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Assessment and prediction of human-elephant conflict hotspots in the human-dominated area of Rajaji-Corbett landscape, Uttarakhand, India

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ABSTRACT

Understanding the dynamics that drive human-wildlife conflict and identifying potential mitigation solutions requires understanding the spatial patterns of conflict. The juxtaposition of ecological preservation and economic growth has led to increased conflicts between humans and Asian elephants *Elephas maximus* in the Rajaji-Corbett landscape of Uttarakhand, India, where the conversion of elephant habitat to agricultural land have increased over the last several decades. We investigated the predictors influencing household-level human-elephant conflicts (HECs) using binomial Generalized Linear Models (GLMs) collected from semi-structured questionnaire-based surveys of 266 households in the human-wildlife interface next to protected areas. Further, we modelled the landscape predictors that influence the spatial distribution of HECs by collecting occurrence data of HECs in 25 km^2 grid units (N = 1473 grids) using Maxent software. We discovered that HECs are directly influenced by the diversity of major and minor crops planted and the proximity to agricultural land (conflicts decreased with increasing distance from the agricultural land). We also observed that the probability of HECs decreased with increasing elevation, increase in road networks, and with increasing slope in the study area; while HECs increased with increase in human population. We discovered that nearly one-fifth of areas sampled (3606.87 km^2) in the Rajaji-Corbett landscape were at high risk of HEC, especially flat, agrarian areas where most people reside. Farmers in the susceptible risk areas identified by our study could lessen the likelihood of crop damage and HEC incidents by cultivating highly profitable alternative crops that are less attractive to elephants. Additionally, implementing mobile-based Early Warning System in high HEC hotspot areas could mitigate crop raiding and potentially reduce the occurrence of HECs. The findings of our study can assist policymakers and park management in designing landscape-scale human-wildlife conflict mitigation strategies tailored to identified conflict hotspots.

1. Introduction

Recent growth of human settlements and agricultural activities throughout Asia has led to the extensive depletion of elephant habitats, degradation of their food sources, diminished landscape connectivity, and a significant decline in elephant populations (Calabrese et al., 2017), Consequently, it influences the conflict between human and elephants (Gubbi, 2012). The conflicts make elephants potentially vulnerable to the effects of habitat deterioration (Gubbi, 2012; Tilman, Clark, & Williams, 2017) outside of Protected Areas (hereafter PAs; particularly along the edges). In the past decade, human-elephant conflict (hereafter HEC) has emerged as a significant challenge in numerous Asian countries (Gross et al., 2021; Hu, Zhang, Du, & Xie, 2021; Shaffer, Khadka, Van Den Hoek, & Naithani, 2019; Thant, May, & Røskaft, 2021). These conflicts have resulted in economic losses (Jiang, Yang, & Isukapalli, 2021), and injury and death among both humans and elephants (Gross et al., 2021; Gubbi, 2012; Hu et al., 2021). Given that human development is often juxtaposed and encroaches upon elephant habitat (Shaffer et al., 2019), HECs are a critical concern for ensuring elephant survival and persistence in countries within their native range.

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It is therefore important to gain a deeper understanding of how dynamic land-use changes at these interfaces, as well as an integrated management approach both inside and outside PAs, are crucial to elephant conservation in landscapes where HECs are prevalent.

Despite numerous research efforts on the status, distribution, and habitat use of elephants in India, as well as the conflicts they cause with people (Sukumar, 1989; Ramesh Kumar, 1994; Baskaran, 1998; Sankar et al., 2001, 2015; Choudhury, 2004; Ramesh, Kalle, Sankar, & Qureshi, 2012a; 2012b; Goswami, Medhi, Nichols, & Oli, 2015; Sukumar & Pani, 2016), critical knowledge gaps persist regarding the socio-ecological drivers of HECs in areas of human-wildlife interface. Previous research suggested that the key drivers of HEC include land use/land cover change, such as changes in natural vegetation, landscape modification, intensification of farming, and urbanization (Lambin et al., 2001), and seasonal food availability inside or on the proximity of the PAs (Sukumar, 1989; Ramesh Kumar, 1994). Other drivers also emerge from elephant habitat degradation in the form of cattle-grazing by humans, competing for resources such as water, infringement from woodcutting and bamboo exploitation, local community collection of Non-Timber Forest Products (NTFPs), and an increase in linear infrastructures (e.g., roads and railways) resulting in more frequent incidents of conflict (Sukumar, 2003; Johnsingh, Raghunath, Pillay, & Madhusudan, 2010; Ramesh, Kalle, Sankar, & Qureshi, 2012a; Sukumar & Pani, 2016).

The Rajaji-Corbett landscape in the Terai region of Uttarakhand is home to two prominent Indian national parks: Rajaji Tiger Reserve (hereafter RTR; 1075 km^2; Upadhyay et al., 2019) and Corbett Tiger Reserve (hereafter CTR; 1288.32 km^2; Shalini & Pant, 2023). RTR is located in the westernmost region, and CTR is the geographic centre of the landscape (Semwal, 2005). The most endangered animals in the Rajaji-Corbett landscape include the Asian elephants that reside alongside a large number of humans (Johnsingh, Ramesh, Qureshi, David, Goyal, Rawat, & Rajapandian, 2004). Some of the challenges to elephant movement in the landscape include deforestation and infrastructure developments (Maria, 2014) that influence their distribution, and thereby influence the spatial patterns of HECs (Billah, Rahman, Abedin, & Akter, 2021). The frequent conflicts are a cause of concern, and understanding the HEC's ecological and socioeconomic context is required to achieve the effective and long-term conservation of Asian elephants and their habitats in this area (van Schaik & Rijksen, 2002).

Despite conservation efforts for Asian elephants in the Rajaji-Corbett region, including HEC assessments (Maria, 2014; Singh & Sharma, 2001), the effects of natural and anthropogenic parameters have rarely been connected to the detailed elephant spatial movement patterns that cause HEC in the Rajaji-Corbett landscape. As a generalist megaherbivore, elephants consume a maximum of 150 kg of forage and 190 L of water daily (Vancuylenberg, 1977; Sukumar, 2003). Thus, a large foraging area is required to provide these fundamental needs, which include a variety of grasses, shrubs, tree leaves, roots, and fruits. In this paper, we first identified the drivers affecting household-level HEC occurrences in the Rajaji-Corbett landscape through a questionnaire survey. At the household level, we hypothesized that elephants are increasingly drawn to browse on irrigated/cultivated nutrient-rich crops such as wheat, rice, vegetables, and sugarcane which are grown in close proximity to forest boundaries (Ramesh et al., 2022). Hence, we predicted that agriculture crop type and distance to nearest agricultural crop field could influence HEC. Second, we identified spatial variables of HEC patterns through hotspot mapping in the Rajaji-Corbett landscape and its adjoining areas using Maxent software. To examine the drivers influencing HEC distribution, we formulated several hypotheses: i) Water availability often influences the movement of elephants which could lead to human-elephant interaction (Wilson, Davies, Hazarika, & Zimmermann, 2015), as water influences the rice based agricultural crop and overall crop density (Wilson et al., 2015). ii) human population growth may escalate HECs across the boundary of PAs (Hart & O'Connell, 1998). iii) terrain factors such as elevation and slope often predict elephant distribution (Wang, Chen, & Shi, 2018) and, thus, HEC hotspots (Sulistiyono, Maulana, Patana, & Purwoko, 2021) and landscape predictors like slope and elevation would play an important role in driving the distribution of HEC. In order to lower the likelihood of a conflict between humans and elephants, this study aims to assist policy makers, park managers, and community leaders by providing a better understanding the intricacies of these spatial patterns.

2. Methodology

2.1. Ethics statement

We obtained permission to conduct the survey from the Principal Chief Conservator of Forest, Uttarakhand Forest Department (letter no. 2949/5 2949/5–6). We obtained verbal consent from the respondents who were interviewed, and they were briefed about the purpose of collecting the information. Additionally, informed consent was obtained from all individual participants included in the study before conducting the surveys, and all respondent information has been protected to ensure that right to privacy was not violated.

2.2. Study area

We conducted our study in Rajaji-Corbett Landscape (RCL) (Fig. 1), which lies in northwest India between 29°15′-30°31′ N 77°52′-78°22′ E at the elevation of 250–1100 m above mean sea level. The total area geographic area of RCL is 3177 km^2. The area comprises Rajaji Tiger Reserve (RTR; 1075 km^2: Upadhyay et al., 2019), Rajaji-Corbett elephant corridor and Corbett Tiger Reserve (CTR; 1288.32 km^2: Shalini & Pant, 2023). Our study was conducted in two levels; (i) the first study (household level questionnaire survey) was conducted in Motichur and Shyampur range of RTR (Fig. 1), (ii) the second study was conducted in five areas (Shyampur range, Motichur range, Chidiyapur range, Rasiyabad, and Lansdowne Forest division) of RCL (Fig. 1). The selected study sites were chosen because of the elephant corridor area and high human-elephant conflict areas (Williams, Johnsingh, & Krausman, 2001; Joshi & Singh, 2011; Joshi & Puri, 2019; Johnsingh, 1994; Babu, Singh, Goyal, & Shruti, 2018; Ogra, 2008). The area is situated in the lesser Himalayan zone and the upper Gangetic plains biogeographic zone (Rodgers & Panwar, 1988). The climate is subtropical type with three distinct seasons (winter, summer, and rainy) with temperatures ranging from 23°C to 46°C in summer and minimum 5°C during winter. The annual rainfall varies between 1200 and 1500 mm. The local population rely on adjacent forest resources such fuelwood, fodder, grass, livestock foraging ground, and locally available non-timber forest products (Badola, 1997; Chandola, Badola, & Hussain, 2007). The vegetation consists of northern tropical moist and dry deciduous forests with dominant species such as Sal (*Shorea robusta*), Rohini (*Mallotus philippensis*), *Kydia calycina,* Shisham (*Dalbergia sissoo*), Khair (*Acacia catechu*), Bargad (*Ficus benghanensis*), *Ougeinia oojeinensis*, Haldu (*Adina cordifolia*), Bahera (*Terminalia bellirica*), and *Terminalia spp*. Prime mammalian fauna of the park consists of tiger (*Panthera tigris*), leopard (*Panthera pardus*), sloth bear (*Melursus ursinus*), striped hyaena (*Hyaena hyaena*), barking deer (*Muntiacus muntjak*), goral (*Nemorhaedus goral*), chital (*Axis axis*), sambar (*Cervous unicolor*), wild boar (*Sus scrofa*), elephant, and among reptilian fauna is the mugger crocodile (*Crocodylus palustris*) and king cobra (*Ophiophagus hannah*) (Joshi, 2016).

2.3. Data collection

We collected HEC data on two spatial scales (household level and landscape level) to analyze their predictors. First, we collected HECs incidents at the household level that occurred between 2020 and 2022, from the villages present within the Motichur and Shyampur ranges, to identify the potential predictors affecting HECs. Second, we collected the HEC incidents (crop raiding, human death/injury, and property

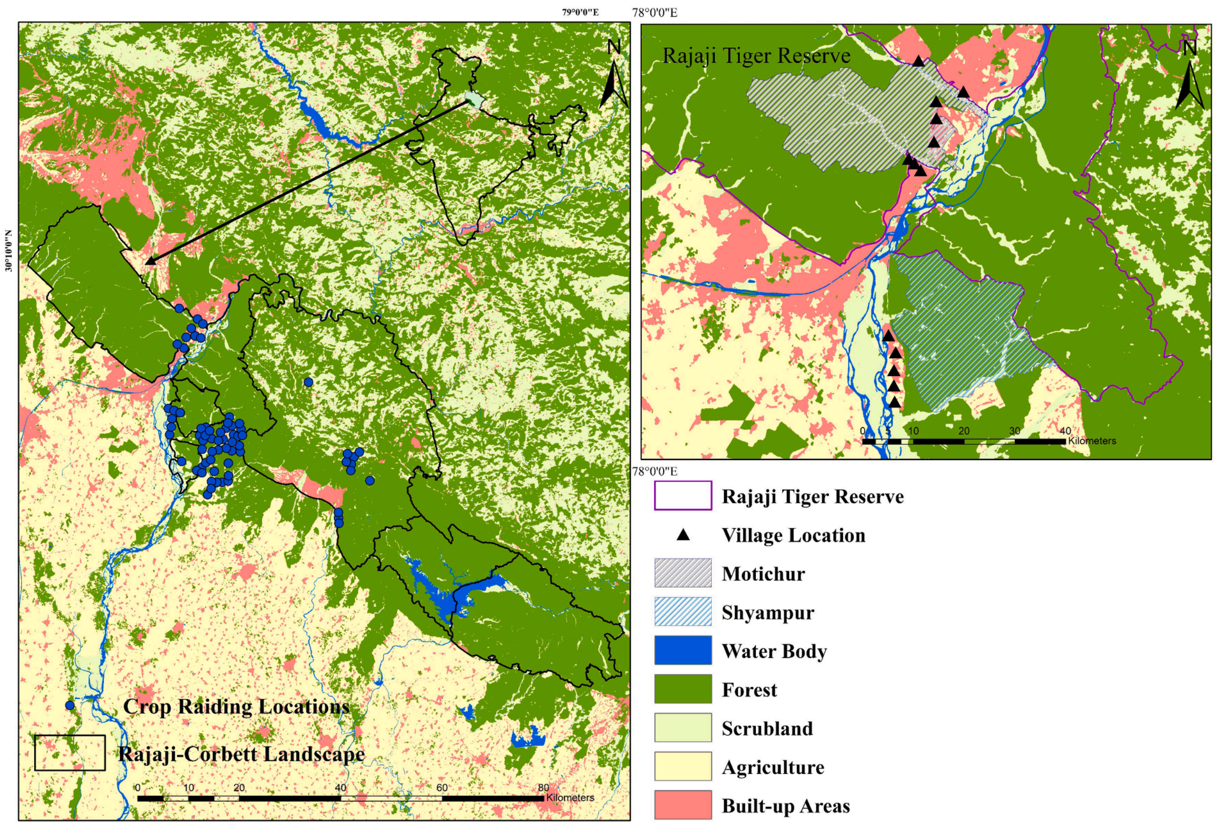

Fig. 1. The Motichur and Shyampur study sites within the Rajaji-Corbett landscape, Uttarakhand. Black Triangles represent the villages where the interviews took place and blue dots represent conflict location used for hotspot mapping in Maxent. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

damage), based on the wildlife damage compensation record, between 2012 and 2022 from the RCL, Uttarakhand Forest Department to map and predict the conflict hotspots and the potential predictors influencing HECs on landscape level. Wildlife damage compensation record refers to *ex-gratia* wildlife damage that represents tangible threats to livelihoods in terms of personal injury, crop and livestock losses, and property damage (Graham, Beckerman, & Thirgood, 2005). We also collected data on the various types of crop loss area by elephants during 2012–2022 from the forest department. Due to low sample size and unreliable locations of HECs incidents on human death/injury and property damage, we only considered the crop raiding locations to map the extent of HECs.

For the household level HECs modeling, we sampled the study sites and collected local people's responses on frequent elephant interactions in the form of crop raiding and human death/injury. The semi-structured questionnaire was constructed following a literature survey (Ramesh et al., 2022; Naha, Sathyakumar, Dash, Chettri, & Rawat, 2019; Appendix 1), and was pre-tested with 30 respondents before being used for the survey. We overlaid a grid of 5 × 5 km cells (25 km^2) across the study area to ensure the spatial coverage of households experiencing conflicts with elephants. We interviewed a total of 266 systematically selected households from 13 villages in both study sites (Motichur and Shyampur range) of RTR between January to May 2022. We used the questionnaire in the local language (Hindi), with a systematic sample of 10 % of families per village and maintaining an average distance of 500–800 m between each residence in the corresponding village. Their responses were later translated into English while analyzing the data. A local forest guard was present initially at the start of each interview for formal introduction about the subject matter and to increase the community acceptance. Prior informed consent was obtained verbally from all participants. Each interview lasted for about 40–45 min.

The questionnaire comprised five sections: i) demography (gender, age, family size, education), ii) employment (occupation, annual income, landholding size), iii) crop area size (in acres), iv) conflicts with elephant, including if there had been any incident of human death/injury and crop raiding by elephants in the family, v) perception about elephants and conservation. We recorded the presence of HEC in the form of attacks on humans, human causalities, and crop raiding was a binary scale as conflict presence (1) or conflict absence (0), while we recorded the prior questions on nominal scales. During the survey, we asked the participants to recall the conflict incidents, to measure the accuracy of HECs. Due to the large number of crop-raiding incidents and the lack of a standardized protocol to estimate crop damage, we did not record extent of crop damage area from our study. Instead, we identified a total of 15 socio-ecological predictor variables (Table S1), chosen based on perception-based studies done in the past (Naha et al., 2019; Ramesh et al., 2022). We visited conflict sites to assess accuracy, based on the Forest Department record of recent human-elephant interactions.

For the landscape level HEC hotspots, we used both the primary and secondary data to generate the risk map for the areas vulnerable to HECs. The secondary data used in the conflict hotspot modeling were collected from the five areas of Uttarakhand Forest Department, India (Shyampur range, Motichur range, Chidiyapur range, Rasiyabad, and Lansdowne Forest division) from 2012 to 2022 with the assistance of forest staff. The department had a register where such events were recorded for payment of *ex gratia* to the victims. We collected official year-wise summary records of total compensation paid out to individual households from the Uttarakhand Forest Department, suffering crop loss and human injury/death by elephants to better understand the nature and extent of human-elephant conflicts. We removed duplicate incidents from the combined primary and secondary survey for accuracy, and compiled all crop raiding data to predict the HEC hotspots.

2.4. Predictor variables

For the household level HECs modelling, we overlaid 1 km^2 sub-sampling grids across our study area using ArcMap 10.8 (Esri, 2020) to calculate all 15 predictor variables (e.g., gender, livelihood, forest visit, forest visit score, major crop and minor crop, agricultural crop cover [%], distance from agriculture, distance from the protected area [PA], distance from forest, distance from the waterbody, distance from the road, human population density, bio-climatic variable [BIOCLIM1 and BIOCLIM12]). We assigned all variables to each household sampled at a resolution of 1 km^2 and calculated 15 predictors for determining household-level HEC (Table S1). For landscape level HECs hotspot modelling, to ensure the spatial coverage for HECs, we selected 10 predictor variables and calculated on a 25 km^2 spatial scale (e.g., built-up density, human population density, elevation [m], slope [degree], TRI [Terrain Ruggedness Index], LULC [Land use and Land cover], NDVI [Normalized Difference Vegetation Index], MNDWI [Modified Normalized Difference Water Index], road density, night light) (Table S2). We explain data collection for all predictor variables in Text S1.

2.5. Data analysis

For our household level HECs modeling, we assigned each binary (yes/no) response of conflict presence or absence from each household as our dependent variables. We standardized all 15 predictor variables which could potentially impact HECs by centering and scaling them around a mean of 0 with a standard deviation of 1. We examined the multicollinearity among variables using VIF (variance inflation factor) < 5 (Shrestha, 2020), and we included the 9 variables in the analyses (Table S3). We fitted Generalized Linear Models (GLMs) with binomial distributions to analyze the predictors on HECs. We formulated all possible models using 9 predictor variables (Table S1) and considered the final model with $\Delta AICc < 2$ (lower $\Delta AICc$ value indicates higher model ranking) using 'dredge' function of package "MuMln" in program R (Burnham & Anderson, 2004). We obtained the final model by averaging the top candidate models ($\Delta AICc < 2$; Burnham & Anderson, 2004) to identify most significant variable contributing towards HEC. In GLMs analysis, we considered $P \leq 0.05$ to be significant and $P \leq 0.10$ to be marginally significant. We performed all statistical analyses for data collected on different parameters of human-elephant conflict in R v. 4.2.1 (R Core Team, 2022) and the IBM SPSS Statistics for Windows, version 26.0 (IBM Corp. 2019, Armonk, N.Y., USA).

For the HECs hotspot prediction mapping, we focused on the Rajaji-Corbett Landscape and the surrounding protected area with previously presented HECs, which extends in six districts (Nainital [4251 km^2], Almora [3139 km^2], Garhwal [5230 km^2], Tehri Garhwal [3642 km^2], Dehradun [3088 km^2], and Haridwar [2360 km^2] (Fig. 2). We selected these HEC hotspot prediction areas based on the previous HECs in that region (Joshi & Puri, 2019; Johnsingh, 1994; Babu et al., 2018; Ogra, 2008; Williams et al., 2001). The study area was stratified into 25 km^2 grid using ArcMap 10.8, which resulted in a total number of 1473 grids. We selected 10 ecologically significant environmental predictors (Table S2; Text S1) and clipped all the spatial layers based on our selected areas at a resolution of 25 km^2 to map the HECs hotspots in the study area (Table S2; Text S1). To check the multicollinearity among variables, we extracted the mean raster value at a resolution of 25 km^2 using the "Zonal Statistics" feature of the "Spatial Analyst Tool" in ArcMap 10.8 (Esri, 2020). We then checked the Variance Inflation Factor (VIF) < 5 (Shrestha, 2020), and found all variables were uncorrelated with each other (Table S4). Thereafter, all spatial layers were reprojected into the same coordinated system and same spatial extent, later converted to raster files (ASCII format) using ArcMap 10.8. Our primary aim was to avoid strong spatial bias for HEC incident locations, so to measure the spatial autocorrelation among HEC incident points (N

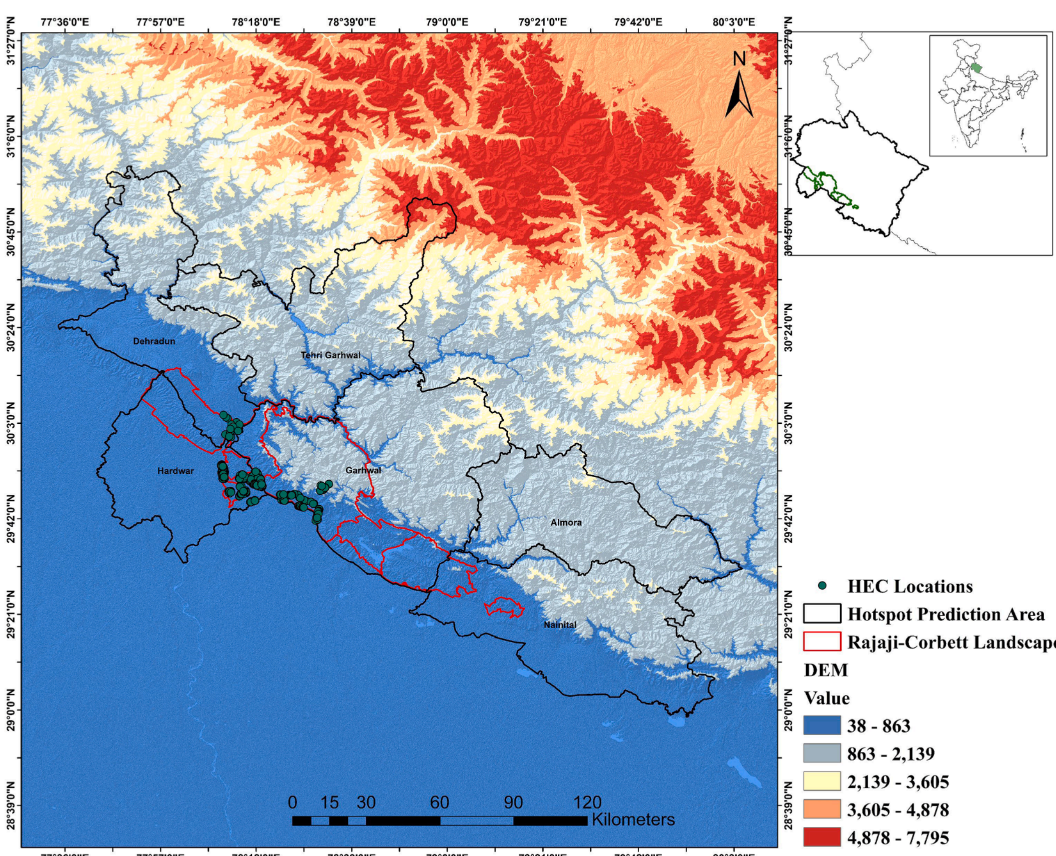

Fig. 2. Elevation map of the study area including the Rajaji Corbett Landscape and area used to predict hotspots of human-elephant conflicts.

= 1,757), we used the function Moran's test (Moran's I) (Cliff & Ord, 1981) in ArcMap 10.8, which we found the HEC data in clustered (z score = 3.71; p = 0.0002; Figure S1). Therefore, all the occurrence data were spatially rarefied to remove spatial autocorrelation which resulted in a total of (N = 68) unique occurrence points with the help of the SDM toolbox in ArcMap 10.8.

To determine the relationship between HECs and the spatial predictors, we used a total of 68 conflict locations as sample data to run presence-only models and predict hotspots of HECs using the Maxent program (Fig. 1). Maxent is an open access-based species distribution program that is used to generate a distribution of certain species/events based on a set of environmental/predictor variables (Phillips, Anderson, & Schapire, 2006). Using the Maxent program we calculated the probability of conflict (human casualty or crop depredation) within each 25 km^2 grid based on the ecological predictors. The final computed model was a probability distribution over all of the grid cells. We created response curves for each predictor variable and used the Jackknife estimator to measure the importance of variables in the final model output. We used 25% of the locations as random test data or training to evaluate the final model performance. We specified a total of 10 replicates, allowing the model to run many times before averaging the output from each model. We employed a total of 500 iterations to provide the final model output with enough time for convergence and robustness. Maxent provides a background or pseudo-absence sample of points, by default selecting 10,000 randomly from the entire research site, as is common with other presence-pseudo absence approaches (Elith & Leathwick, 2009).

3. Results

3.1. Respondents' demographic characteristics

Out of all respondents (N = 266), 62 % were male (N = 165) (Fig. 3a), and 44 % of people were middle-aged (41–60 age class), with an average age of 47 (±SE = 0.9) (Fig. 3c). Most of the people had a primary education (42 %; N = 112), followed by secondary education, graduated and illiterate people (Fig. 3b). Out of all occupations, service and daily wage laborers were the two major occupations, employing nearly 74 % (N = 196) of the people (Fig. 3d). Out of all the respondents, 41 % (N = 110) of annual income ranged between INR 100000–500000 (Fig. 3e). The average livestock owned per household was 3.45 (±SE 0.34). The average landholding size per household was 0.03 (±SE 0.005 ha). The average family size was found to be 6.36 (±SE 0.19). In addition, 57.8 % (N = 154) of households reported being dependent on forest resources for their livelihood (i.e., directly or indirectly for fuelwood, fodder, and water). Out of all the respondents 44 % (N = 117) were dependent on fuelwood as well as alternate fuel, 26 % (N = 68) alone were dependent on fuelwood and 29 % (N = 78) were dependent on commercial fuel.

Between 2012 and 2022, we recorded (N = 1968) HECs incidents from both forest department record (N = 1826) and current survey (N = 142). Out of them crop raiding incidents were reported most (89.27 %, N = 1757), followed by property damage (8.28 %, N = 163), human injury (1.47 %, N = 29), and human death (0.96 %, N = 19) (Fig. 4a). Sugarcane was the most raided crops, followed by rice, wheat, afnd other (vegetables, maize, lentils etc.) (Fig. 5).

We conducted 266 household questionnaires on the presence/absence of HECs, and 53.3 % (N = 142) of households reported HECs. The occupation of respondents who experienced HECs were daily wage laborers (48 %), farmers (32 %), self-employed (14 %), and livestock farming and service holders collectively contributed 3 % (Fig. 4b). A total of 20 crops were grown (N = 158) across the villages, of which the two primary crops most grown were rice (*Oryza sativa*) (55 %) and Rabi/Kharif (predominantly, wheat [*Triticum spp*] (31 %), and were reported to be most frequently consumed by elephants. Sorghum and pearl millets constituted the major secondary crop consumed by elephants (14 %) (Fig. 4c).

3.1.1. Attributes of household level human-elephant conflict

The GLMs analyses showed that the major crop and the distance to the nearest agricultural field significantly affected the HECs at the household level, while minor crop marginally affected the HECs (Table 1). Major crops (ß=0.75, p < 0.05; Table 1; Fig. 6a) and minor crops (ß=0.26, p = 0.07; Table 1; Fig. 6b) had positive effects on HEC.

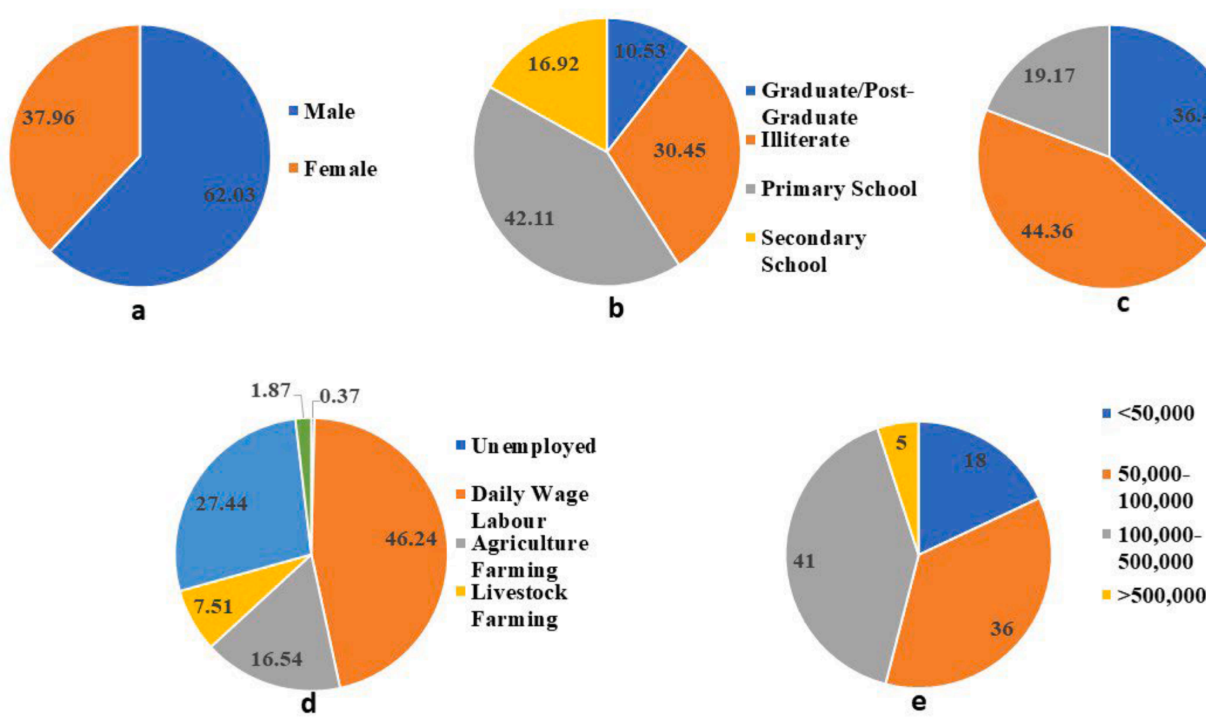

Fig. 3. (3a-3e): (a) gender, (b) educational qualification, (c) age, (d) occupation, € income of the respondents in the Rajaji-Corbett Landscape, Uttarakhand.

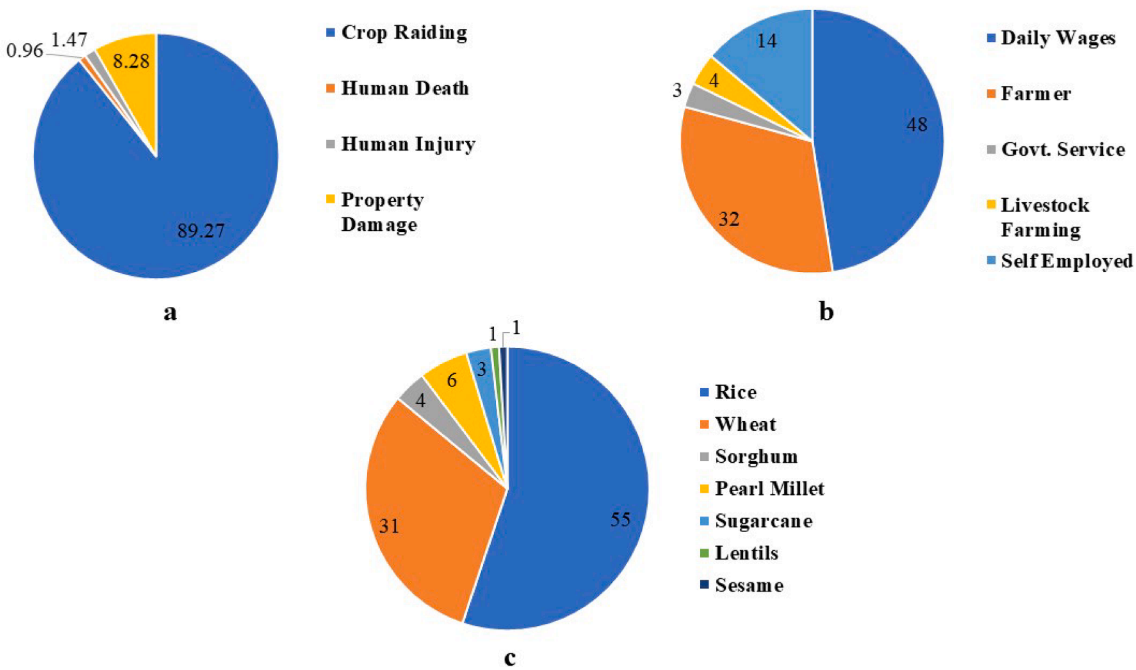

Fig. 4. (4a-4c): (a) Types of human-elephant conflicts, (b) Occupation of respondents who experienced HECs, and (c) Types of crop damage in the Rajaji-Corbett Landscape, Uttarakhand.

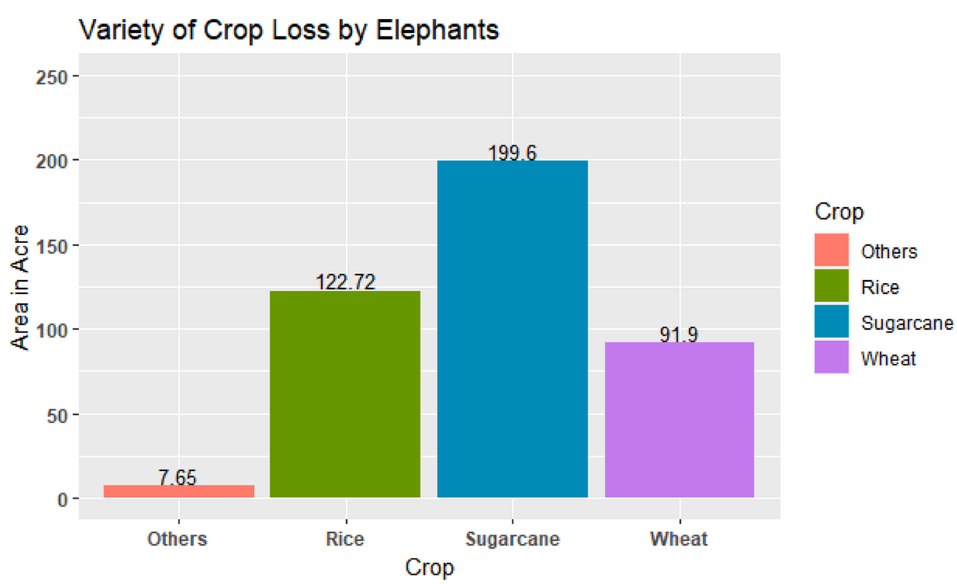

Fig. 5. Area of crop loss from 2012 to 2022 in Rajaji-Corbett Landscape, Uttarakhand.

Furthermore, we found that distance to the nearest agricultural area had a significant negative effect on HEC (ß=-0.42, $p = 0.02$; Table 1; Fig. 6c), as the decrease of HECs with an increasing the distance to agricultural area from each household. Essentially, at the household level, people that grew more diverse crop types and had more agriculture landholding area were more susceptible to HECs (Fig. 6b).

In our model comparison analyses predicting the household level HECs, we obtained eight top models based on smallest ΔAICc values (ΔAICc < 2) (Table 2), with a top model that had $w = 0.21$ (Table 2). After model averaging, the most important predictors were similar to our GLMs analyses. Major crop (ß= 0.72, $P < 0.001$; Table 3; Fig. 6a) and minor crop (ß= 0.22, $P = 0.09$; Table 3) positively affected the household level HECs, as those people who grew diverse crop types and had more agricultural land frequently faced HECs. Furthermore, HECs were negatively affected by the distance to the nearest agricultural area (ß= −0.39, $P < 0.05$; Table 3; Fig. 6c), as the probability of HECs increased with decreasing distance to the agricultural area. The distance to forest edge (unprotected area) (ß= −0.28, $P = 0.08$; Table 3; Fig. 6d) marginally affected the household level HECs, as the probability of HECs increased with decreasing distance to the forest.

3.1.2. HEC occurrence and hotspot mapping

We used a total of 51 and 17 locations for training and testing the 25 km^2 grids. After model convergence and averaging for 10 replicates, we found that the significant predictor variables affecting human-elephant conflicts at this scale included i) elevation (Fig. 7a; Fig. 8) ii) human population density (Fig. 7b; Fig. 8), iii) slope (Fig. 7c; Fig. 8), iv) road density (Fig. 7d; Fig. 8) (Figure S2). The receiver operating

Table 1
Estimated beta coefficients (β) with standard error values (SE) for the Generalised Linear Models (GLMs) (family = binomial) that explain the drivers influencing the probability of human-elephant conflict at household level in Rajaji-Corbett Landscape, Uttarakhand. We note significant values as: $^*p < 0.05$, $^{**}p < 0.01$ and $^{***}p < 0.001$, and used contrasts of Forest Visit (No), Livelihood (Service), and Gender (Female).

Variables	β	SE	z value	Pr(>|z|)
Intercept	−0.05	0.31	−0.17	0.86
Distance from Agriculture	−0.42	0.19	−2.28	0.02*
Distance from forest edge	−0.25	0.19	−1.30	0.19
Distance from water	−0.08	0.17	−0.48	0.62
Distance from road	−0.19	0.19	−0.99	0.32
Crop cover	−0.06	0.20	−0.33	0.73
Major crop	0.75	0.15	4.98	6.14e-07***
Minor crop	0.26	0.14	1.78	0.07.
Forest visit (Yes)	−0.26	0.30	−0.85	0.39
Forest visit (No)				
Livelihood (Agriculture)	0.25	0.49	0.51	0.60
Livelihood (Livestock farming)	0.19	0.58	0.32	0.75
Livelihood (Daily wages)	0.36	0.37	0.97	0.33
Livelihood (Others)	0.22	0.71	0.31	0.75
Livelihood (Service) constant				
Gender (Male)	−0.13	0.30	−0.45	0.66
Gender (Female)				

characteristic curves (AUC) value was 0.90 (Figure S3). The predictor variable with the highest gain when used in isolation (and therefore having the most useful information by itself) was elevation (Fig. 7a; Fig. 8). Based on the response curves generated through Maxent, the probability of HECs decreased with increasing elevation (Fig. 7a), increase in road network (Fig. 7d), and increase in slope (Fig. 7c) whereas it increased with an increase in human population (Fig. 7b).

3.1.3. *HEC hotspot areas*

We generated an HEC probability map with a spatial resolution of 5 km × 5 km, with values ranging between 0 (low probability) and 1 (high probability) (Fig. 9). We used 10 % minimum threshold to define the minimum probability of human-elephant conflict because of the secondary data used to map the conflict hotspot. We categorized these 3 types such as high, medium, and low conflict probability based on 3 probability classes in ArcMap. We classified the output of probability values based on probability distributions as i) 0–0.18, signifying low conflict area; ii) 0.19–0.45, signifying medium conflict; and iii) 0.46–0.78, signifying high conflict area (Fig. 9). The HECs hotspot map shows that the maximum to medium probability of HEC was predicted in the south Dehradun district, Haridwar district, south Garhwal, and south Nainital district where most of the people reside near to the Rajaji-Corbett landscape. We also observed the highest probability of HECs in the south-western part of RTR (Shyampur range and Jheel Mil Jheel reserve forest and its adjacent area) and CTR regions of the study area in a lower altitude compared to the higher altitude (Fig. 9). A total of 3606.87 km^2 (~17% of its area) out of ~ 21,278.18 km^2 of the landscape was estimated to be in the high HECs zone (Fig. 9).

4. Discussion

Our study identified the key variables causing HECs in the Rajaji-Corbett landscape – where humans and elephants coexist. The rapid increase in traffic congestion on the roads that cross this elephant habitat, along with the expansion of agricultural lands, human habitation, and commercialization in the Rajaji-Corbett landscape, have all

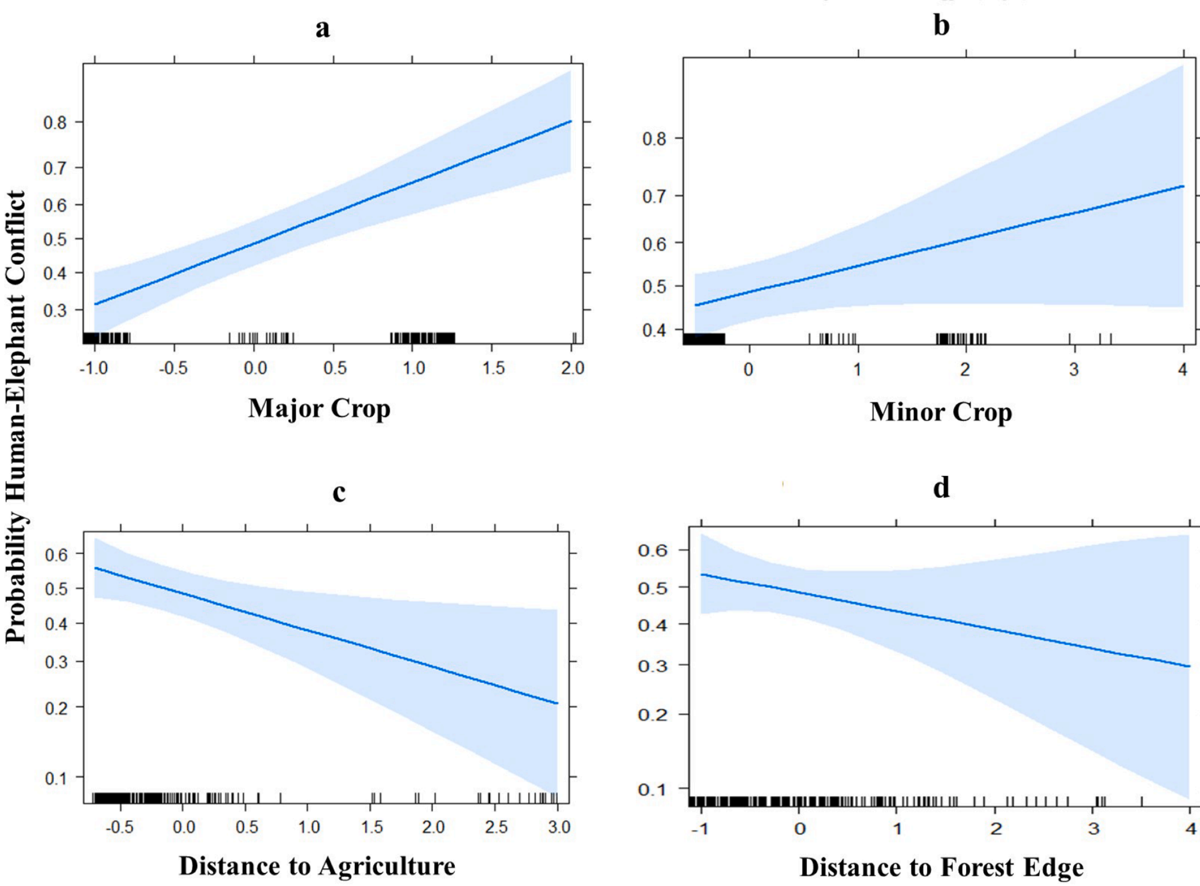

Fig. 6. (6a-6c) The variables in the top model explaining the predicted probability of HECs, including: (a) major crops grown, (b) minor crops grown, (c) distance to nearest agricultural field, (d) distance to forest edge.

Table 2
Results of Generalised Linear Models (GLMs) used to evaluate the variables influencing the household level HEC in Rajaji-Corbett Landscape, Uttarakhand. These model comparisons use Akaike Information Criterion corrected for small sample sizes (AICc), and the top eight models are shown (ΔAICc < 2). We also report the degrees of freedom (df), the change in AICc scores (ΔAICc), the AIC weight (w), and the Loglikelihood (logLik).

Models	Degree of Freedom (df)	logLik	AICc	ΔAIC	*w*
Distance to Agriculture + Distance to Forest edge + Major crop + Minor crop	5	−162.16	334.55	0.00	0.21
Distance to Agriculture + Distance to Road + Major crop + Minor crop	5	−162.52	335.26	0.71	0.15
Distance to Agriculture + Distance to Forest edge + Distance to Road + Major crop + Minor crop	6	−161.58	335.49	0.93	0.13
Distance to Agriculture + Distance to Road + Major crop	4	−163.71	335.56	1.01	0.13
Distance to Agriculture + Distance to Forest edge + Major crop	4	−163.71	335.57	1.01	0.13
Distance to Agriculture + Distance to Forest edge + Forest Visit + Major crop + Minor crop	6	−162	336.33	1.77	0.09
Distance to Agriculture + Distance to Forest edge + Distance to Road + Major crop	5	−163.1	336.43	1.88	0.08
Crop cover + Distance to Agriculture + Distance to Forest edge + Major crop + Minor crop	6	−162.07	336.46	1.91	0.08

Table 3
GLMs model average coefficient (β) with standard error values (SE) of the variables to explain the socio-ecological predictors influencing household level HEC in Rajaji-Corbett Landscape, Uttarakhand. We note significant values as: *p < 0.05, **p < 0.01 and ***p < 0.001.

Variables	β	SE	P
Intercept	−0.05	0.14432	0.7221
Distance to Agriculture	−0.39	0.15622	0.0127 *
Distance to Forest edge	−0.28	0.16187	0.0846.
Major Crop	0.73	0.13701	1e-07 ***
Minor Crop	0.23	0.13554	0.0951.
Distance to Road	−0.24	0.16186	0.1395
Forest Visit (Yes)	−0.15	0.2808	0.5743
Crop cover	−0.07	0.18362	0.6667

posed serious problems for free-roaming elephants (Joshi & Singh, 2011). Our research revealed that the diversity of major and minor crops, distance from agriculture, and distance to forest edge were significant spatial predictors of HECs at the household level; whereas slope, elevation, road density, and human population all predicted the likelihood of HEC's conflict hotspots. The agricultural crop types cultivated by local farmers affected the household-level HECs, and by cultivating alternative crops that elephants find less appealing, farmers in the susceptible risk areas identified by our study could lessen the likelihood of crop damage and conflict. Our conflict risk map identified households that were susceptible to being involved in an elephant conflict primarily in flat terrains dominated by agrarian areas, highlighting the need for better spatial planning for land use. This is very important, considering that we predicted high elephant conflict zones across nearly one-fifth of the total area sampled.

Elephants are forced to use agricultural areas outside of their natural habitat in locations where humans and wildlife coexist due to the decreased availability and quality of elephant habitats in fragmented landscapes (Neupane, Kunwar, Bohara, Risch, & Johnson, 2017; Neupane, Johnson, & Risch, 2017). As a result, there will inevitably be HEC, which will result in the deaths of both humans and elephants (Sukumar, 1990; Venkataramana, Sreenivasa, & H.g., 2017). In our study area, most croplands are near households, which could influence HECs. We discovered spatial factors of HECs that should be addressed to build effective mitigation measures and decrease HECs. Distance to nearest agriculture (the probability of HECs increased with decreasing distance to the agricultural area) and diversification of major and minor crops (people who grew more diverse crops and had more agricultural land) act as significant determinants of household-level HECs. Due to the expansion of agricultural cover near forest boundaries, elephants are frequently attracted to forage on crops like rice, wheat, maize, vegetables, and sugarcane, presumably as a result of their high protein or mineral content (e.g., Sukumar, 1991). Previous studies similarly observed that diversification of major and minor crops influenced HECs in Western Ghats of Southern India (Ramesh et al., 2022). Furthermore, we observed that distance to forest edge had a significant effect on household level HECs, as the probability of HECs increased with decreasing distance to forest edge. In our study area, people residing near the forest are mainly dependent upon forest resources such as fuelwood, fodder, grass and non-timber forest products, which increases interactions, and likely conflicts, with elephants (Ogra, 2009). Previous studies also observed that the distance to forest had significantly affected HECs (Lahkar et al., 2007; Dangol, Ghimire, & Bhattarai, 2020; Ram et al., 2021), as elephants are most likely to raid crops near forests (Graham, Notter, Adams, Lee, & Ochieng, 2010; Chen et al., 2016; Ramesh et al., 2022). Increasing crop consumption may also reflect changes in the amount of natural fodder that is available in PAs (Branco et al., 2019).

Elevation has a direct impact on the local climate, terrain, and soil, which in turn has an indirect impact on plant distribution (Hirzel & Le Lay, 2008) and, consequently, elephant distribution (Wilson et al., 2021). We found that HEC was less likely with an increase in elevation, which is probably because elephants prefer flat terrain and lowland forests to highland forests (Naha et al., 2019). Elephants generally do not prefer high elevations due to the colder temperatures, scarcer food sources, higher energy expenses (Lin et al., 2014; Liu et al., 2018), and steep slopes (Htet et al., 2021). In contrast, a small number of elephants have been observed living in high elevations due to intraspecific competition (Chaiyarat, Youngpoy, & Prempree, 2015), although these occurrences were exceptional. Our results indicated that slope had a negative correlation with occurrences of HECs. Due to their huge body size and differential front-hind limb lengths, Asian elephants avoid steeper slopes (Chen et al., 2021). Elephants prefer low elevations and modest slopes in order to conserve energy (Chaiyarat et al., 2015; de la Torre et al., 2021; Lin et al., 2014; Mohd Taher et al., 2021; Wilson et al., 2021). In the Rajaji-Corbett landscape, most of the lower areas are flat (Verma & Kumar, 2015), and increasing human settlements and cropland in the low-lying areas increases HECs (Wen, Zhou, Li, Xu, & Dong, 2018). We discovered a non-significant correlation between HEC occurrence and water availability in contrast to other studies (e.g., Tsalyuk, Kilian, Reineking, & Getz, 2019; Wilson et al., 2015). The other studies suggested that low water and food availability in protected regions may increase HECs. Although water is generally available in the region, crop raiding and movement of elephants occur near the forest and village areas where water availability is greater and may be the reason for the weak relationship between water availability and crop raiding. We also may have sampled at a resolution that was too coarse and did not account for water bodies that were seasonal or added artificially.

Anthropogenic variables (i.e., road networks) have an adverse effect

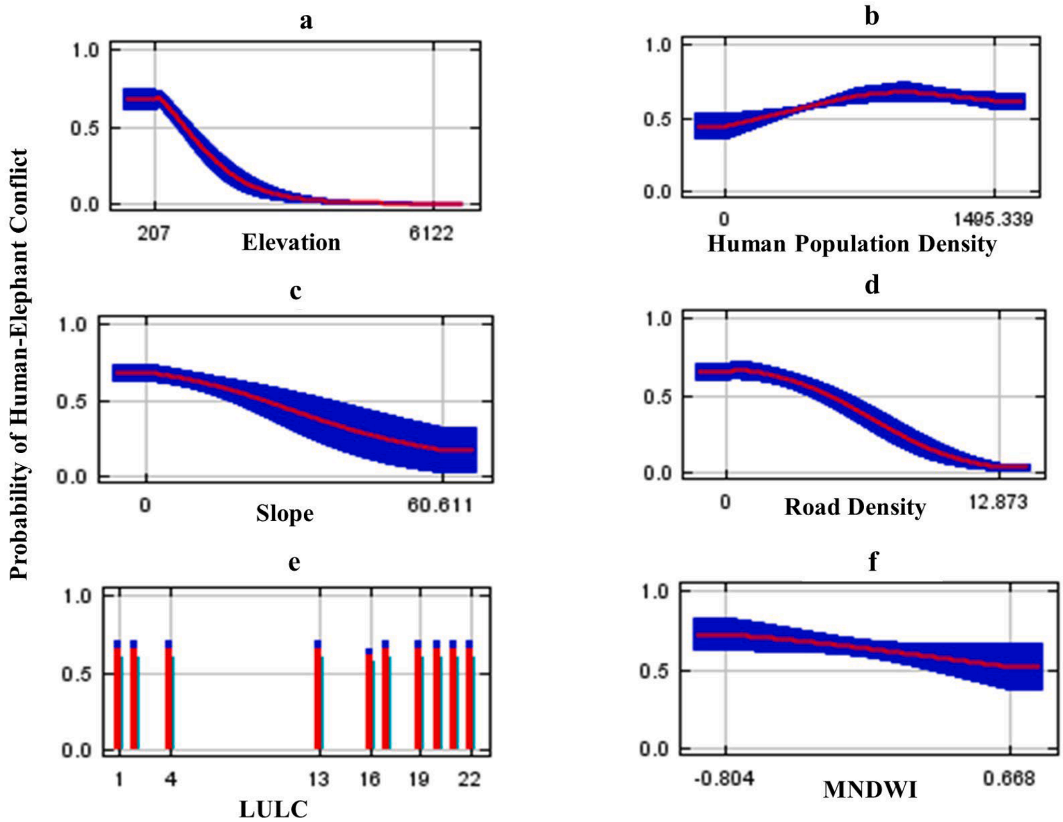

Fig. 7. (7a-7f) Relationships between top environmental predictors and the probability of human-elephant conflict in the Rajaji-Corbett Landscape, Uttarakhand.

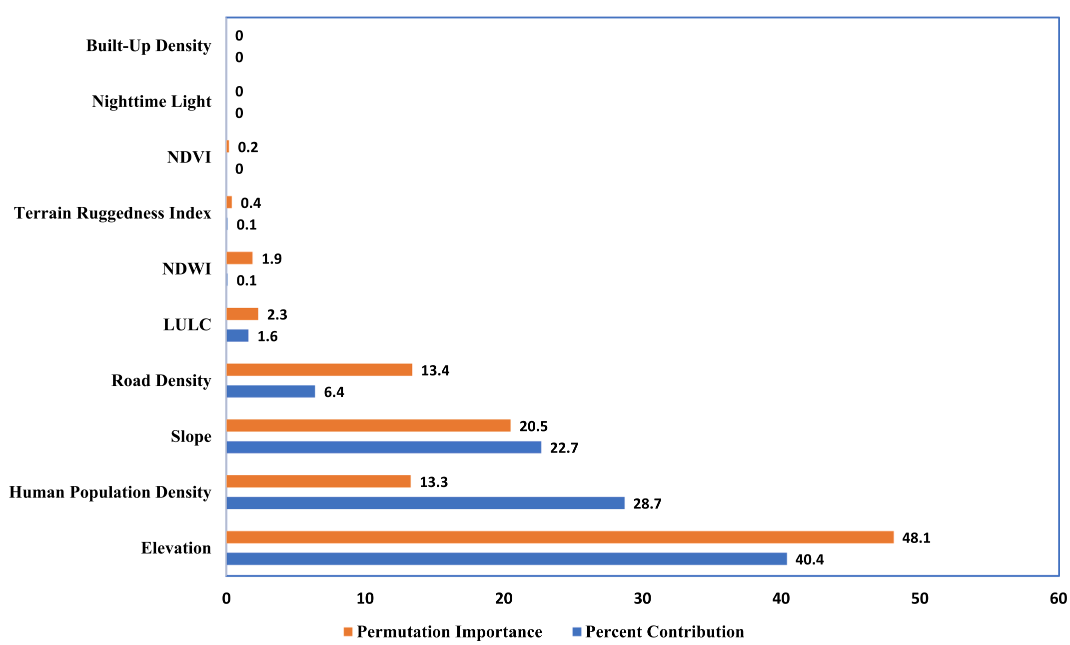

Fig. 8. Variables used in predicting the spatial distribution of human-elephant conflict in the Rajaji-Corbett Landscape, Uttarakhand.

on wildlife movement (Gubbi, 2012; Liu, Dai, Cao, Li, & Zhang, 2016). In our HECs hotspot analysis, we found that road density negatively influenced HECs (the probability of HECs decreased with an increasing road network). Elephants tend to limit their movements in areas with dense road networks (Liu et al., 2017), and expansion of the road network threatens the habitat quality and connectivity across their distribution (Vasudev, Fletcher, Srinivas, Marx, & Goswami, 2023). In our study area, agricultural land lies in proximity to the PA boundary which had less road connectivity, and likely increased risk of HECs. In our study area, the less conflict in the high road density area could also be explained by the Rajaji-Corbett landscape vegetation being fairly open and elephants not needing to use roads for ease of travel (Minwary, 2009). Less conflict in the high road density area could also be explained by the movement of elephants in the agrarian land. But previous

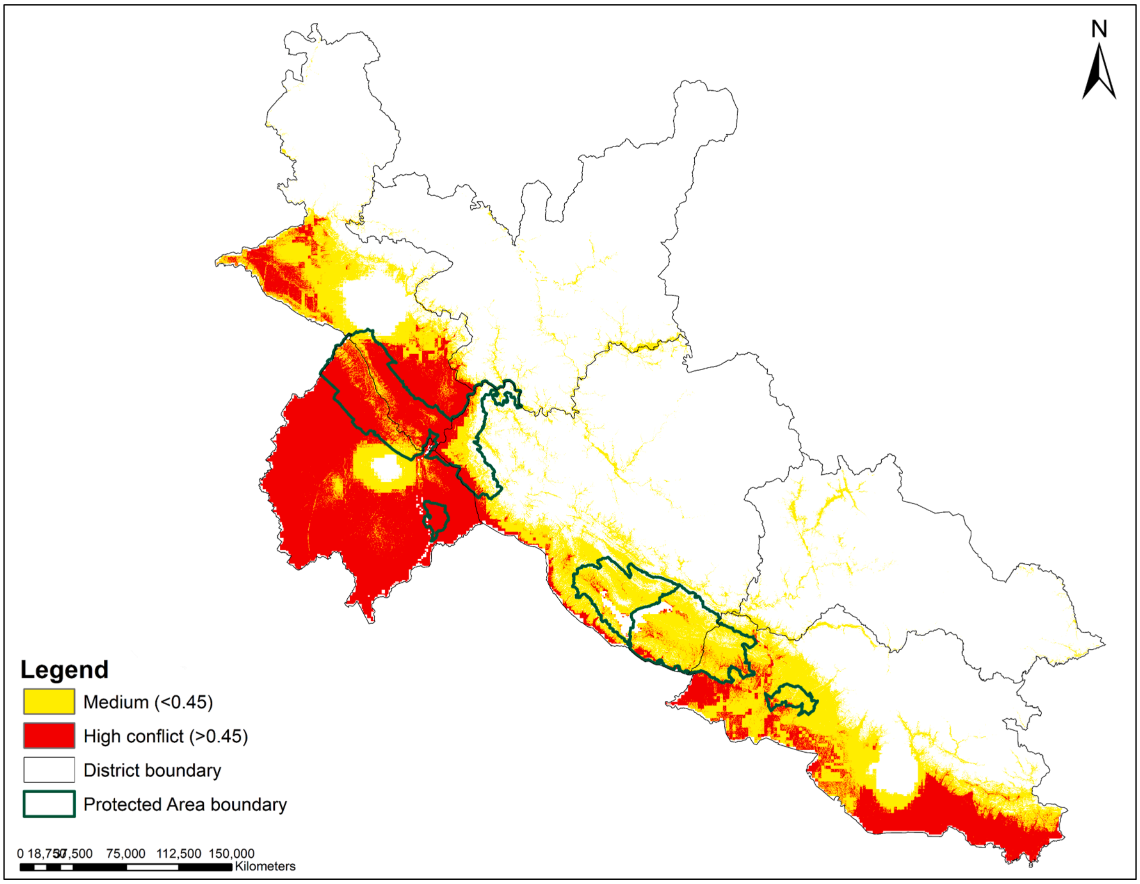

Fig. 9. Human-elephant conflict hotspot probability map showing medium and high conflict probability region in the predicted study area (Dehradun, Haridwar, Tehri Garhwal, Garhwal, Almora, and Nainital).

research indicated that road networks affected HECs positively (Mann, Agrawal, & Joshi, 2019), which could be explained by elephants using roads as foraging routes (Pan, Lin, Luo, & Zhang, 2009). Road networks and narrow pathways facilitate human movement and raise the likelihood of encounters with elephants (Mann et al., 2019). Additionally, we found that high human density areas positively influenced the HEC (the probability of HECs increased with increasing human density). Previous studies also resulted that human population density affected HECs (Rohini, Aravindan, Vinayan, Ashokkumar, & Das, 2016; Wilson et al., 2015). In our study area, humans have modified the forested landscape into agricultural land through habitat encroachment around PAs (Joshi & Singh, 2011). These agricultural areas were generally found close to households; one possible reason could be it helped the respondents in crop guarding by keeping plantations nearby and mitigating HECs. In our HECs hotspot analysis, the major HEC probability region was west Dehradun, Haridwar, and southeast Nainital, which accounted for the high density of people (530.6 people/km^2 $\pm$ 296.4) (Census, 2011, Uttarakhand), which could be the reason for high conflict in that area.

5. Conclusions and recommendations

We discovered potential conflict hotspots for elephants throughout many forest ranges in Uttarakhand, which can aid in the development of practical solutions on the ground to reduce HECs. The study's findings indicate considerable natural land converted to agriculture in Rajaji-Corbett landscape settlements. Human-induced anthropogenic disturbance and encroachment into elephant habitats resulted in expected increases in HECs in the Rajaji-Corbett landscape. Over the last three decades, forests and grasslands in particular have been converted into agricultural land and communities, potentially leading to rise in HECs.

The Rajaji-Corbett landscape is an important elephant habitat in northern India (Singh, 1978), and the elephant corridor between RTR and CTR in the western Himalayan foothills should be protected, as it supports a population of around 2,000 elephants (Johnsingh et al., 2004; Menon & Tiwari, 2017). Elephants frequently come to agricultural fields, which escalate HECs, and we propose enforcing buffer zones and effectively increasing the distance of human settlements and agricultural areas from protected areas and critical elephant habitats to mitigate HECs. This is especially important because the majority of agricultural lands in the study area are located close (0–5 km) to PA boundaries, which likely stimulated crop foraging and escalated conflict situations. Local farmers urgently require village-level crop protection, as well as fine-scale land-use planning around PAs, as an important first step in halting escalating HECs. These efforts, however, must be supplemented with longer-term approaches that distinguish mutually exclusive land-use types and promote farming of alternative products and diverse livelihoods (Ly et al., 2020).

The Uttarakhand Forest Department has used a variety of important mitigation methods to reduce conflict between rural populations and elephants. These include compensation, and the construction of physical barriers such as electric fences, brick or stone walls, and a mobile-based early warning system. Other mitigation methods include the use of noise or fire deterrents, and the deployment of several guards for preventing crop raiding (Badola et al., 2021). Mitigation measures like electric fencing and fire crackers act as a negative stimulus (Mumby & Plotnik, 2018). Even softer mitigation measures such as coating fences in chili peppers (Le Bel, La Grange, & Drouet, 2015) or using bees to deter elephants (King, Douglas-Hamilton, & Vollrath, 2011; King, Lala, Nzumu, Mwambingu, & Douglas-Hamilton, 2017) involve "persuading" the animal that it could potentially avoid a negative experience. The successful implementation of these initiatives has been varied, owing in part to local communities' unsuccessful attempts to maintain these measures efficiently. Payments to encourage coexistence are one potential incentive-based mitigation technique. Financial aid could be provided to local communities under the proposed payments with wildlife by minimizing HECs to ensure the forest corridor's operation. The payments to encourage coexistence project address both the obvious and intangible costs of HECs, as well as the loss associated with relocation of conflict species. For HEC mitigation, the suggested incentive structure incorporates aspects of both compensation programs and alternative livelihood strategies (Badola et al., 2021).

Early warning of crop raiding has been identified as an important element in the successful deterrence of elephant crop raids (Sitati & Walpole, 2006; Sitati, Walpole, & LEADER-WILLIAMS, 2005; Hedges & Gunaryadi, 2010). In our study area, we found that very few areas have installed early warning systems using mobile technology. To ensure the safety of residents, it would be necessary to strengthen the current early warning systems, which would be worthwhile as it is one of the best mitigation measures to avoid HECs (Graham, Adams, & Kahiro, 2012; Li et al., 2018; Pozo, Coulson, McCulloch, Stronza, & Songhurst, 2017; Sitati, Walpole, & LEADER-WILLIAMS, 2005). To safeguard the safety of Asian elephants, early warning systems should be prioritized in high-risk regions where HECs happened regularly from 2012 to 2022. Finally, early warning systems should be implemented in HEC hotspot areas where HECs might emerge in the future. Our study found that sugarcane, rice, and wheat was the most raided crops in terms of area. But in our study area, only the villages within one range (Chidiyapur) primarily cultivated sugarcane. Because the main food crops are wheat and rice, however, most local livelihoods are dependent on the crops grown and further studies are required to evaluate the economic and social implications of changing crop types. Proper land-use planning, weed eradication, and habitat restoration leading to improved forage availability, particularly in the grasslands that serve as crucial elephant corridors, would be practical and positive management actions. We would also recommend the growth of crops that are less attractive or palatable to elephants in those areas identified as having an elevated risk of conflict. Proper and regular management of water resources in crucial corridors, particularly inside forested areas, might reduce the movement of elephants into fringe areas outside PAs. Site-specific information on elephant perceptions and conflict costs identifies areas where mitigation and educational programs can be reconfigured or new opportunities introduced that allow communities to benefit from an elephant presence, thereby increasing tolerance and appreciation for elephants (Shaffer et al., 2019). We also suggest that joint assessment among local forest administrative units, as well as actions that involve robust mitigation strategies, could more effectively focus time and effort on conflict locations. Ultimately, however, maintaining the viability of elephant populations amidst an increasingly inhospitable landscape, while simultaneously balancing the needs of rural livelihoods, remains a critical conservation challenge for northern India.

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CRediT authorship contribution statement

Megha Rani: Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Debashish Panda:** Data curation, Methodology. **Maximilian L. Allen:** Methodology, Validation, Writing – review & editing. **Puneet Pandey:** Writing – review & editing. **Sujeet Kumar Singh:** Conceptualization, Data curation, Funding acquisition, Investigation, Project administration, Supervision, Validation, Writing – review & editing. **Randeep Singh:** Conceptualization, Formal analysis, Methodology, Supervision, Writing – review & editing.

Declaration of competing interest

The author declare the following financial interests/personal relationships which may be considered as potential competing interests: Sujeet Kumar Singh reports administrative support, equipment, drugs, or supplies, and statistical analysis was provided by Amity University Noida. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data used in this study are provided in Supplementary Information.

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Appendix A. Supplementary data

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