Examining leopard attacks: spatio-temporal clustering of human injuries and deaths in Western Himalayas, India

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Shared spaces in Africa and Asia accommodate both humans and big cats. This engenders rare but distinctive cases of human fatalities by lions, tigers, and leopards. Among big cats, leopards have the widest range and occur even among high densities of humans. This increased potential for encounters with humans results in attacks, exemplified most by India where 50% of the states report human injuries and deaths due to leopards. Himachal Pradesh (HP) state reported 30 lethal and 287 non-lethal leopard attacks on humans per year between 2004 – 2015 (N=317). Identifying patterns in big cat attacks on people facilitates targeted interventions for decreasing such fatalities. This study aims to detect if leopards are cluster-causing agents of human injuries and deaths. We identify the patterns of leopard attacks on humans in Himachal Pradesh by examining the following questions: (a) do leopard-attributed attacks on humans cluster in space and time? and among the leopard-attributed attacks (b) do unprovoked attacks on humans cluster spatio-temporally? and (c) what environmental factors are associated with the clustered leopard attacks on humans? We employed a space-time permutation scan statistic commonly used in epidemiology to test for spatio-temporal clustering of leopard attacks. Attacks were spread across 75% (~42,000 km sq.) of HP in 11 out of 12 districts. We found that 23% of attacks clustered into 12 significant spatio-temporal clusters. Nearly 14% of the leopard-attributed attacks (N=317) were unprovoked and attacks displaying "predatory" signs did not form significant clusters. Binomial regression models were run to test association of eight environmental factors with clustered attacks. We found that leopard-attributed attacks farther away from the protected area boundary and closer to the district boundary had higher probability of clustering. The framework developed in this study to identify the outbreak of unprovoked leopard attacks confirms the absence of dedicated "man-eaters" in the study region. This approach can be applied to adaptively manage human-wildlife conflict and it also demonstrates the utility of scan statistic in ecological research.

KEYWORDS

leopard, human-wildlife interaction, spatiotemporal, conflict, clusters, attacks, human-wildlife conflict

1 Introduction

Human deaths due to big cats such as tigers, leopards and lions are rare but distinctive as compared to other causes of human fatalities. The leading cause of human deaths globally is ischemic heart diseases with ~9 million human deaths per year (World Health Organization, 2020). Contrarily, Asian, and African countries such as Tanzania, Kenya, Bangladesh, India, and Nepal report up to 50 attacks due to big cats per year per study region (Jalais, 2008; Kushnir et al., 2010; Dickman et al., 2013; Kushnir et al., 2014; Govindrajan, 2015; Dhungana et al., 2018). Although the media report these stories in a sensational manner, the level of attacks is indisputable (Crown and Doubleday, 2017; Hathaway et al., 2017). A recent global review on human-felid conflict in 30 countries identified that 27% of the scientific publications were leopard-related (N=192), and 21% of the publications were from India (N=186) (Holland et al., 2018). Between 2012- 2013 alone, 78,656 ex-gratia applicants registered across 18 Indian state Forest Departments for damages attributed to wild animals. Almost 25% of the damages were due to leopards and tigers predating on livestock, and causing human injuries and deaths (Karanth et al., 2018). Leopard attacks are reported frequently in Indian states of West Bengal, Gujarat, Uttarakhand, and Maharashtra (Athreya et al., 2013; Bhattacharjee and Parthasarathy, 2013; Sondhi et al., 2016; Kshettry et al., 2017). Due to these interactions, continued persecution is a major threat to survival of leopard populations, in addition to habitat fragmentation and prey depletion (Stein et al., 2017). Since the leopards' geographic range overlap with human-dominated areas, the potential to encounter humans increases, often leading to human fatalities and injuries (Jacobson et al., 2016). In the early 1900's, the fatalities were majorly attributed to "man-eating" or problematic leopards (Nyhus and Tilson, 2010). More recently, human behavior, unsuccessful leopard management regimes and accidental encounters with leopards were determined as the causes of human fatalities due to leopards (Athreya et al., 2011; Kshettry et al., 2017).

The most common pattern of big cat attacks on humans is clustering, where events concentrate over space and time. Spatial clustering could occur due to human behavior patterns overlapping with leopard space use, increasing the interface between them. Studies have shown that the spatial nature of human activities such as bush-pruning in the tea estates of North East-India, non-timber forest produce collection in the buffer regions of a protected area in Western India, and livestock grazing within protected areas in Nepal leads to clustering of leopard-caused attacks (Gurung et al., 2008; Kshettry et al., 2017; Abade et al., 2018). Attack clusters also exhibit seasonal/time-associated patterns seen as increased frequency of attacks on humans by big cats. Additionally, seasonal changes in leopard attack frequency on humans has been attributed to changes in habitat structure, associated human activity and, prey depletions in the wild (Athreya et al., 2011; Shehzad et al., 2015; Acharya et al., 2016).

Detection of such spatial clusters of leopard attacks involves identifying groups of events that are unlikely to have been bounded geographically purely by chance (Aldstadt, 2010). Cluster-causing agents such as crime gangs, disease vectors, or poaching gangs are used to detect crime centers, ivory trade hotspots, COVID outbreaks, and wildlife disease outbreaks (Minamisava et al., 2009; Rashidi et al., 2015; Carricondo-Sanchez et al., 2017; Qi et al., 2020). Commonly, unsupervised learning methods such as Getis-Ord Gi*, or Ripley's K-function are used for scanning a defined area for presence of clusters (Fischer and Getis, 2010). These methods use a fixed distance for scanning an area to detect significant clusters and assume that the observed number of cases are uniformly distributed. In a more variable system such as disease surveillance and human-wildlife conflict detection, the population at risk is geographically heterogeneous and we do not know the dimensions of the cluster a-priory. Scan statistic, a recent advancement in cluster detection, uses a varying window of space-time combination to identify significant clusters (Kulldorff, 2021). However, to maintain relevance, the parameters used to define the bounds of the spatio-temporal window must be chosen based on the cluster-causing agent and its ecosystem.

The spatio-temporal window dimensions of clusters of attacks on humans are affected by many factors. Spatially, the home range size, social organization and presence of disease or injury among big cats affect the area of influence big cats have on humans. Pride-living lions have a greater area of influence on humans than a solitary leopard, due to larger space-use and resource requirements (Packer et al., 2019). Even within leopard populations, characteristics of the habitat determines the home range, or the potential area of influence on humans. Leopard home range varies from 887 km^2 in Namibia to 14.5 km^2 in India, which is driven by human density and prey availability of that site (Snider et al., 2021). On the other hand, temporal variability of clusters depends majorly on time taken to remove a problematic individual.

In the mid 1900's, access to hunters who could eliminate "problem animals" was limited. Records of 1000's of humans affected by one single animal have been popularized where animals were shot dead only after many human deaths had occurred (Patterson, 1907; Corbett, 1944). In contemporary times, credible research conducted on human-killing tigers around Chitwan, Nepal suggests that 56% of the tigers which attacked humans had physical deformities which were seen as "problem animals" and immediately removed from the system (Gurung et al., 2008). No reasons were attributed the rest of the tiger, but they were still removed from the wild. In contemporary times, section 11 of the Wildlife Protection Act in India, accords power to the Chief Wildlife Warden of the state to order removal of a wild animal if it has become dangerous to human life. Such laws exist in other countries, and this ensures, in effect, a shorter temporal influence of the "problem animal" on the surrounding human population. Problem animals are most often display unprovoked attacks on humans characterized by the predatory behavior of stalking, pursuing, and charging. They are the gravest but also the rarest type of big-cat attributed attack on people (Khramtsov, 1995). In India, there are even accounts of leopards entering houses to attack humans in their sleep (Shivakumar, 2003; Thirgood, et al., 2005). It is highly probable that such unprovoked attacks display spatio-temporal patterns detectable through rigorous space-time analysis.

Himachal Pradesh (HP) and Uttarakhand, the north-western mountainous states of India, are recognized for the presence of "man-eating" leopards since the early 1900's. A total of 121 leopards were declared as "problem animals" in Pauri Garhwal (Uttarakhand) between 1990 - 2005 (Naha et al., 2018). In Mandi district (HP) between 2001-13, almost 50% (N=123) of the dead leopards were killed by unknown persons and 8% (N=123) were declared as "problem animals" (Athreya et al., 2015). HP forest department records showed 356 cases of leopard-attributed human injuries and deaths between 2004 – 2015, with an average of 3 human deaths/year. Leopard-human conflict mitigation in these areas is state-managed with the predominant response being leopard lethal control, ex-gratia payments made to victims, and translocations of leopards sighted within villages (Pers. Observation SS, Karanth et al., 2018). The aim of this study is to detect if leopards are cluster-causing agents of human injuries and deaths. We identify the patterns of leopard attacks on humans in Himachal Pradesh by examining the following questions: (a) do leopard-attributed attacks on humans cluster spatio-temporally? and among the leopard-attributed attacks (b) do unprovoked attacks on humans cluster spatio-temporally? and (c) what environmental factors are associated with clustered leopard-attributed attacks on humans?

2 Methods

2.1 Study area

This study was conducted in the state of Himachal Pradesh (HP), India between latitude 30°30' and 33°15' N to 75°30' and 79°0' E. Himachal Pradesh is part of the Western Himalayas sharing a border with Uttarakhand, Punjab, Haryana, Jammu & Kashmir States of India, and international borders with the Tibet autonomous region. The elevation of HP varies from 450 – 7,085 m above sea level, with temperatures ranging from -4°C to 42°C across the seasons of monsoon, summer, and winter. An average of 123.3 humans/km² reside in the 12 districts, with almost 90% of the population living in rural areas (Jreat, 2006; Government of India, 2011). HP ranks 22nd on the state economy list with 45% of its net state domestic produce due to agriculture, and 7% of the GDP due to the tourism industry (India Brand Equity Foundation, 2021).

With a total area of 55,673 km² HP has 27% of its area under tree cover, which is higher than most Indian states (Forest Survey of India, 2019).

Almost 15% of the forests are protected under five national parks, 26 wildlife sanctuaries and three conservation reserves (Forest Department Himachal Pradesh, 2021). The flora and faunal diversity of HP is attributed to the steeply varying altitude and climatic conditions. Housing almost 7% of the country's diversity of flora, there are nine forest types in HP ranging from dry alpine forests to tropical thorny forests (Jreat, 2006). HP has the iconic snow leopard (*Panthera uncia*) and a range of other carnivores such as Himalayan black bear (*Ursus thibetanus laniger*), Tibetan fox (*Vulpes ferrilata*), red fox (*Vulpes vulpes*) and leopards (*Panthera pardus fusca*). Herbivores such as
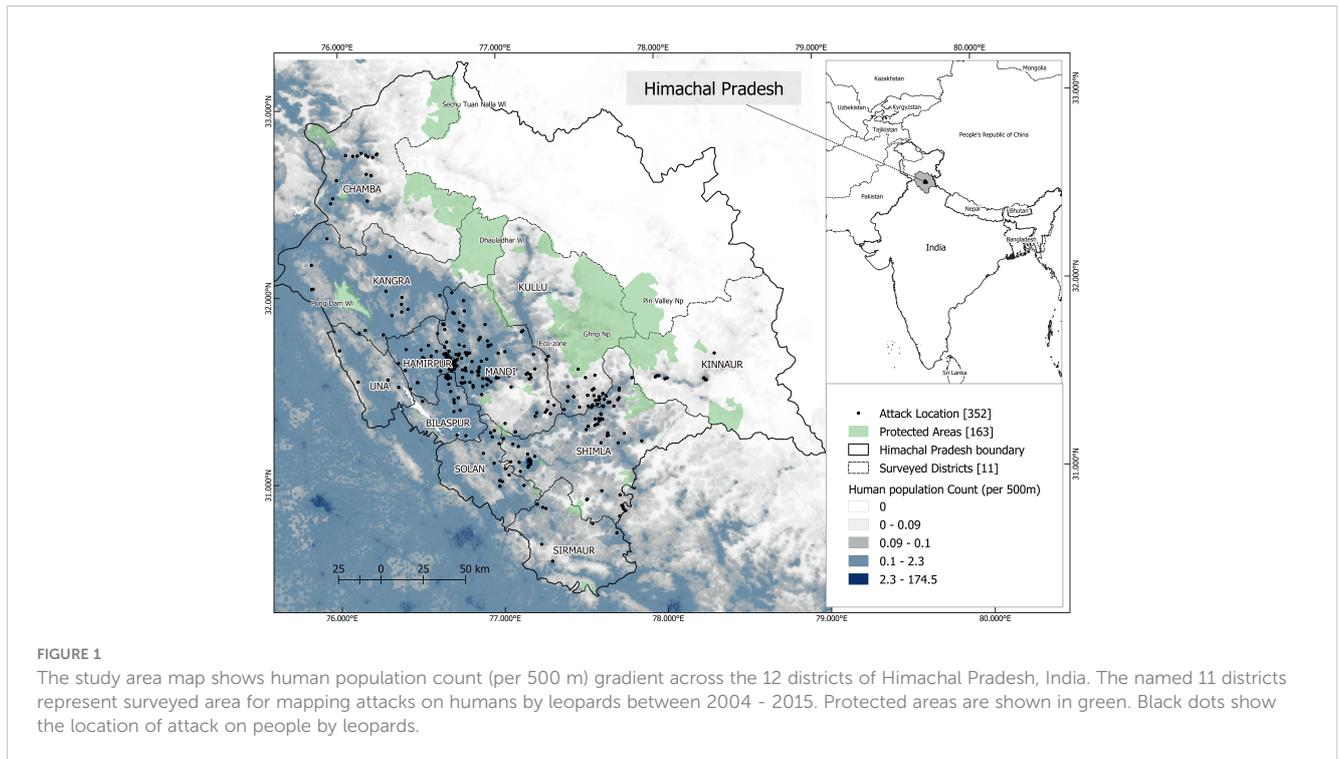
Himalayan ibex (*Capra sibirica*), bharal (*Pseudois nayaur*), gorals (*Nemorhaedus goral*), musk deer (*Moschus leucogaster*) and Himalayan thar (*Hemitragus jemlahicus*) are present. The survey was carried out in the 11 districts out of 12 where leopard presence was reported (Figure 1). Leopards are the most widespread carnivore of the state and unlike the neighboring Indian state of Uttarakhand, the co-predator tiger is absent in the landscape.

2.2 Data collection and processing

This collaborative study with the Himachal Pradesh Forest Department commenced by obtaining records of ex-gratia payments made to humans attacked by leopards between 2004 to 2015. Each ex-gratia applicant was visited to (a) validate the site of attack and confirm the species that was involved (b) to record the exact location of leopard attack (c) conduct interviews of humans who were directly involved in the incident. Questionnaire surveys were conducted between November 2014 and July 2015 through a total survey effort of approximately 13,437 kms in Himachal Pradesh. "Attacks" were defined as human injuries or deaths that were attributed to leopards. Attacks were defined as "unprovoked" when the leopard was described to exhibit one or more stages of a non-human prey hunt: (1) a bite on the neck/nape (2) dragging of the body away from the attack site, and (3) ultimately feeding on the body in a secure place. Attacks that were not displaying these characteristics were termed "other" attacks. The resulting database of discrete count data spanning a 11-year duration (2004 Jan - 2015 Jan) was used for cluster analysis. Since most people were unable to recall the exact date of attack, we only recorded the month and year of attack. The research protocols were approved by the Institute Ethics Committee (Human Studies) of Wildlife Conservation Society-India (No. IEC. 2019/5).

2.3 Detection of leopard-attributed cluster of attacks on humans

We used SaTScan, QGIS and R software to conduct cluster analysis (QGIS Development Team, 2020; R Core Team, 2020; Kulldorff and Information Management Services, 2021). The scan statistic method was developed primarily to conduct disease surveillance studies (Kulldorff and Nagarwalla, 1995). We applied scan statistic into the human-wildlife conflict system to detect clusters of leopard attacks on humans, using the software SaTScan (Kulldorff et al., 2005). Apart from one other study comparing species-specific spatio-temporal patterns of attacks on humans, previous applications of the scan statistic in wildlife conservation have been limited to wildlife disease detection, habitat/kill site selection and wildlife crime (Webb et al., 2008; McPhee et al., 2012; Rashidi et al., 2015; Carricondo-Sanchez et al., 2017; Packer et al., 2019). We drew parallels of disease systems to the human-leopard conflict system in this analysis. We defined "clusters" as areas with sustained leopard-attributed human injuries/deaths (henceforth attacks). Each attack is a "case", the exact GPS location of attack is where the "disease contracting"

FIGURE 1
The study area map shows human population count (per 500 m) gradient across the 12 districts of Himachal Pradesh, India. The named 11 districts represent surveyed area for mapping attacks on humans by leopards between 2004 - 2015. Protected areas are shown in green. Black dots show the location of attack on people by leopards.

occurred and, the human population at the year of attack is the "population-at-risk". The leopard was seen as a "disease-causing agent". To conduct cluster analysis, we used a space-time scan statistic model within SaTScan which can be visualized as a cylindrical window with a circular base of space (R) and height of time (T) (Kulldorff et al., 2005). This cylindrical window then moves to "scan", using all possible combinations of space and time, to create overlapping cylinders within the study region and study duration. We defined the bounds of Tmax to Tmin (maximum and minimum time duration of the clusters) and Rmax (maximum radius of the cylinder base) in the analysis. Scan statistic is ideal for retrospective analysis where the scanning is repeated every month for every space combination (Kulldorff et al., 1998). Monte-Carlo simulations were used to detect windows with significantly (α = 0.05) higher attacks than the background, thus identifying clusters.

To determine whether leopard attacks on humans clustered, we used two types of models that represented the distribution probability of attacks in the study (a) All-attacks model: null hypothesis was that attacks are Poisson-distributed with constant spatio-temporal risk within and outside a cluster. The human population represented the control population-at-risk (b) Unprovoked-attack model: the null hypothesis was that unprovoked attacks (those that displayed predatory signs towards a human) are Bernoulli-distributed with probability of being attacked unprovoked within a cluster = probability of being attacked unprovoked outside the cluster. Total attacks (unprovoked + other) were used as the control population-at-risk (Kulldorff and Nagarwalla, 1995; Kulldorff et al., 1998). We used the same run parameters for both models, to ensure consistency (Supplementary Table 1). We established the bounds of this scan-

statistic model based on leopard ecological parameters appropriate to the region (Supplementary Table 1). We used the largest home range of a leopard close to the study site, a male leopard in Nepal (64 km^2), and set Rmax to 5.34 km (Odden and Wegge, 2005). We added 38% of the area to the Rmax estimate to include the possibility that the planimetric methods underestimate mountainous leopard home ranges (Farhadinia et al., 2020). The time bounds were set based on the generation length of a leopard which was 7.42 years (Stein et al., 2017). Monte-Carlo likelihood-based estimations were determined over 999 iterations. Scanning windows with P-value < 0.05 were considered significant.

2.4 Identifying environmental factors affecting clustered leopard-attributed attacks

Using the identified significant clusters, we fit a model to study factors potentially associated with clustered attacks on humans. For that, we used the glm () function with a binomial family and a logit link in R. The binomial response variable was whether the attack location belonged to a significant cluster (1) or was isolated (0). The predictor variables, or covariates, were chosen based on studies documenting environmental factors associated with big cat-attributed attacks on humans (Table 1). The underlying assumption of the analysis was that attack clusters occur when covariates influence the probability of encounter between a human and a leopard.

The six numerical covariates (1) change in human population count, (2) elevation, (3) distance to protected area (PA), (4) distance to district boundary (DB), (5) distance to river, and (6) change in

TABLE 1 The nine covariates used in the binomial regression model to determine environmental factors that affect clustered attacks by leopard on people.

No	Covariate	Reasoning	Source and resolution
1	Change in non-tree vegetation since 2000	Leopards are found in areas with greater ground cover (Kshettry et al., 2017)	MODIS VCF (500m) (DiMiceli et al., 2017a)
2	Land use type	Big cats have stable population in forests which sometimes act as source population (Loveridge et al., 2010)	MODIS (300m), 2004 – 2015 (Friedl and D, 2019)
3	Change in Land use (LU) type since 2001	Areas with recent deforestation, and abandonment of land have higher risk of attacks by big cats (Gurung et al., 2008)	MODIS (500m), 2001- 2015 (Friedl and D, 2019)
4	Change in human population count since 2000	Areas with higher densities of human and leopard have evidence of intensive management interventions, leading to attacks (Athreya et al., 2011)	World pop (500m) 2000 – 2015 (Gaughan et al., 2013)
5	Distance to PA (Protected Area)	Human-wildlife conflict has been seen to occur at the protected area boundary in Central Indian landscape and Nepal (Gurung et al., 2008; Karanth et al., 2012b; Dhanwatey et al., 2013)	Calculated on QGIS using the distance tool
6	Distance to DB (District Boundary)	Translocation of leopards, when done, is usually at the administrative boundary (Pers. comm. Athreya, 2022)	Calculated on QGIS using the distance tool
7	Presence of unprovoked attacks	Unprovoked attacks displayed by big cats are usually concentrated spatio-temporally (Packer et al., 2019)	Categorized post-collection
8	Distance to river/ streams	Leopards live and take refuge in river valleys (SS, Personal Observation)	Calculated on QGIS using the distance tool
9	Elevation	In Himachal Pradesh, separation of leopards and snow leopards based on elevation has been observed (SS, Personal Observation).	ASTER DEM (NASA/METI/AIST/Japan Spacesystems and U.S./Japan ASTER Science Team, 2019)
10	Cluster ID	Covariates may influence attacks in a related manner within a cluster (Legendre, 1993).	SaTScan analysis output

The assumption is that cluster of attacks (CoA) occur when covariates influence the probability of encounters between human and leopards. The associated reasoning for inclusion and source of each covariate, including the spatial autocorrelation covariate, Cluster ID is detailed.

non-tree vegetation, were scaled using z-score. All nine covariates were checked for correlation using Spearman's method in R. The remote-sensed covariates (1) non-tree vegetation land use (MODIS VCF), (2) human population count (Worldpop), and (3) elevation (ASTER) were extracted using Google Earth Engine for each year (2004 - 2015) and rescaled to 500m (DiMiceli et al., 2017b; Gorelick et al., 2017). Distance from PA was calculated using the NNJoin tool in QGIS (QGIS Development Team, 2020). The point sampling tool in QGIS was used to sample covariate values at each location of leopard-attributed attacks.

We incorporated the temporal aspect by calculating the trend in the relevant covariates from the year 2000 to the year of attack. Trends in human population counts, non-tree vegetation and land cover were incorporated in the analysis. The other five covariates (elevation, unprovoked/other, distance to protected area, distance to district boundary, distance to river) did not vary temporally and remained fixed in the analysis. Multiple models were fitted using the step () function in R. This function chooses a model based on AIC values in a stepwise algorithm. A global model with all covariates is used at the start and at each step it drops one covariate which decreases the AIC when removed from the model. The entire process repeats until it becomes that no single variable can be dropped (Table 2). Further, to account for any spatial autocorrelation, we used the cluster ID (ranging from 1 to 12) as

a random effect variable in a mixed effect model with a fixed intercept, using the buildmer package in R.

3 Results

This study was conducted to detect spatio-temporal clusters of attacks (CoA) that occurred on humans due to leopards in Himachal Pradesh (HP), India and to investigate potential environmental factors influencing the formation of these clusters. From a total of 416 cases of human injury/death due to leopards collated from the Forest Department records, we ground-validated 356 attacks between January 2004 – January 2015. Cases without date, location, and those outside the span of 2004 – 2015 were excluded in the analysis. Finally, we had a pool of 317 complete cases which constituted 30 lethal and 287 non-lethal injuries sustained by humans due to leopard attacks. Multiple humans attacked in one incident were considered as a single case. The areas with leopard attacks on humans had on average 4.19 humans/300 m^2. There were 47 unprovoked attacks (N= 317) between 2004 - 2015. Attacks were found to affect 57% of HP state (Total state area = 55,673 km^2) spread over 11 out of 12 districts. The attacks were not evenly distributed across the twelve years with maximum attacks, almost 20%, occurring in 2012 (X^2 = 115.32,

TABLE 2 Candidate models developed during the step-function binomial regression analysis to estimate factors affecting clustered attacks by leopards on humans in Himachal Pradesh between 2004 - 2015.

No	Step function model composition	AIC
Step 1	Unprovoked attack + Elevation + Human population count change since 2000 + Landcover change since 2001 + Distance to PA + Distance to DB + Distance to river + Change in non-tree cover since 2000 + Land Cover type	323.24
Step 2	Unprovoked attack + Elevation + Landcover change since 2001 + Distance to PA + Distance to DB + Distance to river + Change in non-tree cover since 2000 + Land Cover type	321.37
Step 3	Unprovoked attack + Elevation + Landcover change since 2001 + Distance to PA + Distance to DB + Distance to river + Land Cover type	319.50
Step 4	Unprovoked attack + Elevation + Landcover change since 2001 + Distance to PA + Distance to DB +Distance to river	317.53
Step 5	Unprovoked attack + Elevation + Distance to PA + Distance to DB + Distance to river	315.66
Step 6	Unprovoked attack + Elevation + Distance to PA + Distance to DB	314.05
Step 7	Elevation + Distance to PA + Distance to DB	313.02
Step 8	Distance to PA + Distance to DB	312.77

The nine covariates used in the model creation were: Change in non-tree cover since 2000, distance to protected area (PA), distance to district boundary (DB), distance to river, presence of unprovoked attacks, change in human population count since 2000, land cover, change in landcover since 2001 and elevation.

df = 11, p < 2.2 e-16) (Figure 2). Thus, the attacks on humans by leopards were not evenly spread over space and time in Himachal Pradesh.

3.1 Detection of leopard-attributed cluster of attacks on humans

Using the space-time scan statistic, we identified significant spatio-temporal clusters of leopard-attributed attacks on humans in Himachal Pradesh. In the analysis, CoA (cluster of attacks) were allowed to range from 0.1 to 5.4 km radius and 1- 50 months in duration (Figure 3). The Poisson model, detecting if all attacks clustered, (N=325), identified 12 significant clusters out of 21 total (Figure 4). The 12 significant CoAs ranged from 0.4 km to 5.24 km in radius, and 1- 20 months in duration (Figure 3). The Bernoulli model, examining if unprovoked attacks clustered (Unprovoked attacks=47), identified five CoA with none of them significant

(Figure 4). These unprovoked attack clusters ranged in radius from 1.38 km to 4.61 km, and in duration from 7 - 44 months. A plot of radius of cluster of attack vs the duration showed that 66% of the significant clusters (N=12) were of a duration < 5 months (Figure 3).

3.2 Identifying environmental factors affecting clustered leopard-attributed attacks

The 12 significant clusters (p-value <0.05) from the Poisson model, analyzing if all types of attacks clustered, were used for further analysis. Almost 23% of the attack locations were found within 12 significant clusters (N=317). The covariates were mildly correlated using the Spearman's test of pairwise correlation with values ranging between -0.4 to 0.2 (Supplementary Figure 1). The binomial regression model with response variable as attacks
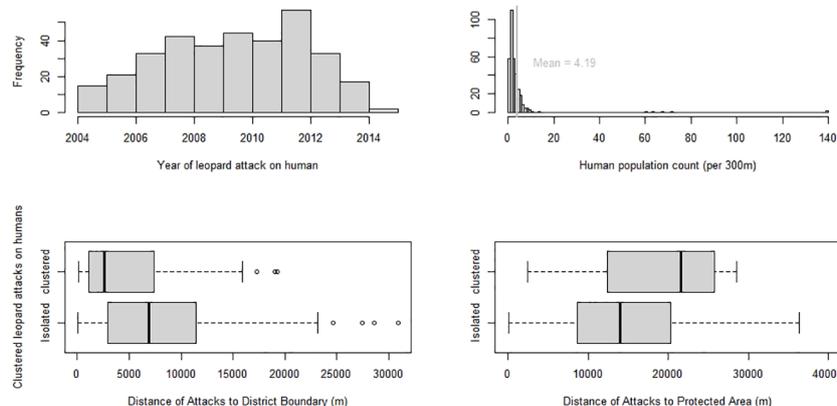

FIGURE 2
A plot of characteristics of cluster of attacks (CoA) on humans due to leopards with histograms on (i) year-wise spread of attacks from Jan 2004 - Jan 2015 (ii) human population count at location of attack at the year of attack (per 500 m) and box plots of clustered attacks by leopards on humans vs (iii) distance of attack to district boundary (iv) distance of attacks to protected area boundary.
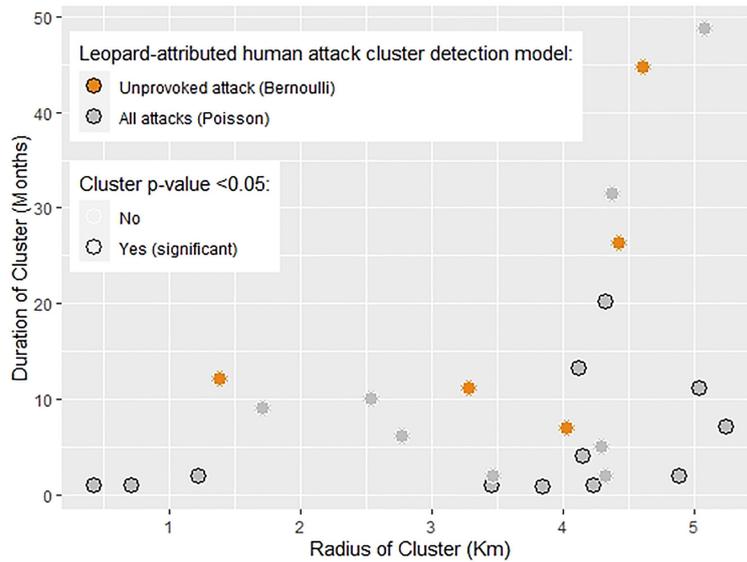
FIGURE 3
Leopard-attributed human injuries and deaths tested for clustering using the spatial scan statistic yielded clusters of attacks (CoA). This graph indicates the relationship between radius and duration of these CoA which were allowed to vary from 0.1 - 5.4 km and 1 - 50 months respectively. Clusters were significant if they had a p-value < 0.05 using the Monte-Carlo likelihood-based simulation. There were 12 significant (black outlined dots) and 13 non-significant clusters (white outlined dots) in total. The two types of models detecting these clusters were (a) Bernoulli model (orange dots) with case= unprovoked attacks and control = all attacks, and (b) Poisson model (grey dots) with case= all attacks and control = human population count. This graph indicates that 9 out of 12 significant clusters had a duration of less than 10 months, but widely varying radius.
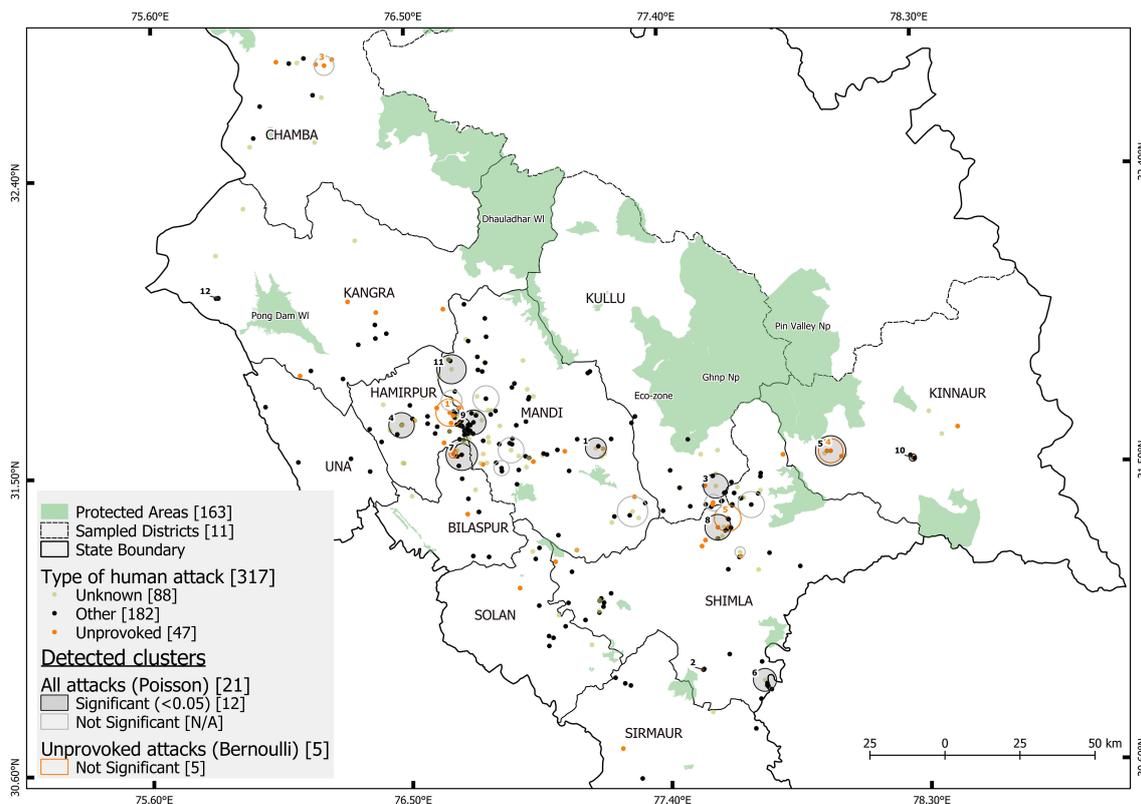

FIGURE 4
Map showing the cluster of attacks (CoA) detected using space-time scan statistic and GPS location of leopard-attributed attack on humans (N=317). Attacks were categorized as "Unprovoked" (orange dots), "other attacks" (black dots) and "Unknown" (buff dots) for those that could not be categorized. SaTScan cluster-detection software was applied using two models: (a) Poisson probability model (all attacks) detected 12 significant clusters (grey filled circles) and 9 non-significant clusters (grey outline circles) (b) Bernoulli probability model (Unprovoked attacks) detected five non-significant clusters (orange outline cluster). The cluster numbers of CoA are shown in black and orange.

belonging to a significant cluster of attack (CoA) (1= attacks in clusters, 0= isolated attacks), was run for eight models (Table 2). Cluster ID, the random effect used to test for spatial autocorrelation among the covariates, was used in a mixed effect model and the model did not converge. Further, the number of points within each cluster were too small (median number of attacks within a cluster = 5). Hence, a random effect was not considered for drawing inferences in this study. We used GLM binomial regression for the modelling process. The largest significant effect was of the distance to district boundary covariate which measured the distance of the attack location to the closest district boundary. This was a negative association, where an attack closer to the district boundary was 0.6 times more likely to belong to a CoA (cluster of attack) (Table 3). Clustered attacks were closer to the district boundary (median = 2.6 km) than the isolated attacks (median = 6.8 km) (Figure 2). Distance to protected area (PA) was the other significant covariate which measured the distance between the attack location and the closest PA boundary. It was a positive association, i.e., attacks that were farther away from the PA were 1.4 times more likely to belong to a CoA (Table 3). Isolated attacks were closer to the protected area boundary (median = 13.8 km) versus the clustered ones (median = 22.7 km) (Figure 2).

4 Discussion

In this study we show that leopard attacks on humans are spatio-temporally clustered in Himachal Pradesh. We found 317 confirmed cases of attacks on people by leopards which contained 30 deaths and 287 injuries between 2004 - 2015. These attacks were spread across 75% (~42,000 km^2) of Himachal Pradesh, India, in 11 out of 12 districts. However, a focused area of 31,605 km^2 was intensely affected by these attacks, constituting 57% of the state. Over the 11 years, attacks were found to be unevenly distributed, with 2012 being the maximum attack year (5 fatalities, 52 injuries). Our analysis identified 12 significant clusters over a total area of 41.6 km^2 and a total duration of 5.4 years.

Our input for the cluster detection analysis was set to define an "outbreak" of leopard attacks as if it were caused by one animal. We hypothesized that attacks cluster spatio-temporally, while considering the human population distribution. We detected the presence of 12 significant clusters of attacks (CoA). The subsequent hypothesis was that unprovoked attacks (leopard attacks that displayed predatory signs and occurred without any provocation from the person)

clustered spatio-temporally. We did this considering the total number of attacks that occurred during the study as the control. We found no significant unprovoked clusters. Although 14% of the leopard-attributed attacks (N=317) were unprovoked in nature, attacks displaying "predatory" signs did not form significant clusters of attack (CoA). This shows that the prevalence of unprovoked attacks by leopards on humans was consistent spatio-temporally through the study at a rate of 3 attacks per year. Additionally, non-predatory attack signatures displayed by a "problem animal" became part of the control in the unprovoked attack model.

In India, with the support of the Wildlife Protection Act's "declaration of an animal as dangerous to human life" clause, and a proactive community, removal of a problem animal is expedited almost immediately following a human death (Pers. comm, Sat Pal Dhiman, 2019). Additionally, leopard deaths due to human-related causes are high in the region with almost half of the leopard deaths attributed to unnatural causes (Kumar et al., 2017). Thus, we suspect that it is improbable that clusters spanning greater than a few months in contemporary times could be attributable to a single leopard, whether unprovoked or otherwise. Our study found that approx. 70% of the significant clusters were < 5 months in duration, with mixed attack types. Rather than one dedicated leopard causing human attacks, it is more likely that leopards in human-dominated landscapes encounter people often, leading to short seasonal clusters. This is indicated by a spike in attacks during the months November – February, but not a significantly higher rise. Clusters were higher in the December month of several years. This study contributes to disproving the existence of sustained dedicated "man-eater" individuals which operate in clustered space and time.

To determine if all attacks were equally influenced by environmental factors, we compared attacks within clusters (clustered) to attacks outside clusters (isolated). We chose nine environmental factors based on research literature that identified drivers of leopard attacks on people. The factors were elevation, change in non-tree cover, land cover type, change in land cover, distance to river, distance to district boundary, distance to protected area (PA) boundary, human population, and whether the attack was unprovoked or not. Among the tested ones, distance to PA was an important factor with attacks farther away from a PA predisposed to being clustered.

Most of the clustered attacks were 22 km away from the closest protected area boundary, whereas isolated attacks were as close as 0.5 km. This contrasts with other studies which found greater attacks on humans by tigers and lions occurring closer to a PA

TABLE 3 Binomial regression models were run with the response variable as leopard attacks on humans belonging to cluster of attacks (clustered attacks= 1, isolated attacks= 0).

No	Covariate	Beta estimate	Standard error	95% Confidence Interval for Odds Ratio		
				Lower	Odds Ratio	Upper
1	Intercept (Land use - Crop)	-1.23***	0.15	0.21	0.29	0.39
2	Distance to protected area	0.34*	0.14	1.07	1.41	1.86
3	Distance to district boundary	-0.54***	0.18	0.40	0.58	0.81

Nine covariates were used in the modelling process and a step function was used for model selection based on AIC values. There were two significant covariates detected in the process- distance to district boundary and distance to protected area.
Significance. codes (p-value): '***' 0 - 0.001; '*' 0.01 - 0.05.

(Gurung et al., 2008; Karanth et al., 2012a; Banerjee et al., 2013; Dhanwatey et al., 2013). This exemplifies that attacks can only occur in areas of overlapping big cats site-use with people's site-use. Studies mostly document lesser site-use by big cats in human-use areas. For instance, in Tanzania, leopard site-use decreased with decrease in protection status of that land, with villages having the least site-use (Abade et al., 2018). However, in the mountainous terrain of Himachal Pradesh, leopard site-use is higher in river valleys, agricultural fields, and foddergrass lands (Shivakumar. S, personal observation). It is plausible that human-leopard encounters are inevitable in such areas of high non-tree cover and medium human activity, regardless of the protection status of that land. In fact, in West Bengal, India, spatial clustering of attacks on humans in a mosaic landscape (forests, tea plantations, agricultural fields, and human settlements) was influenced by ground cover and not the level of site-use of leopards (Kshettry et al., 2017). More such studies in shared landscapes are needed to support the active presence of big cats away from protected areas.

On the other hand, the covariate 'distance to district boundary' had the opposite effect on clustered attacks in this study. Attacks closer to the district boundary were more likely to belong to a cluster. Clustered attacks were as close as 0.93 km (median distance = 26 km) to the district boundary and isolated attacks were ~ 69 km away from the boundary. Often, leopards are captured due to public pressure and released near district borders (Personal communication, Vidya Athreya, 2022). A study on translocation of leopards in the south-western Indian state of Maharashtra found that attacks near the leopard release sites showed a 325% spike in the frequency of attacks on humans (Athreya et al., 2011). In Himachal Pradesh, translocations used to occur in the past. It is plausible that clustering of attacks over a short duration of time and at district boundaries could potentially be due to translocations in the region between 2008 – 2012. But this is an educated guess since no records exist. This argument can be further strengthened by evaluating the effects of leopard removal on attacks in the region.

Over time, the attacks peaked in 2008-2012 and declined subsequently (Figure 2). Attacks have further decreased from 2015 - 2018 with only five leopard-attributed injuries reported in 2018 through the state of Himachal Pradesh (Pers. comm, Sat Pal Dhiman, 2022). This decrease in attacks by leopards, is counter-intuitive to the general perception propagated by the media, but quite common in India (Bhatia et al., 2013). In the neighboring state of Uttarakhand, leopard-attributed deaths reduced to 154 (2006-2016) from 556 (1998-2005) (Naha et al., 2018). The causes of this decline speculated by the authors were large-scale killing of female leopards and, rural-urban migration. In a human modified landscape of Western Maharashtra, 10 potentially dangerous large carnivores reside per 100 km^2. Negligible attacks on humans by these leopards and hyenas occurred from 2006 – 2009, with a momentary spike in attacks during the leopard translocation period (Athreya et al., 2011, 2013). In Mumbai city, a minimum of 20,000 humans per km^2 stay adjacent to a national park, where attacks on humans by leopards decreased from 2001 - 2011, despite high densities of leopards (Bhatia et al., 2013; Surve et al., 2022). Unlike the general perception of increase in attacks on people due to

leopards in India, this study adds evidence to the decreasing trend of leopard attacks.

This framework of identifying leopard attack outbreaks of unprovoked nature proposed in this study aided in disproving the sustained presence of dedicated "man-eaters" in the study region. Most significant spatio-temporal clusters were caused over short periods consisting of mixed attack types. This indicates the presence of seasonal attacks rather than leopard individual-driven attacks. Further study into the seasonal human behaviors of the landscape can aid in identifying the drivers of seasonal patterns of attacks.

The findings of this study can contribute to the leopard management policy of Himachal Pradesh, particularly in spatial prioritization of leopard-attributed human attack mitigation. Approximately 325 Forest Administrative units called Beats constituting the border regions of Hamirpur, Bilaspur, Mandi, Shimla and Kullu have been identified as a hotspot for spatio-temporal clusters of leopard attacks on humans. These areas can be prioritized for conflict mitigation approaches and awareness building campaigns. Further investigation in these regions could also reveal the non-environmental determinants of human attacks by leopards such as leopard translocations, retaliatory killing of leopards and even leopard abundance fluctuations that could lead to attacks. This study's framework has wide application in human-wildlife conflict mapping of large mammals globally. Location of human-wildlife interaction, date/time of interaction and the appropriate parameter settings are the only required inputs to replicate this analysis. The results can generate interesting insights providing vital management inputs to reduce human-wildlife conflict.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by Institute Ethics Committee (Human Studies) of Wildlife Conservation Society-India (No. IEC. 2019/5). Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

Author contributions

SS: formal analysis, writing-original draft, data curation, conceptualization. VA: conceptualization, project administration, funding acquisition, writing-review, and editing. KK: writing – review, funding acquisition, supervision, resources. MO: conceptualization, methodology, writing – review and editing. DC-S: methodology, writing – review and editing. SV: validation, writing – review and editing. SD: resources and validation. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fcosc.2023.1157067/full#supplementary-material

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