Human–elephant conflict in expanding Asian elephant range in east-central India: implications for conservation and management

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Abstract Chhattisgarh, India, harbours a metapopulation of 250–300 Asian elephants *Elephas maximus* that has expanded its range from neighbouring states since 2000. Elephants in the state occur across a mosaic of forests interspersed with agricultural settlements, leading to frequent interactions with people, some of which culminate in conflict. We assessed patterns of crop losses as a result of elephant incursions, at two spatial scales. We found widespread crop losses, with 1,426 settlements in and around 10 forest divisions and four protected areas reporting elephant-related crop losses during 2015–2020. At the landscape scale, spanning c. 39,000 km^2, intensity of habitat use by elephants, forest cover and number of forest patches explained variations in intensity of crop losses. At a finer spatial scale, covering c. 1,200 km^2 of forest–agriculture matrix in Surguja, probability of crop loss was low near roads but high close to forest patches and was also affected by patch heterogeneity. Both male and female elephant groups fed on crops. As areas with high crop losses are also areas used intensively by elephants, management to increase elephant occupancy in relatively large and connected forest patches is imperative, to minimize crop losses and improve elephant conservation. Concomitantly, expansion of elephant range into agricultural areas that lack forests should be discouraged. In forest divisions, options to reduce negative human–elephant interactions include institutionalizing elephant monitoring, transparent and prompt ex gratia payment for crop losses, and the use of portable physical barriers.

Keywords Asian elephant, cropland, east-central India, *Elephas maximus*, human–wildlife interactions, range expansion, refuge habitats

Introduction

The Convention on Biodiversity emphasizes the need for effective management of human–wildlife interactions to minimize potential conflicts and foster coexistence in shared landscapes (CBD, 2023). Amongst the many forms of conflicts arising from negative human–wildlife interactions, crop losses as a result of incursions by wildlife are widespread and involve a range of species, from locust swarms to birds, rodents, primates, ungulates and megaherbivores (Woodroffe et al., 2005; Karanth et al., 2013; Conover & Conover, 2022). Large mammals are frequently the focus of concern as they can pose risks to both human safety and livelihoods. In biodiversity-rich Asian countries, the costs of human–wildlife conflict such as crop losses are often borne by economically disadvantaged communities (Bandara & Tisdell, 2003; Gulati et al., 2021). Recurrent conflict-related costs can financially destabilize families, pit them against wildlife conservation and render coexistence tenuous (Gubbi, 2012; de la Torre et al., 2021). Timely and effective conflict resolution is essential to foster coexistence for ecologically important species with extensive range needs (Natarajan et al., 2021).

The global wild Asian elephant *Elephas maximus* population is c. 50,000 (Williams et al., 2020), making it the least numerous of the three extant Proboscideans (Thouless et al., 2016). In Asia, elephants occur in 13 countries, with > 60% of the global population in India (Pandey et al., 2024). In addition to institutional mechanisms and legislation that protects elephants and their habitats (Pandey et al., 2024), the deep-rooted cultural significance of elephants in India elicits favourable public opinion towards elephant conservation (Vasudev et al., 2020). However, although ivory poaching is under control, escalating human–elephant conflict is a significant conservation challenge (Pandey et al., 2024). As a result of negative human–elephant interactions, > 500 human lives are lost annually, several hundred people are injured, and > 11 million ha of cultivated crops are affected (Gulati et al., 2021). As agriculture and allied activities provide food, income and employment for nearly 61% of the rural populace (Chand & Singh, 2022), crop losses are a threat to livelihoods.

Given its relevance to both elephant conservation and human welfare, crop foraging by elephants has been extensively studied in both Africa and Asia (Sukumar, 2003; Chiyo et al., 2011; Gross et al., 2018; Branco et al., 2019; Bastille-Rousseau et al., 2020; de la Torre et al., 2021). The general reasons for elephants foraging in crops include (1) using crops to offset scarcity of natural forage arising from habitat loss (Balasubramaniam et al., 1995), (2) optimal foraging (Pyke,

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1984), as crops may be a concentrated source of nutrition (Sukumar, 2003; Gubbi, 2012), (3) compensating for nutrient deficiencies in their regular diet (Sukumar, 1990; Osborn, 2004), and (4) a male strategy to gain reproductive advantage through better expression of musth, which confers a competitive advantage in male-specific agonistic interactions (Sukumar, 2003; Chiyo et al., 2011). Elephants feed on cultivated crops almost exclusively during the night, probably because of a perceived landscape of fear (Troup et al., 2020), as crop foraging entails considerable risks (LaDue et al., 2021). Lower crop foraging during bright moonlit nights exemplifies the avoidance of people (Corde et al., 2024). The inherent risks associated with foraging in the human domain usually preclude female herds from foraging in crops (Sukumar, 1991; Chiyo et al., 2011). Exceptions to this general pattern occur in landscapes characterized by high interspersion of natural forests and agriculture and where there is large-scale dispersal of elephants into human-dominated areas (Datye & Bhgawat, 1995). Although the general underlying factors for crop foraging by elephants are understood, context-specific knowledge is required to generate unifying theories that are useful for development of enduring strategies to address conflict.

The state of Chhattisgarh in India harbours an elephant metapopulation that has expanded its range from neighbouring Odisha and Jharkhand by passive dispersal since 2000 (Natarajan et al., 2023a). Unlike the natal dispersal of individual animals driven by evolutionary motivators (Bilby & Moseby, 2023), dispersal in this case is characterized by the mass movement of elephants from previous home ranges, presumably induced by environmental factors such as habitat saturation. Although elephants occurred historically in Chhattisgarh, they went locally extinct during the 1920s and returned only from 1988 onwards (Areendran et al., 2011; Natarajan et al., 2023a). The contemporary elephant range in Chhattisgarh, harbouring 250–300 elephants, continues to expand, with a concomitant increase in human–elephant conflicts (Natarajan et al., 2023a). Data from GPS satellite collars on 10 elephants indicated a mean annual elephant home range (95% minimum convex polygon) of 3,000 km², with profound individual variation (Nigam et al., 2022). Home ranges in Chhattisgarh are larger than in other areas in Asia (Sukumar, 2003; Williams, 2005; Fernando et al., 2008) as the elephants are distributed over fragmented habitats interspersed with human-use areas, where they exhibit extensive exploratory movements (Nigam et al., 2022). Increasing human–elephant interactions in the state have been attributed to such exploratory dispersal (Natarajan et al., 2023a,b). Although Chhattisgarh is a forest-rich state with extensive areas of potential elephant habitat, securing forest for long-term elephant conservation requires the development of effective conflict mitigation strategies.

Addressing conflict with elephants in Chhattisgarh requires knowledge of the ecological and social underpinnings of human–elephant interactions (IUCN, 2023). Although conservation managers have responded with a range of strategies, an assessment of the various aspects of human–elephant conflict is required. Because assessments are often scale-sensitive, evaluations at different spatial scales would be useful for disentangling the effects of environmental covariates, in particular because of the large home ranges of elephants in Chhattisgarh. Here, we evaluate patterns of crop losses from elephant foraging, at two spatial scales. The landscape-scale assessment, which covers nearly 80% of the elephant range in Chhattisgarh, is relevant for developing long-term plans and defining appropriate approaches for mitigating human–elephant conflict. The fine-scale assessment within a major conflict hotspot is relevant for quantifying crop losses and evaluating underlying spatial processes to help with preparing site-specific management plans. We assessed variations in the intensity of crop losses caused by elephants at the landscape scale and identified potential spatial correlates, and we quantified crop losses by elephants and assessed their spatial determinants at a finer spatial scale. Based on inductive reasoning we formulated hypotheses and a priori predictions for both objectives (Table 1). The novelty of our assessment lies in the context of a dispersing elephant population characterized by large and unstable home ranges.

Study area

Northern Chhattisgarh is part of the Central Highlands, comprising rugged hills, flat hilltops and forested plains (Rodgers & Panwar, 1988) over an elevation range of 400–1,200 m. More than 50% of the landscape is forested, with a mean annual rainfall of 800–1,600 mm and temperatures ranging from 5 °C during winter to 40 °C during summer. Rice is widely cultivated, together with seasonal vegetables, local varieties of pulses, maize, wheat and sugarcane. The forests are predominantly sal *Shorea robusta*-dominated moist and dry deciduous formations (Champion & Seth, 1968). The central plateau contains reserves of coal and iron ores, and mines and associated development have proliferated. The landscape is predominantly rural, with a human population density of c. 150 per km². Over 55% of the local populace are forest-dependent Kunwar, Baiga, Gond, Pando, Kudako, Pahari Korwa and Oraon communities (Nigam et al., 2022).

We assessed landscape-level crop loss in 10 Forest Divisions: Surguja, Surajpur, Balrampur, Jashpur, Manendragarh and Koriya administered under Surguja Forest Circle, and Katghora, Korba, Raigarh and Dharamjaigarh administered under Bilaspur Forest Circle (Fig. 1). The landscape includes four protected areas: Guru Ghasidas National Park (1,411 km²) and Tamor Pingla (543 km²), Semarsot (430 km²) and Badhalkol (104 km²) Wildlife Sanctuaries. We assessed fine-scale crop losses in a 1,200 km² conflict

TABLE 1 Selected covariates, based on a priori hypotheses regarding their potential influence on the intensity and probability of crop losses caused by Asian elephants *Elephas maximus* at the landscape and fine scales during 2015–2020 and February 2019–February 2020, respectively, in Chhattisgarh, India (Fig. 1). The land-use and land-cover map was a pre-classified layer developed by National Remote Sensing Centre of the Indian Space Research Organization during 2018.

Covariate	Measurement	A priori hypothesis
Landscape-scale assessment		
Intensity of elephant habitat use (hab-use)	Chhattisgarh Forest Department monitors elephant herds daily, collecting information on elephant presence. We collated presence information for 3 years (2017–2019), created an elephant habitat use map & assigned a value of high, medium, low or sporadic intensity of habitat use to each grid cell.	Intensity of crop losses will be high in areas of high use by elephants
Forest cover (for-cov)	Area (km^2), from the land-use & land-cover map	Crop losses will be high near forests, as forest cover is a determinant of elephant occurrence (Anoop et al., 2023)
Forest patch (for-pat)	Number of distinct forest patches, from the land-use & land-cover map	Intensity of crop losses will be high in grid cells with many forest patches as elephants could move between patches
Built-up area (blt-up)	Area (km^2), from the land-use & land-cover map	Elephants avoid grid cells with built-up areas because of disturbance & low crop availability
Fine-scale assessment		
Distance from road (dis-rod)	Euclidean distance (km) from grid cell centroid to nearest road, from the land-use & land-cover map	Crop losses by elephants will be low near roads because of better human vigilance there
Distance from forest (dis-for)	Euclidean distance (km) from grid cell centroid to nearest forest patch, from the land-use & land-cover map	Crop losses will be high near forest patches as elephants use them as refuges
Forest edge (for-edg)	Perimeter (km) of forest patches, from the land-use & land-cover map	A longer perimeter will result in higher probability of crop losses
Extent of agriculture (agr-cov)	Area (km^2), from the land-use & land-cover map	In areas with a high ratio of agricultural area to forest area, there will be a higher probability of crop losses
Distance from human settlement (dis-set)	Euclidean distance (km) from grid cell centroid to nearest settlement, from the land-use & land-cover map	In areas closer to human settlements, probability of crop losses will be lower
Mean shape index of forest patches (msi)	Mean of the sum of each patch's perimeter divided by the square root of the patch's area, from the land-use & land-cover map; indicates shape complexity and overall patch heterogeneity	Elephants will select forest patches with high mean shape index, as greater heterogeneity reflects better forage & microhabitat conditions for elephants

hotspot at the intersection of Surguja, Surajpur and Balrampur Forest Divisions in Surguja Circle (Fig. 1).

Methods

Secondary crop-loss data

For the landscape-level assessment we collated crop-loss records for 2015–2020, from Forest Departments. When elephants cause crop loss, the putative victim files a complaint with the Range Officer through the local Forest Guard. The Forest Range staff record crop-loss information and forward it to the Divisional Forest Officers for processing of compensation. Because of the administrative effort involved, villagers seldom report minor losses. Thus, there will be some level of under-reporting in all of the forest divisions. As we were interested in the broad spatial variations across northern Chhattisgarh, we assume that under-reporting will not affect our results, as this is expected to be uniform across forest divisions. To determine the intensity of crop loss per grid cell (Hoare, 1999; see data analysis below), we used the mean number of crop-loss days per grid cell for 2015–2020. We did not use the area of crops lost, as this is prone to measurement error.

Primary crop-loss data

We assessed fine-scale crop losses during February 2019–February 2020. We conducted this assessment only for a single year as it was logistically intensive. Two trained project assistants and a researcher recorded crop loss information. Enumerators coordinated with forest guards and local villagers to record crop type, location, growth stage at which damage occurred, and number of elephants involved and their sex. We used a measuring tape to record the approximate length and width of the area of crops lost. Because of the intensive monitoring of elephants by Chhattisgarh Forest Department and daily behavioural monitoring of elephants by the Wildlife Institute of India for a telemetry project during 2017–2021, we believe most crop losses were detected.

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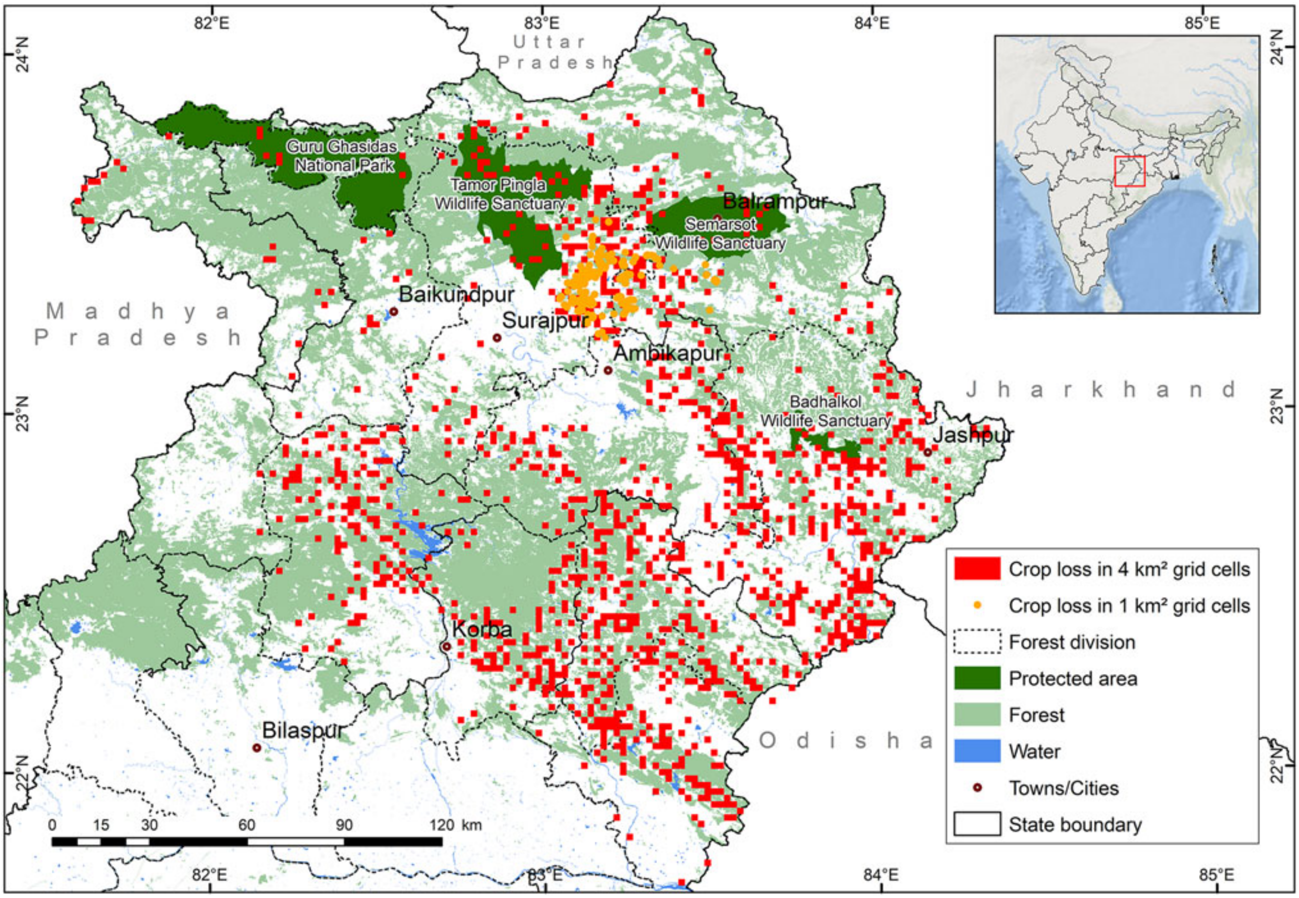

FIG. 1 Forest cover in northern Chhattisgarh, India, indicating the area in which we studied crop loss as a result of incursions by Asian elephants *Elephas maximus* at a landscape level (in 4 km^2 grid cells) during 2015–2020 and at a fine scale (in 1 km^2 grid cells) during February 2019–February 2020. (Readers of the printed journal are referred to the online article for a colour version of this figure.)

Data analysis

For the landscape-level assessment we overlaid a grid of 4 km^2 cells across northern Chhattisgarh. The cells were large enough to accommodate independent crop loss events and for the evaluation of covariate effects. As our objective was to assess variation in crop loss intensity, we excluded cells with no reported losses, resulting in a total of 1,126 cells. For each cell we calculated the mean number of crop-loss days per gid cell for 2015–2020. If multiple villages were located within a cell, we calculated the mean number of crop-loss days per grid cell pooled across villages. We used linear regression models to evaluate the effect of potential explanatory variables on the intensity of crop losses. We assumed the response variable, the mean number of crop-loss days per grid cell, followed a Gaussian distribution (Zuur et al., 2009).

For the fine-scale assessment we overlaid a grid of 1 km^2 cells on the intensive study area. This cell size allowed us to capture variations in the probability of crop loss. We eliminated cells with 100% forest cover and no crop fields, resulting in a total of 1,076 cells. We assumed that the response variable, the presence (1) or absence (0) of crop loss incidents, followed a binomial distribution.

We determined the covariates forest cover, number of distinct forest patches, built-up area and extent of agriculture, distance to the nearest road, settlement and forest, and length of forest perimeter from a pre-classified 10-m resolution map developed by the National Remote Sensing Centre of the Indian Space Research Organization for Chhattisgarh Forest Department.

We scaled the continuous explanatory variables used for both landscape-level and fine-scale analyses with the *Z* score transformation, to facilitate the interpretation of model coefficients (Zuur et al., 2009). We evaluated models with the Akaike information criterion (AIC), comparing plausible models in the candidate set with the intercept-only model (Burnham & Anderson, 2002). We compared the *Z* scores and confidence intervals of the model-averaged regression coefficients to rank the relative influence of covariates. For the top-ranking binomial regression models, we calculated the area under the receiver operating curve (AUC), with a cut-off value of ≥ 0.7 considered a good fit (Sitati et al., 2003). To compare the magnitude of crop losses

TABLE 2 Summary of model selection results for spatial variation in intensity of crop losses caused by Asian elephants at the landscape scale during 2015–2020.

Model[1]	AIC[2]	ΔAIC[3]	Akaike weight	Deviance	−2 log likelihood (df)	Cragg–Uhler R^2
crop-int ~ hab-use + for-cov + for-pat	3,396.5	0.0	0.423	1,329.4	1,691.2 (7)	0.12
crop-int ~ hab-use + for-cov + for-pat + msi	3,398.2	1.7	0.179	1,329.1	1,691.1 (8)	0.12
crop-int ~ hab-use + for-pat*for-cov	3,398.3	1.8	0.166	1,329.3	1,691.2 (8)	0.12
crop-int ~ hab-use + for-cov + for-pat + msi + blt-up	3,399.2	2.7	0.108	1,328.0	1,690.6 (9)	0.12
crop-int ~ hab-use + for-pat*for-cov + msi	3,400.2	3.7	0.067	1,329.1	1,691.1 (9)	0.12
crop-int ~ hab-use + for-pat*for-cov + msi + blt-up	3,401.2	4.7	0.041	1,327.9	1,690.6 (10)	0.12
crop-int ~ hab-use + for-cov	3,402.9	6.4	0.000	1,339.4	1,695.4 (6)	0.11
crop-int ~ hab-use	3,440.4	43.9	0.000	1,387.2	1,715.2 (5)	0.08
crop-int ~ for-cov	3,487.4	90.9	0.000	1,451.6	1,740.7 (3)	0.03
crop-int ~ for-pat	3,515.8	119.3	0.000	1,488.6	1,754.9 (3)	0.01
crop-int ~ msi	3,518.0	121.5	0.000	1,491.5	1,756.0 (3)	0.01
crop-int ~ blt-up	3,522.7	126.2	0.000	1,497.8	1,758.3 (3)	0.01
crop-int ~ 1 (intercept only)[4]	3,523.4	126.9	0.000	1,501.3	1,759.7 (2)	

[1]crop-int, intensity of crop loss; see Table 1 for description of other covariates.
[2]AIC, Akaike information criterion.
[3]ΔAIC, difference in AIC to the best-performing model.
[4]As this is an intercept only model, R^2 is not applicable.

TABLE 3 Parameter estimates for covariates included in the top models for landscape-scale intensity of crop losses caused by elephants during 2015–2020 (Table 2).

Variable[1]	Estimate ± SE	95% CI	Z	P
Intercept	0.35 ± 0.06	0.225–0.473	5.55	$< 2 \times 10^{-16}$***
hab-use:low	−0.66 ± 0.09	−0.832–−0.495	7.73	$< 2 \times 10^{-16}$***
hab-use:medium	−0.61 ± 0.08	−0.768–−0.443	7.33	$< 2 \times 10^{-16}$***
hab-use:sporadic	−0.69 ± 0.12	−0.920–−0.456	5.82	$< 2 \times 10^{-16}$***
for-cov	0.19 ± 0.05	0.109–0.271	4.61	4.1×10^{-6}***
for-pat	0.08 ± 0.03	0.025–0.128	2.90	0.0036**
msi	0.00 ± 0.04	−0.093–0.054	0.23	0.6375
Interaction:for-pat & for-cov	0.01 ± 0.04	−0.057–0.083	0.16	0.7707

[1]See Table 1 for description of covariates.
**P < 0.01; ***P < 0.001.

caused by solitary elephants and groups (≥ 2 elephants), we used Kruskal–Wallis χ^2 tests (Sokal & Rohlf, 2012). We performed statistical analyses in *R 3.5.3* (R Core Team, 2019), and extracted geographical variables using *ArcGIS 10.6* (Esri, USA).

Results

Landscape-level intensity of crop loss

During 2015–2020, crop losses resulting from elephant incursions were reported from a total of 1,426 villages and settlements (c. 20% of those in the landscape; Fig. 1) in 10 Forest Divisions and four protected areas across seven districts of northern Chhattisgarh. We evaluated 13 linear regression models to examine the influence of covariates on the intensity of crop loss (Table 2). There were no collinearity issues amongst covariates (variance inflation factor < 2; Zuur et al., 2009). For the three models with comparable support (ΔAIC < 2), we averaged the covariates across models to obtain parameter estimates (Table 3). The covariates in the top models were elephant habitat use, area of forest, number of forest patches and mean shape index of forest patches (Table 3). Nearly 47% of crop-loss reports were from areas of intensive habitat use by elephants (the reference category represented in the intercept in Table 3), compared to 23% from medium-use and 21% from low-use areas. Nearly 85% of crop loss incidences were reported in grid cells with forest cover. Intensity of crop losses caused by elephants was also positively correlated with the number of forest patches within grid cells but not with the mean shape index of forest patches (Table 3).

Fine-scale patterns of crop loss

We recorded 363 incidences of crop foraging by elephants from 60 villages and settlements in the intensive study area during February 2019–February 2020. The total area

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TABLE 4 Summary of model selection results for fine-scale probability of crop loss caused by Asian elephants during February 2019–February 2020.

Model[1]	AIC	ΔAIC	Akaike weight	Deviance	−2 log likelihood (df)	Cragg–Uhler R^2
crop-prob ~ dis-rod + dis-for + msi	725.7	0.0	0.439	717.7	358.8507 (4)	0.10
crop-prob ~ dis-rod +msi	726.1	0.4	0.350	720.1	360.0735 (3)	0.10
crop-prob ~ dis-rod + dis-for + msi + for-edg	727.1	1.4	0.210	717.1	358.5853 (5)	0.11
crop-prob ~ dis-rod	745.3	19.6	0.000	741.3	370.6602 (2)	0.06
crop-prob ~ msi	757.7	32.0	0.000	753.6	376.8308 (2)	0.04
crop-prob ~ dis-for	759.1	33.4	0.000	755.1	377.5677 (2)	0.04
crop-prob ~ for-edg	768.2	42.5	0.000	764.2	382.1143 (2)	0.02
crop-prob ~ 1 (intercept only)[2]	779.1	53.4	0.000	777.1	388.5518 (1)	
crop-prob ~ dis-set[2]	779.1	53.4	0.000	775.1	−387.5713 (2)	
crop-prob ~ agr-cov[2]	779.2	53.5	0.000	775.2	−387.6202 (2)	

[1]See Table 1 for description of covariates.
[2]R^2 is not applicable.

TABLE 5 Parameter estimates for covariates included in the top models for fine-scale probability of crop losses caused by Asian elephants during February 2019–February 2020.

Variable[1]	Estimate ± SE	95% CI	Z	P
Intercept	−2.24 ± 0.12	−2.47–−2.01	19.42	$< 2 \times 10^{-16}$***
dis-rod	0.53 ± 0.09	0.35–0.71	5.71	$< 2 \times 10^{-16}$***
dis-for	−0.29 ± 0.20	−0.68–0.09	1.49	0.135
msi	0.39 ± 0.14	0.11–0.67	2.70	0.007**
for-edg	−0.12 ± 0.16	−0.43–0.20	0.72	0.469

[1]See Table 1 for description of covariates.
**P < 0.01, ***P < 0.001.

of crop loss from elephant incursions was 12.4 ha, comprising sugarcane, rice, maize, wheat, tomatoes, seasonal vegetables, mustard, green peas and local varieties of pulses. Loss of sugarcane was greatest (5.81 ha, 214 crop-loss days), followed by rice (3.50 ha, 64 crop loss-days), maize (1.73 ha, 23 crop loss-days) and wheat (0.68 ha, 42 crop loss-days). Losses of other crops were relatively minimal. The period of losses to cereals and maize mirrored the local crop cultivation cycles. Crop losses caused by elephant groups were higher than losses caused by solitary elephants (11.2 ha vs 1.2 ha; Kruskal–Wallis $\chi^2 = 305.78$, df = 237, P = 0.001).

We evaluated 10 binomial regression models to compare grid cells with and without crop losses caused by elephants (Table 4). Collinearity between covariates was not significant (variance inflation factor < 4). Three models in the candidate list were comparable (ΔAIC < 1.4), with an adequate fit (AUC = 0.71) and were averaged to estimate parameters (Table 5). Distance to the nearest road best explained variations in the presence/absence of crop loss caused by elephants (Table 5), with probability of crop loss increasing with decreasing distance from roads. Approximately 67% of the grid cells with elephant-related crop losses were > 3.5 km from the nearest road. The probability of crop loss also increased in forest patches with a relatively high mean shape index (Table 5), but not with distance to the nearest forest or length of the forest perimeter (Table 5).

Discussion

Landscape-level patterns of crop loss

Although the elephant population of Chhattisgarh is relatively small (Natarajan et al., 2023a), crop losses caused by elephants were widespread across c. 39,000 km² of forest–agriculture mosaic. Patterns of crop loss were primarily explained by the intensity of elephant habitat use, with crop losses higher in locations of intensive habitat use. This is probably a result of both bulls and groups of female elephants foraging on crops in human-dominated areas, a situation that is less likely in relatively intact forest habitats, where female herds seldom forage on agricultural crops (Sukumar, 2003; Williams, 2005; Ahlering et al., 2011; Chiyo et al., 2011).

In Chhattisgarh the boundaries between forest and agricultural areas are diffuse, presenting a continual opportunity for elephants to forage in a range of crops. In social animals such as elephants, foraging strategies can spread across a population through cultural learning (Lee & Moss, 1999). Thus, even opportunistic exposure to crop foraging can become a reward-guided behaviour (Ball et al., 2022) if the perceived risks associated with crop consumption are low.

In human-dominated landscapes, elephant crop foraging behaviour not only affects the livelihoods of farming

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communities but also has a negative effect on elephant conservation, as illustrated by the relatively high elephant mortalities that result from conflict (Goswami et al., 2014; LaDue et al., 2021). These mortalities indicate that crop foraging is a high-risk, maladaptive strategy for elephants in the long term. As documented in social animals such as bottlenose dolphins and primates, maladaptive foraging entails the selection of suboptimal areas as habitat without considering the threats to survival (Delibes et al., 2001; Donaldson et al., 2012; Hale & Swearer, 2017). Given this, the ongoing expansion of elephants into human-dominated areas with patchy forest cover in east-central India could be analogous to the paradigm of an ecological trap (Battin, 2004), with long-term negative impacts on elephant conservation (Pandey et al., 2024).

Forest cover and number of forest patches also influenced the intensity of crop losses caused by elephants. Forest cover is often the main determinant of elephant occupancy (Anoop et al., 2023), and crop losses were minimal in areas that lacked such cover. The higher crop losses in areas with more forest patches suggest elephants select patchy habitats over relatively intact habitats, to maximize crop foraging opportunities.

Fine-scale patterns of crop loss

As expected, the probability of elephants feeding on crops was low in fields near roads. Plausible explanations for this include a higher detection rate of elephants near roads, better vigilance by farmers and the response measures that limit elephant movement. In our study site there is a network of unpaved roads and trails that facilitate patrolling with vehicles. Response teams comprising forest staff and volunteers from the local group Hathimitra Dal (Friends of Elephants) patrol the roads in vehicles that carry public address systems for disseminating information on elephant movement, helping farmers reinforce crop guarding. Although roads have negative effects on tropical forest ecology (Laurance et al., 2009), in this predominantly agricultural landscape with sparse forest cover, mapping the existing road network and using it strategically for patrolling can support early warning of potential incursions of elephants into crops.

Our findings also showed that crop damage by elephants was more likely to occur close to forest patches. This is consistent with research conducted in human-dominated forest–agricultural systems harbouring elephant populations (Graham et al., 2010; Bal et al., 2011; Goswami et al., 2015). Although the estimated effects indicated only a weak relationship with probability of crop loss by elephants, we urge caution when carrying out habitat improvement activities such as surface water augmentation in small forest patches, as these areas could become daytime refuges for elephants and hence perpetuate conflict. The variations in probability of crop loss by elephants were further explained by the effect of the mean shape index of forest patches. In Surguja, high values of the mean shape index indicate habitat heterogeneity, with a mosaic of environmental conditions within the patch. Elephants seem to prefer such forest patches over those that are more homogeneous.

In Surguja, although elephants consumed 10 crop types, losses were substantial only for sugarcane, rice, maize and wheat. Losses of sugarcane to elephants occurred throughout the year. To minimize losses, cultivation of crops that are less palatable for elephants has been widely advocated in various landscapes (Gross et al., 2016; Neupane et al., 2017). However, the political economy and other complex socio-economic factors dictate farmers' choice of crops, and thus it is overly simplistic to suggest that cultivation of alternative crops is a solution. In economically disadvantaged districts affected by negative human–elephant interactions, switching to alternative crops could potentially affect the food security of local communities. Even if alternative crops are planted in patchy habitats, considering both the high mobility and generalist diet of elephants, conflict could simply be deflected to new areas.

Management implications

Our work demonstrates that the environmental variables chosen a priori could explain spatial variations in both the intensity of crop loss at the landscape scale and the probability of crop loss at a fine scale. The monitoring of elephants in human-dominated landscapes could provide data to facilitate improved understanding of negative human–elephant interactions. The predictive power of the models might be enhanced by including behavioural variables such as movement of individuals and space-use decisions by elephants. For instance, observations of radio-collared elephants in Chhattisgarh indicate significant movement across forest patches by elephants in response to both conspecific attraction and avoidance (L. Natarajan, pers. obs., 2018–2020). Such movements are common rather than exceptional, and would be difficult to explain only through reference to environmental variables. Furthermore, human behavioural responses to crop foraging by elephants can be strong determinants of the spatial patterns of crop losses (Sukumar, 2003). This indicates the need for long-term behavioural monitoring of elephants in human-dominated areas.

As our research shows that areas with high crop losses are also areas that elephants use intensively, management to increase the time elephants spend within large and connected forest patches could be critical in the long term. In Surguja, the forest complex of Tamor Pingla Wildlife Sanctuary, Guru Ghasidas National Park and connected habitats in Surajpur and Balrampur Forest Divisions could harbour more elephants than at present if habitat improvement activities could be prioritized. In addition, to minimize crop losses at the interface between agricultural areas and forest, the use of portable barriers should be trialled, as the high perimeter-to-area ratio of forest patches, the interspersion of forest with agriculture and variable elephant home ranges preclude the use of permanent barriers in northern Chhattisgarh. In addition, it may be appropriate to institutionalize the participatory elephant monitoring already occurring in Chhattisgarh. Even moderately effective interventions such as daily community monitoring of elephants and of negative interactions with people, the development of site-specific early-warning measures and the timely payment of ex gratia relief to affected communities could significantly contribute to reducing the impacts of crop losses caused by elephants (Denninger Snyder & Rentsch, 2020).

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Conflicts of interest None.

Ethical standards This research abided by the *Oryx* guidelines on ethical standards and followed the guidelines of the British Sociological Association.

Data availability The data that support the findings of the study are available upon resonable request from the corresponding author. The data are not publicly available as they are part of a long-term study.

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