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Where leopards die: identifying mortality hotspots in northern Pakistan

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Abstract

Human–wildlife conflict poses a major threat to large carnivores worldwide, particularly in human-dominated landscapes where their persistence increasingly depends on effective coexistence strategies. This study employs geostatistical and time-series analyses to identify conflict hotspots, temporal trends, and key anthropogenic drivers of human-induced leopard (*Panthera pardus*) mortality in Azad Jammu and Kashmir, Pakistan. We applied kernel density estimation, hotspot analysis, and multiscale geographically weighted regression to assess spatial patterns of mortality, identify underlying drivers, and examine temporal trends. Based on 178 verified leopard mortality records collected between 2000 and 2023, retaliatory killings following livestock depredation emerged as the primary cause of death, accounting for 63% of cases, with mortality peaking during autumn and winter. Spatial analyses revealed a high concentration of leopard mortalities in areas adjacent to and outside protected area boundaries. Furthermore, distance to protected areas and proximity to human settlements significantly influenced mortality risk, operating across variable spatial scales. Our findings indicate that leopard killings intensify where fear, misinformation, and economic losses intersect. These results emphasize the importance of landscape-level conservation planning, improved conflict mitigation strategies, and the integration of human-dominated areas into carnivore conservation frameworks. This study provides spatially explicit evidence to support targeted management interventions and policy actions for leopard conservation in Azad Jammu and Kashmir.

KEYWORDS
conservation planning, human–wildlife conflict, *Panthera pardus*, retaliatory killing, spatial analysis

1 | INTRODUCTION

Large carnivores are globally threatened yet ecologically pivotal species, playing a critical role in regulating prey populations, maintaining trophic cascades, and shaping broader ecosystem structure and function (Lovari et al., 2009; Ripple et al., 2014). Due to their status as keystone species and apex predators, their decline can destabilize ecosystems by affecting vital ecological processes, changing species interactions, and upsetting food webs (Duffy et al., 2007; Eisenberg, 2013; Sergio et al., 2008).

The common leopard (*Panthera pardus*), one of these carnivores, is notable for its remarkable ecological adaptability. It can live in various environments, including desert scrublands and tropical forests, and it can thrive in landscapes that have been altered by humans (Athreya et al., 2016; Nowell & Jackson, 1996). This generalist strategy has allowed leopards to persist where other large cats, such as tigers (*Panthera tigris*), have disappeared (Athreya et al., 2013; Jacobson et al., 2016; Roberts, 1977). Despite their adaptability, leopards are listed as Vulnerable by the IUCN Red List (Stein et al., 2025) and Critically Endangered in Pakistan's National Red List (Sheikh & Molur, 2005), highlighting the growing threats to their survival.

Historically widespread across Pakistan, leopards now survive in fragmented populations confined to the highland regions of Baluchistan (or Balochistan), Sindh, and the Hindukush/Himalayan forests of Khyber Pakhtunkhwa, Punjab, and Azad Jammu and Kashmir (AJK, Roberts, 1977; Shehzad et al., 2015). Recent studies indicate a population decline and range contraction due to anthropogenic pressures (Akrim et al., 2017, 2021; Danish et al., 2023; Kabir et al., 2014).

Leopards in AJK face a range of anthropogenic threats. Border fences and expanding road networks impede transboundary movements, especially in politically sensitive regions (Farhadinia et al., 2018). Additional pressures include habitat degradation, deforestation, mining, infrastructure expansion near protected areas (PAs), prey depletion, poaching for skins and bones, and retaliatory killings by livestock owners (Akrim et al., 2021; Athreya & Belsare, 2007; Kabir et al., 2013; Roberts, 1977; Sheikh & Molur, 2005). Among these, retaliatory killings are particularly concerning, often targeting reproductively important individuals (Akrim et al., 2021; Bagchi & Mishra, 2006; Graham et al., 2005). Understanding the location-specific drivers of such conflicts and identifying mortality hotspots is therefore essential for developing effective, targeted conservation interventions. Without proactive strategies, leopards risk extinction in Pakistan, as previously occurred with lions and tigers (Roberts, 1977).

PAs are central to global biodiversity conservation strategies, particularly for large carnivores and their prey (Rodrigues et al., 2004; Wolf & Ripple, 2018). While they help preserve habitat integrity and buffer against anthropogenic pressures (Brooks et al., 2004; Butchart et al., 2012), many PAs remain ineffective due to inadequate management, underfunding, and isolation from broader landscapes (Di Minin & Toivonen, 2015; Dudley et al., 1999; Joppa et al., 2008). Moreover, many are too small to support viable carnivore populations, forcing animals to move into adjacent human-dominated areas where threats persist (Finnegan et al., 2021; López-Bao et al., 2017).

Increasingly, conservationists advocate for integrated landscape approaches and "land sharing" models that promote coexistence in human-dense regions (Chapron et al., 2014; Terraube et al., 2020; Woodroffe & Ginsberg, 1998). To inform such approaches, understanding the spatial patterns of wildlife mortalities is essential. Spatial event data, such as conflict-related mortalities, allow researchers to identify mortality hotspots, evaluate risk factors, and allocate conservation resources more efficiently (Ramp et al., 2005; Ruda et al., 2018).

Despite increasing reports of leopard mortality and its critically endangered status in Pakistan, especially in AJK, there has been little spatially informed research to understand the patterns and drivers of these events (Ahmad et al., 2016, 2022). Human–leopard conflict has predominantly been understood and documented in relation to livestock losses, with most existing studies conducted inside the PAs (e.g., Athreya et al., 2020; Constant et al., 2015; Deka et al., 2025; Naha et al., 2018). Consequently, conflict dynamics and leopard mortalities occurring outside PAs remain poorly documented, as the absence of wildlife staff beyond park boundaries allows retaliatory killings of predators to go largely unnoticed. Leopard mortalities in buffer zones are often attributed to increasing leopard populations; however, this assumption lacks empirical assessment of prey availability or actual leopard population trends. Such unverified assumptions risk obscuring early warning signs of population decline and may undermine timely conservation interventions for leopards in human-dominated landscapes. The aim of this study was to assess the spatial distribution of leopard mortality in areas known for healthy populations of leopards and to highlight risk zones and temporal trends from 2000 to 2023. By integrating spatial and temporal data, this research provides essential insights into the identification of leopard mortality hotspots, improving the human-leopard conflict mitigation and guiding more effective conservation planning in this biodiverse Himalayan region.

2 | MATERIALS AND METHODS

2.1 | Study area

AJK lies within the Himalayan foothills of northern Pakistan, encompassing an area of approximately 12,216 km^2 between latitudes 33°–36°N and longitudes 73°–75°E (Figure 1). The region exhibits an elevation gradient, ranging from 205 to 6,176 m above sea level, which supports diverse topography. Southern areas are characterized by plains and valleys, while the northern zones transition into rugged mountainous terrain. The climate is predominantly subtropical highland, with an average annual rainfall of 1,300 mm and temperature extremes ranging from 45.2°C (maximum value) to −2.6°C (minimum value).

AJK gives refuge to a wide variety of habitat types, from tropical thorn forests in Bhimber District to snow-covered alpine zones in the Neelum Valley. This ecological diversity sustains a rich assemblage of wildlife (Ahmad et al., 2016; Ahmad et al., 2025; Akrim et al., 2017; Fida et al., 2025; Kabir et al., 2017; Qamar et al., 2012), including threatened species such as the snow leopard (*Panthera uncia*), Himalayan brown bear (*Ursus arctos isabellinus*), Himalayan black bear (*Ursus thibetanus*), gray wolf (*Canis lupus*), musk deer (*Moschus leucogaster*), and woolly flying squirrel (*Eupetaurus cinereus*). Other notable fauna include the gray langur (*Semnopithecus ajax*), barking deer (*Muntiacus muntjac*), and Indian pangolin (*Manis crassicaudata*).

2.2 | Data collection

We collected data on leopard mortalities by using a combination of direct and indirect methods to ensure comprehensive coverage across the study period (2000–2023). For events prior to 2007, records were primarily obtained through indirect sources, including focus group discussions with local wildlife experts, herders, and community members, following a semi-structured approach (Stewart & Shamdasani, 2014). Additionally, published and unpublished reports were reviewed to compile historical mortality incidents. For post-2007 data, direct verification was prioritized: reports of leopard deaths were gathered through community informants and a dedicated Facebook page (https://www.facebook.com/community-based-conservation-of-leopard-in-Pakistan-1682616665319910), which allowed real-time monitoring of incidents across AJK. Each reported case was field-verified by the research team, with mortalities confirmed as human-induced only when supported by physical evidence such as bullet wounds, snare injuries, or signs of blunt-force

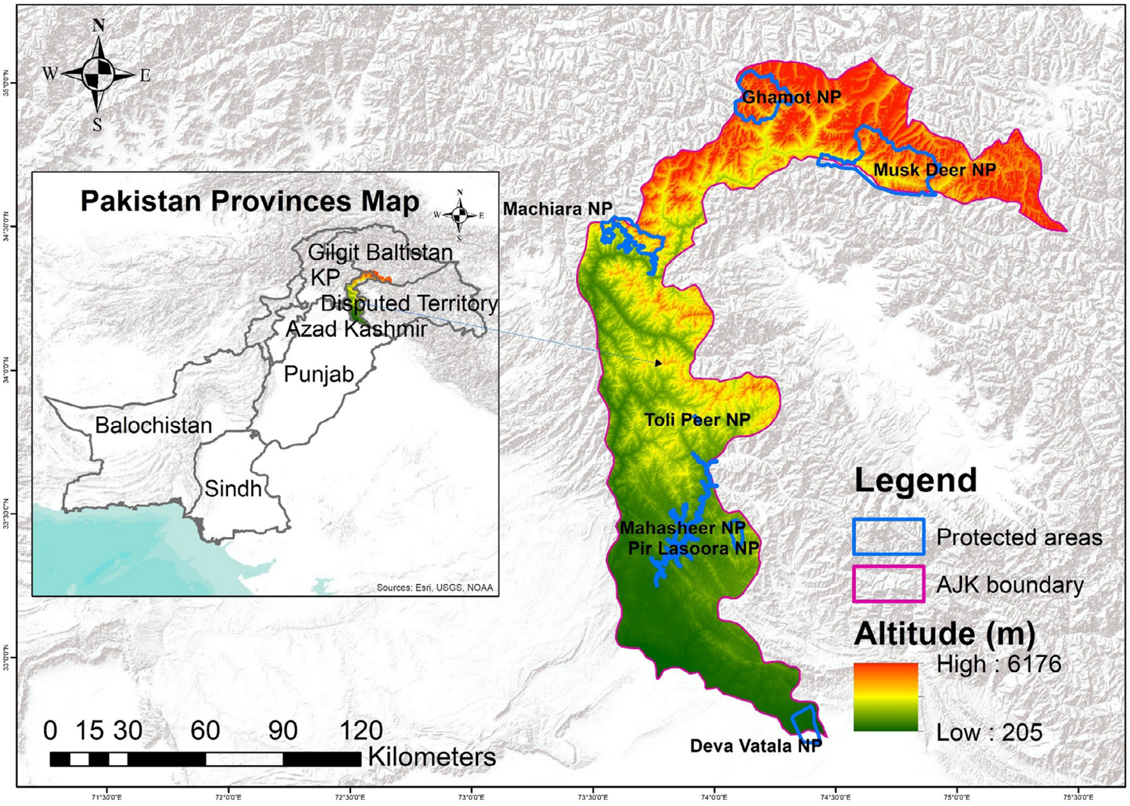

FIGURE 1 Map of the study area in Azad Jammu and Kashmir (AJK), Pakistan.

trauma. To maintain data reliability, unverified or ambiguous cases were excluded. For some records, spatial coordinates were unavailable, and while these were not included in the spatial analysis, they were still accounted for in the overall assessment of leopard mortalities.

2.3 | Spatial analyses

To comprehensively characterize the spatial and spatiotemporal patterns of human-induced leopard mortalities, we applied a four-step analytical framework in ArcGIS Pro (Version 3.1.5, 2023) that integrates exploratory visualization, statistical confirmation of spatial clustering, temporal trend detection, and spatial modeling of underlying drivers. We used kernel density estimation (KDE), optimized hotspot analysis (OHSA), emerging hotspot analysis (EHSA), and multiscale geographically weighted regression (MGWR) in a complementary manner, with each method addressing a distinct analytical objective.

2.3.1 | Temporal analysis and modeling

To describe temporal patterns in leopard mortalities, we summarized annual mortality counts from 2000 to 2023 in R environment version 4.4.0 (Appendix S1). Temporal trends were visualized using locally estimated scatterplot smoothing (LOESS) in R environment version 4.4.0, a non-parametric method that highlights underlying patterns in time-series data without assuming a specific functional form or extrapolating beyond the observed values (Jacoby, 2000, Appendix S2).

2.3.2 | Kernel density estimation

We first applied KDE as an exploratory spatial tool to visualize the overall intensity and distribution of leopard mortality events across the landscape (De Smith et al., 2007; Silverman, 2018). Using the Kernel Density for Point Features tool in ArcGIS Pro (Version 3.1.5, 2023), we generated a continuous raster surface representing the concentration of mortality events around each recorded location. KDE produces a smoothed depiction of spatial patterns, which is particularly useful for identifying areas of relatively high and low mortality pressure and for visually highlighting potential hotspots at the human–wildlife interface (Kalinic & Krisp, 2018).

Because KDE is a descriptive technique and does not test whether observed clusters differ significantly from random spatial patterns, its outputs were used solely to guide subsequent statistically rigorous analyses.

2.3.3 | Optimized and emerging hotspot analyses

To formally test whether leopard mortalities were spatially clustered beyond random expectation, we conducted OHSA using the Getis–Ord Gi* statistic in ArcGIS Pro (Version 3.1.5, 2023). In this step, patterns suggested by KDE were subjected to statistical validation. OHSA identifies clusters of high or low values that are unlikely to occur by chance, thereby adding inferential rigor to hotspot detection (Kalinic & Krisp, 2018; Zerbe et al., 2022).

Mortality points with spatial coordinates ($n = 119$) were aggregated into 628 hexagonal bins (6.5 km × 5.6 km), a geometry selected to reduce directional bias and edge effects. The tool automatically identified an optimal spatial scale of 16,894 m for neighborhood definition, and false discovery rate correction was applied to control for multiple comparisons. Statistically significant hot-spots and cold-spots were identified using a threshold of $|Z| > 1.96$ ($p < 0.05$), thereby distinguishing areas of consistently elevated mortality risk from those where apparent clustering could be attributed to chance.

While OHSA captures spatial clustering at a single time scale, it does not account for how hotspot patterns evolve over time. To address this limitation, we applied EHSA, which explicitly integrates temporal dynamics to identify trends such as intensifying, diminishing, or persistent hotspots (Betty et al., 2020), in ArcGIS Pro (Version 3.1.5, 2023).

We constructed a space–time cube using 4 km hexagonal bins and 1-year temporal intervals spanning 2000–2023. The analysis employed an 8 km spatial neighborhood and a 10-year temporal window, combining the Getis–Ord Gi* statistic with the Mann–Kendall trend test (Geary, 1949; Getis & Ord, 1992; Mann, 1945). Following ESRI's classification scheme, each spatial unit was categorized into hotspot trend types, including new, consecutive, intensifying, persistent, sporadic, diminishing, or historical (Betty et al., 2020; Bunting et al., 2018). EHSA thus enabled identification of locations where leopard mortality risk is not only high but also increasing or sustained through time, providing critical insight for prioritizing conflict-mitigation efforts.

2.3.4 | Multiscale geographically weighted regression

To move beyond hotspot identification and explicitly examine the drivers of spatial variation in leopard mortality, we applied MGWR. Unlike KDE and hotspot analysis, which describe where mortality is concentrated and how it changes over time, MGWR addresses why these patterns occur by modeling spatially varying relationships between mortality and anthropogenic predictors (Cupido et al., 2021; Fotheringham et al., 2017; Oshan et al., 2020).

Implemented in ArcGIS Pro (Version 3.1.5, 2023), the MGWR model evaluated the influence of three predictors on leopard mortality density: distance to PAs, distance to human settlements, and the human footprint index (Williams et al., 2020). Predictor-specific bandwidths were optimized using a golden-section search algorithm, converging after three iterations.

We fitted the MGWR model using scaled (standardized) variables (mean $= 0$, SD $= 1$), so coefficients are interpretable in standardized units and are comparable in magnitude across predictors. These coefficients describe the direction and relative strength of the association between leopard mortality and each explanatory variable at different spatial locations. Accordingly, both positive and negative coefficient values are expected; negative coefficients indicate decreasing mortality risk with increasing distance from a given feature (e.g., PAs or settlements), rather than distance itself. Coefficient values are presented without transformation to preserve directional information essential for interpretation.

3 | RESULTS

3.1 | Leopard mortality temporal patterns

Field surveys and verified secondary records documented 178 common leopard mortality events over a 24-year period (2000–2023), placed in 122 geographic positions (Table S1), yielding an annual mean of 7.41 ± 1.09 deaths (±standard error, SE). Mortalities occurred throughout the year but demonstrated significant seasonal variation ($\chi^2 = 13.73$, $\text{df} = 3$, $p = 0.0032$), with the highest incidence recorded in winter (34%, $n = 61$), followed by autumn (29%, $n = 51$), summer (21%, $n = 37$), and spring (16%, $n = 29$).

Time series analysis identified significant interannual variation in leopard mortality, ranging from 2 to 21 deaths per year. Based on visual and statistical diagnostics, three temporal phases were observed: (i) relatively low mortality from 2000 to 2010 (mean $= 4.6 \pm 0.7$ SE); (ii) moderate increases during 2011–2018 (mean $= 6.4 \pm 1.1$ SE); and (iii) elevated mortality from 2019 to 2023 (mean $= 13.6 \pm 2.4$ SE, Figure 2).

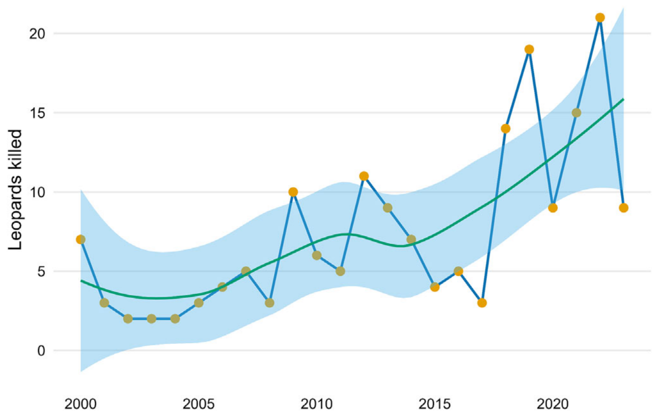

FIGURE 2 Trends in leopard mortality in Azad Jammu and Kashmir. Observed annual leopard mortalities from 2000 to 2023 with a locally estimated scatterplot smoothing trend line (green) and 95% confidence interval (shaded area).

3.2 | Leopard mortality details

Sex- and age-class information were available only for leopard mortality events recorded between 2008 and 2023. During this period, a total of 150 leopard were documented. Of these, 35 individuals (23.3%) were adult males, 51 (34.0%) were adult females, and 64 (42.7%) were cubs or subadults, indicating that younger individuals constituted the largest proportion of recorded mortalities. Adult female mortalities consistently exceeded male mortalities across years and increased during periods of elevated overall mortality. The high representation of cubs and sub-adults suggests increased vulnerability during early stages, potentially associated with dispersal and exposure to human-dominated landscapes. Most mortality events (63%, $n = 112$) were attributed to retaliatory killings following livestock depredation. Additional causes included carcasses with unknown causes (18%, $n = 32$), preventive killings in response to perceived threats to humans or livestock (12%, $n = 21$), and opportunistic killings when leopards entered human settlements (7%, $n = 13$). In addition to confirmed records, 23 mortality reports could not be spatially or biologically verified and were classified as unidentifiable; these cases were excluded from analysis but indicate that actual leopard mortality may be higher than documented.

3.3 | Protected versus non-protected areas

Spatial distribution revealed a strong disparity between protected and non-PAs. Most mortalities (88.5%, $n = 108$) occurred outside PAs, whereas only 11.5% ($n = 14$) were

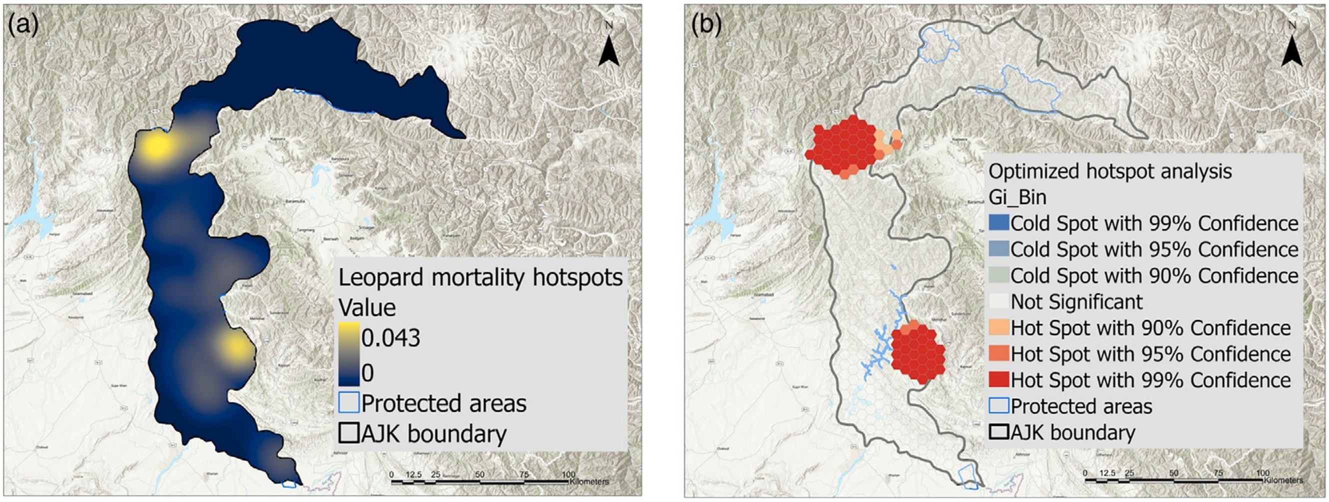

FIGURE 3 Kernel density hotspots of conflict-induced leopard mortality in Azad Jammu and Kashmir (AJK) (a). Optimized hotspot analysis of conflict-induced leopard mortality in AJK (b).

recorded within designated protected zones. For the remaining leopard mortalities, the available information was insufficient to determine whether they occurred within or outside PAs.

3.4 | Kernel density estimation

KDE revealed spatial heterogeneity in mortality intensity, with high-density clusters located near the boundaries of Machiara, Pir Lasoora, and Deva Vatala National Parks. These hotspots were primarily situated in human–wildlife interface zones.

The OHA corroborated KDE results (Figure 3), identifying 70 statistically significant hotspot hexagons across the study region (628 hexagons total, Appendix S3). Two major clusters were observed in the northwestern and southern-central regions of AJK. Hexagon-based incident counts ranged from 0 to 0–7, with a mean of 0.1879 and an SD of 0.6482. The analysis used a 16,894 m distance band and accounted for spatial dependence through False Discovery Rate correction.

3.5 | Optimized and emerging hotspot analyses

The EHSA using a space–time cube (4 km resolution; 1-year interval) detected 138 statistically significant hotspot locations (11.7% of total). Most were consecutive hotspots ($n = 94$), indicating sustained mortalities over time (Appendix S4). Additionally, eight locations were classified as intensifying hotspots, seven as new hotspots, and five as persistent hotspots (Figure 4). Twenty-two sporadic hotspots were observed, along with a single diminishing and one historical hotspot. Spatially, these clusters overlapped substantially with Machiara, Tolipir, Pir Lasoora, and Deva Vatala National Parks (Figure 4).

3.6 | Multiscale geographically weighted regression

The MGWR model explained 93.5% of spatial variability in leopard mortalities (adjusted $R^2 = 0.9347$), outperforming the traditional GWR model (adjusted $R^2 = 0.9108$), indicating improved explanatory power and interpretability (Appendix S5). Distance to PAs was the most influential variable (mean coefficient $= -0.6149$), significant in 74.6% of spatial units and operating at a local spatial scale (bandwidth = 30 neighbors, Figure 5, further details are provided in Figure S1).

Distance to settlements also showed a negative association (mean coefficient $= -0.0870$), significant in 45.1% of features. The human footprint index exhibited a weak and spatially inconsistent effect (mean coefficient $= -0.0047$), significant in only 2.46% of features (Figure S1 and Appendix S5).

4 | DISCUSSION

4.1 | Drivers and patterns of leopard mortality in human-dominated landscapes

The common leopard, classified as a vulnerable habitat-generalist species, thrives across diverse habitats. Leopard populations across their range, including AJK, are

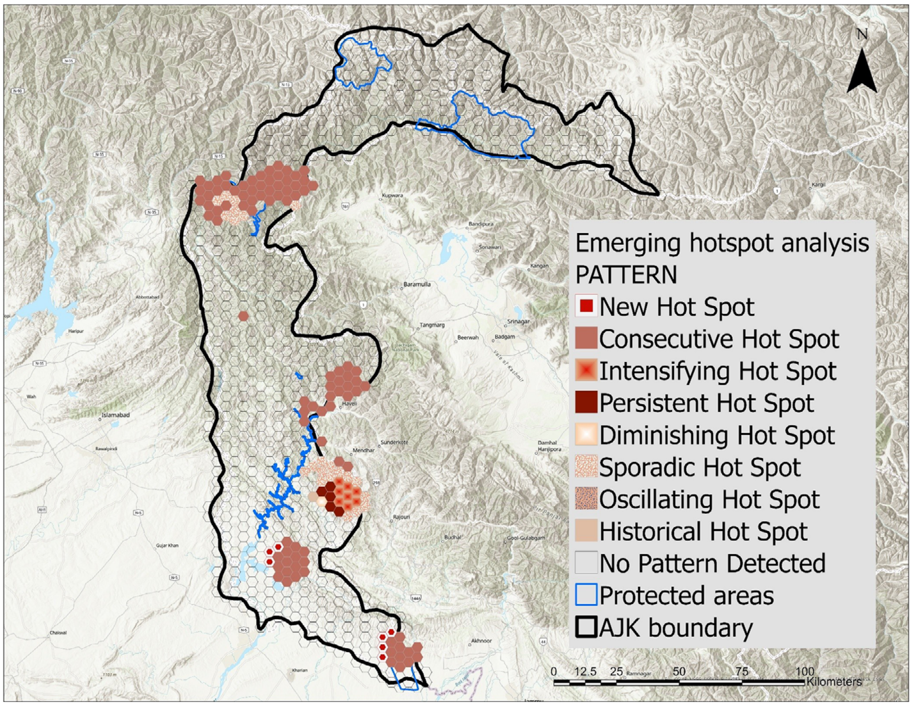

FIGURE 4 Emerging hotspot analysis of common leopard mortality in Azad Jammu and Kashmir (AJK) from 2000 to 2020. The map shows spatial patterns of statistically significant hotspots derived from a space–time cube analysis with a 4-km spatial resolution and 1-year temporal resolution. Hotspot types include new, consecutive, intensifying, persistent, sporadic, diminishing, and historical hotspots, representing different temporal trends in leopard mortality. Protected areas are overlaid to highlight regions of conservation importance.

declining due to habitat loss, prey depletion, habitat fragmentation, and retaliatory killings (Akrim et al., 2018; Baral et al., 2021; Bhandari et al., 2019; Kabir et al., 2014). Livestock depredation makes leopards vulnerable to retaliatory killings, and human attacks provoke a strong response and are rarely tolerated by communities (Dhungana et al., 2018; Penteriani et al., 2016). This study reports systematic insights into leopard mortality, with 7.41 (±1.09 SE) for the year. Leopard mortalities are occurring in the absence of any reliable population benchmarks against which their impact can be evaluated, raising serious conservation concerns. Although leopard killings in areas outside protected boundaries are often attributed to presumed population increases, such explanations remain speculative without supporting evidence. In this context, even moderate levels of persistent mortality may have disproportionate consequences for population viability, highlighting a critical knowledge gap in leopard conservation planning. Retaliatory killing can thus hamper carnivore population sustainability as well as impede the recovery of threatened populations (Kaczensky et al., 2011).

The observed seasonal variation, with mortality peaking in winter and autumn, cold temperatures reduce prey availability and increase livestock depredation and conflict incidents (Akrim et al., 2023; Baral et al., 2021; Dhakal et al., 2023; Shivakumar et al., 2023).

Retaliatory killing following livestock depredation emerged as the dominant cause of leopard mortality, accounting for nearly two-thirds of all recorded deaths. This finding reinforces the long-standing narrative that livestock loss remains a primary driver of human–leopard conflict; however, the substantial proportion of mortalities attributed to unknown causes and preventive killings highlights an underappreciated dimension of conflict. Preventive and opportunistic killings suggest a climate of fear and low tolerance toward leopards in human-dominated landscapes, where even perceived threats may trigger lethal responses. In the absence of systematic monitoring and rapid response mechanisms outside PAs, such killings are likely underreported, further obscuring the true scale of anthropogenic leopard mortality in AJK.

Leopards engage in livestock depredation, often involving surplus killing, which heightens human intolerance and retaliatory killings (Farhadinia et al., 2017; Khorozyan et al., 2017; Parchizadeh & Belant, 2021). In some cases, leopards were killed not only in retaliation but also for the illegal trade of their valuable skins (Asad et al., 2019; Irshad et al., 2018). Our study only included verified records of leopard mortality; however, unconfirmed or unidentified cases suggest that actual mortality figures are likely higher. The conflict-induced mortality rate in AJK exceeds that reported from Ayubia National Park and surroundings, where six leopards were killed annually between 2005 and 2015 (Khan et al., 2020) and the 2.31 leopards/year killed in retaliation or self-defense in Khyber Pakhtunkhwa from 1989 to 2007 (Lodhi, 2007). However, it remains lower than the central mid-hills of Nepal, where 12 leopards were killed per year between 2015 and 2019 (Baral et al., 2021). The comparatively lower mortality in our area may be due to

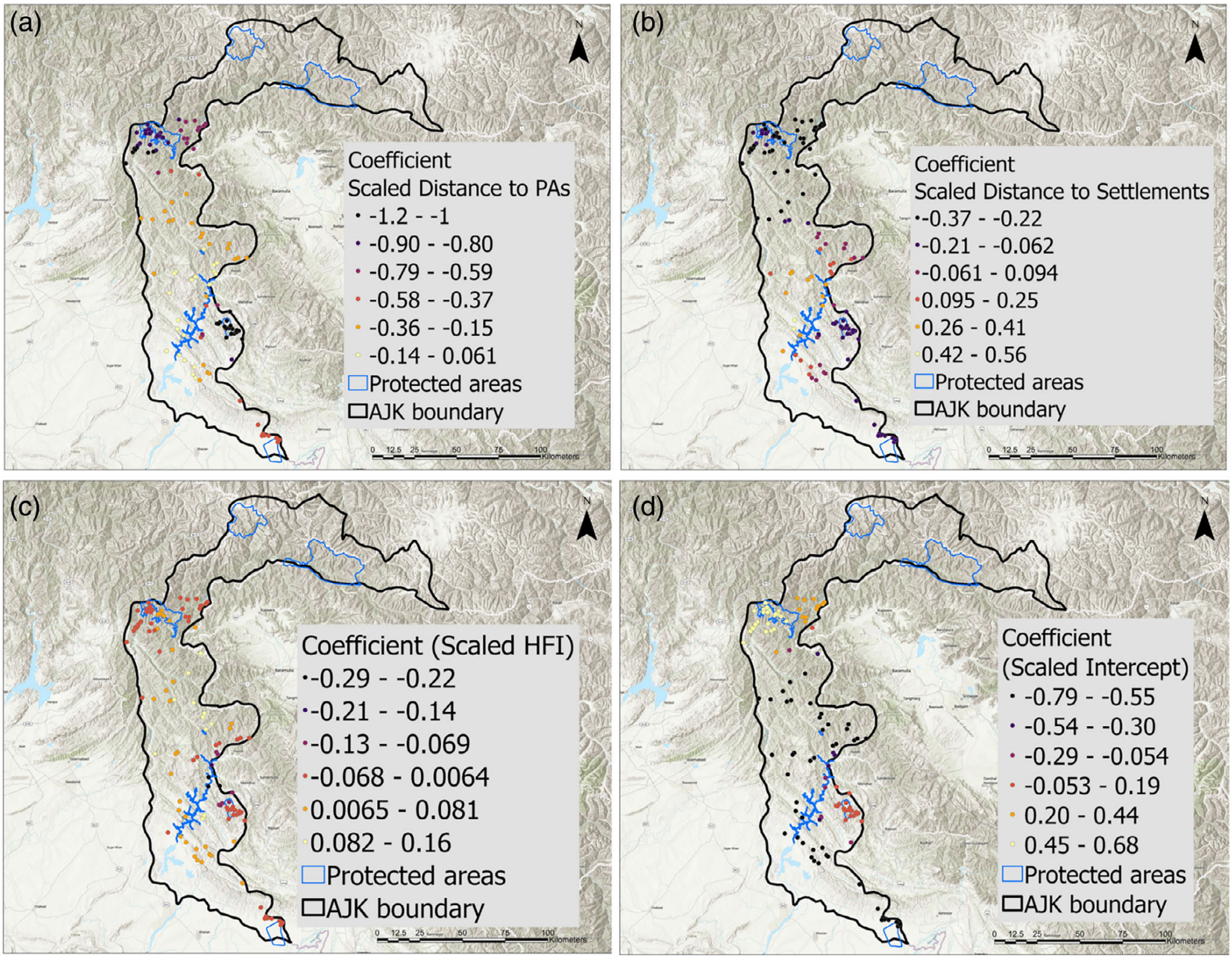

FIGURE 5 Spatial distribution of the multiscale geographically weighted regression coefficient showing the relationship between leopard mortality density and (a) distance to protected areas, (b) distance to human settlements, (c) human footprint index (HFI), and (d) model intercept across Azad Jammu and Kashmir (AJK). Mapped values represent scaled (standardized) regression coefficients rather than raw predictor units; coefficients are centered at zero, with negative values indicating decreasing mortality risk with increasing distance from a given feature. Color gradients depict the magnitude and direction of local associations. Summary statistics, coefficient ranges, and the proportion of statistically significant local coefficients are provided in Appendix S5.

fewer leopard attacks on humans than in Nepal, where such incidents are notably higher (Baral et al., 2021; Maskey et al., 2001).

The strong spatial disparity between protected and non-PAs is a striking finding, with nearly 90% of leopard mortalities occurring outside PAs. This pattern underscores the effectiveness of PAs alone in safeguarding wide-ranging leopards, particularly in regions where PA coverage is small and fragmented. The concentration of mortalities in non-protected and buffer areas reflects the reality that leopards in AJK persist largely within multi-use landscapes, where human presence, livestock, and infrastructure dominate. The lack of wildlife staff, formal reporting mechanisms and enforcement outside protected boundaries likely contribute to both higher mortality rates and lower detection probabilities, masking the severity of population losses.

Conservation of large carnivores in PAs with high human use or habitation is challenging due to ecological, political, and socioeconomic factors (Akrim et al., 2021). PAs alone are often too small to sustain viable leopard populations, forcing leopards to traverse human-dominated landscapes (Finnegan et al., 2021; Havmøller et al., 2019; Johansson et al., 2016; Webb et al., 2020). Communities living within or near PAs depend on livestock for their subsistence, which has resulted in an upsurge in the number of livestock, often at densities many times greater than wild prey species (Khorozyan et al., 2015). Settlements near PAs face more depredation due to large leopard home ranges and low wild prey densities (Akrim et al., 2018; Snider et al., 2021). Leopards in Pakistan often rely on livestock for survival (Akrim et al., 2023; Shehzad et al., 2015), and agro-pastoralism increases conflict due to dependence on forest grazing and punitive responses. Human population expansion adjacent to PAs has led to carnivore habitats being destroyed and a decline in prey abundance (Mbise et al., 2020). Consequently, conflict escalates and eventually leads to retaliatory killing of carnivores (Ikanda & Packer, 2008; Packer et al., 2005).

Time-series analysis revealed a clear escalation in leopard mortalities since 2019, with annual deaths more than doubling compared to the early 2000s. While such increases are often interpreted as evidence of growing leopard populations, this assumption is problematic when there is no baseline data on leopard abundance or prey availability. Without independent population assessments, rising mortality trends may instead indicate intensifying conflict pressure, habitat saturation, or declining tolerance levels rather than demographic resilience.

Spatial analyses consistently identified mortality hotspots clustered around the boundaries of Machiara, Pir Lasoora, Deva Vatala, and Tolipir National Parks. KDE, OHSA, and EHSA all converged on the same pattern: leopard killings are concentrated in human–wildlife interface zones rather than within protected cores. The prevalence of consecutive and intensifying hotspots suggests that these areas are not experiencing isolated or random events but rather sustained conflict over time. Such spatial persistence indicates chronic structural drivers such as land-use change, livestock grazing patterns, and limited conflict mitigation rather than short-term anomalies.

Our MGWR model showed distance to PAs was the strongest predictor of leopard mortality, indicating that leopards face greater threats closer to these zones. This suggests that leopards, as wide-ranging carnivores, frequently move beyond protected boundaries, increasing their exposure to human-dominated landscapes where the likelihood of conflict is significantly higher (Akrim et al., 2025; Finnegan et al., 2021; Ghoddousi et al., 2020; Jacobson et al., 2016). Livestock kept along the edges of core habitats often attract leopards, escalating the risk of depredation and subsequent retaliatory killings (Abade et al., 2018). The weaker and inconsistent effects of the human footprint index suggest that fine-scale interactions such as proximity to settlements and livestock practices may be more important than broad measures of human pressure in explaining leopard killings.

4.2 | Conservation implications

The northern Pakistan constitutes important potential habitat for leopards as well as other threatened species (e.g., Ahmad et al., 2022, 2024; Fida et al., 2024; Goursi et al., 2021; Rehan et al., 2024); however, climate change–driven disturbances, including recurrent forest fires and progressive habitat loss, have intensified human-leopard interactions. Seasonal agricultural practices temporarily provide cover, but post-harvest exposure of females with cubs frequently results in retaliatory killing of adults and poaching or capture of cubs, posing a serious risk to the long-term viability of local leopard populations (Bulungu, 2024). Furthermore, given that over 60% of leopard killings are retaliatory following livestock depredation, it is a priority to implement rapid and fair compensation schemes, along with community education programs focused on leopard behavior and coexistence practices (Nguyen et al., 2025). In data-deficient regions, even moderate levels of sustained anthropogenic mortality may have disproportionate demographic consequences, potentially leading to sudden and irreversible population losses.

Persistent and increasing mortality, concentrated outside PAs and close to the buffer areas, mainly in the absence of population baselines, represents a critical blind spot in current conservation planning (Schuster et al., 2023). Rather than formal expansion of PA cores—which may be socially or politically constrained—management should prioritize functionally expanded buffer zones that integrate wildlife conservation with regulated human use. These zones should be delineated using hotspot maps to identify high-risk interface areas requiring immediate intervention (Vynne et al., 2014). In addition, context-specific management strategies are required for different PAs. For example, around Pir Lasoora National Park, where hotspots overlap with dense settlements and high livestock reliance, mitigation efforts should focus on reducing economic losses through compensation or insurance schemes and strengthening community participation in conflict response. Conversely, around Deva Vatala National Park, where hotspots are more localized along forest edges and movement corridors, management should emphasize boundary-focused interventions, including strategic fencing, early-warning systems, and seasonal patrolling during high-risk periods.

Overall, these findings highlight the need to shift PA management from a static, core-focused approach to a dynamic, landscape-level strategy, where hotspot analyses guide the spatial prioritization of buffer zone management, community-based mitigation and enforcement efforts. Such an approach would substantially improve the feasibility and effectiveness of human–leopard conflict mitigation in AJK and similar human-dominated conservation landscapes.

5 | CONCLUSIONS

This study provides a long-term, spatially explicit assessment of common leopard mortality in AJK, revealing a sustained increase in conflict-related killings and a strong clustering of mortalities in human–wildlife interface zones surrounding PAs. By integrating time-series analyses with multiple hotspot detection methods and multi-scale regression modeling, we show that leopard mortality is spatially structured and strongly driven by proximity to PA boundaries and human settlements.

Importantly, the hotspot maps generated here offer direct guidance for targeted, site-specific interventions. In Pir Lasoora National Park, where consecutive and intensifying hotspots coincide with dense settlements and high livestock dependence, priority actions should focus on predator-proof corrals, improved herding practices, rapid-response conflict teams, and community-based livestock insurance or compensation schemes to reduce retaliatory killings. In contrast, hotspots around Deva Vatala National Park are more localized along park edges, suggesting frequent leopard movements across boundaries; here, strategic fencing of key corridors, seasonal patrols, and early-warning systems are likely to be more effective in reducing preventive and opportunistic killings.

Across the region, the concentration of nearly 90% of mortalities outside PAs highlights the limitations of core-focused conservation and underscores the need for buffer-zone–centered management. Persistent and intensifying hotspots identified through KDE, OHA, and EHSA should be used to prioritize enforcement, community engagement and mitigation efforts, particularly during winter and autumn when mortality peaks.

Finally, the sharp increase in leopard mortality since 2019, in the absence of population baselines, should not be interpreted as evidence of demographic resilience but rather as intensifying conflict pressure. The integrated analytical framework presented here provides a practical decision-support tool for data-deficient landscapes, enabling conservation planning to move beyond generic recommendations toward feasible, locally adapted strategies for long-term human–leopard coexistence.

AUTHOR CONTRIBUTIONS

Conceptualization: Muhammad Kabir, Faizan Ahmad, Muhammad Rehan, and Muhammad Raqeeb. *Methodology*: Muhammad Kabir., Faizan Ahmad, Muhammad Rehan, and Muhammad Raqeeb. *Investigation*: Muhammad Kabir., Faizan Ahmad, Muhammad Rehan, and Muhammad Raqeeb. *Writing—original draft*: Muhammad Kabir., Faizan Ahmad, Muhammad Rehan, Muhammad Raqeeb, Asma Ul Husna, and Luciano Bosso. *Writing—review and editing*: Muhammad Kabir., Faizan Ahmad, Muhammad Rehan, Muhammad Raqeeb, Asma Ul Husna, and Luciano Bosso.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

All the data are available in the main document and supplementary materials.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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