



Geospatial Identification of Human–Wildlife Conflict Hotspots in the Southern Western Ghats

G. M. Pavithra¹  · G. V. Venkataramana¹  · S. Vazeed Pasha²  · C. Sudhakar Reddy³  · B. Swarada²  · V. K. Dadhwal² 

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Abstract

It is crucial to understand the spatio-temporal dynamics of human–wildlife conflict (HWC) due to its serious consequences. This study analysed 34,596 unprecedented, geotagged HWC data points from the Southern Western Ghats of Karnataka, collected from 2019 to 2023. The data were categorized into human–elephant conflicts (HEC), human–carnivore conflicts (HCC), and other types. To identify the factors influencing these conflicts, we integrated various geospatial layers, including land use land cover (LULC), tree loss data, digital elevation model (DEM), road network, and settlements. We employed a range of geoprocessing and visualization tools such as spatial grid analysis, clustering, kernel density estimation, optimized hotspots, and spatial interpolation using kriging. Elephants, tigers, leopards, wild boars, and gaurs contributed to 99.6% of incidences, with HEC accounting for 92.1% of incidents and 87.4% of the total compensation. Key impacting factors included a loss of 5741 hectares of tree cover over the past two decades (at a rate of 261 ha/year), road network (53%), elevation between 1000–1500 m (86%), and settlements. Elephants were responsible for all types of damages across all proximities. The spatially explicit HWC field data demonstrated significant advantages over the conventional approaches. The generated HWC clusters and hotspots provide valuable insights for effective HWC management practices. These hotspots are crucial for strategic planning and can be effectively applied to other similar landscapes globally.

Keywords Human–wildlife conflict · Geospatial analysis · Hotspot · Conflict mitigation

✉ G. M. Pavithra
pavithrakesari@gmail.com

✉ G. V. Venkataramana
Gvvenkataraman1970@gmail.com

S. Vazeed Pasha
vazeedpashashaik@gmail.com

C. Sudhakar Reddy
drsudhakarreddy@gmail.com

B. Swarada
swaradabadhe99@gmail.com

V. K. Dadhwal
dadhwalvk@hotmail.com

¹ Department of Studies in Environmental Sciences, University of Mysore, Manasagangotri, Mysore, Karnataka, India 570 006

² School of Natural Science and Engineering, National Institute of Advanced Studies (NIAS), Indian Institute of Science (IISc) Campus, Bengaluru, India 560 012

³ Forest Biodiversity and Ecology Division, National Remote Sensing Centre, Hyderabad, India 500 037

Introduction

Globally, human–wildlife conflict (HWC) is a growing concern, with more than 75% of the world’s rural populations living in proximity to wildlife, leading to increasing interactions and confrontations (Abas et al., 2025). A recent review indicates that HWC affects more than 40% of protected areas worldwide, resulting in thousands of human and wildlife fatalities annually and significant crop and livestock losses (Leslie et al., 2019; Long et al., 2020). HWC incidents likely number in millions per year, though precise counts are unavailable due to inconsistent reporting (Peterson et al., 2010). In rural agricultural regions, conflicts devastate crops, with elephants alone damaging over 500,000 hectares annually in India, causing up to 40% yield losses in affected areas (WWF, 2021). Between 2018 and 2023, India recorded approximately 2950 human fatalities from elephant and tiger attacks, with elephants accounting for 90% (Abas et al., 2025). Economic losses, including crop damage and livestock losses, may reach hundreds of millions

to billions of USD yearly, with India alone estimating \$17 million from elephant conflicts (Sarma & Barpujari, 2025). Developing regions face the heaviest burden, exacerbated by limited mitigation resources (Dickman et al., 2023).

HWC alters wildlife sustainability and human well-being mainly in the affected regions and has become a prevalent challenge (Long et al., 2020). The study of HWC has gained considerable research attention and vitality as it focuses on critical challenges in biodiversity conservation, human safety, and sustainable development (Abas et al., 2025; Woolaston et al., 2021). The most populous country like India would have the most impact. India has a high population of tigers and Asian elephants. In India, the average compensation paid for human mortality in the country is Rs. 1.91 lakhs and the average compensation paid for injury is Rs. 6185 but HWC is not reduced to date (Gulati et al., 2021). Globally, biodiversity hotspots are known for their rich flora and fauna. In India, the Western Ghats are recognised as a global biodiversity hotspot and recognised as an ecologically fragile region. It is home to the largest population of elephants and tigers in India, followed by leopards. Recent past these key biodiversity areas threatened by deforestation, invasive alien plant species (IAPS) and fragmentation. This led to HWC, including HEC and HCC, occurring concurrently over time and space in different biodiversity rich areas (Prasad et al., 1979; Krishnamurthy et al., 2010; Kumara et al., 2014; Madhusudan et al., 2015; Köpke et al., 2021; Gunawansa et al., 2024). Apart from protected areas (PAs), buffer zones, such as forest fringes, which were facing this issue are a major issue in day-to-day life. The local farmers regularly face conflicts in terms of crop damage maximum by large mammals, as well as birds, reptiles, rodents, pests, and insects (Dow & Boydell, 2019).

In the Southern Western Ghats, the traditional approach of relocating problematic animals to new areas was employed to mitigate HWC and alleviate the situation (Woolaston, 2022). There are some successful mitigation strategies that depend on considering both ecological and temporal dynamics (Baldo et al., 2023; Rathnayake et al., 2022). A recent review revealed that 15.4% of HWC studies used livestock-guarding dogs as a mitigation technique, resulting in a significant reduction in animal losses (Ashish et al., 2022; Karanth et al., 2018; Long et al., 2020). Conservation management in these areas restricts activities that may negatively impact the environment, while agroforestry, particularly in coffee-growing regions, is crucial for preserving biodiversity and mitigating negative land-use impacts (Gunawansa et al., 2023; Muthanna & Bawa, 2021; Srinivasan et al., 2020).

Several anthropogenic and natural factors threaten the Western Ghat Biodiversity Hotspot (WGBH). Socio-economic factors contribute significantly to HWC. Habitat destruction, fragmentation, urbanization, and agriculture,

lead to a decline in available wildlife habitats, driving animals closer to human settlements (Gubbi & Kumar, 2014; Kumar & Singh, 2020; Muthanna & Bawa, 2021; Srinivasan et al., 2020). The expansion of agricultural land, particularly monoculture crops, offers food sources that attract wildlife into farming areas, resulting in crop damage and potential conflicts (Brundu et al., 2020). Croplands and plantations, particularly coffee, Teak, and other developmental projects within the wildlife reserve, cause conflicts (Gunawansa et al., 2024; Ramachandra et al., 2022). These monoculture commercial plantations are not suitable habitats for wildlife and potential threat to biodiversity and wildlife (Brundu et al., 2020; MoEFCC, 2017, 2023). According to invasive alien species, pose a potential threat to wildlife habitats. The ongoing land-use changes in the Kodagu-Nagarhole belt are transforming local ecosystems and significantly impacting habitat quality (Joshi, 2023; Joshi et al., 2023). A recent study by Swarada et al. (2024a) reveals landslides also caused significant forest loss in a key protected area. Spatial constraints and the timing of human activities often escalate the likelihood of conflicts (Asaikutti et al., 2022; Karanth et al., 2018).

Treves and Karanth (2003) reported poverty and limited livelihood opportunities can drive communities to exploit wildlife, intensifying conflict. Another reason for HWC is the lack of adequate buffer zones or wildlife corridors (Ashish et al., 2022; Kumar & Singh, 2020). Additionally, compensation schemes, while offering relief, may create dependency and fail to address the root causes of HWC (Inskip & Zimmermann, 2009a). Therefore, socio-economic factors like livelihood dependence, urbanization, and inadequate mitigation measures play a key role in HWC. Seasonal variations and climate change can alter wildlife behaviour, pushing animals out of their normal ranges and into areas inhabited by humans, especially during extreme weather conditions when animals are forced to search for food or shelter (Madhusudan, 2003; Treves & Karanth, 2003). Poaching and illegal hunting also contribute to the disruption of natural wildlife populations, leading to competition for resources and pushing animals into human-dominated areas such as roads (Gaynor et al., 2018). Furthermore, livestock grazing in or near wildlife habitats exacerbates competition for resources like water and grazing land, increasing conflict between humans and wildlife (Gubbi & Kumar, 2014; Inskip & Zimmermann, 2009b). Together, these factors contribute to the complexity of HWC and the need for integrated, context-specific mitigation measures.

There are six elements in all HWC and integrated management are, monitoring, mitigation, response, policy, prevention, understanding, and management (Leslie et al., 2019). The e-Parihara web portal, an initiative by the Karnataka Forest Department, is aimed at reducing the impact of HWC by providing financial compensation to victims'

families, reducing retaliatory killings, and promoting peaceful coexistence. The Sakala Yojana, a flagship program by the Government of Karnataka, ensures time-bound delivery of public services, emphasizing prompt and efficient governance (<https://www.sakala.kar.nic.in/>). The Centre for e-Governance's system allows forest officials to document comprehensive reports, including photographs and details of HWC incidents. These reports are processed through a web interface workflow for claim approvals, facilitating effective communication between officials and affected families (Shah et al., 2022). This initiative provides a dataset with concise, geotagged information, making it more updated, advanced, readable, and reliable. Analysing such data aids in mitigating conflict issues on the ground (<https://eparihara.aranya.gov.in/>).

Literature suggests that understanding ecological patterns is crucial in addressing HWC issues using a spatially explicit approach (Chen et al., 2013; Chrétien et al., 2015; Madhusudan et al., 2015). Several recent studies have demonstrated the value of spatially explicit data and GIS-based tools in analyzing HWC patterns. For instance, Chen et al. (2013) developed a spatially explicit insurance scheme using geotagged conflict data, while Chrétien et al. (2015) used thermal UAV imagery to detect wildlife presence near settlements. Techniques like kernel density estimation, spatial clustering, and interpolation have been successfully applied to identify conflict hotspots and corridors (Gunawansa et al., 2024; Rathnayake et al., 2022). These geospatial methodologies enhance our ability to capture the temporal and spatial distribution of conflicts, offering a scientific foundation for strategic mitigation. The traditional methods do not adequately capture the HWC patterns with time and space due to the lack of continuous and systematic data. In this context, this research aimed at how geospatial technologies can be utilized to address HWC. The present study aims to understand the species-specific intensity of HWC and identify conflict clusters, hotspots, and influencing factor analysis.

Materials and Methods

Study Area

The Southern Western Ghats, a biodiversity hotspot, intersect Karnataka, Kerala, and Tamil Nadu. The total study area covers 5987.57 km², wherein 17,801 km² is a part of Karnataka's Nilgiri Biosphere Reserve, which includes the Kodagu, Mysore, and Hassan districts. The elevation across the study area ranges from approximately 94 m in the valleys to over 1683 m in the hilly zones, influencing both biodiversity and conflict distribution. Key biodiversity sites like Nagarhole Tiger Reserve (Rajiv Gandhi National Park), Brahmagiri Wildlife Sanctuary, and Pushpagiri

Wildlife Sanctuary form vital corridors linking Kudremukh National Park and other reserves, facilitating wildlife movement and genetic exchange. Brahmagiri Sanctuary connects to Kerala's Aralam Sanctuary, separated from Nagarhole by coffee plantations, supporting biodiversity and ecosystem restoration (Jorgensen et al., 1978; Madhusudan & Karanth, 2002). Nagarhole hosts 127 tigers with a density of 11.82 per 100 km² which is under UNESCO World Heritage consideration (<https://wii.gov.in/nagarhole-tiger-reserve>). The study sites represent the following forest ranges H.D. Kote, Hunsur, Madikeri, Metikuppe, Mysore, Nagarhole, Sakaleshpura, Somwarpet, Thithimathi, and Virajpet (Fig. 1).

Methodology

The present research was carried out in these stages: (a) HWC geotagged primary data was collected from the Karnataka Forest Department (KFD) for 2019–2023, (b) attribute and spatial evaluations were performed, (c) conflict hotspots were identified using spatial tools such as spatial cluster analysis, Kernel density, optimized hotspot analysis and spatial Kriging to identify HEC hotspots. Field observations were carried out at selected conflict sites during 2021–2023 to assess wildlife (WL) impact on agriculture, plantations, property, humans and livestock. In the attribute evaluation process, we filtered the data by removing the rejected HWC cases, while the spatial evaluation involved removing non-geotagged or incorrectly located entries from the database. The HWC database was categorized by species, grouping large mammals, carnivores, and others into classes such as HEC, HCC, and others.

The classification of damage types was also conducted to determine the percentage of economic losses associated with crops and livestock. Spatial data was checked and analysed to find patterns over both yearly and quarterly periods. Quality flagging was applied to ensure data accuracy and the correctness of geotagged information. Annual tree loss data (2001–2022) from Global Forest Watch (GFW) was analysed (<https://www.globalforestwatch.org/>). Total tree loss was correlated with HWC incidents at the range level to evaluate vegetation loss impact on human–wildlife interactions. Grid-based spatial and temporal assessments at 1 km² grid cells were conducted to identify conflict zones. Furthermore, we examined statistically significant spatial clusters of hotspots and cold spots based on high and low values. This study utilised the various data sets from various sources the details provided in Table 1.

Kernel density estimation (KDE) was applied to visualize the intensity of HWC incidences by calculating the density of events in a defined neighborhood, using a quadratic kernel function (Silverman, 2018). This technique smooths the distribution of HWC points across the landscape and

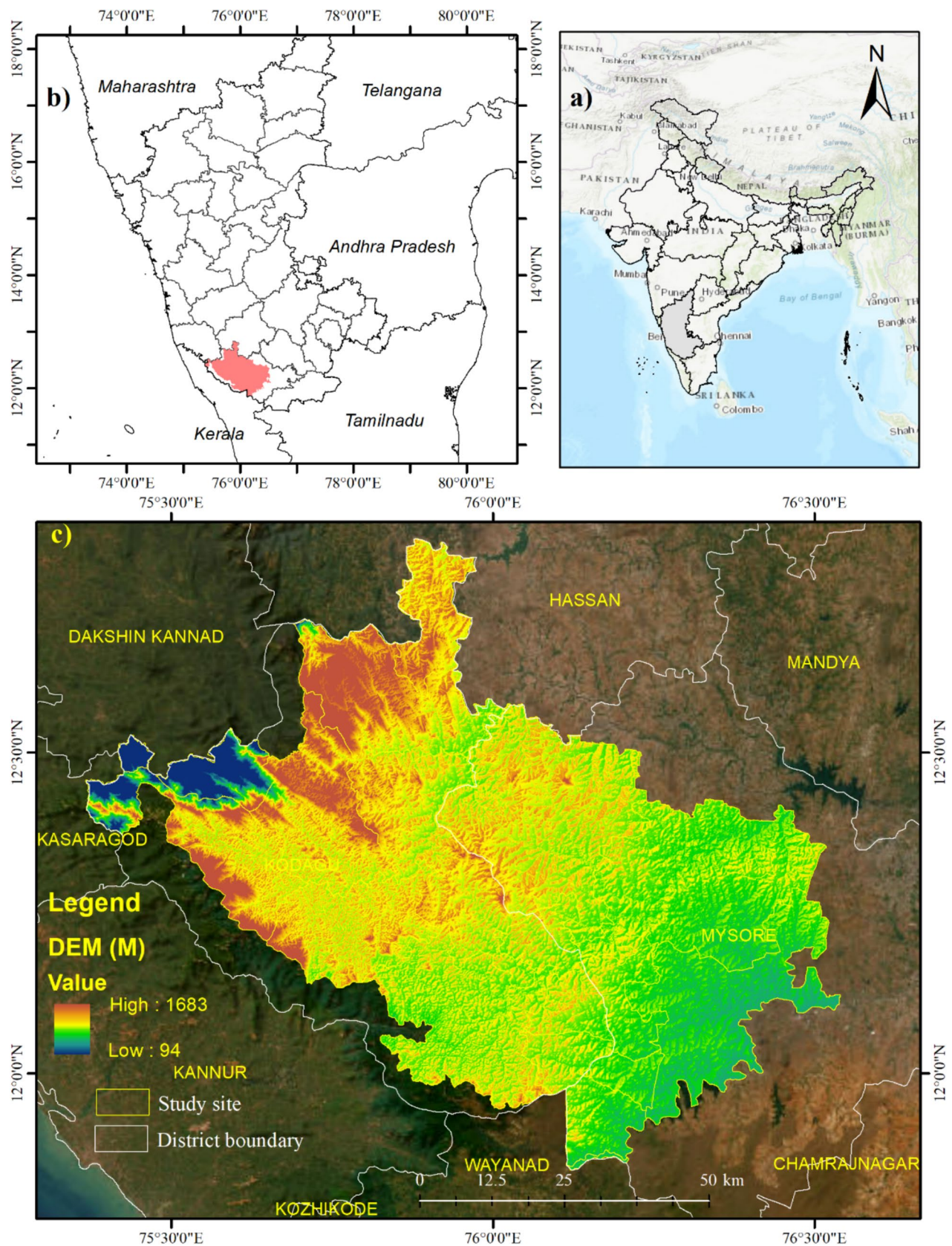


Fig. 1 Study area map showing: **a** India's map with Karnataka marked; **b** Southern Western Ghats; and **c** digital elevation model (30 m) with high-resolution satellite map illustrating the study site

Table 1 Geospatial datasets used in the study

Data type/resolution	Year	Source
HWC incident data (point-based)	2019–2023	https://eparihara.aranya.gov.in/
Land use land cover (LULC) (10 m)	2022	European Space Agency, Sentinel-2A (Copernicus) https://scihub.copernicus.eu/
Tree loss (30 m)	2001–2022	Global Forest Watch https://www.globalforestwatch.org/
Digital elevation model (DEM) (30 m)	2000	SRTM (USGS) https://earthexplorer.usgs.gov/
Road network (shapefile)	2021	OpenStreetMap derived data www.gisenglish.geojamal.com

highlights areas with a higher probability of conflict occurrence. Cluster and outlier analysis and Optimized Hotspot Analysis (Getis-Ord Gi*) were used to identify statistically significant spatial clusters of high and low conflict zones (Getis & Ord, 1992). The Getis-Ord Gi* statistic computes a z-score for each feature, identifying “hotspots” (clusters of high values) and “cold spots” (clusters of low values), providing confidence levels for the spatial significance of each cluster. These tools were implemented in ArcGIS 10.8 and Q-GIS software to generate spatial conflict hotspots and delineate critical areas of human–wildlife interaction.

Influencing Factor Analysis

To understand the influencing factor analysis, HWC data was integrated with various spatial layers: LULC, DEM, road network and settlement. The LULC 2022 year data was derived from Sentinel-2A satellite imagery at 10-m resolution. A hybrid classification technique (digital and visual) was employed to map different LULC classes. Elevation values were extracted from Shuttle Radar Topography Mission (SRTM) DEM (30 m) data to quantify landscape heterogeneity on HWC. Road network data was obtained from (www.gisenglish.geojamal.com) and the impact of roads on HWC was estimated at 100-m and 500-m proximities. A buffer of 100 m, 200 m, and 500 m was generated to identify the influence of human pressure. The overall methodology adopted in the study is depicted in Fig. 2.

Results

This study provides a comprehensive analysis of HWC from 2019 to 2023 in the southern Western Ghats. The study examined 34,596 HWC cases and 17 animal species involved in the conflicts, highlighting the intensity and complexity of incidents. Results indicate a significant rise in HWC cases from 4192 to 11,874 between study periods. The total compensation paid increased from 28.44 million Rs. to 104.11 million Rs. For the study period. The year-wise cases and compensation details are provided in Fig. 3.

Quarterly HWC Trend Analysis

The highest frequency of HWC occurs in the third quarter (Q3) from July to September, accounting for 30.9% of cases and 32.1% of total compensation. The fourth quarter (Q4) from October to December follows with 29.4% of cases and 28.6% of compensation. The first quarter (Q1) from January to March documents 21.3% of cases and 19.4% of compensation, while the second quarter (Q2) from April to June records 18.3% of cases and 19.9% of compensation. When considering the quarterly order based on average cases, Q3 leads with 2745 cases, followed by Q4 with 2388 cases, Q2 with 1625 cases, and Q1 with 1512 cases (Figure S1).

The elephants were responsible for the majority of cases (31,854), accounting for 92.1% of incidents and 87.4% of the total compensation paid (235.86 million Rs.). Whereas, Tigers and leopards were ranked second, with 324 and 1087 cases respectively, resulting in compensations of 15.08 million Rs. and 9.76 million Rs. Other species like wild boars, gaurs, and spotted deer had fewer cases and lower compensation amounts. The total compensation paid for all incidents was 269.78 million Rs. The individual animal-wise conflict and compensation details are presented in Table 2.

Most of the incidents and compensation were found in the Kodagu Circle, amounting to 2697.83 million Rs. (94.81%). The Mysore Circle received 139.60 million Rs. (5.17%) of the total, while the Hassan circle had the lowest compensation in the southern Western Ghats. Two ranges, Ponnampet and H.D Kote, contributed 45.45% of the compensation (Table 2). Of the total 10 ranges listed, which account for 93.92% of the cases and 92.49% of the total compensation, the top six ranges contributed to a significant loss of 82% (3931.8 ha). These same six ranges also accounted for 81.60% of the damages, with 26,518 cases out of the total 32,496 cases (Table 3).

The study revealed significant results regarding human–wildlife conflict (HWC) incidents and the associated compensation. The highest number of cases involved horticulture, floriculture, and plantations, with 21,890 incidents resulting in a total compensation of 154.18 million Rs. Crops were also heavily impacted, with 7406 cases and a compensation of 42.68 million Rs. Human

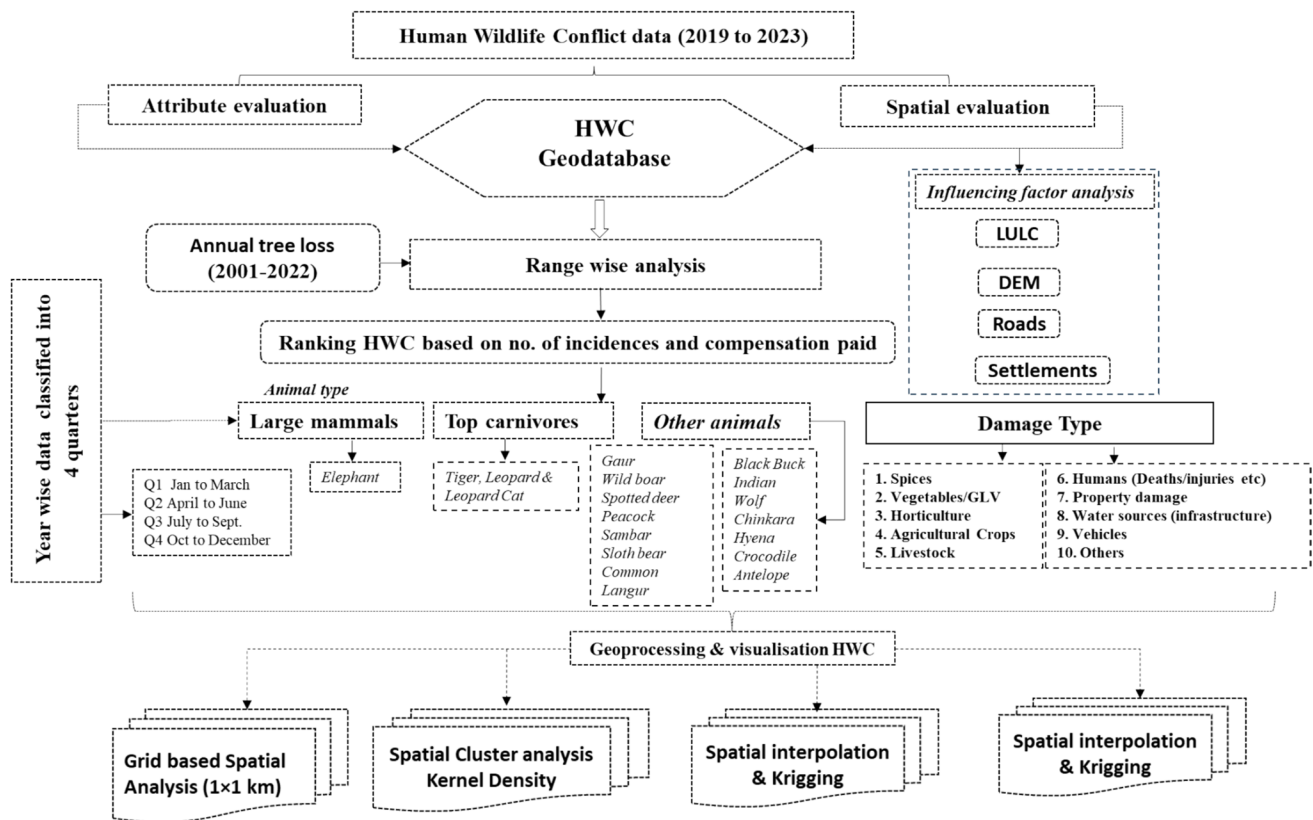
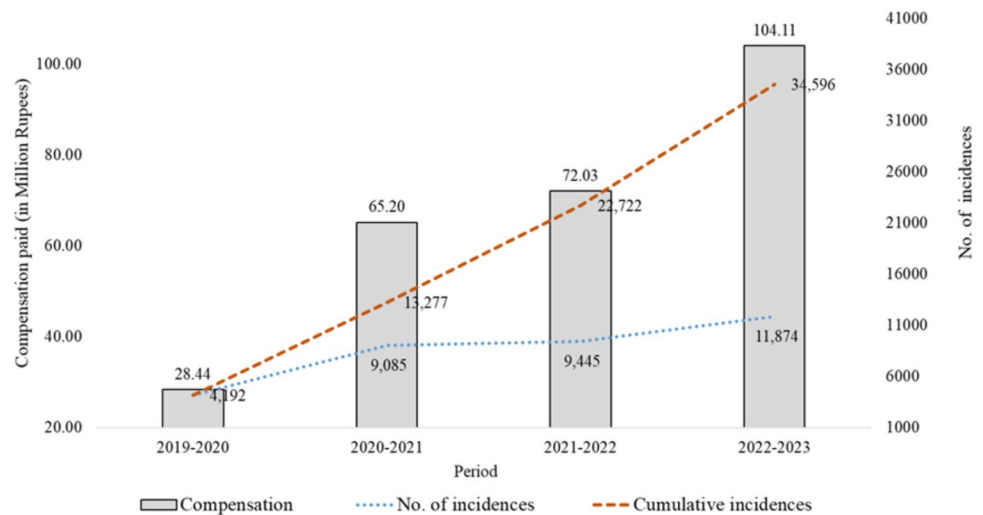


Fig. 2 The flow chart depicts the overall methodology used in the study

Fig. 3 Increase in HWC incidents and compensation from 2019 to 2023



deaths and injuries, though fewer in number (91 cases), accounted for a substantial compensation of 28.02 million Rs.

Livestock losses were significant, with 1424 cases leading to a compensation of 17.03 million Rs. The study also highlighted the impact on spices, with 1536 cases and a compensation of 11.63 million Rs. Water sources and property damage were other notable categories, with 580 and

506 cases respectively, resulting in compensations of 5.23 million Rs. and 3.94 million Rs.

Other categories, including vegetables, vehicles, and miscellaneous damages, also contributed to the overall conflict scenario. Vegetables were affected in 499 cases, with a compensation of 2.91 million Rs., while vehicle damages were reported in 78 cases, leading to a compensation of 0.8 million Rs. (Fig. 6 and Table 4).

Table 2 HWC incidences number of cases and the Compensation paid details

Animal involved (scientific name)	No. of cases	Compensation (million Rs.)	No. of cases (%)	Amount (in %)
Elephant (<i>Elephas maximus</i>)	31,854	235.86	92.1	87.4
Tiger (<i>Panthera tigris</i>)	324	15.08	0.9	5.6
Leopard (<i>Panthera pardus</i>)	1087	9.76	3.1	3.6
Wild Boar (<i>Sus scrofa</i>)	983	6.38	2.8	2.4
Gaur (<i>Bos gaurus</i>)	211	1.89	0.6	0.7
Spotted Deer (<i>Axis axis</i>)	54	0.32	0.2	0.1
Peacock (<i>Pavo cristatus</i>)	29	0.1	0.1	0
Sambar (<i>Rusa unicolor</i>)	11	0.08	0	0
Sloth Bear (<i>Melursus ursinus</i>)	10	0.07	0	0
Common Langur (<i>Semnopithecus entellus</i>)	9	0.07	0	0
Leopard Cat (<i>Prionailurus bengalensis</i>)	6	0.05	0	0
Black Buck (<i>Antelope cervicapra</i>)	4	0.03	0	0
Chinkara (<i>Gazella bennettii</i>)	4	0.03	0	0
Indian Wolf (<i>Canis lupus pallipes</i>)	4	0.02	0	0
Hyena (<i>Hyaena hyaena</i>)	3	0.02	0	0
Crocodile (<i>Crocodylus</i> spp.)	1	0.01	0	0
Four-horned Antelope (<i>Tetracerus quadricornis</i>)	2	0.01	0	0
Grand total	34,596	269.78		

Table 3 Range-wise magnitude of tree loss area and HWC severity

Ranges	Tree loss in ha (2001–2022)	No. of cases (2019–23)	Amount in mil. Rs	Amount in %
Ponnampet	817.60	9618	78.05	31.28
H.D Kote	119.60	4681	35.35	14.17
Thithimathi	272.10	2374	26.31	10.54
Kushalnagar	476.30	2837	22.93	9.19
Virajpet	506.00	4412	22.75	9.12
Somavarpet	535.70	2596	16.85	6.75
Bhagamandala	391.80	2209	15.84	6.35
Hunsur	65.30	1070	11.48	4.60
Madikeri	1116.20	1386	10.89	4.36
Shanivarasanthe	470	1313	9.07	3.64
Total	4770.60	32,496	249.51	

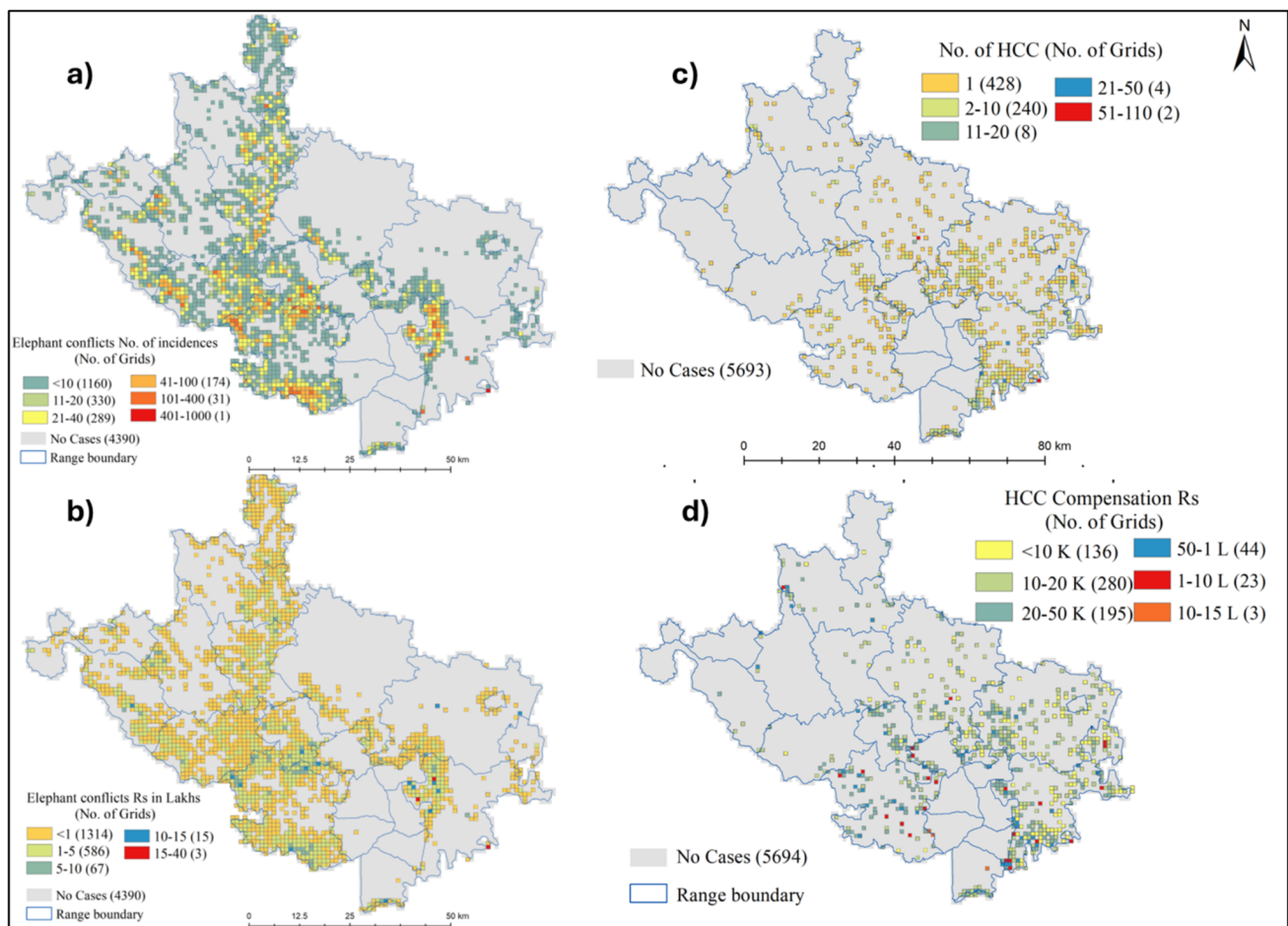
Gridwise Spatial Tracking of HWC Conflicts

Of the total grids, 1985 grids were identified as HEC, and 682 grids were classified as HCC based on the number of cases. The spatial analysis of HEC grids reveals the severity of the conflict. Incidents are categorized into six classes, with the class < 10 having the most incidents, followed by the 11–20 class with 330 incidents. The grid with the highest conflict intensity was found in the H.D. Kote range, which falls into the 401–1000 incidents class. The compensation trends corroborate these findings. Grids with high compensation amounts ranging from 10 to 15 lakhs included 15 grids, and 3 grids fell into the 15–40 lakhs class.

The HCC results show that most cases were found in grids with one incident, followed by grids with 2–10 incidents, accounting for 428 and 240 cases, respectively. Six grids accounted for the majority of the cases, with four grids in the 21–50 cases class and two grids in the 51–110 cases class. In the compensation paid class, the 0.01–0.02 million Rs. grids accounted for 280 grids, followed by the 0.02–0.05 million Rs. grids class with 195 grids. Twenty-three grids were identified in the 0.1–1 million Rs. compensation paid class. The three grids with the highest compensation fell into the 1–1.5 million Rs. compensation class. Figure 4 depicts the total incidents and compensation intensities geo-visualized on a 1 km² spatial grid.

Table 4 Statistical comparison between conflict and damage type

Conflict type	HEC		HCC		Other WL		Total	
Damage type	No. of cases	Amount (million Rs.)	No. of cases	Amount (million Rs.)	No. of cases	Amount (million Rs.)	No. of cases	Total amount (million. Rs.)
Horticulture, floriculture, and plantations	21,890	152.38	3	0.02	287	1.78	22,180	154.18
Agri. crops	6507	38.25	3	0.02	896	4.41	7406	42.68
Humans (death/injuries)	59	17.86	13	8.12	19	2.04	91	28.02
Livestock	22	0.31	1395	16.65	7	0.07	1424	17.03
Spices	1443	11.14	–	–	93	0.49	1536	11.63
Water sources	580	5.23	–	–	–	–	580	5.23
Property damage	506	3.94	–	–	–	–	506	3.94
Others	275	3.08	3	0.08	18	0.19	296	3.35
Vegetables	494	2.87	–	–	5	0.04	499	2.91
Vehicles	78	0.8	–	–	–	–	78	0.8
Total	31,854	235.86	1417	24.89	1325	9.03	34,596	269.78

**Fig. 4** Spatial grid map showing: **a** spatial distribution of occurrences and compensation paid between 2019–2023 for HEC, and **b** HCC

Identifying Spatial Clusters and Hotspots

The spatial cluster analysis and optimized hotspot analysis indicated the different magnitudes of HWC. The major conflict clusters identified in the four forest ranges namely, Ponnampet, Virajpet, H.D Kote and Thithimathi. The various types of clusters and hotspots (high values), and cold spots (low values) are depicted in the Fig. 5.

The number of incidents varied widely ranging from as few as 1 to as many as 212. Similarly, the compensation paid also showed a broad range from 1288 thousand Rs to 16.24 lakh Rs. The spatial interpolated HEC map shows the

high-intensity conflict hotspots in are Ponnampet, Thithimathi and Virajpet ranges (Fig. 6). These areas experienced a higher frequency of incidents indicating a significant level of HEC. In contrast, the Hunsur and HD Kote ranges were identified as large hotspots suggesting a broader but less intense conflict area. Interestingly, Ponnampet showed a random distribution of hotspots implying a heterogenous pattern of HEC in this area. Various influencing factors were identified by integrating LULC, tree cover loss, elevation, roads, and settlements. LULC analysis indicated 46.4% HWC found in managed forests (plantations and Orchards) followed by forest (26.8%) and agricultural land (23.8%).

Fig. 5 Spatial clusters of HWC from **a** kernel density and **b** optimized hotspot analysis

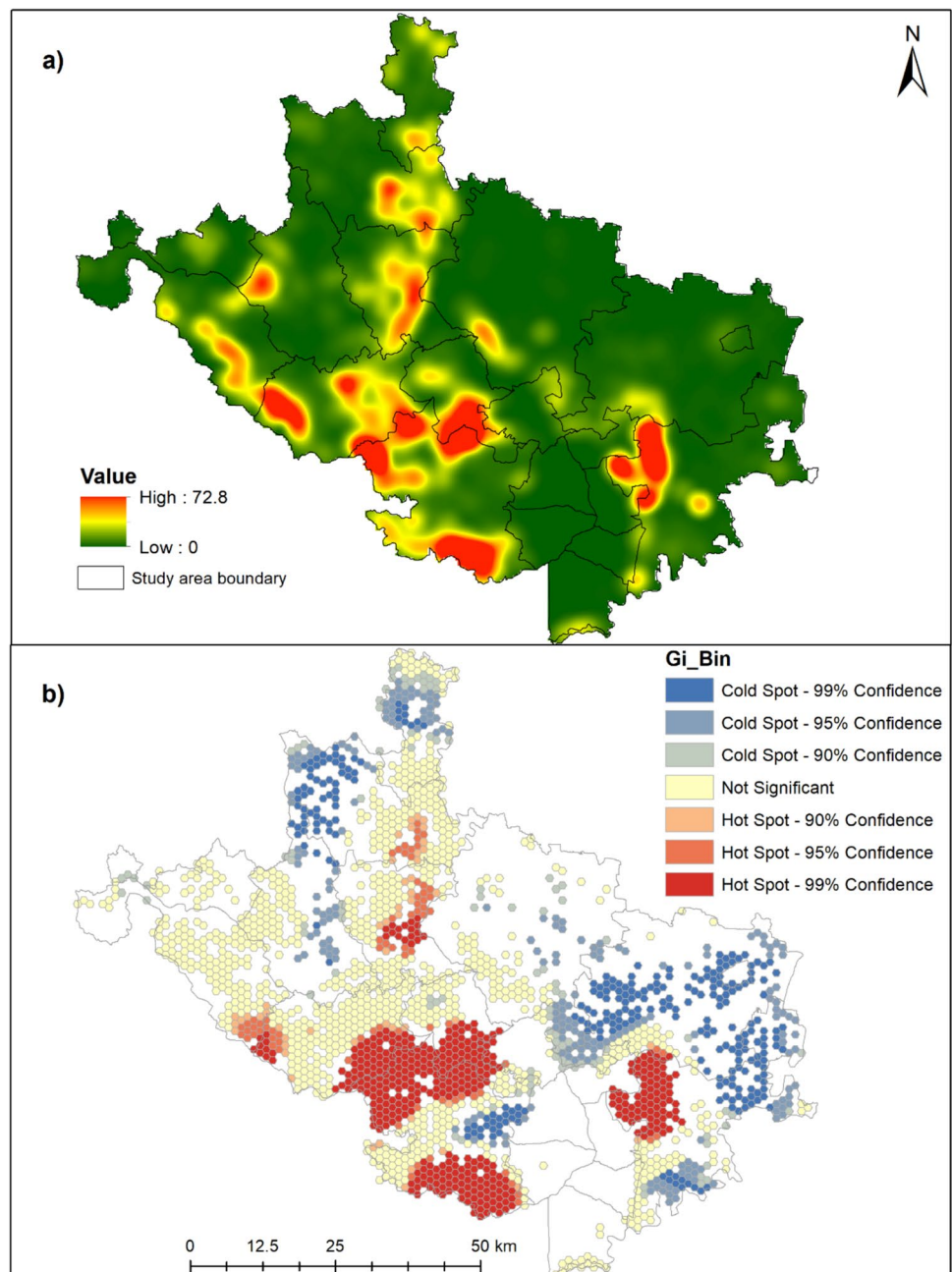


Fig. 6 Spatial interpolated HEC hotspots of by kriging **a** incidences and **b** compensation

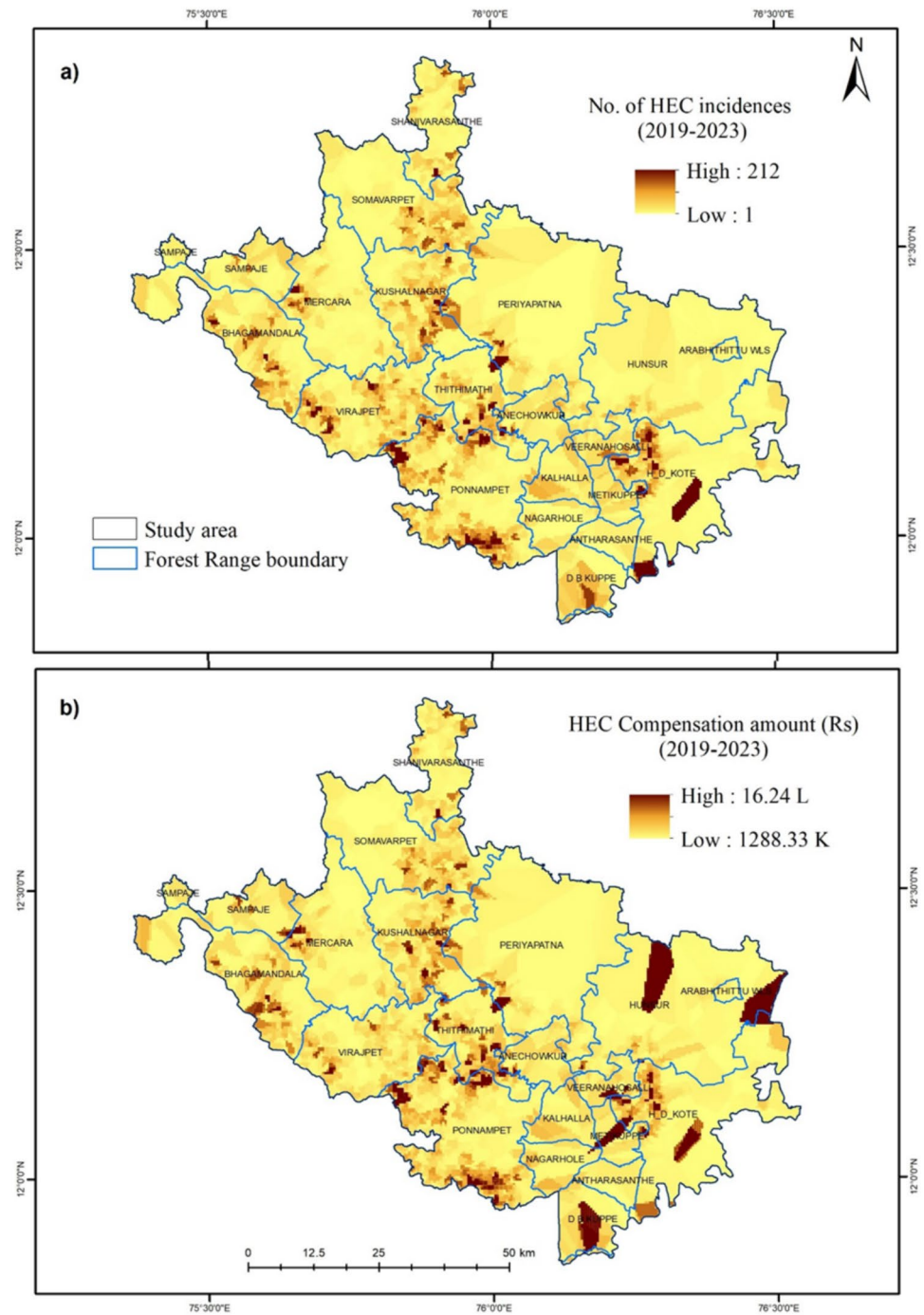


Figure 7 shows the different LULC distributions across the study area.

Analysing Two Decades of Tree Loss (2001–2022)

Geospatial analysis from 2001 to 2022 revealed a total tree loss of 5741 hectares, with an average annual loss of 261 hectares. The lowest loss occurred in 2002, while

2018 experienced the highest, averaging 372 hectares annually. Tree loss increased from 41.61% in 2001–2012 to 58.39% in the following decade, reflecting a 16.78% rise and a loss of 963.49 hectares. The most significant tree loss, averaging 372 hectares annually, occurred between 2002 and 2018. Figure 8 illustrates the annual tree loss over two decades (2001–2022), highlighting anthropogenic pressure.

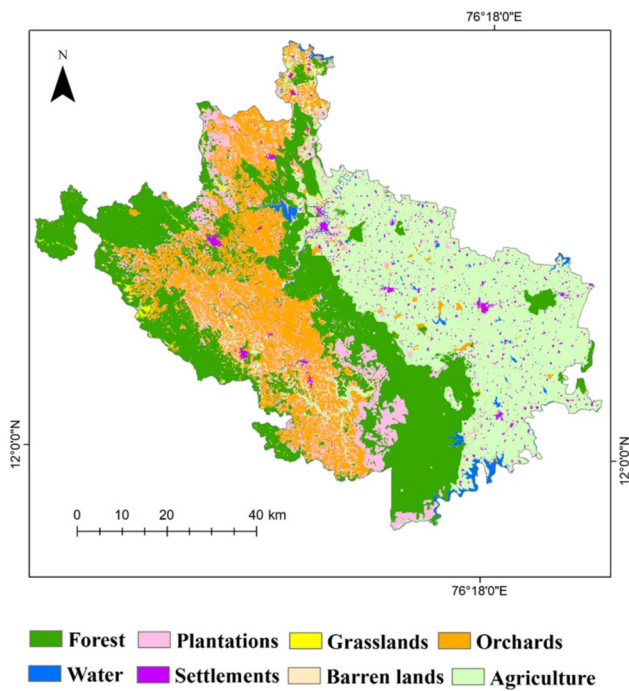


Fig. 7 Map representing Land use land cover (LULC) distribution across the study area

Influence of Settlements, Roads and Elevation

A sum of 5,221 conflicts have occurred in different settlement proximities, with 17% within 100 m, 15.4% within 200 m, and 66.69% within 500 m of settlements. The HEC cases exponentially increased in all the proximities whereas HCC dominated in the 100 m proximity. About 85% of conflicts are caused due to elephants within all proximities. Within these proximities, crop damage accounts for 56.3%, mainly due to wild boars and elephants. The distribution of conflicts within defined proximities from settlements is depicted in Fig. 9.

Fig. 8 Graph showing the annual tree loss in the study from 2001 to 2022



The HWC was significantly affected by roads, with 28.67% within 100 m and 71.32% within 500 m. Elephants are the primary contributors to conflicts. Crop damage is predominantly caused by elephants (97.8%), with gaurs accounting for 1.45% of cases. The data suggests that road networks disrupt wildlife movement patterns, exacerbating crop depredation due to increased accessibility of cultivated food sources along these corridors. Elevation also contributed to the most human–wildlife conflict (HWC) incidents within the 750–1000 m elevation range, primarily driven by elephants (86%), indicating their habitat preferences. Carnivore-related conflicts (39.7%) are more prevalent at lower elevations (500–750 m), closer to forest edges and human settlements.

Discussion

This study demonstrates the potential of spatially explicit HWC data in capturing spatial and temporal clusters and hotspots. There is a significant increase in both the incidences and compensation claims, highlighting the extensive impact of these conflicts on various sectors. According to the statistics about 22 wild animals were involved in conflicts, wherein 17 animals were attributed to various conflicts (Tables 1 and 3). Between 2019–2021 there were lower HWC incidents, which is mainly due to reduced human activity during COVID-19 (Chakma, 2020; Modak et al., 2020; Siche, 2020). Among these, five species namely Elephant, Tiger, Leopard, Wild Boar, and Gaur contributed to 99.6% of HWC cases as well as 99.7% of the total compensation claims. A notable concentration of HWC was identified in specific quarters mainly Q3 July–September and Q4 October-to-December (Figure S1) indicating the severity of the damages. There are numerous reasons for the HWC, mono-plantations plantations are not a suitable habitat for wildlife, particularly elephants, and pose challenges highlighting the need for ecologically viable HEC mitigation (MoEFCC,

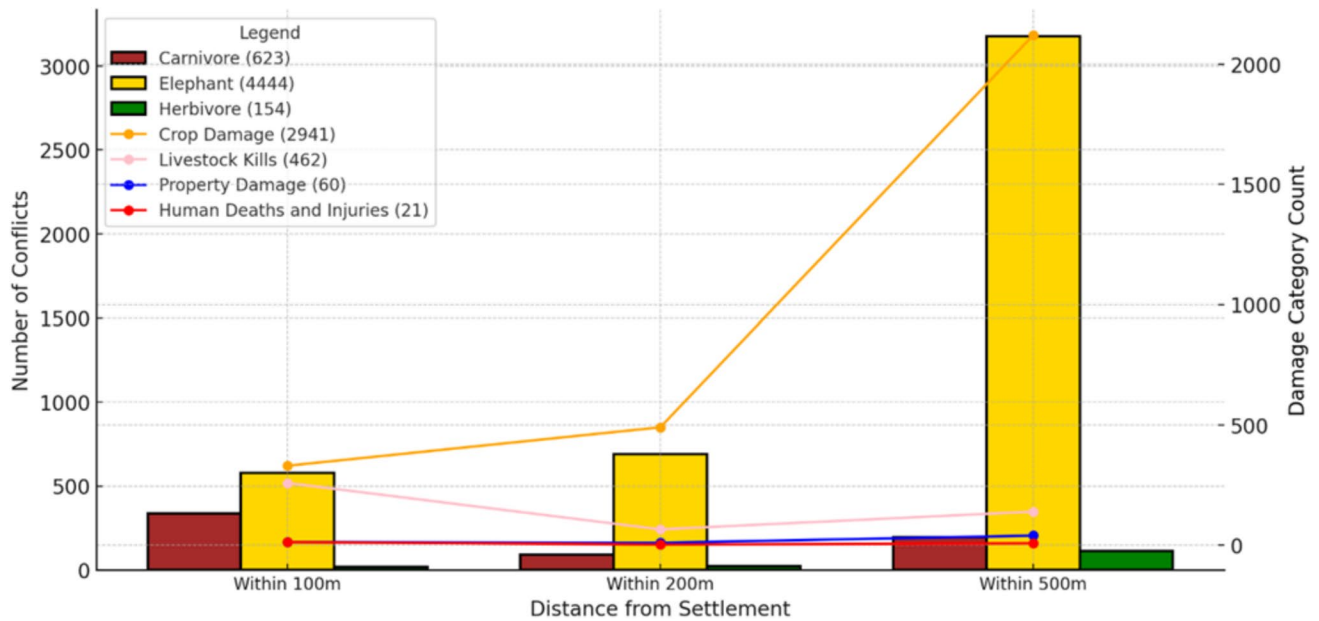


Fig. 9 Conflict distribution in different proximities of settlement by animal group and damage category

2017, 2023). Studies indicate the colonial period establishment of mono-plantations in the study region (Ramachandra et al., 2022; Swarada et al., 2024b). This study demonstrates that HWC occurred mainly in agriculture, plantations, and orchards. Influencing factor analysis revealed the HWC distribution across the elevation zones, proximities to roads and settlements (Figs. 9 and 10). The Majority of HCC occurred near settlements whereas, HEC was found in the agricultural lands. These findings highlight the profound impact of

elephants on agricultural productivity, infrastructure, and human safety, necessitating robust mitigation strategies in high-risk LULC zones.

HEC emerged as a major issue of conservation, socio-economic and environmental protection (Gunawansa et al., 2023b). In the context of increasing human footprint, the role of settlement and road infrastructure promotes the HEC (Gaynor et al., 2018). The present study site is home to 1400–1700 large mammals, hence, it is critical to understand

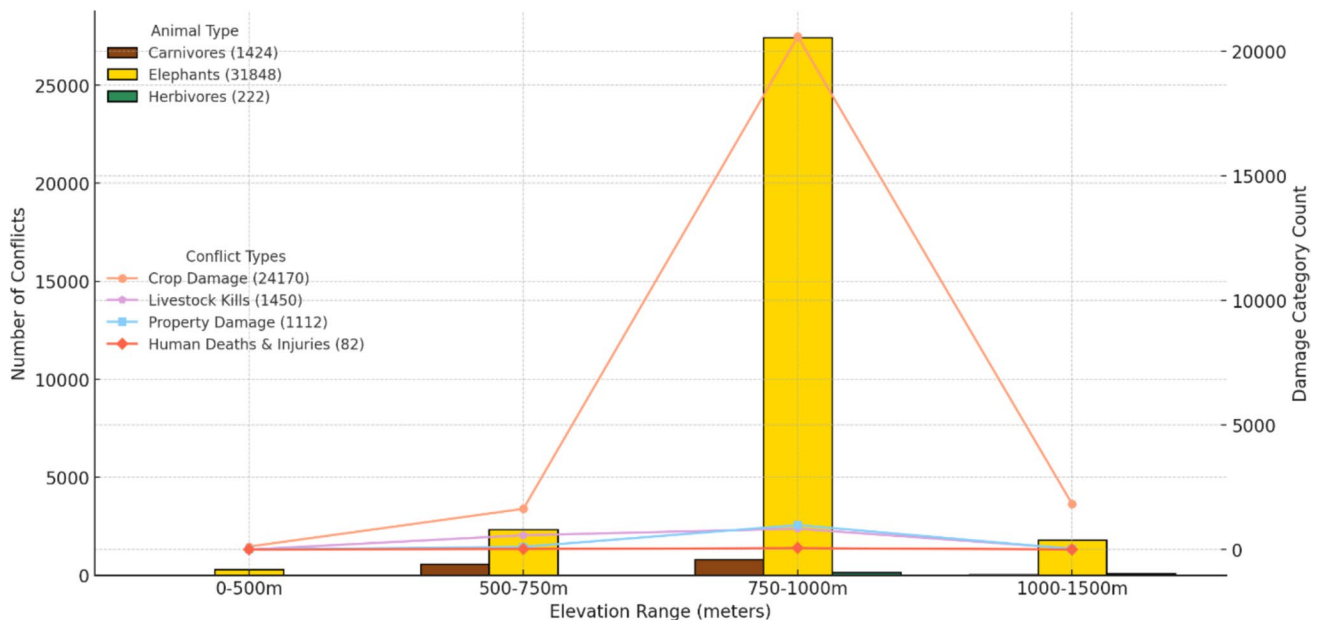


Fig. 10 Conflict distribution in different elevations by animal type and damage Category

the spatial and temporal hotspots of HEC as it causes maximum damage. Field observations identified parts of Ponnampet and H.D. Kote ranges are under conflict hotspots, followed by Thithimathi, Kushalnagar, and Virajpet (Figs. 6, 9 and 10). The present study reveals that elephants are the major contributor to all types of conflicts and are attributed to 92.1% of incidents and 87.4% of the total compensation. Spatial grid analysis showed the distribution of (a) HEC and HCC incidents and compensation (2019–2023). According to the Karnataka Forest Department (2023) report Virajpet and Madikeri are classified as high risk, followed by Virajpet, Mysuru, Nagarahole, and Madikeri (WL), and Hunsur at moderate and low risk categories. Transboundary elephant movement across Bhutan, Nepal, and Bangladesh complicates the HEC administration (MoEFCC, 2023). Underreported incidents may lead to poor management at various scales (Chen et al., 2013; Rathnayake et al., 2022).

Human–carnivore conflict (HCC) is a major cause of livestock depredation, with tigers causing significant damage, including livestock and human casualties, across five divisions. Leopards were involved in 1,087 incidents, mainly involving goats, calves, cows, oxen, sheep, and humans. A leopard cat was involved in a few incidents with livestock. Wild boars accounted for 70% of incidents and 94.5% of compensation, while gaur and spotted deer contributed to 21% and 3.5% of cases, respectively. Secondary herbivores, comprising 13 species, contributed minimally to incidents and compensation. Human population growth exacerbates conflicts, especially in rural areas of Hassan, Kodagu, and Mysore districts. Urbanization is increasing in these regions, with varying rates, further impacting the dynamics of human–wildlife interactions (<https://censusindia.gov.in/census>). Habitat disturbance severely impacts wildlife, and this study highlights a rising trend in tree loss, coupled with increasing incidents, and compensation (Fig. 7) this will pose a threat to HWC. In the Western Ghats, despite its ecological significance, tree loss increases HWC risks (Baldo et al., 2023), with habitat changes rising temperatures and enhancing heat retention increasing further conflicts (Richter et al., 2022). A study by Baldo et al. (2023) showed substantial damage due to elephants, and an estimated 600 human and 100 elephant fatalities, adversely affecting agricultural land and farmers. However, field observation revealed elephant mortality by human activities, such as electrocution, road accidents, poaching, and train collisions, significantly impact the decline of elephant populations (La Grange et al., 2022; Palei et al., 2014; <https://aranya.gov.in/aranyacms>). Habitat changes further exacerbate health risks, including Elephant Endotheliotropic Herpesvirus (EEHV) (Kochagul et al., 2018; Noronha et al., 2021; Williams et al., 2001). Studies suggest cost-effective mitigation measures such as elephant-proof trenches (EPTs) and solar-powered deterrents (Asaikutti et al., 2022; Lenin & Sukumar, 2008). Another

study reveals that conflicts are more frequent in mosaic forests near agriculture than in dense forests (Irwin, 2021). The generated hotspots are found in the mosaic landscapes of the study area which are mainly covered with natural forests, mono and mixed plantations and agricultural land (Fig. 7).

Hence, technological advancements, including camera traps, UAVs, and acoustic monitoring, aid in wildlife detection and conflict prediction (Chrétien et al., 2015). GPS tracking and remote sensing provide habitat insights, supporting targeted interventions (Sukumar, 1992). Laser-integrated fencing and YOLO CNN algorithms improve real-time detection and conflict management (Leonid et al., 2023; Meenakshi et al., 2022). The present study area encompasses the Nagarhole tiger reserve, which is part of three significant Tiger Corridors (TC 22–24) (ISFR, 2021), highlighting the need for conflict mitigation strategies. Engaging local communities and mapping conflict zones using seasonal and location-specific data is essential for prevention (Bennett, 2016).

Conclusion

The present study demonstrates that integrating in-situ geolocated HWC data with geospatial layers significantly enhances the understanding of HWC hotspots and clusters, revealing a rise in incidents as well as compensation claims. To mitigate these challenges, we recommend the expansion of protected areas based on wildlife density, the removal of invasive plant species, and empowering indigenous communities through traditional knowledge along with advanced management. However, this study's limitation includes the exclusion of socio-economic drivers and species behavior due to data constraints. Future research should incorporate participatory surveys, behavioral ecology, camera trap data, and telemetry to refine species-specific risk assessments and strengthen evidence-based conflict mitigation planning.

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Declarations

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