linnell, and K. Skogen. 2011. *Wildlife–Human Interactions: From Conflict to Coexistence in Sustainable Landscapes*. Final Report from a Joint Indo-Norwegian Project 2007–2011. NINA Report 736. Trondheim: Norwegian Institute for Nature Research. https://www.nina.no/archive/nina/pppbasepdf/rapport/2011/736.pdf

Wildlife Institute of India. 2025. *Status of Elephants in India: DNA-Based Synchronous All-India Population Estimation of Elephants (SAIEE 2021–2025)*. Dehradun: Wildlife Institute of India.

Zakaria, N., H. Juahir, S. M. M. Nor, N. H. M. Hanapi, H. H. W. Jusoh, N. Z. M. Afandi, and M. T. Abdullah. 2024. "Elephant Research Challenges and Opportunities: A Global Bibliometric Analysis." *Ecological Informatics* 82:102662. https://doi.org/10.1016/j.ecoinf.2024.102662