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RESEARCH ARTICLE

Ecological and anthropogenic drivers of leopard (*Panthera pardus fusca*) attack occurrence on humans in Nepal

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Abstract

1. The negative impact of large carnivore presence in human-dominated landscapes manifests as livestock depredation and in extreme cases as attacks on humans. In the case of conflict with leopards in Nepal, attacks resulting in human fatality have become more frequent over time, thus creating an urgent socio-ecological and management issue.
2. We estimated the occurrence of leopard attacks in Nepal from human-leopard conflict cases reported in the media. We used occupancy models to analyse data collected from online news reports on incidents of leopard attacks on humans to explore drivers of leopard attacks on a landscape scale. Our results suggest that the probability of occurrence of leopard attack is associated with human population density, terrain ruggedness and livestock density.
3. The human population density effect may be indicative of a density-dependent relationship, where attacks are more likely in areas where an increased abundance of humans increases encounter rates with leopards. The positive effect of livestock density suggests that livestock may be drawing leopards into human settlements, and consequently increasing the likelihood of attacks on humans. Terrain ruggedness might be offering ideal conditions to facilitate attacks on humans, for example remoteness and high amounts of cover to launch ambush attacks.
4. We provide inference and insights into key determinants of leopard attacks on humans on a landscape scale. These insights can be used to guide future research, inform mitigation measures to reduce leopard attacks and foster a better understanding of the interaction between people and leopards.
5. This study demonstrates the applicability and novelty of using a hierarchical modelling framework applied to freely and publicly available media reports to inform the applied management of human-wildlife conflict at a national scale.

KEYWORDS
animal attacks, human-wildlife conflict, media analysis, Nepal, occupancy modelling, *Panthera pardus fusca*

1 | INTRODUCTION

Large carnivores are among the most threatened animals on the planet (Wolf & Ripple, 2017). They are charismatic species and evoke both fear and admiration among humans while having integral roles in maintaining ecosystem functioning and health (Ripple et al., 2014). Humans have extensively modified the earth's land surface (Hooke et al., 2012): hence, carnivores are increasingly forced to share landscapes with humans (Chapron et al., 1979). Many iconic large carnivores such as brown bears (*Ursus arctos*), pumas (*Puma concolor*), jaguars (*Panthera onca*), tigers (*Panthera tigris*) and leopards (*Panthera pardus*) persist in landscapes that have been altered by humans (Bista et al., 2021; Guerisoli et al., 2019; Joshi et al., 2013; Lamb et al., 2020). In shared spaces, the relationship between people and carnivores is not static and many forms of interactions occur, resulting in both positive (e.g. tourism benefits) and negative (e.g. conflict) outcomes (Bhatia et al., 2021; Bhattarai et al., 2021; Durant et al., 2022).

Human–large carnivore conflict is increasing in many landscapes (Boronyak et al., 2020) and is one of the crucial issues faced by communities that share space with large carnivore (Dickman, 2010). The presence of carnivores living in human-modified landscapes can result in negative outcomes such as livestock depredation, human fatalities and persecution of the carnivores themselves (Inskip & Zimmermann, 2009). If such negative interactions persist over an extended period, it can intensify conflict among conservation stakeholders and can jeopardise public support for conservation (Pooley et al., 2017). Such conflicts also may endanger the long-term survival of the species due to retaliatory killings, with human persecution being one of the leading causes of global population declines of carnivores (Ripple et al., 2014).

Attacks on people by large carnivores are an extreme manifestation of human-carnivore conflict and occur albeit rarely across the distributional range of many species (Bombieri et al., 2019; Goodrich, 2010; Packer et al., 2019; Western et al., 2021; White & Gehrt, 2009). A systematic review of the literature suggests that among different taxonomic groups, big cats (*Panthera* sp.) are found to be in frequent conflict with humans (Holland et al., 2018). Attacks on humans by different species of this genus such as tigers (*Panthera tigris*), leopards (*Panthera pardus*) and lions (*Panthera leo*) often are structured by spatial heterogeneity and centred in certain geographic locations (Dhanwatey et al., 2013; Packer et al., 2019). For instance, lion attacks in Tanzania are positively associated with low densities of natural prey and certain types of human activity like people sleeping outdoors in temporary huts, while leopard attacks in India were found to be more common in land-use types such as tea estates and areas of scrub cover, which are frequently used by both people and leopards (Kshettry et al., 2017; Naha et al., 2018; Packer et al., 2005). The apparently idiosyncratic nature of conflict events means that producing robust and transferable inferences into where attacks on people by large carnivores are likely to occur is challenging. There remains a pressing need to understand the spatial distribution and main drivers of carnivore attacks on people to inform mitigation measures to facilitate coexistence between humans and large carnivores (Morehouse & Boyce, 2017).

Leopards are the most widely distributed solitary large carnivore globally, occurring in more than 70 countries across Asia and Africa (Stein, 2015). Leopards are found in a variety of habitats such as grasslands, tropical forests and alpine regions (Jacobson et al., 2016) and are also known to persist in densely human-inhabited areas (Odden et al., 2014a). Leopards are generalist predators with a broad dietary niche (Hayward et al., 2006). In Nepal, the Indian or Common leopard (*Panthera pardus fusca*) is found throughout the country excluding the Himalayas (Jnawali et al., 2011). While leopards and people have been living in proximity for generations, the frequency of human-leopard conflicts have been increasing, typically in the form of livestock and pet predation but also in the more extreme case of attacks on humans (Acharya et al., 2016a). Among all forms of human-leopard conflict, attacks on humans (particularly children) have the most severe consequences, often resulting in human death. In Nepal, leopards are second only to Asian elephants (*Elephas maximus*) in terms of human attack incidents that result in human injury and death (Acharya et al., 2016b; Baral et al., 2021). The causes of human attacks by leopards remain equivocal and research on their drivers and mitigation measures could help reduce their frequency. Human-leopard conflict research in Nepal to date has been largely focused on livestock depredation (Dhungana et al., 2019; Koirala & Raubenheimer, 2012) and investigation of factors influencing leopard attacks on humans is lacking.

Collecting data on human-wildlife conflict incidents across a large geographic scale is difficult due to logistical constraints (time, funding, human resources, etc.) and even more so for conflict incidents related to a wide-ranging and elusive carnivore like leopards. Studies on human-leopard conflict based on compensation records (Baral et al., 2021) provide useful information regarding patterns and correlates of conflict events. However, not all conflict incidents that occur are reported. This implies either the event did not occur or was simply not reported, creating a false absence scenario. Thus, for a better understanding of human-wildlife conflict by accounting for the events that may have been missed in reporting, occupancy models offer a useful probabilistic framework (Athreya et al., 2015). Occupancy models are widely applied for both ecological and non-ecological problems such as human-wildlife conflict, illegal wildlife trade, palaeobiology and disease where the detection of any event may not be perfect (Mackenzie et al., 2002). Occupancy models are essentially a set of species distribution models that accounts for species being missed while conducting surveys at a site (Mackenzie et al., 2002). For example, if a field technician surveys an area for deer absence or presence to estimate deer distribution, not seeing deer or signs of its presence during the survey does not mean the deer is absent from the site. Imperfectness (due to the season of the survey, time of the day, weather conditions, etc.) in the observation process may hinder the surveyor's ability to detect deer presence. Similarly, if a human-wildlife conflict event is not reported, it does not mean that the conflict event did not occur in a certain area. Thus, for a meaningful understanding of conflict occurrence and its determinants "false absences" need to be accounted for in the analysis, and occupancy models provide such a framework to account for imperfect observations.

The drivers of the increased conflict between humans and leopards include landscape features (e.g. ruggedness), livestock composition and abundance (type and number), natural prey depletion (e.g. ungulates), and habitat composition (e.g. forest, scrub cover; Acharya et al., 2017; Adhikari et al., 2020; Naha et al., 2018, 2020; Shehzad et al., 2015). Increased forest cover due in part to community-led forestry programs (Shrestha et al., 2018) have contributed to the expansion of the distribution of leopards in Nepal, allowing leopards to recolonise habitats outside of protected areas (Acharya et al., 2016a). Livestock and dogs are common diet items (up to 85% of the total diet), based on an analysis of leopard scats collected from human-dominated regions (Shehzad et al., 2015). This demonstrates the leopard's capability to adapt to novel prey in human-modified landscapes where natural prey bases are depleted. In Nepal, leopard occupancy has been reported to be positively associated with human population density and livestock, demonstrating the potential for overlap between leopards and people, increasing the likelihood of human-leopard conflict (Kandel et al., 2020a; Lamichhane et al., 2021). Against this backdrop, in this study, we tested the following hypotheses- leopard attack occurrence: (1) is higher in areas with higher forest cover, (2) is higher in areas with greater scrub cover, (3) is higher in areas with more rugged terrain, (4) is positively associated with higher densities of alternate prey (livestock) and (5) is higher in areas with high human population density.

To test these hypotheses, we collate information on leopard attacks on humans in Nepal from news articles published in online sources (Athreya et al., 2015; Chauhan et al., 2021) in regions where leopards occur and employ an occupancy model to predict the occurrence of leopard attacks on humans. News records come from many reporters distributed across large geographic regions and can provide useful detection/non-detection data that could be used in occupancy models (MacKenzie et al., 2018). Our approach sources data from online news and current affairs websites and combines it with covariate data remotely extracted from spatial datasets and secondary sources to understand the drivers and occurrence of human attacks on a landscape scale.

Based on our findings and model inferences, we then discuss potential conflict mitigation measures and future pathways for research to elevate our understanding of the leopard attacks on humans in Nepal and in other comparable social and ecological settings. Our analysis represents the most comprehensive account of leopard attacks on humans modelled for our study system.

2 | METHODS

2.1 | Study area

In this study, we focus our analysis on the 640 administrative units that encompass the entire range of leopards in Nepal (See Figure 1) (Jnawali et al., 2011). The administrative units, which are primarily differentiated based on human population density, are mainly of two types—municipalities and rural municipalities (municipalities hereafter) are located within larger administrative units, that is districts (Figure 1).

2.2 | Data collection

In December 2019, we searched the internet for news related to leopard attacks on humans that occurred in our study region between the years 2015–2019. To standardise the search, we used keywords such as “leopard”, “leopard + attack”, “leopard + attack + Nepal” and “leopard + Nepal + (district names)” in both Nepali and English on the Google search engine (www.google.com). We used Google because there is no dedicated search engine or repository for news reports available in Nepal. For each record, we noted the district name, municipality name and date of the incident where the attack occurred. Since the news articles did not report the exact locations (coordinates) of attack incidents, we worked at the smallest spatial scale possible, the municipality. In this study, we are interested in predicting the probability of leopard attacks and identifying their drivers across the region.

2.3 | Occupancy modelling of leopard attacks

Occupancy models use data from repeated surveys of sites, where the detection or non-detection of a species in each survey is recorded. There are two important sub-components in occupancy models—the observation component and the process component (Mackenzie et al., 2002). The observation component estimates detection probability (p) and its determinants (survey covariates) while the process component estimates the probability of occurrence (psi, ψ) in the site and its determinants (site covariates) (Mackenzie et al., 2002). In our study, the occurrence of leopard attacks on humans is assumed to be a function of the ecological and social properties of the landscape and our ability to detect leopard attacks relies on the reporting of the leopard attack in the media, and our ability to find it. Thus, this approach explicitly accounts for attacks that may not have been reported reports we were unable to find.

We estimate the occurrence of leopard attacks using a hierarchical modelling framework approach, specifically single-species occupancy models (Mackenzie et al., 2002). This approach estimates the probability of a leopard attack, accounting for imperfect detection of leopard attack news, and enables modelling of leopard attack detection and occurrence as a function of covariates. We conducted our modelling at the scale of municipalities (sites) as this can facilitate the planning of conflict mitigation measures and the allocation of financial resources, which tend to be implemented at the municipal level. The study area is 640 municipalities, hereafter sites, with the extent of sites mirroring the distribution of leopards in Nepal (Jnawali et al., 2011). While there is a high degree of variance ($5.37–1649\,km^2$; mean = $149.50\,km^2$), the average area of our sites

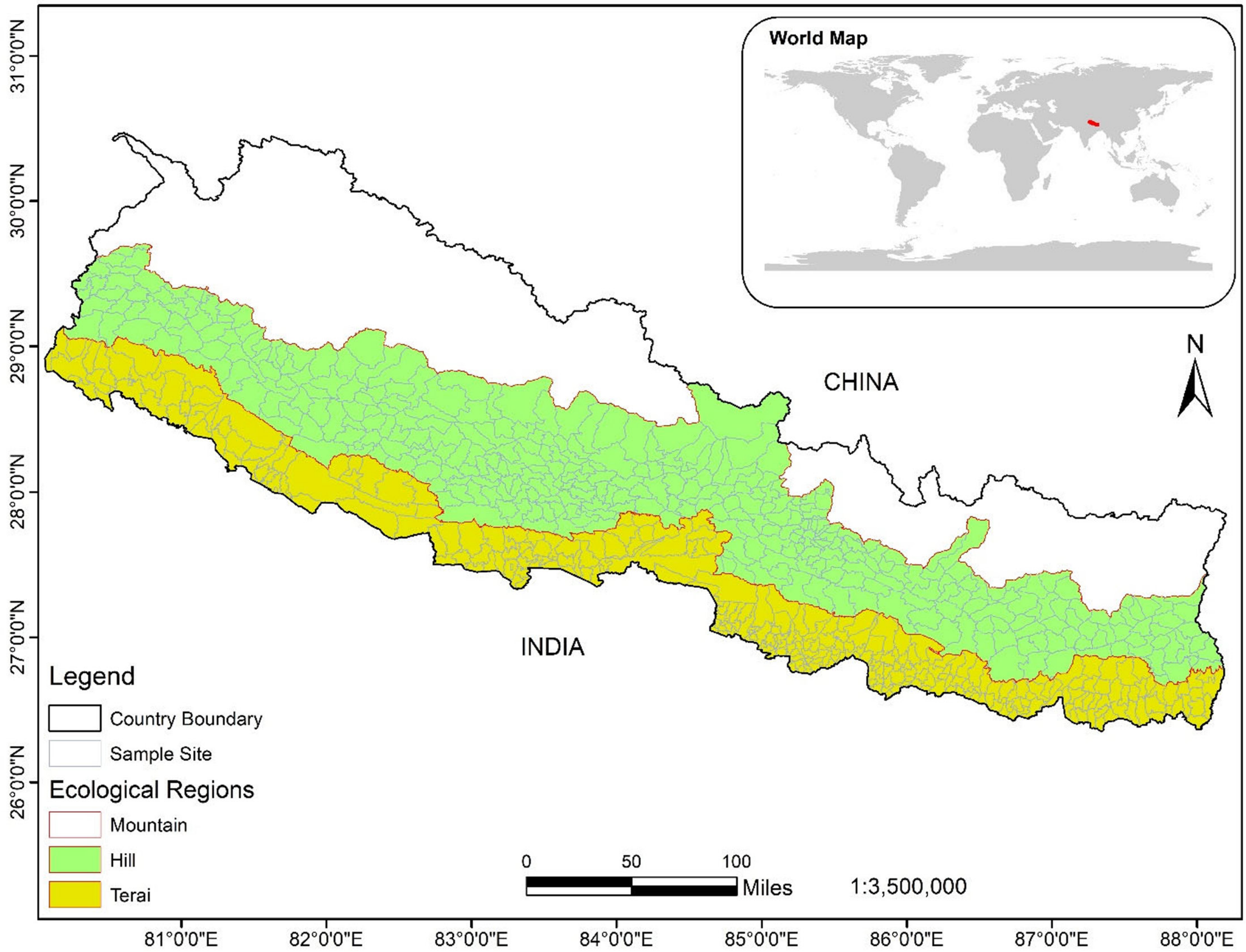

FIGURE 1 Nepal and the 640 municipalities included in the modelling of leopard attack occurrence on humans. (Map republished from (Survey Department, 2020) under a CC BY licence, with permission from the Survey Department, original copyright, 2020).

is reasonably consistent with estimates of the home range size of leopards, that is 177.47 km^2 reported from the similar geographical area as in our study landscape and thus is a suitable spatial scale for the species (Naha et al., 2021). We include the area of a municipality as a fixed covariate on both detection probability (p) and occupancy (ψ) to account for the varying sizes of our study sites.

We used the year of attack (2015–2019) as our survey occasion, which resulted in a detection (1)/non-detection (0) matrix of leopard attacks with five occasions for each site. We considered five landscape variables (Table 1) that had previously been observed to influence the occurrence of leopard attacks (Bista et al., 2021; Naha et al., 2018, 2020). These variables were related to landscape composition (e.g. the proportion of forest, proportion of scrub cover and terrain ruggedness), availability of alternate anthropogenic prey (e.g. livestock density) and the abundance of humans (e.g. human density).

The application of occupancy modelling, which accounts for imperfect detection in the detection—non-detection data generated through surveying the media for news reports of attacks, is necessary for robust inference. In our study, detections of leopard attacks are dependent on—(a) the leopard attack being reported to officials, (b) the leopard attack being subsequently reported in the media and (c) our ability to find the media article during our online search. Thus, it is necessary to adopt an approach that explicitly accounts for false negatives resultant from these multiple conditions present in our observation process. We considered two site-level covariates: area of the site (km^2) and human population density (people per km^2) to account for variation in detection probability due to size differences of municipalities. We also considered two observation covariates; the occasion number (year); and a time effect (time), parameterised as a two-level factor that accounted for an apparent change in detection probability between the first year and later years (i.e. $j = 1$ vs. $j > 1$). This is analogous to a traditional behavioural effect whereby the previous reporting of leopard attacks may influence reporting in subsequent years; our earlier efforts to fit a more classic behavioural effect resulted in poor model fit. All continuous covariates were scaled and standardised to have unit variance and a mean of zero. Prior to the analysis, we checked

TABLE 1 Descriptions of covariates (municipality level) and their hypothesised influence (positive or negative) on detection probability (*p*) and the probability of leopard attacks on humans (ψ) in Nepal.

Covariates	Description	Value range Minimum—maximum (average)	Hypothesised influence *p*	Psi (ψ)
Area	The total area of the municipality	$5.37km^2$–$1649.22km^2$ ($149.50 km^2$)	–	Na
Time	A behavioural effect whereby reporting of leopard attacks increases over time parameterised as a two-level factor – $j=1$ and $j>1$	1–2	+	Na
Human population density	Total human population density (humans/km^2) of the municipality using a spatial population dataset at www.worldpop.org for 2017	$8.39/km^2$–$33{,}717/km^2$ ($606.85/km^2$)	+	+
Year	Survey year from 2015 to 2019	1–5	+	Na
Scrub cover	Percentage of land in a municipality classified as other wooded lands using 2019 LULC data (Acharya et al., 2017)	0–19.66 (2.68)	Na	+
Forest	Percentage of land in a municipality classified as forest using the 2019 LULC data (Uddin et al., 2021)	0–87.66 (40.17)	Na	+
Topographic ruggedness index	The average topographic ruggedness index of a municipality was calculated using an SRTM digital elevation model (30 m; Riley & Degloria, 1999). Lower values represent flat surfaces, higher values represent elevated/rugged surfaces	2.49–67.03 (24.86)	Na	+
Livestock density	The number of livestock (cattle, buffalo and goat)/km^2 in a municipality using the livestock of the world database (Gilbert et al., 2018)	$0/km^2$–$883.42/km^2$ ($185.30/km^2$)	Na	+

for collinearity among all covariates and excluded cropland as it was highly negatively collinear with forest cover. There was no further evidence of collinearity between the remaining covariates (VIF score < 3, Supplementary Information Tables S1 and S2).

We adopted a two-stage model fitting procedure (Karanth et al., 2011). In the first stage, we used the Akaike information criterion (AIC) ranking to find the most parsimonious model for detection probability, while keeping the occupancy parameter constant (i.e. ψ (.)) (Morin et al., 2020). In the second stage, we fixed the top-ranked detection model (i.e. *p*(top)) and considered all possible additive combinations of our five occupancy covariates to explain variation in the occurrence of leopard attacks on humans. To avoid variable-selection ambivalence resulting from using 95% confidence intervals with an information theoretic approach, we used 85% confidence intervals when considering parameter estimates (Arnold, 2010).

The occupancy analysis was conducted in R (R Core Team, 2021) using the package "unmarked" for model fitting (function *occu* ()) (Fiske & Chandler, 2011). The AIC-based model ranking was conducted using the package "MuMin". The function *mb.gof* ()) in the package AICmodavg was used to test the goodness of fit of the global model (Mazerolle, 2020). We used this to calculate the overdispersion parameter *c-hat* ($\hat{c}$) for model selection and adjustment of parameter standard errors (MacKenzie & Bailey, 2004). We found no evidence for lack of fit ($p=0.19$); however, the global model displayed overdispersion ($\hat{c}=1.35$). Thus, quasi-AIC (QAIC) model selection with a $\hat{c}$ adjustment of 1.35 was used for all subsequent model selections and QAIC weights were used for model averaging and adjustment of standard errors.

3 | RESULTS

Our search generated 72 reports of leopard attacks on humans between 2015 and 2019 at 54 of 640 sites. QAIC ranked model selection from the first stage of model fitting implemented for detection suggested that detection probability was influenced strongly by a single observation covariate: time (*t*), which displayed an increase in the detection probability of leopard attacks over time ($\alpha_{time}=1.26$, 85% CI = 0.46–1.13). The top detection model had clear support with all other parameters showing evidence of redundancy (see Tables 2 and 3). The mean detection probability of leopard attacks on humans from the top-ranked model was 0.08 (85% CI = 0.06–0.12).

At the scale of the municipality, model selection results with the top detection parameter fixed show clear support for human population density, terrain ruggedness and livestock density predicting leopard attacks on humans (see Table 3). The top-ranked model predictions showed that human population density ($\beta_{human}=2.59$, 85% CI = 0.74–4.43), terrain ruggedness ($\beta_{ruggedness}=1.32$, 85% CI = 0.80–1.84) and livestock density ($\beta_{livestock}=0.70$, 85% CI = 0.18–1.21), all had positive relationships with the predicted probability of leopard attacks (Figures 2 and 3) the area (km^2) of municipalities had a negative effect ($\beta_{area}=-0.59$, 85% CI = −1.10 to −0.07) on the probability of leopard attack occurrence. The landscape-scale predictions from the top model show how ruggedness, livestock density and human population density jointly affect the probabilities of leopard attacks on humans across the region can be seen in Figure 4. The top-ranked model predicted a mean probability of leopard attack occurrence of 0.19 (85% CI = 0.11–0.29).

4 | DISCUSSION

Our study indicates that large carnivore attacks on humans are likely determined by endemic factors related to landscape features, anthropogenic prey (livestock), and human density across the landscape. Leopard attacks on humans in Nepal are more likely to occur in municipalities with high human population density, rugged terrain and high livestock density. We demonstrate that occupancy models offer a useful probabilistic framework to predict the occurrence of conflict incidents in relation to chosen covariates from the landscape while accounting for imperfect reporting in publicly available data of human-wildlife conflict. These results not only provide insights into the drivers of leopard attacks on scales meaningful to the management of wildlife populations and conflict, but they also identify critical factors within the landscape which could be prioritised to address human safety.

TABLE 2 Model selection table for observation covariates influencing the detection probability of leopard attacks reported in the online media in Nepal from 2015 to 2019. Only models with ΔQAIC <2 are displayed. ΔQAIC compares the models and differences greater than two units suggest models are of considerably lower inferential quality. The area of a municipality is held constant in all models and not displayed in the table for clarity. Ψ = probability of site occupancy (probability of leopard attack occurrence) at the municipality level; (.) indicates that the parameter was held constant; *p* is detection probability of leopard attack, *K* is the number of model parameters and −2logL is the logarithm of the negative likelihood function; QAIC is quasi Akaike's information criterion used for model ranking, ΔQAIC is the difference in QAIC value between the top model and other models in the set and ωQAIC is the relative likelihood of the model in the set.

Model	*K*	−2logL	QAIC	Δ_{QAIC}	ω_{QAIC}
ψ (.)*p*(time)	4	−261.22	397.0	0.00	0.42
ψ (.)*p*(time + year)	5	−261.14	398.9	1.88	0.17
ψ (.)*p*(time + human)	5	−261.22	399.0	2.00	0.16

The positive association between terrain ruggedness and attack is consistent with findings from Uganda where leopard attacks on livestock are more likely in rugged areas that are close to human settlements (Braczkowski et al., 2020). A recent study from Nepal found that terrain ruggedness is also positively associated with leopard occupancy (Lamichhane et al., 2021). As occupancy-abundance relationships have been reported to be close to linear for other low-density, solitary carnivores, for example, fishers (*Pekania pennanti*) (Linden et al., 2017), it could be that leopard abundance is higher in rugged terrains, and it is the higher abundance of leopards in these areas that is the driver of the increased occurrence of leopard attacks on humans. Here, we provide support for the hypothesis that ruggedness in these areas could provide habitat for leopards released from competition with tigers from the protected areas located in the lowlands, which subsequently may drive this likelihood of attacks on humans (Harihar et al., 2011). Previous studies have reported increased leopard attacks in the hill region of Nepal but without clearly identifying the underlying mechanism (Acharya et al., 2016b; Baral et al., 2021). While our hypothesis remains speculative, future studies that capture information on leopard density may provide additional insights to test this hypothesis. Another potential reason for ruggedness being positively associated with attack probability could be because leopards are ambush hunters and expert climbers (Hubel et al., 2018). Thus, rugged terrain may provide ideal conditions to facilitate attacks on humans, for example remoteness, and high amounts of cover to launch ambush attacks. Prioritizing conservation interventions in rugged areas (e.g. providing resources to raise awareness of potential leopard attacks and support safety measures) could help to increase preparedness, thus reducing human injury and fatalities. The area of the municipality was kept fixed in our analysis to account for variation in the size of the municipalities, but it had a negative effect on leopard attack occurrence. Determining the precise mechanistic links between the increased likelihood of leopard

TABLE 3 Model selection table for landscape covariates influencing the probability of leopard attack occurrence on humans throughout the 640 municipalities of Nepal in 2015–2019. Listing the top-ranked models with ΔQAIC <2. ΔQAIC compares the models and differences greater than two units and suggest models that are of considerably lower inferential quality. The best performing detection model (From Table 2: Ψ (.) *p*(time) was held constant for all models and the area of the municipality was fixed on Ψ, both are not displayed in the model for clarity. Ψ = probability of site occupancy (probability of leopard attack occurrence) at the municipality level; *K* is the number of model parameters, −2logL is the logarithm of the negative likelihood function; QAIC is quasi Akaike's information criterion used for model ranking, Δ_{QAIC} is the difference in QAIC value between the top model and other models in the set and ωQAIC is the relative likelihood of the model.

Model	*K*	−2logL	QAIC	Δ_{QAIC}	ω_{QAIC}
ψ (Ruggedness, human population, livestock)	8	−247.82	385.13	0.00	0.24
ψ (Ruggedness, human population, livestock, scrub)	9	−247.32	386.40	1.26	0.13
ψ (Ruggedness, human population, livestock, forest)	9	−247.40	386.52	1.38	0.12
ψ (Ruggedness, human population)	7	−250.31	386.82	1.69	0.10
ψ (Ruggedness, human population, scrub)	8	−249.05	386.96	1.82	0.10

attacks in smaller municipalities poses a challenge. Nevertheless, a possible hypothesis to support this could be that smaller municipalities potentially receive relatively limited federal budget allocations, leading to insufficient funding for habitat and wildlife management. As a result, reduced funding could impede the implementation of effective measures to mitigate the problem, thereby exacerbating human-wildlife conflicts, such as attacks by carnivores on humans, within these smaller municipalities.

The human population density was another factor positively affecting the occurrence of leopard attacks on humans. The increased presence of humans and their associated activity amplifies human-leopard proximity (Ogutu et al., 2016; Woodroffe, 2000) potentially leading to attacks. There is potential for a density-dependent relationship, where greater numbers of humans lead to a greater probability of attacks by leopards simply as a function of increased encounter rates with humans. Another potential explanation for attacks in areas with high human density could be the greater presence of dogs. The presence of dogs is known to positively influence leopard occurrence as well as the probability of leopard attack on livestock in human-dominated landscapes (Athreya et al., 2016, 2020). Leopards in most of their distributional range in Nepal (particularly in the midhill region) are thought to have a shortage of natural prey (barking deer, *Muntiacus muntjak*, and wild boars, *Sus scrofa*) due to poaching (Acharya et al., 2016b; Bhattarai et al., 2016). The reduction in natural prey could result in leopards' prey-switching to an alternate resource base such as abundant and easy-to-capture feral and pet dogs (May, 1977). Leopards are reported to prefer small—medium-sized prey (<25 kg) that live in small groups, and thus pose a minimal risk during capture (Hayward et al., 2006). Dogs satisfy all these criteria and may provide a highly abundant, and easily

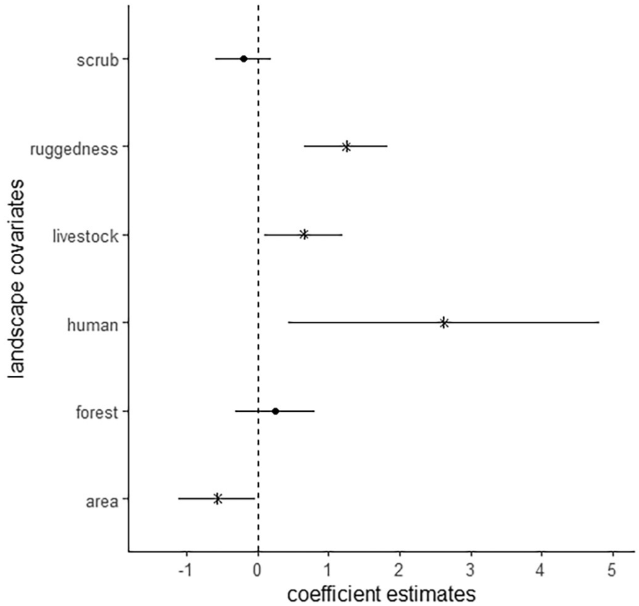

FIGURE 2 Factors affecting the probability of leopard attack occurrence with 85% confidence intervals. Asterisks represent coefficients with strong relationships to the probability of leopard attack occurrences on humans (i.e. confidence intervals do not overlap 0).

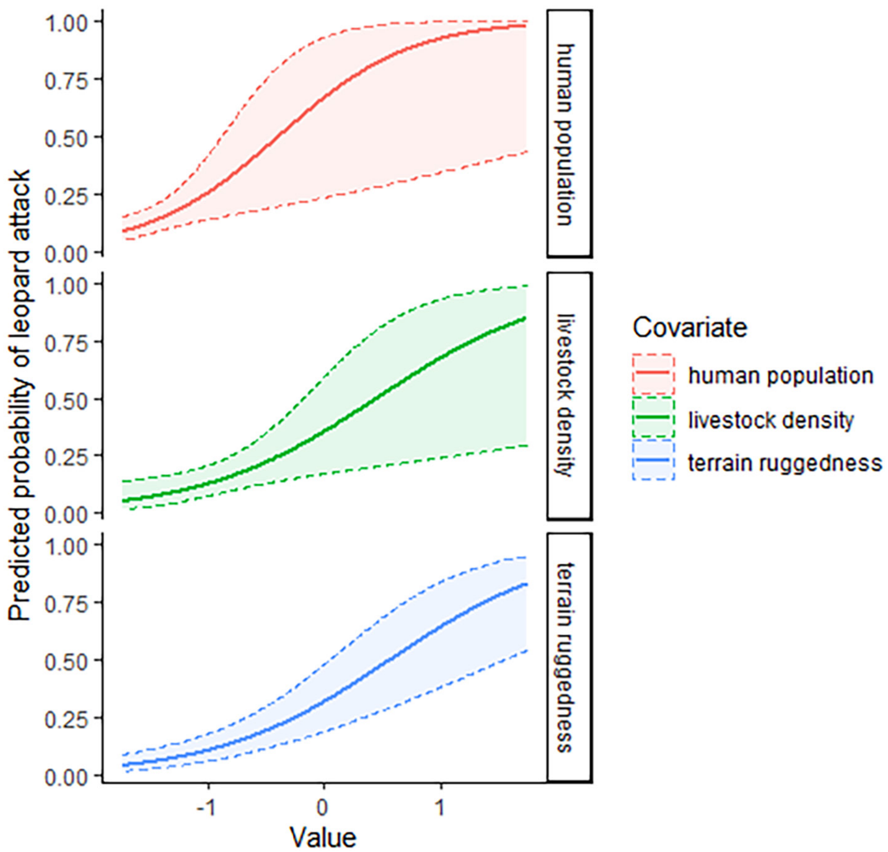

FIGURE 3 Relationship between the probability of leopard attack occurrence on humans and important covariates as determined through occupancy analysis (human population density, livestock density, and terrain ruggedness) with corresponding 85% confidence intervals (shaded region) from the top model for 640 municipalities.

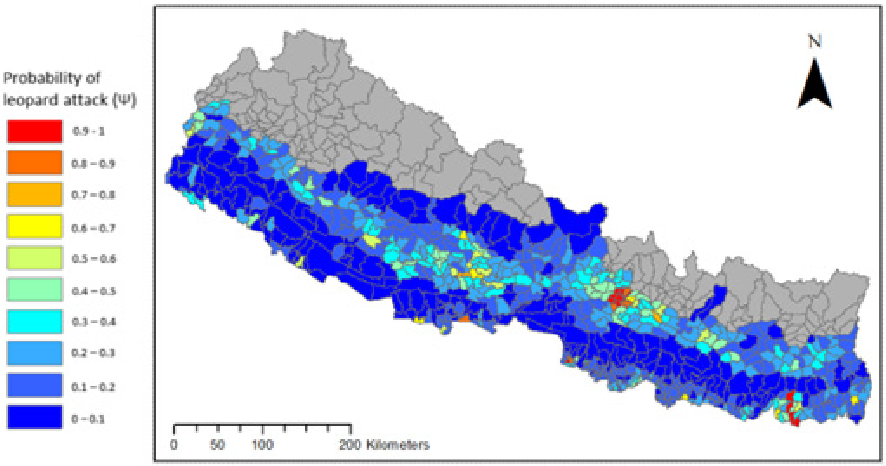

FIGURE 4 Probability of leopard attack occurrence (predicted from top model) on humans across 95,698 km^2 of Nepal from 2015 to 2019. Grey areas show municipalities outside of the leopards' reported distribution range and thus were not predicted.

accessible resource. Dog density is typically higher in areas with a dense human population (Pantha et al., 2020), and in such areas, leopards may target dogs, thereby increasing encounters with humans, and subsequently contributing to attacks on humans. Due to the unavailability of data on dog density for our study area, we were not able to explore this hypothesis in our analysis, but leopard-dog dynamics via occupancy and diet analysis could be a fruitful area to explore in future studies.

Our result showing livestock density as a key determinant of leopard attack corresponds with our a priori hypothesis that a higher number of livestock per unit area increases the probability of attacks on humans. Studies have shown that poor livestock protection coupled with low density of natural/wild prey density leads to the depredation of livestock by large carnivores (Kandel et al., 2020b; Kshettry et al., 2018; Shehzad et al., 2015). In Nepal, many scat-based studies have reported significant proportions of livestock in the leopard diet (Dhungana et al., 2019; Kandel, 2019; Lamichhane et al., 2019), which substantiates the case that leopards in some circumstances are relying on livestock as a prey resource. Thus, in our study system, it could be possible that leopards are prey switching to livestock which are easily accessible as key prey (Kuiper et al., 2022). In this context, when leopards are drawn toward easily available livestock either in sheds or grazing in or near human settlements, the probability of encountering humans also increases. In addition, livestock husbandry practices in Nepal are not "predator proof" and animals are often kept or reared in areas that are either open or loosely protected (i.e. wooden fences). This scenario of abundant, easily accessible prey is likely to drive prey-switching behaviour, subsequently resulting in an increased probability of humans being caught in the "crossfires" of leopard-livestock interactions and increasing the chance of attacks on humans. Reducing the probability of an attack on humans thus requires regularly monitoring hotspot areas for leopard presence and activity (i.e. with camera traps). Such efforts can be implemented in partnership with local institutions like community forest user groups or municipalities and could form a basis for establishing a novel citizen-led human-wildlife conflict early warning system program (Gurung et al., 2008; Lamichhane et al., 2017). In addition, given that livestock is an important source of local livelihood and will continue to be present in high density in the landscape, it is also equally important to safeguard livestock to avoid leopards in human settlement areas. There is a growing body of literature on livestock predation by leopards that could offer useful insights to formulate innovative, local and cost-effective solutions such as improved livestock corrals, flashlights and studded collars to deter leopards and better protect livestock that will also contribute to human safety (Athreya et al., 2020; Khorozyan et al., 2020; Lesilau et al., 2018).

The scrub cover was a redundant parameter in modelling the occurrence of leopard attacks on humans. This result does not conform with the previous work (Naha et al., 2020), which reported a negative relationship between leopard attacks and scrub in Nepal. In Nepal, agricultural land abandonment is increasing due to a shortage of agricultural workforce which is reverting farmlands to areas of scrubs and bushes (Subedi et al., 2021). The popular narrative suggests that additional scrublands surrounding human settlements may provide space and concealment for leopards further extending their habitat range closer to human settlement and thus increasing the probability of human encounter and/or attack (Morin et al., 2020). However, our results challenge this narrative. The promotion of agroforestry has been recommended as an intervention to integrate farming practices with biodiversity conservation and could be a win-win approach in Nepal to retain such scrublands that are contributing to the re-wilding of the landscape which potentially could benefit both people and leopards (Puri et al., 2021).

Human-large carnivore conflict is often driven by certain 'problem' individuals rather than the whole population (Linnell et al., 1973). A study on problem tigers in Nepal indicated that transient sub-adults without territories are more likely to cause conflict with humans than other age or sex classes (Lamichhane et al., 2017). An investigation of leopard mortality in Nepal reported that 50% of leopard mortality cases had anthropogenic causes, mainly lethal control, and retaliatory killings; 31% of those were sub-adult leopards (Thapa, 2014). Transient sub-adults, in their effort to establish territories (ranging widely), could colonise edge habitats due to core forest areas being occupied by resident individuals (Lamichhane et al., 2017). This may result in such transient individuals encountering humans at a higher rate, thus contributing to an increase in human-leopard conflict. Further research would be required to ascertain which leopards are involved in the conflict and if certain individuals, ages, and sex classes are disproportionately problematic.

Rescue and translocation of problem leopards, which is an ad-hoc management practice in Nepal has already been identified as an ineffective measure to address the human-leopard conflict (Odden et al., 2014b). Thus, the focus might be better placed on identifying "problem sites" with site-specific mitigation strategies. Such strategies could be based on the allocation of resources to areas with a high probability of attacks to support mitigation measures and management action. Adopting non-invasive techniques such as camera trapping and genetic sampling in areas with varying human population densities and landcover types could generate the required baseline information regarding spatial and temporal patterns of human-leopard conflict and leopard ecology (Arnold, 2010; MacKenzie & Bailey, 2004). Furthermore, such studies, if paired with scat collection and diet analysis, could provide insights into leopard prey preference, the contribution of feral species as prey and livestock depredation (Acharya et al., 2016b). We also highlight that future studies would be wise to adopt an interdisciplinary approach and investigate not only the drivers of ecological processes but also explore the human dimension of the conflict between people and leopards. This is particularly crucial in the context of Nepal where people are less positive toward the conservation of leopards in comparison to tigers (Dhungana et al., 2022). Findings could then be synthesised to develop context-dependent conflict mitigation strategies to secure human lives as well as identify leopard conservation priorities.

In this study, we used information from online news reports in an occupancy framework to estimate the probability of leopard attack occurrence on humans in Nepal. Although similar studies have been conducted in the past to estimate species distribution and conflict using news reports and occupancy modelling (Athreya et al., 2015), our effort is extensive because the occupancy framework has been employed for studying conflict at a national scale using publicly available data. This is the first study in Nepal that estimates the occurrence of an attack by a large carnivore on humans and its determinants at a landscape scale using a probabilistic framework that accounts for imperfect detection. This approach could also be used in a variety of contexts where a systematic survey of conflict incidents is challenging while prediction and determinants of wildlife attacks on humans are critical for public safety. Our study demonstrates that using publicly available datasets if coupled with an appropriate statistical method can aid in developing spatially explicit management plans to target specific areas where conflicts are most likely to occur. This enables a "problem site" identification approach to the management of human-wildlife conflict rather than the prevailing "problem individual" approach (Lamichhane et al., 2017).

AUTHOR CONTRIBUTIONS

Shashank Poudel, Angela K. Fuller and Richard C. Stedman conceived the idea and designed the analysis. Shashank Poudel and Shravan Kumar Ghimire performed the search to collect the data. Shashank Poudel curated the data and Joshua P. Twining analysed the data; all authors contributed to manuscript drafts and approved for publication.

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CONFLICT OF INTEREST STATEMENT

The authors report no conflict of interest.

DATA AVAILABILITY STATEMENT

The data used in this study is available online at the Harvard Dataverse repository: https://doi.org/10.7910/DVN/NLQKXQ.

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SUPPORTING INFORMATION

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

Table S1. VIF results from full model.

Table S2. VIF results from full model with crops removed.

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