

# Who is most at risk? Factors associated with fatal outcomes of leopard attacks in a sugarcane-dominated landscape of Bijnor, northern India

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## Research Article

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# Abstract

Human-leopard interactions are increasing across human-dominated landscapes in India, yet the factors associated with fatal attack outcomes remain poorly understood. We evaluated fatal versus non-fatal outcomes for 142 victims from 138 verified direct leopard attack incidents recorded in Bijnor district, northern India, during 2019–2025. Incidents were compiled from Forest Department records, complaint registers, archived media reports, field investigations, and semi-structured interviews. Associations between attack outcome and demographic, social, temporal, behavioural, and site-context variables were first examined using contingency analyses. Eight biologically informed logistic-regression models were then compared using Akaike's Information Criterion corrected for small sample size (AICc) on a common complete-case dataset of 142 victims. The top-ranked model included victim age class, party presence, and season (Akaike weight = 0.788). Compared with adults, children had higher odds of a fatal outcome (odds ratio [OR] = 9.18, 95% confidence interval [CI] = 3.22–30.47). Individuals accompanied by others had lower odds of a fatal outcome than solitary individuals (OR = 0.08, 95% CI = 0.03–0.22). Compared with summer, attacks during the monsoon had higher odds of a fatal outcome (OR = 4.71, 95% CI = 1.55–15.40). Older adults and winter did not differ significantly from their reference categories. The final model showed good discrimination (AUC = 0.837, 95% CI = 0.769–0.905). Prevention efforts could prioritize child supervision, group movement in dense crops, improved visibility around settlement edges, and monsoon-focused warnings. These findings concern severity among reported attacks and should not be interpreted as estimates of population-level attack risk.

## 1. Introduction

Conflict involving large carnivores is a growing conservation challenge in landscapes where persistent or recovering carnivore populations share space with dense human populations (Conover, 2002; Inskip and Zimmermann, 2009; Lamb et al., 2020; Bombieri et al., 2023). Livestock depredation is the most frequent form of conflict in many landscapes, but attacks on people are its most severe consequence. Such attacks threaten human life and livelihood, intensify fear, affect public support for conservation, and can prompt urgent management actions (Loe and Roskaft, 2004; Dhanwatey et al., 2013; Acharya et al., 2016). Because attacks are uncommon relative to daily human-carnivore encounters, carefully documented case series remain important for identifying recurring circumstances and developing proportionate safety measures (Penteriani et al., 2016; Bombieri et al., 2023).

The leopard (*Panthera pardus*) is unusually adaptable among large felids. Across South Asia, leopards occupy protected forests, plantations, agricultural mosaics, and peri-urban settings, sometimes at high density near people (Athreya et al., 2013; Kshetry et al., 2017; Paul et al., 2024). Tall production crops, tea plantations, riparian vegetation, and wooded field boundaries provide concealment and movement cover, while domestic animals and free-ranging dogs may supplement wild prey (Vijayan and Patil, 2002; Athreya et al., 2016; Kshetry et al., 2018). These conditions permit coexistence but also create opportunities for sudden close encounters during farming, travel, resource collection, or routine activity near settlements. Human injuries and fatalities attributed to leopards have consequently been reported

in across several regions of India and Nepal (Bhattacharjee and Parthasarathy, 2013; Acharya et al., 2016; Sidhu et al., 2017; Naha et al., 2018; Shivakumar et al., 2023).

Previous research has largely examined where and when conflict occurs, including spatial clustering, landscape predictors, or community perceptions (Kshetry et al., 2017; Naha et al., 2018, 2020; Ankit et al., 2021). These studies are essential for understanding encounter occurrence, yet the factors associated with encounter occurrence are not necessarily those associated with severity once physical contact has begun. Once an attack occurs, its outcome may depend more directly on victim characteristics and the immediate social, temporal, and behavioural context of the encounter. Existing evidence suggests that children are disproportionately represented among fatalities, whereas attacks involving accompanied individuals are less likely to result in death (Treves and Naughton-Treves, 1999; Garrote et al., 2017; Penteriani et al., 2017; Bombieri et al., 2023). Seasonal conditions and encounter circumstances may also influence attack outcomes, but their relative importance remains poorly understood and may vary among landscapes (Naha et al., 2018). Therefore, identifying factors associated with fatal versus non-fatal leopard attack outcomes remains an important knowledge gap in human-leopard conflict research, particularly in shared agricultural landscapes.

Distinguishing attack severity from attack occurrence has direct management value. Measures intended to reduce encounters with leopards differ from those intended to reduce mortality after an encounter, including child supervision, group movement, and rapid access to medical care. A case-only analysis such as ours begins with people who have already been attacked and therefore addresses severity rather than the probability of being attacked. Its strength is a narrower question: among people already attacked, which routinely recorded characteristics are associated with fatal versus non-fatal outcomes? Keeping this estimand explicit helps avoid interpreting a high fatality proportion within attacks as evidence that a particular group is more likely to be attacked. In the absence of local evidence, management responses may be reactive, including capture, or translocation after a serious incident (Athreya et al., 2007, 2011; Naha et al., 2018). A severity-focused analysis can therefore help identify groups and circumstances requiring priority without implying that every leopard presence represents equivalent danger.

Bijnor district, Uttar Pradesh, provides a pertinent case study. Its agricultural matrix surrounds the Amangarh Tiger Reserve and adjoining forest divisions, and sugarcane occupies extensive areas for much of the year. Leopards use this shared landscape, and both fatal and non-fatal attacks have been recorded since 2019 (Chauhan and Ahmed, 2025). Nevertheless, no quantitative study has tested the relative support for competing explanations of fatal outcome in this landscape.

We therefore analysed verified direct leopard attacks recorded during 2019–2025 to evaluate demographic (age class and gender), social (party presence), temporal (season and time period), behavioural (activity and posture), and site-context predictors associated with fatal outcomes. We hypothesized that (1) children would have higher odds of fatal outcomes than adults because of greater physical vulnerability, (2) solitary victims would have higher odds of fatal outcomes than accompanied

victims because companions may provide immediate assistance or interrupt attacks, and (3) monsoon attacks would have higher odds of fatal outcomes than those during summer and winter because increased vegetation density may reduce visibility and delay detection or rescue. Our inference is explicitly conditional on an attack having been reported and verified; it does not estimate the probability that a person or activity will result in an attack.

## 2. Materials and methods

### 2.1 Study area

The study was conducted in Bijnor district, Uttar Pradesh, India (29°02'-29°58' N, 78°00'-78°57' E), covering approximately 4,561 km<sup>2</sup>. Bijnor lies in the Upper Gangetic Plains at the western edge of the Terai Arc Landscape and the Shivalik foothills (Rodgers and Panwar, 1988; Biswas et al., 2023). The district contains reserve and production forests, cropland, plantations, wetlands, rivers, irrigation canals, and densely settled villages. Human population density is approximately 807 persons/km<sup>2</sup>, about 74.9% of residents are rural, and agriculture and allied activities are major livelihoods (Directorate of Census Operations, Uttar Pradesh, 2016). Approximately 16.4% of the district population is multidimensionally poor (MPI = 0.07; NITI Aayog, 2023).

The study extent included the Bijnor Social Forestry Division, Amangarh Tiger Reserve, and Najibabad Forest Division. These forests form part of the Rajaji-Corbett conservation landscape (Johnsingh and Negi, 2003). Recorded forest cover represents approximately 549 km<sup>2</sup> (11.8% of the district), whereas net sown area is approximately 3,960 km<sup>2</sup> (Directorate of Economics and Statistics, 2015; MSME-Development Institute, Agra, 2016). The large extent of cultivated land underscores the predominantly agricultural character of the landscape in which people and leopard interact.

Bijnor experiences a tropical monsoonal climate; most annual rainfall occurs during June-September (Bhatla et al., 2023). Sugarcane is the principal crop, followed by wheat, rice, and eucalyptus and poplar plantations. Approximately 2,639 km<sup>2</sup> was under sugarcane during the 2023–2024 growing season (Munjal, 2024). Harvesting generally extends from November to April, with a December-March peak, but staggered planting and harvesting leave standing cane in parts of the landscape during most months (NITI Aayog, 2020). Rapid monsoon growth produces tall, dense stands that can reduce visibility and provide cover for wildlife (Rajput et al., 2023). Rivers, canals, wetlands, plantations, and crop mosaics further contribute to habitat heterogeneity within areas used daily by people.

The mammal assemblage includes Indian leopard (*Panthera pardus fusca*), Bengal tiger (*Panthera tigris tigris*), Asian elephant (*Elephas maximus*), fishing cat (*Prionailurus viverrinus*), swamp deer (*Rucervus duvaucelii*), hog deer (*Axis porcinus*), and nilgai (*Boselaphus tragocamelus*) (Paul et al., 2018; Reza et al., 2024; Khadija et al., 2025). Figure 1 shows land cover and the 132 verified incidents for which spatial coordinates were available.

## 2.2 Incident compilation and verification

Leopard attacks were compiled from official records of the Bijnor Social Forestry Division and Najibabad Forest Division, Forest Department complaint registers, archived online news reports, field investigations, and interviews. Departmental records were consistently available from 2022 onward. Earlier incidents (2019–2021) were identified primarily through complaint registers and archived reports and subsequently verified through local filed checks. Field monitoring during 2025 documented new incidents through site visits and interviews. Capture and rescue records for 2021–2025 were extracted separately to summarize management responses; these operations were not treated as predictors of victim outcome.

An attack was defined as direct physical contact between a leopard and a person resulting in injury or death (Bombieri et al., 2023; Shivakumar et al., 2023). Sightings, non-contact encounters, contact limited to clothing, injuries not attributable to a leopard, and motorcycle-related reports lacking verifiable physical contact were excluded. Human-initiated encounters - including approaching, chasing, checking, rescuing, or attempting to capture a leopard, and intervention to protect livestock - were excluded because they represent a different exposure process. Secondary victims injured while rescuing a primary victim were also excluded from the severity analysis.

Field verification used a standardized incident questionnaire and semi-structured interviews with victims, relatives, eyewitnesses, village representatives, and Forest Department staff. Interviews documented victim characteristics, timing and activity, party presence, attack setting, leopard behaviour, and post-incident response. Media-identified cases were retained only after local corroboration. Likely predatory behaviour was assigned only when available evidence indicated prey-oriented actions such as killing followed by dragging, carrying, attempted removal, or partial consumption, consistent with Penteriani et al. (2017). Because motive cannot be established reliably from retrospective accounts, this category is described as "likely predatory" rather than treated as definitive intent. The screening process is summarized in Supplementary Figure S1. Research permission was granted by the Uttar Pradesh Forest Department (Letter No. 1649/23-2-12(G), 17 December 2024).

The use of complementary sources was intended to improve case ascertainment and contextual detail. Official registers supplied dates, administrative locations, outcome, and management action; field visits and interviews were used to resolve encounter circumstances and screen media reports. A record was excluded when direct contact, species attribution, outcome, or another essential eligibility element could not be corroborated. Information quality nevertheless differed among cases and years. For this reason, the analysis emphasizes victim-level outcome associations and does not treat the observed annual increase as a direct measure of changing incidence.

## 2.3 Analytical dataset and variable classification

The initial compilation contained 148 incidents involving 169 people: 115 incidents reconstructed for 2019–2024 and 33 documented in 2025. After verification and eligibility screening, the descriptive

dataset comprised 142 direct-attack incidents involving 146 primary victims. Field verification was completed for 132 attack incidents (93.0%). Four incidents involved two primary victims each and contributed eight victims (5.5% of the analytical sample). The victim was the unit of analysis because fatality is an individual outcome. Multi-victim incidents represented 2.8% of attacks; because clustering was limited to four incidents, models did not include an incident-level random effect. Potential residual non-independence is acknowledged as a limitation.

Separating incidents from victims was necessary throughout data handling. An incident was a single leopard-human event, whereas each directly attacked primary person contributed one outcome record. This distinction prevents rescue-related injuries from being counted as equivalent initiating encounters and permits age and party attributes to remain victim-specific. It also means that map symbols represent incidents, annual and demographic summaries represent victims, and capture operations represent management events; denominators are stated for each result to avoid mixing these units.

Outcome was coded fatal (1) or non-fatal (0). Predictors were defined a priori: age class (child, 0–15 years; adult, 16–59; older adult, 60 or more), gender, party presence (alone or accompanied), season (summer, March-June; monsoon, July-September; winter, October-February), time period, activity, posture, and attack-site context. Time was grouped as morning twilight (05:00–08:00), daytime (08:00–17:00), evening twilight (17:00–20:00), and nighttime (20:00–05:00). Full coding is provided in Supplementary Table S1. Variables describing victim or companion response, tool use, barriers, leopard disengagement, and information source were retained for description but excluded from multivariable models because of missingness, sparse categories, temporal ordering, or their post-attack nature.

Four victims lacked usable information required by the common model dataset, leaving 142 victims from 138 incidents for candidate-model comparison. All eight candidate models were fitted to this same complete-case dataset so that AICc values were directly comparable. Descriptive statistics used all 146 victims where the relevant variable was available.

## 2.4 Statistical analysis

Fatal and non-fatal counts were cross-tabulated for each predictor. Pearson chi-square tests were used when expected frequencies were adequate; Fisher exact tests were used otherwise. For significant chi-square tests, standardized residuals identified cells contributing to the association. Significant multi-category Fisher tests were followed by pairwise Fisher tests with Holm adjustment. Cramer's V summarized effect size. Age in years was compared between outcome groups using a Wilcoxon rank-sum test with effect size  $r$ . These bivariate analyses were descriptive and were not used as a variable-selection filter.

Fatality was modelled using binomial generalized linear models with a logit link. Generalized variance-inflation factors were inspected before fitting. Eight biologically motivated candidate models represented null, vulnerability, social-protection, temporal, exposure, integrated-vulnerability, seasonal-integrated, and global hypotheses (Table 1). Models were ranked by AICc, delta AICc, and Akaike weight

(Supplementary Table S2). The model with the lowest AICc was used for primary inference, and nested models were compared with likelihood-ratio tests. Coefficients are reported as odds ratios with Wald 95% CIs.

Table 1

*A priori* candidate logistic regression models representing alternative biological hypotheses for variation in fatal outcome.

| Model | Hypothesis               | Predictors                          | Rationale                                                                     |
|-------|--------------------------|-------------------------------------|-------------------------------------------------------------------------------|
| M0    | Null                     | Intercept only                      | Fatality is constant across attacks.                                          |
| M1    | Vulnerability            | Age class + gender                  | Physical vulnerability varies with age and gender.                            |
| M2    | Social protection        | Party presence                      | Companions may improve detection, deterrence, and rescue.                     |
| M3    | Temporal risk            | Season + time period                | Exposure and encounter conditions vary temporally.                            |
| M4    | Exposure context         | Activity + posture + site context   | Behaviour and setting may affect detection and escape.                        |
| M5    | Integrated vulnerability | Age class + party presence          | Combines individual vulnerability and immediate social protection.            |
| M6    | Seasonal integrated risk | Age class + party presence + season | Combines vulnerability, social protection, and seasonal encounter conditions. |
| M7    | Global                   | All eight predictors                | Reference model containing every measured predictor.                          |

The candidate set was intentionally limited and hypothesis-based rather than generated by automated stepwise selection. Delta AICc describes the relative distance from the best-supported model within this specified set, while Akaike weight describes relative support conditional on the candidate set. Neither statistic proves that a model is true or that an included variable is causal. Because AIC values are comparable only for models fitted to identical observations and response data, the same 142-victim complete-case dataset was used for every candidate, including models that did not themselves require the variables responsible for missingness.

Estimated marginal means were calculated on the response scale, with Tukey-adjusted pairwise contrasts where appropriate. Exploratory models replacing season with time period and including age-by-party and age-by-season interactions were examined separately and are reported in Supplementary File 1. Simulation-based residual diagnostics assessed uniformity, dispersion, outliers, and conditional quantile patterns; Cook's distance assessed influence. McFadden and Tjur pseudo- $R^2$  values summarized explanatory power. Internal discrimination was described by the ROC AUC with 95% CI, and stability was evaluated using repeated 10-fold cross-validation. These measures represent internal rather than external validation.

Analyses were conducted in R 4.5.1 using *readxl*, *rcompanion*, *MuMIn*, *car*, *performance*, *DHARMa*, *broom*, *emmeans*, *pROC*, and *boot*. Scripts and analytical data are provided as Supplementary Scripts 1–2 and Supplementary Data 1–2. The study map used the Esri 2021 Land Cover dataset at 10 m resolution and was prepared in QGIS 3.44 "Solothurn" (Esri, 2022; QGIS Development Team, 2025).

## 3. Results

### 3.1 Victim and attack characteristics

The 142 verified incidents involved 146 primary victims, of whom 45 had fatal and 101 had non-fatal outcomes. Annual totals increased sharply after 2022, reaching 44 victims in 2023, 31 in 2024, and 34 in 2025 (Fig. 2A). Because observation systems differed among years, these counts should not be interpreted as a standardized temporal trend.

Summer accounted for 61 victims (11 fatal, 50 non-fatal), winter for 50 (15 fatal, 35 non-fatal), and the monsoon for 35 (19 fatal, 16 non-fatal; Fig. 2B). The sample included 46 children (23 fatal), 85 adults (17 fatal), and 15 older adults (5 fatal; Fig. 2C). Forty-three victims were alone (26 fatal), whereas 103 were accompanied (19 fatal; Fig. 2D). There were 89 male victims (22 fatal) and 57 female victims (23 fatal).

Victim age ranged from 0.6 to 70 years (mean  $\pm$  SD =  $31.3 \pm 20.0$ ; median = 34). Fatal victims were younger (median = 14 years, IQR = 10–40,  $n = 45$ ) than non-fatal victims (median = 36, IQR = 18–46,  $n = 101$ ; Wilcoxon  $W = 1688.5$ ,  $P = 0.013$ ). The effect size was small ( $r = 0.21$ ), indicating considerable overlap between distributions.

Daytime accounted for 65 victims (15 fatal), evening twilight for 39 (19 fatal), morning twilight for 26 (3 fatal), and nighttime for 16 (8 fatal). Most victims were in agricultural settings (115; 33 fatal), followed by settlement settings (27; 12 fatal). One non-fatal forest case and three cases without usable site context were excluded from context comparisons. Seventy-four victims were in a low posture (26 fatal) and 69 were upright (19 fatal); posture was unavailable for three. Activities were agricultural or livelihood-related for 72 victims (17 fatal), routine movement or resource use for 47 (19 fatal), and recreational or resting for 27 (9 fatal). Table 2 consolidates category counts, fatality proportions, and bivariate tests.

Table 2

Distribution of fatal and non-fatal outcomes across victim and attack characteristics. Fatality percentage is calculated within each category. Tests evaluate the variable as a whole.

| Variable            | Category                | Fatal n | Non-fatal n | Fatality (%) | Test         | P       | V    |
|---------------------|-------------------------|---------|-------------|--------------|--------------|---------|------|
| Age class           | Child                   | 23      | 23          | 50.0         | Fisher exact | < 0.01  | 0.29 |
|                     | Adult                   | 17      | 68          | 20.0         |              |         |      |
|                     | Older adult             | 5       | 10          | 33.3         |              |         |      |
| Party presence      | Alone                   | 26      | 17          | 60.5         | Chi-square   | < 0.001 | 0.41 |
|                     | Group                   | 19      | 84          | 18.4         |              |         |      |
| Gender              | Male                    | 22      | 67          | 24.7         | Chi-square   | 0.046   | 0.17 |
|                     | Female                  | 23      | 34          | 40.4         |              |         |      |
| Season              | Summer                  | 11      | 50          | 18.0         | Chi-square   | 0.001   | 0.31 |
|                     | Monsoon                 | 19      | 16          | 54.3         |              |         |      |
|                     | Winter                  | 15      | 35          | 30.0         |              |         |      |
| Time period         | Morning twilight        | 3       | 23          | 11.5         | Fisher exact | < 0.01  | 0.34 |
|                     | Daytime                 | 15      | 50          | 23.1         |              |         |      |
|                     | Evening twilight        | 19      | 20          | 48.7         |              |         |      |
|                     | Nighttime               | 8       | 8           | 50.0         |              |         |      |
| Attack-site context | Agricultural            | 33      | 82          | 28.7         | Chi-square   | 0.113   | 0.13 |
|                     | Settlement              | 12      | 15          | 44.4         |              |         |      |
| Activity            | Agricultural/livelihood | 17      | 55          | 23.6         | Chi-square   | 0.145   | 0.16 |
|                     | Movement/resource use   | 19      | 28          | 40.4         |              |         |      |
|                     | Recreational/resting    | 9       | 18          | 33.3         |              |         |      |

Notes: Context analysis excludes one forest case and three cases without usable context. Posture totals are 143 (three unavailable). Exact multi-category post hoc comparisons are reported in the Results. V = Cramer's V. Exact P values are shown where available; Fisher exact results are presented as thresholds.

| Variable                                                                                                                                                                                                                                                                                                                | Category | Fatal n | Non-fatal n | Fatality (%) | Test       | P     | V    |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------|---------|-------------|--------------|------------|-------|------|
| Posture                                                                                                                                                                                                                                                                                                                 | Low      | 26      | 48          | 35.1         | Chi-square | 0.328 | 0.08 |
|                                                                                                                                                                                                                                                                                                                         | Upright  | 19      | 50          | 27.5         |            |       |      |
| Notes: Context analysis excludes one forest case and three cases without usable context. Posture totals are 143 (three unavailable). Exact multi-category post hoc comparisons are reported in the Results. V = Cramer's V. Exact P values are shown where available; Fisher exact results are presented as thresholds. |          |         |             |              |            |       |      |

## 3.2 Encounter context and management responses

Of the 142 verified leopard attack incidents, 66 met the study's criteria for likely predatory behaviour, including all 45 fatal attacks. Partial consumption was recorded in 16 fatal cases. Seven victims died after transport to a medical facility; the remaining deaths occurred at or near the attack site. Defensive objects were reportedly used in six fatal incidents. Among non-fatal incidents (n = 97) for which disengagement could be categorized, leopards withdrew without direct intervention in 42 and after victim resistance, companion intervention, crowd arrival, or other human action in 47; disengagement information was unavailable in four. Four incidents involved attacks on multiple victims. Defensive objects such as spades, sickles, buckets, or sugarcane stalks were used in 39 non-fatal incidents. These response variables were described but not modelled because they occur during or after the attack and may be strongly affected by outcome.

All 27 settlement incidents occurred along village edges adjoining agricultural land. Twenty-three occurred between 18:30 and 06:30. Electricity was reported at the time in only two cases; other attacks occurred under poor or absent illumination. Partial barriers such as open gates or low walls were present in six cases.

Five leopards (two adult males and three adult females) were killed after attacks on people. Forest Department records listed 73 management-driven captures during 2021–2025 in response to attacks on people, livestock depredation, or repeated settlement sightings. Twenty captures followed attacks on people (16 fatal and four non-fatal incidents). Only four captured animals showed obvious sign of injury, advanced age, or poor condition; the remaining individuals appeared to be in good physical condition. Captured leopards were moved to zoos or forest sites, but individual identification and post-release monitoring were unavailable, preventing evaluation of whether removal reduced subsequent risk.

## 3.3 Bivariate and multivariable predictors

Attack Outcome showed bivariate association with age class, party presence, gender, season, and time period (Table 1). Children had a higher fatal proportion than adults (Holm-adjusted  $P = 0.0019$ ); comparisons involving older adults were not significant. Fatal outcomes were overrepresented among solitary victims, during the monsoon, and, more weakly among female victims. Evening-twilight fatality

exceeded daytime and morning-twilight fatality, and nighttime fatality exceeded morning twilight in adjusted pairwise tests. Site context, activity, and posture were not associated with outcome.

For party presence, standardized residuals were + 5.01 for solitary victims and – 5.01 for accompanied victims ( $\chi^2 = 25.12$ ,  $P < 0.001$ ). Monsoon fatalities were overrepresented (residual = 3.45), whereas summer fatalities underrepresented (residual = -2.84;  $\chi^2 = 13.73$ ,  $P = 0.001$ ); winter was close to expectation. Female victims showed a weaker positive association with fatal outcome (residual = 2.00;  $\chi^2 = 3.98$ ,  $P = 0.046$ ). Time-period post hoc tests indicated higher fatality in evening twilight than daytime (adjusted  $P = 0.021$ ) or morning twilight (adjusted  $P = 0.007$ ), and at night than during morning twilight (adjusted  $P = 0.042$ ). These unadjusted associations were not interpreted as independent effects.

The seasonal-integrated model containing age class, party presence, and season received the strongest support (AICc = 137.9, weight = 0.788; Supplementary Table S2). It outperformed the integrated age-plus-party model ( $\Delta\text{AICc} = 3.93$ ) and the global model ( $\Delta\text{AICc} = 4.10$ ). Adding season to age and party presence improved fit (likelihood-ratio chi-square = 8.26, df = 2,  $P = 0.016$ ).

In the top-ranked model, children had higher odds of a fatal outcome than adults (OR = 9.18, 95% CI = 3.22–30.47,  $P < 0.001$ ). Accompanied victims had substantially lower odds of fatal outcome than solitary victims 0.08 times the odds compared with solitary victims (OR = 0.08, 95% CI = 0.03–0.22,  $P < 0.001$ ), whereas the odds of fatal outcome were higher during the monsoon than during summer attacks (OR = 4.71, 95% CI = 1.55–15.40,  $P = 0.008$ ). Neither older adults nor winter differed significantly from their respective reference categories (Table 3, Supplementary Figure S2).

Table 3  
Top-ranked logistic regression model for fatal leopard attack outcome (n = 142 victims).

| Predictor contrast                                                                                                                                                                                                                                                                   | Beta   | SE    | OR   | 95% CI     | P       |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------|-------|------|------------|---------|
| Child vs adult                                                                                                                                                                                                                                                                       | 2.217  | 0.566 | 9.18 | 3.22–30.47 | < 0.001 |
| Older adult vs adult                                                                                                                                                                                                                                                                 | 0.266  | 0.774 | 1.30 | 0.27–5.88  | 0.732   |
| Group vs alone                                                                                                                                                                                                                                                                       | -2.505 | 0.544 | 0.08 | 0.03–0.22  | < 0.001 |
| Monsoon vs summer                                                                                                                                                                                                                                                                    | 1.550  | 0.581 | 4.71 | 1.55–15.38 | 0.008   |
| Winter vs summer                                                                                                                                                                                                                                                                     | 0.212  | 0.529 | 1.24 | 0.44–3.53  | 0.688   |
| Notes: Reference levels are adult, alone, and summer. OR = odds ratio; CI = confidence interval. Positive coefficients indicate higher log-odds than the reference category. The group contrast is coded group versus alone and therefore has a negative coefficient and OR below 1. |        |       |      |            |         |

Estimated marginal means showed the same pattern, with predicted fatal-outcome probabilities highest for children (0.74, 95% CI = 0.55–0.87), solitary victims (0.71, 95% CI = 0.53–0.85), and monsoon attacks (0.65, 95% CI = 0.43–0.82; Fig. 3). Tukey-adjusted contrasts are in Supplementary Table S3.

The model had McFadden pseudo- $R^2 = 0.293$  and Tjur $R^2 = 0.332$ . Apparent discrimination was good (AUC = 0.837, 95% CI = 0.769–0.905; Supplementary Figure S3), and repeated 10-fold cross-validation yielded a mean prediction error of 0.161. Global uniformity, dispersion, and outlier tests shown in the diagnostics were non-significant, but the combined conditional-quantile diagnostic detected localized departures and several observations exceeded the heuristic Cook's-distance threshold (Supplementary Figure S4). The direction and magnitude of central effects were broadly consistent across diagnostic and exploration analyses, but uncertainty, possible influential observations, and the absence of external validation limit predictive claims.

Exploratory replacement of season by time period and the two interaction models did not overturn the directions of the primary age, party, and seasonal associations (Supplementary File 1). These models were not part of the pre-specified candidate set and were not used to redefine the main result. Sparse cells and wide uncertainty also limited inference about whether the association with companionship varied across age classes and whether age effects differed by season.

## 4. Discussion

This study distinguishes whether a documented leopard attack becomes fatal from the broader question of where attacks occur. Among 142 verified victims in Bijnor, age class, party presence, and season received the strongest support in the candidate model set, whereas gender, time, period, activity, posture, and broad site context were not retained in the top –ranked model. Children and solitary victims had the highest predicted probabilities of a fatal outcome, adjusted fatality, and the odds of fatality were higher during the monsoon than during summer. These associations were supported by the best-ranked *a priori* model, although wide confidence intervals, localized residual departures, and potential influential observations require cautious interpretation.

Children showed the clearest demographic vulnerability. Their odds of fatal outcome were more than nine times those of adults, although adults constituted the largest group of attack victims. Similar patterns have been reported across leopard landscapes in India, including Pauri Garhwal, North Bengal, Valparai, and the Western Himalaya, where children and younger age classes have been disproportionately represented among fatalities (Bhattacharjee and Parthasarathy, 2013; Kumar et al., 2017; Sidhu et al., 2017; Naha et al., 2018; Shivakumar et al., 2026). Comparable patterns have also been reported in broader reviews of large-carnivore attacks, suggesting that greater vulnerability of children is not unique to leopard attacks (Treves and Naughton-Treves, 1999; Penteriani et al., 2017; Bombieri et al., 2023; Mahajan et al., 2025). Smaller body size and reduced physical capacity to resist or escape an attack, together with a potentially limited ability to recognize danger cues and respond effectively without immediate adult assistance, may make comparable encounters more consequential for children.

The result should not be interpreted as evidence that children experience the highest encounter rate. Adults were attacked more frequently in our dataset, plausibly reflecting greater participation in agricultural, travel, and livelihood activities. Because our analysis is conditional on an attack having

occurred, the result identifies greater vulnerability to a fatal outcome contact rather than greater probability of being attacked. This distinction supports targeted measures, including supervision of children near dense crops and village edges, age-appropriate school programmes, and safe-group arrangements for walking or farm activities.

Party presence was independently associated with a lower probability of a fatal outcome. Accompanied victims had substantially lower odds of a fatal outcome than those who were alone. Companions may facilitate earlier detection, increase the apparent size and deterrent capacity of the group, interrupt an attack, prevent dragging, and shorten the time to assistance or medical care. Several non-fatal incidents in Bijnor ended after companions or nearby residents intervened, although response information was incomplete and was therefore not included in the multivariate analysis. Garrote et al. (2017) similarly found that party composition influenced outcomes of large-carnivore attacks, and solitary victims were common among leopard attacks reported from the Himalaya and Iran (Naha et al., 2018; Parchizadeh and Belant, 2021). Evidence from crocodile attacks likewise indicates that the presence of another person can facilitate rescue and prevent victims from being removed from the immediate vicinity (Fukuda et al., 2015).

Group presence, however, should not be interpreted as a guarantee of safety, and poorly coordinated responses may increase risks to both people and leopards. The finding instead supports practical preventive measures, including avoiding work alone in standing sugarcane where feasible, maintaining visual or verbal contact among workers, carrying a charged communication device, and establishing procedures for alerting others without surrounding or pursuing a leopard. Because group size and the nature and timing of companion intervention were incompletely recorded, future incident records should distinguish between individual companions and larger groups and document the timing and type of intervention. Risk communication should also preserve the conditional nature of this association: higher fatality among solitary victims after an attack should not be interpreted as evidence that people walking alone face a high absolute probability of being attacked. Such framing can support public safety while avoiding exaggerated perceptions of risk associated with leopard presence alone.

Season was associated with attack outcome differently from attack frequency. More victims were attacked during summer, but monsoon attacks had higher odds of fatal outcome than summer attacks. This divergence reinforces the difference between exposure and severity. A comparable pattern has been reported in Nepal, where seasonal variation in fatalities differed from that in overall attack frequency, while studies from Pauri Garhwal and North Bengal demonstrate that seasonal patterns vary among landscapes (Acharya et al., 2016; Naha et al., 2018). In Bijnor, the higher probability of a fatal outcome during the monsoon may reflect seasonal changes in agricultural conditions and human activity. Rapid growth of sugarcane and other vegetation may reduce visibility, increase the likelihood of close encounters, and limit opportunities for early detection or intervention. However, these mechanisms were not directly measured at the incident level and should therefore be considered hypotheses rather than demonstrated explanations. Crop height and density, visibility distance, rainfall, work intensity, response time, leopard movement, and prey availability were not quantified for individual attacks.

Field observations provide some additional context. Leopard cub rescues in Bijnor were concentrated between February and June, overlapping with the sugarcane harvesting period, when attacks were frequent but predominantly non-fatal. This temporal pattern suggests that breeding-related factors alone may not explain the higher fatality observed during the monsoon. Available livestock-depredation records also suggested greater depredation during the monsoon, although these observations were not standardized and were not included in the present analysis. Studies from tea estates, shrub-dominated habitats, and sugarcane landscapes have similarly linked dense vegetation with leopard–human encounters (Athreya et al., 2013; Kshetry et al., 2017; Badhe and Jaybhaye, 2023). Prospective monitoring that measures crop structure, visibility, rainfall, human activity, and response time at individual incidents would help test whether seasonal vegetation conditions contribute to the observed association with fatal outcomes.

Time period was associated with outcome bivariate analysis but did not improve the best-supported multivariable model. Fatal proportions were high during evening twilight and nighttime, and most settlement attacks occurred during darkness with poor lighting. These patterns are biologically plausible because leopards often show greater activity during crepuscular and nocturnal hours, while reduced visibility may limit detection and opportunities for avoidance (Odden et al., 2014; Carter et al., 2015). However, time of attack may co-vary with season, activity, party presence, and attack setting, and its lack of support in the multivariable model cautions against interpreting darkness as an independent predictor of fatality. Nevertheless, the concentration of settlement attacks during low-light conditions has practical relevance and supports measures such as improving lighting around settlement edges, maintaining visibility along frequently used paths, and discouraging unsupervised movement by children during periods of low visibility.

Gender showed only a weak bivariate association with fatal outcome and was not retained in the best-supported multivariable model. The higher crude fatal proportion among women may reflect differences in age distribution, activity, party presence, treatment access, or other unmeasured factors rather than an intrinsic sex effect. Similarly, activity and posture were not independently associated with outcome within the broad categories available in our dataset. These null findings should not be interpreted as evidence that fine-scale behaviour is irrelevant. Collapsing diverse agricultural tasks into broad categories and posture into only two classes may have obscured short-distance mechanisms, such as bending within sugarcane, carrying loads, supervising children, or having both hands occupied.

Agricultural settings contained most victims and 33 of the 45 fatalities, yet broad site context was not associated with fatal outcome after an attack. The concentration likely reflects the dominant land use and exposure environment of the study landscape rather than an independent effect of agricultural setting. Sugarcane and other tall crops can provide cover for leopards in close proximity to people, as reported from western India and North Bengal (Vijayan and Patil, 2002; Athreya et al., 2013; Bhattacharjee and Parthasarathy, 2013). However, the agricultural-versus-settlement classification used here was too coarse to capture potentially relevant features such as crop type, height, harvesting stage, distance to cover, illumination, or escape routes. Nearly all attacks occurred outside reserve forest,

emphasizing that prevention and risk-reduction measures need to operate across shared production landscapes rather than being confined to protected areas.

Approximately half of verified incidents were classified as likely predatory, and partial consumption was recorded in 16 fatal cases. Behaviours such as dragging, carrying, concealment, and consumption are compatible with prey-oriented behaviour, but retrospective accounts cannot establish motivation with certainty (Penteriani et al., 2017; Bombieri et al., 2023). Importantly, a fatal outcome alone should not be interpreted as evidence of predatory intent. Differences from studies reporting fewer predatory-like cases may reflect genuine ecological variation, but may also arise from differences in definitions, documentation quality, or case selection (Shivakumar et al., 2025). Standardized incident documentation should therefore record the sequence of contact, initial distance, body regions injured, dragging or carrying, consumption, evidence of cubs, leopard condition, and human actions before and during the encounter.

Leopards in human-used landscapes often rely on domestic dogs, goats, calves, and other anthropogenic prey (Athreya et al., 2016; Kshetry et al., 2018). Field observations in Bijnor also indicate frequent depredation of calves, goats, and dogs. These observations do not support a simple prey-scarcity explanation for human attacks, although diet and prey availability were not quantified in this study. Integrated research combining leopard diet, wild and domestic prey availability, livestock husbandry, leopard density, and human activity is needed before attributing attack behaviour to food limitation.

Documented management responses raise questions about the routine use of capture and translocation. Seventy-three capture operations occurred during 2021–2025, including 20 after attacks on people, but only four captured animals showed obvious injury, old age, or poor condition. Without individual identification through photographic or genetic evidence, telemetry, and before–after monitoring, captured leopards cannot be reliably linked to particular attacks, and the effects of removal on subsequent conflict cannot be evaluated. Translocated leopards may move through unfamiliar human-dominated landscapes and can remain involved in conflict (Athreya et al., 2007, 2011). Removal may be justified for an individually identified high-risk animal, but routine or indiscriminate capture may displace rather than resolve conflict. Management decisions should therefore be guided by standardized evidence, transparent criteria, veterinary assessment, and post-release monitoring.

Outcome may also be influenced by what occurs after physical contact. In Bijnor, companions, residents, or crowds interrupted several non-fatal incidents, and seven fatal victims survived long enough to reach a medical facility. These observations point to a post-attack response chain that was not fully measurable in the dataset, including recognition, safe interruption, first aid, transport, and definitive treatment. Future incident records should document time from attack to rescue, transport mode, injury location and severity, time to medical facility, and treatment received. Such information could identify potentially modifiable factors influencing survival that demographic and seasonal models cannot

capture. Community guidance should emphasize alerting trained responders and seeking urgent trauma care while discouraging dangerous pursuit, crowd encirclement, or attempts to handle a leopard.

## 4.1 Management implications

The results support a focused, prevention-oriented management approach. First, child-centered measures should include school- and village-level education, supervision during outdoor activities near crops, and safe accompaniment along routes bordering dense vegetation. Second, farmers and resource users should be encouraged to work in pairs or groups in standing sugarcane, particularly during the monsoon, while avoiding pursuit or crowding of a sighted leopard. Third, visibility should be improved along settlement edges and frequently used paths through selective vegetation management and reliable lighting. Predator-resistant night enclosures, secure disposal of food waste, and management of attractants associated with free-ranging dogs may further reduce leopard activity around residences.

Monsoon-focused advisories should be linked to local crop and field conditions rather than issued as generic warnings. Rapid-response teams and village contacts can help verify sightings, secure incident sites, keep crowds at a safe distance, and facilitate timely medical transport. Incident records should include georeferenced location, exact time, crop stage, visibility, group size, distance to assistance, injury pattern, treatment delay, leopard behavior, and management response. Consistent prospective records would allow stronger evaluation of factors associated with attack severity and whether specific interventions reduce encounters or fatal outcomes.

Implementation should be monitored rather than assumed to be effective. Where feasible, villages or time periods could be compared before and after introduction of measures such as improved lighting, supervised school routes, paired field work, or monsoon-specific alerts, while accounting for differences in reporting effort and human exposure. Relevant indicators should include verified encounters, attacks, response time, time to medical treatment, and fatal outcomes, rather than relying solely on the number of leopards captured. Participatory review involving farmers, women, children, health workers, and Forest Department personnel could help identify measures that are feasible during peak agricultural activity and avoid shifting risk toward groups with fewer resources.

## 5. Conclusions

Fatal outcomes following verified leopard attacks in Bijnor were most strongly associated with childhood, being alone, and the monsoon season. These factors describe severity after an attack has occurred, rather than the population-level probability of encountering or being attacked by a leopard. Targeted child supervision, paired or group movement in dense crops, improved visibility at settlement edges, season-specific communication, rapid medical response, and standardized incident documentation therefore represent practical management priorities. Prospective studies integrating crop phenology, vegetation structure, human exposure, leopard space use, and response time are needed to

test the mechanisms underlying these associations and improve evidence-based risk reduction while supporting coexistence in shared agricultural landscapes.

## Declarations

## Competing Interests:

The authors declare that they have no competing interests.

## Author Contribution

SC - Conceptualization, Data Collection, Data Curation, Formal Analysis, Funding Acquisition, Methodology, Software, Validation, Visualization, Writing – Original Draft Preparation, Writing – Review & Editing  
KA - Conceptualization, Methodology, Validation, Funding Acquisition, Review & final draft Editing, Supervision, Permission  
MKP - Validation, Visualization, Writing – Review & Editing  
KH - Data Curation, Methodology, Software  
GS - Investigation, Review

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## Data Availability

The data used for the generalized linear models and bivariate chi-square tests of independence are provided in the Supplementary Information. Requests for access to the underlying data used in this study can be provided on request.

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## Figures

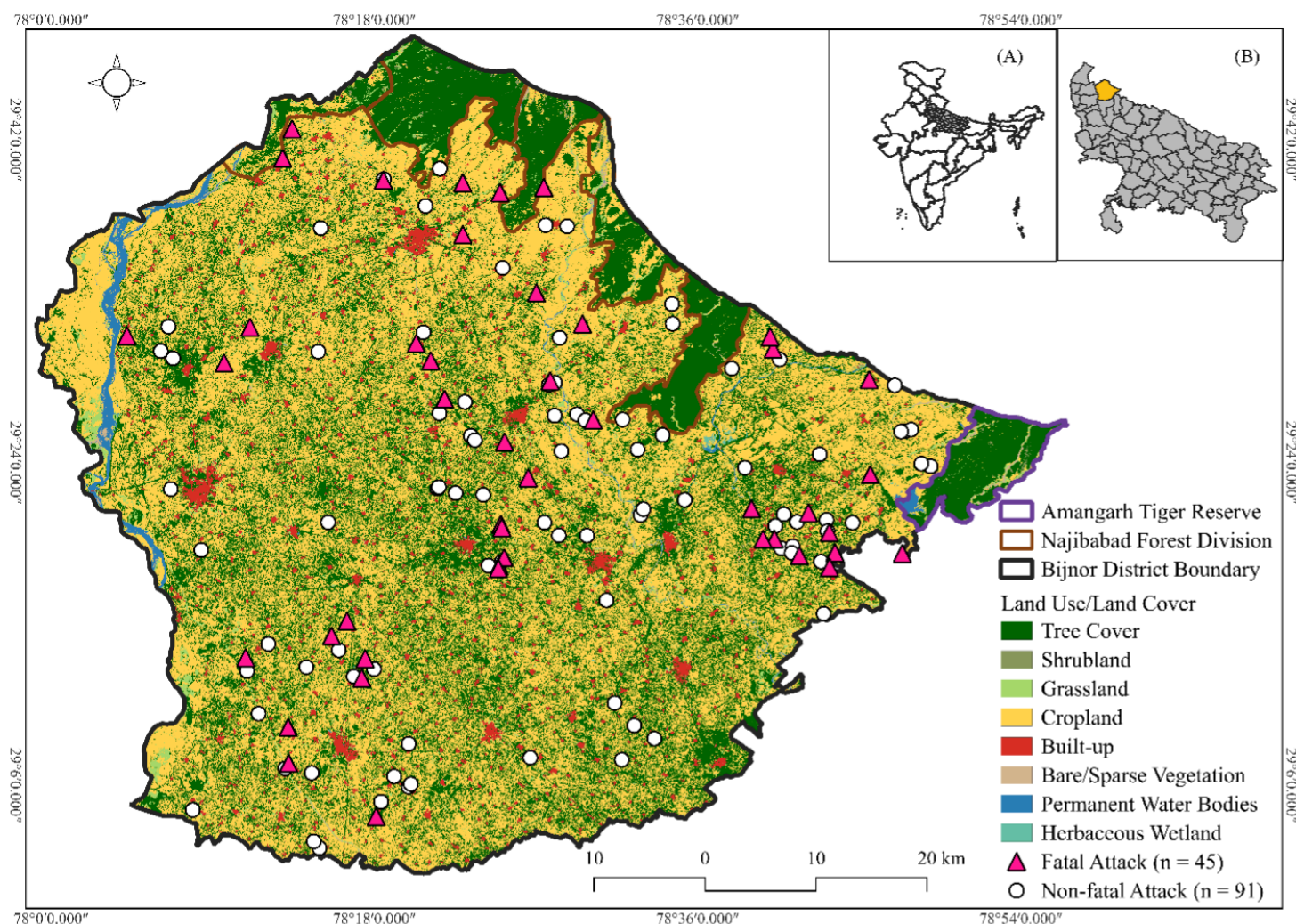


**Figure 1**

Study area and spatial distribution of verified leopard attacks in Bijnor district, Uttar Pradesh, India. Land-use and land-cover classes are from the Esri 2021 Global Land Cover dataset. Locations were available for 132 of 142 incidents: 45 fatal (pink triangles) and 87 non-fatal (white circles). Insets show Uttar Pradesh within India (A) and Bijnor district within Uttar Pradesh (B).

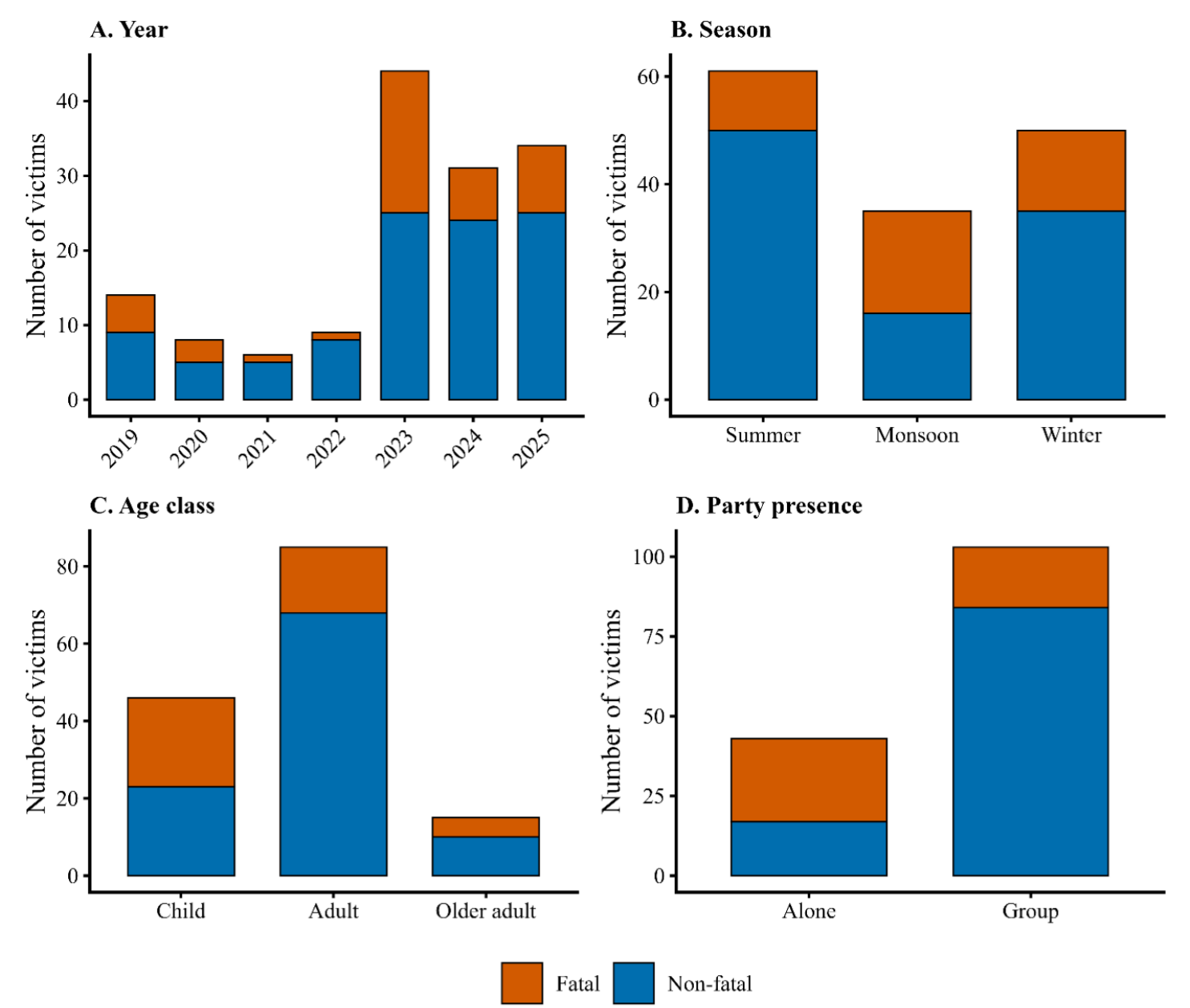


**Figure 2**

Numbers of fatal and non-fatal leopard-attack victims in Bijnor district during 2019-2025 by year (A), season (B), age class (C), and party presence (D). Annual counts are unstandardized and reflect variation in record availability and verification effort.

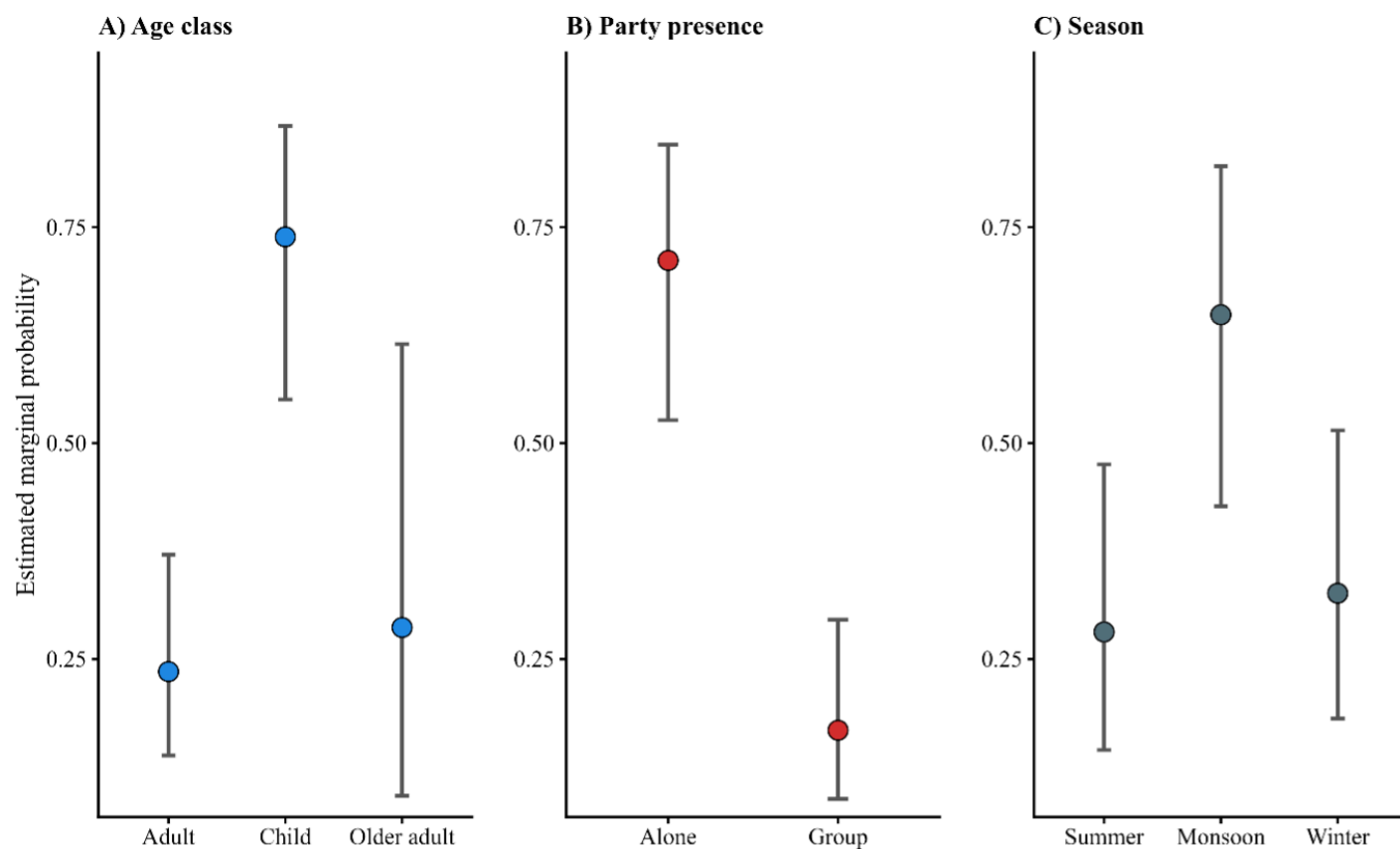


**Figure 3**

Estimated marginal probabilities of a fatal outcome from the top-ranked logistic regression model, with 95% confidence intervals, for age class (A), party presence (B), and season (C).

## Supplementary Files

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