J. Mt. Sci. (2023) 20(12): 3464-3475 e-mail: jms@imde.ac.cn http://jms.imde.ac.cn
https://doi.org/10.1007/s11629-023-8007-8

Original Article

Understanding human-leopard conflict in the 'Mid-hill' region of western Nepal

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Citation: Lamichhane S, Thapa A, Thapa MS, et al. (2023) Understanding human-leopard conflict in the 'Mid-hill' region of western Nepal. Journal of Mountain Science 20(12). https://doi.org/10.1007/s11629-023-8007-8

Abstract: Livestock rearing and agriculture are the main sources of community-based livelihoods in western Nepal. Across the rural mid-hills region of Gandaki Province, leopards are the top predator and frequently depredate livestock and attack humans. Spatiotemporal patterns of human-leopard conflicts (HLC) in Nepal are poorly known at the provincial and national scales, which are essential to formulating effective conflict mitigation strategies and implementing them in the field. This study aims to analyze the spatiotemporal pattern of HLC by applying Maxent modeling to covariates relating to known and registered conflict cases (n=842) collected from Nepalese government offices. We found that cases of HLC have been increasing significantly over the past five years. We also concluded that mid-elevation, south-facing slopes were more susceptible to HLC, but that mean annual temperature was by far the most important predictor of HLC; overall livestock density and proximity to roads were also important, but secondarily so. Although we found the increase in human fatalities to 2.16/year was significant (p<0.05), overall human injuries were down slightly, though not significantly (5.16/year; p>0.05). However, we also found an increasing trend in livestock depredation rates for this same five-year period (p<0.05), which averaged 159.6 head/year among incidents reported. We also found that winter was the main season when depredations occurred, and that goats were the most depredated of all livestock. A total US $86,892.25 ($17,378.45/year) of economic losses were incurred by communities during this time, with 78.57% of the total value reimbursed as compensatory relief through the government's relief fund. We recommend that the use of predator-proof livestock corrals, greater awareness in local communities about wildlife behavior, better animal husbandry and security practices, and a more

Received: 19-Mar-2023
1st Revision: 23-Oct-2023
2nd Revision: 10-Nov-2023
Accepted: 14-Nov-2023

efficient compensation program, can improve coexistence between leopard populations and human communities in western Nepal.

Keywords: Coexistence; Compensation; Economic loss; Human-wildlife conflict; Livestock depredation; Maximum entropy; Problem animals; Sustainable livelihood

1 Introduction

Human-wildlife conflict has emerged as a major concern to wildlife conservation worldwide (Woodroffe et al. 2005; Dowie 2011). Human encroachment on otherwise natural habitat is causing widespread biodiversity loss, and this degradation has resulted in more frequent conflicts between wildlife and humans over shared resources (Distefano 2005; Woodroffe et al. 2005; Inskip and Zimmerman 2009; Torres-Romero et al. 2020). This includes greater rates of livestock depredation and attacks on humans, both of which can lead to increased lethal retaliatory measures against predators (Treves and Karanth 2003; Gurung et al. 2008; Thapa 2009).

In Nepal and other parts of the Indian subcontinent, leopards (*Panthera pardus fusca*) depredate livestock in rural communities across the different ecological region's (Oli 1994; Tamang and Baral 2008; Thapa 2009; Bhattarai 2009; Acharya et al. 2016; Baral et al. 2021), often causing substantial financial losses in the process (Shalu et al. 2023). This may be due to a decrease in the density of wild prey, which can affect all predators (e.g., Patterson et al. 2004) by imposing opportunity costs of them. Although leopards mostly attack livestock grazing inside or near forest areas (Acharya et al. 2016; Lamichhane et al. 2018; Shalu et al. 2023), they also venture into farms, protected area buffer zones, and urban areas, often to prey on dogs and livestock; this also increases the threat they pose directly to humans (Athreya et al. 2013; Ramesh et al. 2020). Among all large cats, leopards in particular may cause more livestock-related conflict because their optimal prey size may be between 10 - 40 kg (Hayward et al. 2006).

Distributed widely across Nepal, leopards from lowlands (< 100 m) to elevations (> 4000 m); they frequent a broad range of habitats, including tall grasslands, dense and sparse tropical forest, temperate and subtropical forest, sub-alpine zones, vegetative scrub, and steep mountainous terrain (Jnawali et al. 2011; Thapa 2011; Baral et al. 2022; Poudel et al. 2023). Although the suitability of many original habitats for leopards was compromised due to extensive land use change for agricultural development (Thapa 2011), recent restoration of forest corridors, the expansion of community forestry programs, and improved management of protected areas across Nepal, have all improved habitat for leopards. Still, due to their territorial nature and potential interspecific pressure from tigers living in core protected areas, leopards inhabit more buffer zones and community forests, the consequences of which are usually greater levels of conflict (Thapa 2011; Lamichhane et al. 2018).

The spatiotemporal patterns of all human-wildlife conflict are poorly documented at the provincial and national level in Nepal and indeed, across the Indian subcontinent. This limitation hinders strategic planning for effective human-leopard conflict (HLC) mitigation planning on the ground, as well as the timely recompense of disaffected communities through compensation schemes (Goodrich 2010; Acharya et al. 2016; Dhungana et al. 2018; Shalu et al. 2023). An explicit understanding of livestock depredation patterns is crucial to effectively prevent or reduce the frequency or severity of human-carnivore conflicts (Dar et al. 2009). Additionally, the use of spatial risk modelling based on conflict locations in the physical environment could be a practical tool for predicting and mapping conflict hotspots (Treves et al. 2011; Miller 2015; Ruda et al. 2018) and thus, a basis for future planning.

Maximum Entropy (MaxEnt) modelling (Phillips et al. 2006) is among the more useful approaches in mapping out the spatial patterns of human-carnivore conflict (Constant et al. 2015; Vilar et al. 2016; Naha et al. 2019; Sharma et al. 2020). Our study aims to (a) understand the covariates associated with spatial and temporal distribution of HLC, (b) analyze the economic losses and associated relief or compensation payments, and (c) map the risk of HLC along the human-leopard habitat interface. We hope results can inform the development of a program or programs to facilitate coexistence between people and carnivores across the region.

2 Study Area

Gandaki Province (area: 21,733km^2) (27°20' N ~ 29°20' N; 82°52' E ~ 85°12' E) encompasses 11 political districts in Nepal (Fig. 1). Topographically, Gandaki Province is a diverse landscape, ranging from only 60 m asl in the south to > 8000 m asl in the north; it includes habitats spanning the Himalayas, Mid-Hill region, and Terai Arc along the country border with India. Gandaki also includes the majority of the Chitwan-Annapurna Landscape (CHAL) that encompasses climatic zones spanning both subtropical to temperate monsoon eco-physiographical zones, including subtropical forests, temperate broadleaf forests, conifer forests, alpine ecosystems, and semi-desert rain shadows. The temperate to subtropical areas are characterized by intensive farming on hillside terraces, whereas most of the region's mountains consist of high steep slopes, deep gorges, and cold temperate climates. The average minimum and maximum reported temperatures range from 5°C-40°C, and the province includes a range of average annual rainfall ranges, from as low as 165 mm (Lo Manthang; Mustang), to a high of 5,244 mm (Lumle; Kaski). More than 3,430 plant species have been recorded in the CHAL (BPP 1995), including almost 100 species endemic to Nepal. Important representative floral species include *Shorea robusta*, *Dalbergia sissoo*, *Adina cordifolia*, *Schima wallichii* and *Castanopsis indica*; these are often mixed with *Cedrella toona* and *Alnus nepalensis* along streams and in areas with high water tables. The subtropical coniferous forests on the dry southern slopes are heavily dominated by *Pinus roxburghi* (MoFE 2016).

Gandaki Province shelters many charismatic and threatened species, such as tiger *Panthera tigris*, greater one-horned rhinoceros *Rhinoceros unicornis*, Asiatic elephant *Elephas maximus*, gaur *Bos gaurus*, snow leopard *Panthera uncia*, wolf *Canis lupus*, and brown bear *Ursus arctos* (MoFE 2016).Threatened species in the mid-montane forests include dhole *Cuon alpinus*, Indochinese clouded leopard *Neofelis nebulosa*, alpine musk deer *Moschus chrysogaster*, and Himalayan red panda *Ailurus fulgens* (MoFE 2016). Our study emphasizes the mid-hill districts of Gandaki Province, *i.e.*, Syangja, Kaski, Parbat, Baglung, Myagdi, Tanahun, Lamjung and Gorkha (effective study area of approximately 5,919 km²), all of which lies outside Nepal's major protected area network shown in Fig. 1.

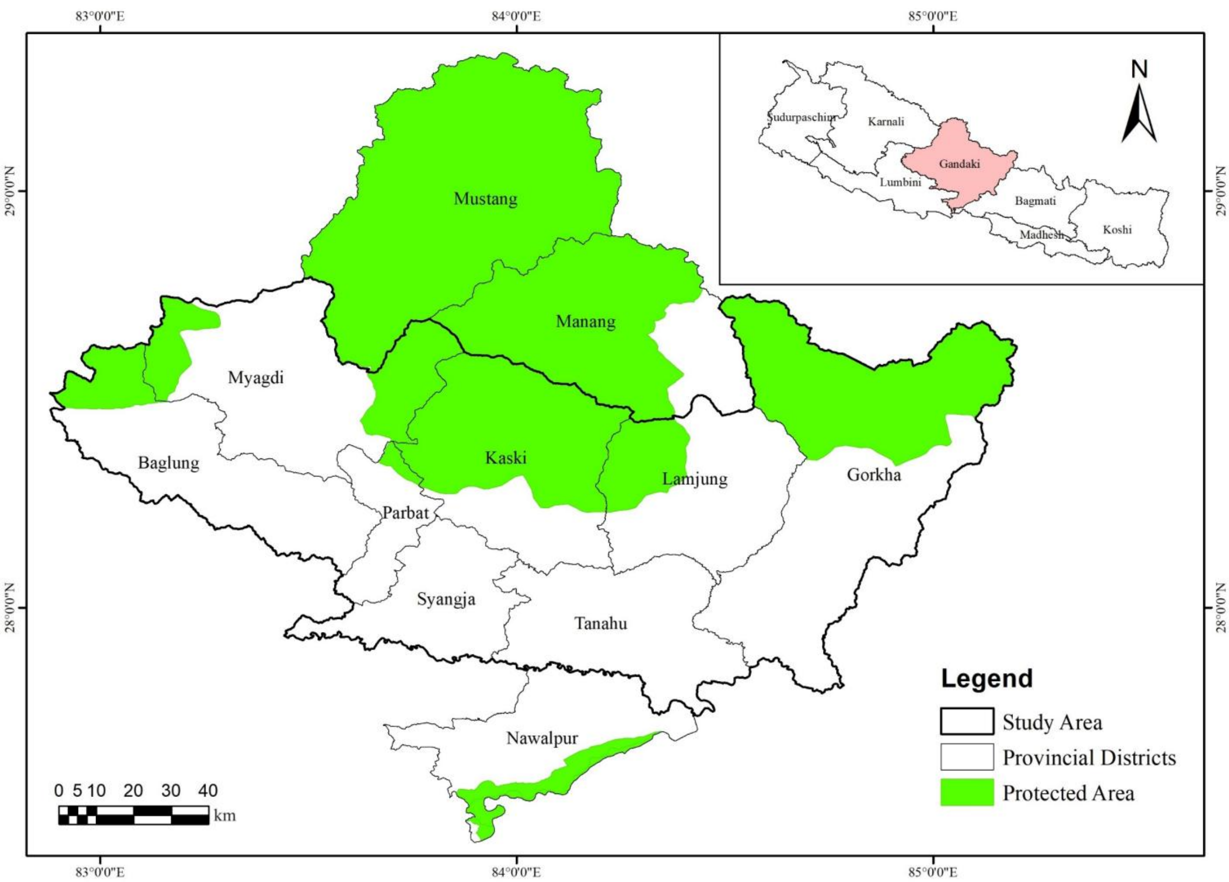

Fig. 1 Study area map with provincial districts of Gandaki Province in western Nepal.

3 Methods

3.1 Data collection

Between 2015 to 2019, we collected data on leopard-related conflict across the mid-hill region of Gandaki Province including incidents of human death/injury and livestock depredation. This information also included data on relief payments associated with conflict cases registered with Divisional Forest Offices, the Province Ministry, the Department of Forest & Soil Conservation, and the Department of National Parks and Wildlife Conservation, which we collected between January - April 2020. Registered cases and payments for human death/injury, as well as all livestock depredation records, were collected and then annotated as to general location, season/date, and time of registration. The specific location of each attack was also recorded via global positioning system (GPS) as provided by Divisional Forest Offices (DFO). For those cases where it was not feasible to record GPS location, the centroid of each "ward" was used to approximate the location of the conflict event. A ward is the smallest administrative entity in Nepal (mean = 4.35 km^2), and data are readily available at this level (Acharya et al. 2017).

For each registered conflict event, we documented the (i) type of conflict (human death/human injury/livestock depredation), (ii) time of incident (24-h period, year, month, and season), (iii) location of conflict (forest, house, road, farmland, cattle shed, coral), and (iv) relief amount claimed and received. Each 24-h period was further subdivided into four-hour intervals (12AM-4AM, 4AM-8AM, 8AM-12PM, 12PM-4PM, 4PM-8PM, 8PM-12AM) (Naha et al. 2020). Each year was then divided into four seasons consisting each of three months (winter: January-March; Summer: April-June; Spring/Monsoon: July-September; Autumn: October-December). Applications for recompense examined also included information on the amount of relief claimed and provided based on the market value of livestock lost. During field visits, we triangulated and cross-validated these data using semi-structured questionnaire (N=156) to survey randomly selected owners who lost livestock to leopards.

3.2 Data analysis

We analyzed incident data to investigate possible spatiotemporal patterns of leopard attacks on people and livestock. We used simple linear regressions to examine trends in livestock depredation across the five years for which we collected data. Using Program R 3.6.0 (R Development Core Team 2015), we also used a chi-square (χ^2) test to examine annual, seasonal, and monthly variation in livestock depredation. We then summed economic losses and relief payments for each year based on the dates of all incidents, and converted these losses to US dollars ($) using the mean currency conversion rates from Nepalese Rupees for each particular year (Gubbi 2012). We did this to account for possible inflationary changes or cost-of-living adjustments.

To develop conflict risk map, we selected nine predictor variables (Appendix 1) based on their ecological importance in predicting HLC, including anthropogenic, climatic, topographical, land cover, hydrological, and livestock density variables (Naha et al. 2018; Sharma et al. 2020). To examine the effects of roads, a potentially important anthropogenic variable reflecting "urbanization", we extracted the Euclidean distance between each site and the nearest road to that site, using Open Street Map (Haklay and Weber 2008). We also incorporated terrain elevation, slope, and aspect, as potentially important leopard habitat and movement variables in Nepalese mid-hill districts, as well as the Euclidean distance between the location of each incident to the nearest water bodies. To assess the role and importance of livestock density in predicting depredations by leopards, we downloaded the global dataset on livestock density (Robinson et al. 2014) and incorporated everything relevant to our study region. We then converted all nine predictor variables to raster files (ASCII format) in ArcGIS 10.3 (ESRI, Redlands, USA) to effectively integrate and evaluate them in our models. We found no strong autocorrelations for all pairwise comparisons between the variables we included (Appendix 2).

To minimize the effect of spatial clustering and thus spatially-related (*i.e.*, non-independent) conflict occurrences, we used a grid size of 5 km × 5 km, the approximate mean home range area for leopards in India (Odden et al. 2014); this helped to improve the independence (Phillips et al. 2017) of data for mapping depredation risk. We then randomly selected 30% of the total data points to evaluate model performance and completed 20 iterations using a default setting of 10,000 maximum background points to improve the robustness of the final model output. This helped us generate response curves for each predictor variable, which we jackknifed (*i.e.*, resampled using a subsample of points) to effectively measure the relative importance of each predictor variable. Model outputs yielded probability estimates (*i.e.*, between 0 and 1) permitting the ranking of probability distributions from lowest to highest (Phillips et al. 2006). To plot sensitivity vs. specificity for all possible thresholds of accuracy for the model, we used the Receiver Operating Characteristics (ROC) curve under the Area Under the Curve (AUC) to train and test the data. Finally, to evaluate model strength of evidence, we applied the following guidelines to our findings with respect to the value of AUC: 0-0.5 = no discrimination, 0.5-0.69 = poor discrimination, 0.7-0.79 = reasonable discrimination, 0.8-0.89 = excellent discrimination, and >0.9 = exceptional discrimination (Vilar et al. 2016).

4 Results

4.1 Spatial and annual distribution of HLC

Between 2015-2019, we recorded a total of 842 incidents of human and livestock loss and injury resulting from HLC across eight districts of Gandaki Province. Of these, 44 incidents involved attacks on humans (29.5% death and 70.5% injury), whereas 798 involved depredations of livestock. Over this period, we found that the number of conflict incidents (SD=171.93, mean=167) increased annually over this period (R^2= 0.90, p<0.05) (Fig. 2). The annual mean number of human deaths and non-lethal human injuries was 2.6 (SD = 2.88) and 6.2 (SD = 1.64) respectively, during this five-year period. Human deaths attributed to leopards increased linearly during this time (R^2=0.82, p<0.05), whereas the annual decrease we observed in non-lethal human injuries was not statistically significant (R^2=0.22, p>0.05) (Fig. 3). Human deaths were recorded in five of the eight provincial districts in Gandaki. Interestingly, over two-thirds of the major lethal encounters occurred in Tanahu district (69%), which was followed by Syangja (8%), Baglung (8%), Parbat (8%) and Kaski (7%) districts. Nonlethal human injuries were also recorded across five of the eight districts; most occurred in Lamjung (29%), followed by Syangja (23%) and Kaski (23%) districts, with the least occurring in Tanahu (16%) and Parbat (6%) districts.

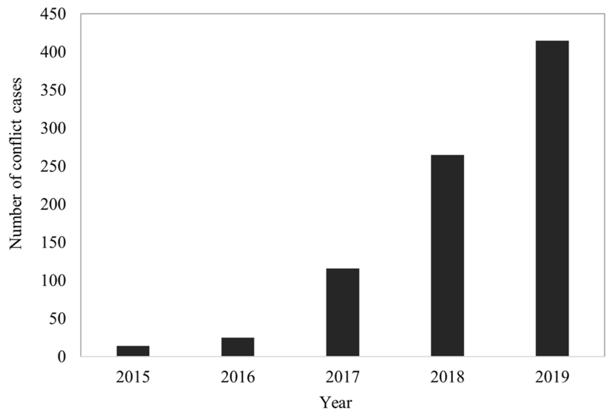

Fig. 2 Number of conflict cases of human and livestock loss and injury resulting from human-leopard conflict.

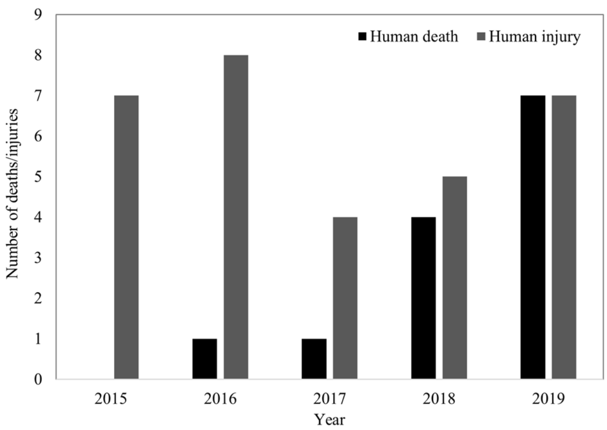

Fig. 3 Human death & injury caused by leopard attacks.

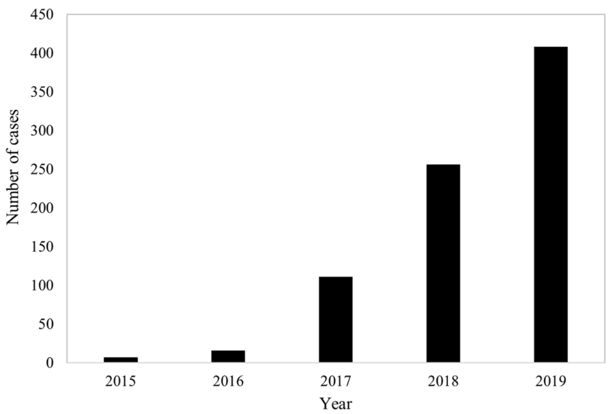

Fig. 4 Livestock depredation caused by leopard attacks.

The mean annual livestock depredation rate across Gandaki Province was 159.6 (SD = 170.56) (Fig. 4), a trend that increased significantly between 2015-2019 (R^2=0.90, p<0.05). Among all districts, most attacks on livestock occurred in Syangja (59.7%), followed by Parbat (16.7%), Gorkha (9.4%), Kaski (6.5%), Tanahu (5.5%), Lamjung (1.5%), Baglung

(0.4%), and Myagdi (0.3%). Most livestock depredation-related conflict incidents occurred at corrals (Fig. 5), whereas the fewest incidents occurred on or along roads. Importantly, goats constituted the livestock class depredated most by leopards (88%); whereas significantly lower depredation occurred on cow (5%), buffalo (3%), ox (3%), sheep (0.6%) and pigs (0.4%).

4.2 Diel and seasonal distribution of HLC

We found that the majority of HLC incidents (54.04%) were reported to have occurred both in the middle of the night (12AM-4AM; 27.32%), and middle of the day (12PM-4PM; 26.72%). The fewest attacks occurred from mid-morning to noon (8AM-12PM; 3.33%) (Fig. 6). Overall, the timing of livestock depredations varied significantly among years (χ^2=34.57, df = 20, p<0.05), with the greatest variation being in 2019. The highest and lowest number of conflict cases were recorded in June and November, respectively (Fig. 7). The highest number of conflict incidents generally occurred during winter, followed in declining order by summer, the monsoon season ("Spring"), and autumn (Fig. 8). Livestock depredation rates also varied significantly across both months (χ^2=71.43, df=44, p<0.05) and seasons (χ^2=50.51, df=12, p<0.05) of the year.

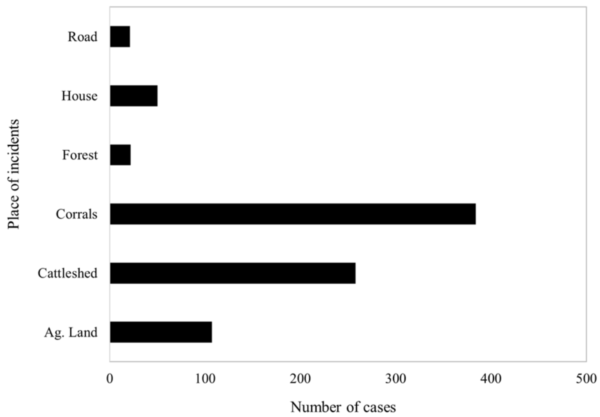

Fig. 5 Place of occurrence of leopard attacks.

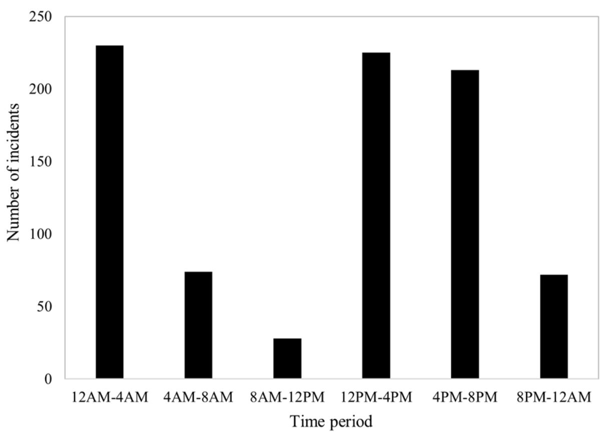

Fig. 6 Time of occurrence of leopard attacks.

4.3 Economic losses and relief payments

In the last five-year period, a total of USD $189,341.6 was paid to HLC affected families through relief mechanisms established by DFOs. The majority (54%) of relief payments were provided to families suffering human deaths, followed by livestock depredation (36%), and for treatment of non-lethal human injury (10%). We estimated total economic losses due to depredations to be about USD $86,892.25, with an annual mean = $17,378.45/year during the study period (Table 1). The Most total financial losses were associated with goat depredations (82.6%), followed by depredations of ox (8%), buffalo (6.4%), cow (2.5%), sheep (0.3%) and pig (0.2%). During 2015-2019, the total compensation for livestock depredations by leopards covered 78.57% of the estimated value of the total losses.

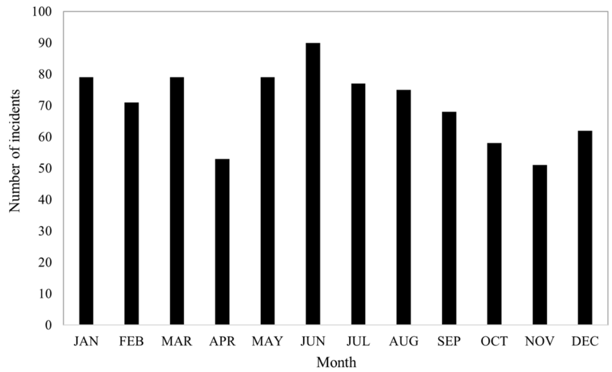

Fig. 7 Month of occurrence of leopard attacks.

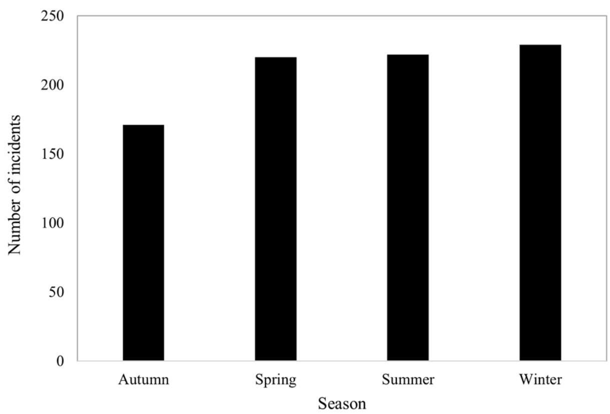

Fig. 8 Season of occurrence of human leopard conflict.

Table 1 Economic losses and compensation payments made towards livestock depredation.

Livestock Type	Amount (US$)	Fiscal Year					Total (US$)
		2015	2016	2017	2018	2019	
Buffalo	Economic Loss	128.17	0	769.03	341.79	4272.40	5511.40
	Compensated	85.44	0	640.86	170.89	3032.55	3929.76
Cow	Economic Loss	0	0	683.58	205.07	1281.72	2170.38
	Compensated	0	0	469.96	2025.12	1256.08	3751.17
Goat	Economic Loss	427.24	1623.51	12902.67	22643.77	34179.27	71776.47
	Compensated	316.15	1384.26	2375.45	16352.22	33194.48	53622.58
Ox	Economic Loss	256.34	85.44	213.62	3417.92	2990.68	6964.02
	Compensated	128.17	85.44	213.62	3341.02	2785.61	6553.87
Pig	Economic Loss	0	0	85.44	85.44	0	170.89
	Compensated	0	0	85.44	76.90	0	162.35
Sheep	Economic Loss	0	0	0	85.44	213.62	299.06
	Compensated	0	0	0	85.44	170.89	256.34
Total Economic Loss		811.75	1708.96	14654.36	26779.46	42937.71	86892.25
Total Compensated		529.77	1469.70	3785.35	22051.61	40439.63	68276.08

4.4 Predicting conflict risk

Of the 842 total HLC occurrences, 136 occurrences were spatially independent based on our understanding of leopard home ranges in South Asia; therefore, we included only these in our MaxEnt modeling efforts. Based on the AUC of our training data (0.92) and test data (0.89), we found our model to be highly accurate (Appendix 3), and the congruence of AUC values indicated high predictive power. Following model convergence and averaging, we determined that all predictor variables, including annual temperature, livestock density, distance to road, and distance to forest cover, were ecologically significant factors in predicting areas of HLC across Gandaki Province. We found however that the greatest association with HLC by far was with annual temperature (46%), more than three times as important as the next most important variables: livestock density (13%), distance to road (12.5%), and distance to forest cover (6.9%) (Fig 9). Our HLC conflict risk map (Fig 10) also confirmed that the southern and central districts in the province exhibited a much higher risk of HLC relative to the northern highlands.

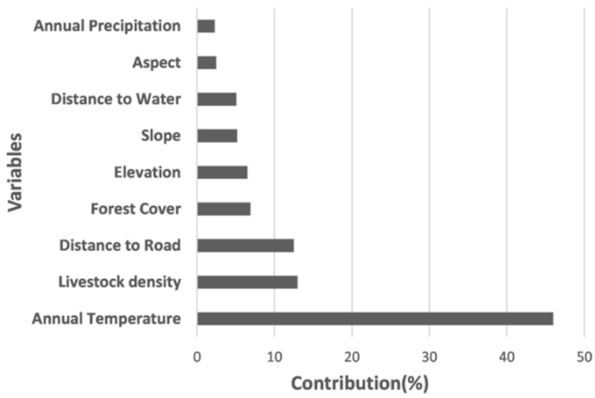

Fig. 9 Predictor variables contribution in predicting areas of HLC.

5 Discussions and Conclusions

Most areas in the mid-hills of Nepal have endured some pressure by leopards on livestock. The mid-hill mountain forests are generally not part of the larger protected area (PA) network; rather, these areas are underrepresented in Nepal's PA network, and most forest patches are close to human settlements (Paudel and Heinen 2015). Our spatial analyses highlighted considerable variation in the frequency of leopard attacks across Gandaki Province, with losses highest in the Syangja district. Michalski et al. (2006) found that more frequent carnivore-related livestock depredations in Brazil were recorded in human-dominated areas with high forest coverage. Although many studies have found that leopards can live in human-modified landscapes (Odden et al. 2014; Constant et al. 2015; Acharya et al. 2017), the increasing trend in HLC we observed may have been due to increased forest fragmentation, a decrease in prey density, changes to livestock herding practices, and the gradual drying up of water resources due to overuse and/or drought (Thapa 2011; Acharya et al. 2016; Kabir et al. 2014). Importantly, reduced availability of native prey species has also been proposed as a cause for leopards switching to "secondary" (e.g., domestic) prey species (Khorozyan et al. 2015), which would obviously lead to higher livestock depredation rates (Dhungana et al. 2019). In our study, goats accounted for the majority of livestock depredations by leopards. Although leopard prey on a wide range of species, from arthropods to adult sambar (*Rusa unicolor*) or even gaur (*Bos gaurus*), they prefer medium-large mammals weighing between 10-40 kg (Hayward 2006), and even small-medium sized mammals ranging from 2-25 kg (Lovari et al. 2013). Goats have an average body size of between 5-25 kg (Lovari et al. 2013); combined with their lack of defensive behaviors, this makes them particularly susceptible to rapid killing and easy "dragging" (Dhungana et al. 2019). Additionally, the proportionally lower rates of depredation on cattle we found is similar to the finding of other studies across south Asia, including Bhutan, India, and Pakistan (Sangay and Vernes 2008; Athreya et al. 2016; Khan et al. 2018; Shalu et al. 2023).

Human incidents and livestock depredation cases increased linearly over our five-year study period. Human deaths showed an increasing trend, where children under 10 years old constituted most victims (76%), mostly over the past two years. This trend coincided with increases in human development activities in the mid-hills, which may have influenced leopard predatory behavior. For example, the increased development of road networks in the mid-hills has led to more forest fragmentation and work in the region; this greater "non-traditional" human presence possibly led to more people exposed to predatory behavior by leopards. Silwal et al. (2016) reported that for areas around Chitwan, increased populations of the offending species, habitat loss, and increased mobility of animals as a consequence of the former two, are all potential contributions to increased HLC.

The frequency of depredations was greatest during dry periods; a shortage of natural forage during leaner times could have led to greater overlap between leopards and livestock, with relatively few measures in place to prevent depredations (Acharya et al. 2016). In winter for example, a general lack of natural grass and fodder important to stall/corral feeding, often forces people to graze their livestock nearer the forest, where they are more vulnerable to predators (Thapa 2011). A recent study in India reported conflict patterns that may have resulted from some of the same seasonal conditions similar to our study area (Naha et al. 2020). Prior studies from Chitwan National Park (Dhungana et al. 2019), Bhutan, and Pakistan (Sangay and Vernes 2008; Dar et al. 2009) also arrived at similar conclusions. Additionally, as the summer (i.e., another dry period) corresponds with peak agriculture, farmers are usually highly engaged in crop production, and may thus be more likely to leave their livestock unattended or poorly guarded (Sangay and Vernes 2008). Negligence in herding or tending to livestock was a main contributor to livestock depredation by

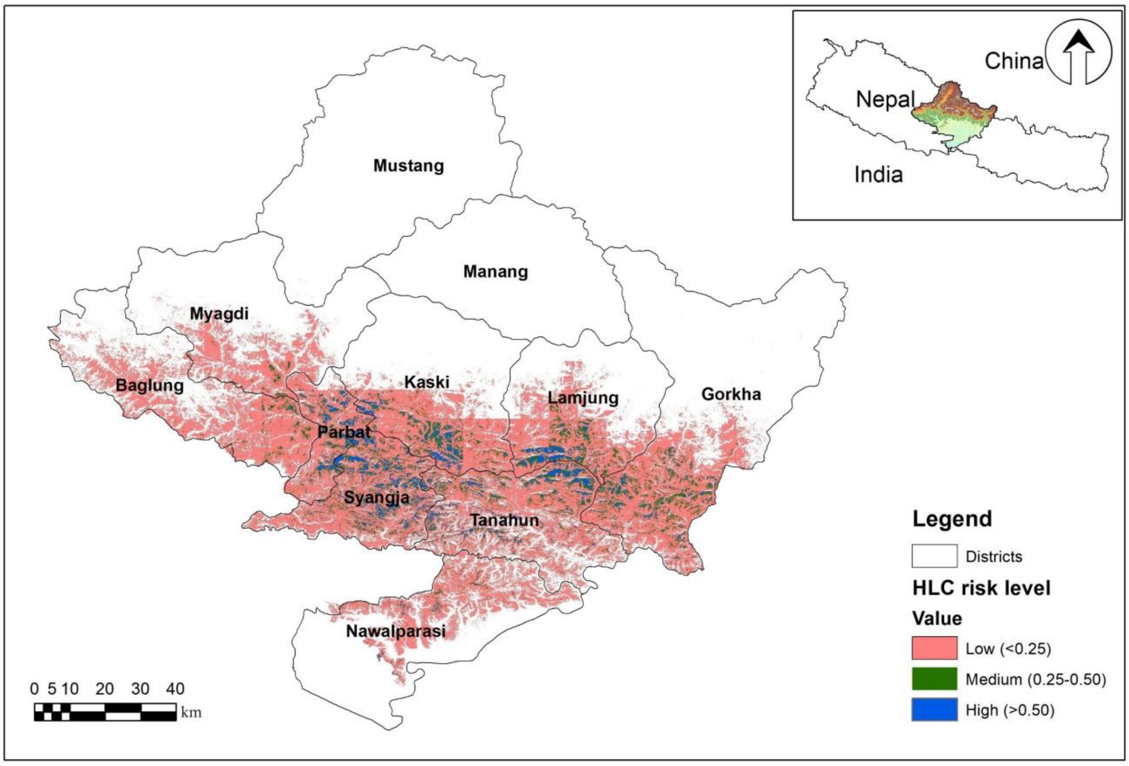

Fig. 10 Conflict risk map.

lions (Maclennan et al. 2009). Moreover, the middle of the night and middle of the day, which coincided with the most vulnerable times for livestock in our study, are when livestock are least likely to be tended to due to human inactivity, and activity elsewhere, respectively. In contrast however, Shalu et al. (2023) found that for the relatively dry state of Gujarat in India, livestock depredations tended to occur more during the monsoon season, possibly due to the greater than usual vegetative cover such rains can bring.

Economic losses incurred by local communities resulting from loss of livestock can ultimately compromise livelihoods. In our study, economic losses and compensation payments for livestock depredation increased annually across the duration of the study period. Interestingly, livestock populations in the mid-hill's region of Gandaki Province (Appendix 4 are fluctuating (MoALD 2022), largely due to local residents having more diverse sources of income and livelihood options than before (e.g., serving as a migrant worker, agricultural production); however, livestock market value is also now increasing rapidly (ADB 2017; Consolee et al. 2020; Baral et al. 2021,2022). This also explains why our estimates of total financial losses resulting from livestock depredation are on the rise. The provision of fair payments for livestock depredations therefore, either by government, insurance companies, or other sources, can have positive impacts for leopards and communities alike in rural, subsistence regions (Dhungana et al. 2019). We should note that in 2013, the Government of Nepal endorsed a compensation/relief scheme by way of the statute, "Wildlife Damage Relief Guideline 2069", which has as its aim the promotion of coexistence between people and wildlife through compensation for livestock losses. Despite this clearly articulated policy goal, numerous factors can compromise the efficient distribution of relief funds to locals, including the following: (1)insufficient information or awareness among locals about the process to apply for such relief; (2)the logistical challenges in preserving, producing, verifying, and sharing evidence; (3) the time and cost needed to complete this 'verification to compensation' process; and (4) the generally cumbersome bureaucracy of these and related governmental processes. As Lamichhane et al. (2019) stated, > 90% of the respondents in the buffer zone of Chitwan National Park were not satisfied with the existing payment mechanism due to its lengthy, bureaucratic process, and general inaccuracy in estimating losses.

We found annual temperature to be an incredibly important predictor of human-leopard conflict. Gupta et al. (2017) reported that local climatic trends, of which average temperatures are a reflection, ultimately shape vegetation characteristics and thus wildlife habitats. Among *Panthera* species, leopards are the most generalist in their habitat and habits; they have a wider latitudinal and longitudinal distribution than any other 'true' big cat (Stein and Hayssen 2013), with higher tolerance towards variation in climatic conditions and habitat types (Stein et al. 2020). Changes in local climate in the mid-hills in Nepal may be affecting their distribution, movements, home ranges, and hunting behavior, forcing leopards to adapt, and bringing them into greater proximity with humans. Overall livestock density also contributed to the frequency of HLC across Gandaki. Although leopards mostly depredated goats, they also preyed upon a wide variety of domestic prey, including sheep, pigs, poultry, and even buffalo. Somewhat surprisingly, we found that the probability of HLC was highest in areas with moderately dense livestock concentrations, rather than in the highest livestock density areas. Consistent with this however, is that communities living along the fringe areas of forests in northern India, generally raised and managed "moderate" numbers of livestock for subsistence support (Bargali and Ahmad 2018).

Road networks also played a significant though secondary role in HLC. As Nepal is undergoing rapid infrastructure and development investments, this is resulting in more forest fragmentation (Clements et al. 2014; Carter et al. 2020). Additionally, roads, highways, and sometimes small footpaths, opened areas to human access and increased the proximity and frequency of human wildlife conflict (Sharma et al. 2020).

Forest cover alone was only a marginally important in predicting conflict, less so than what other studies from the Himalayan region of Bhutan (Rostro-García et al. 2016), North Bengal and Pauri Garhwal of India (Naha et al. 2020), and Tamil Nadu of southern India (Ramesh et al. 2020), have concluded. In this part of Nepal however population growth created pressure to convert unprotected forests into arable agricultural land, and these lands are still increasingly opened for grazing. Although dense vegetation cover can increase the risk of predation from large carnivores (Kolowski and Holekamp 2006; Miller et al. 2015; Beattie et al. 2020), multi-use matrices and "working landscapes" of mixed open and closed habitats often experience high rates of livestock depredation (Naha et al. 2020; Ramesh et al. 2020). The national forest coverage In Nepal was recently estimated at 44.74%, including sparser, secondary forest; the majority of the increase in forest cover has occurred in the mid-hills (DFRS 2015).

Elevation and proximity to water appeared to be less important in influencing HLC. Conflict did occur more frequently at relatively lower elevations particularly in the southern and central mid-hills, but it is likely leopard occurrences were also greater in these areas. Another study reported on the high incidence of leopards along southern, more gentle slopes in India *i.e.*, high predicted occurrence on slopes of 2.5° (Rather et al. 2020). Other studies in the Western and Eastern Ghats of southern India, have reported on the closer occurrence of leopards to water sources (Karanth et al. 2013; Ramesh et al. 2020).

We believe our conflict risk map will be helpful to conservation planning efforts and compensation schemes targeting the mitigation of HLC across Gandaki. As HLC occurs more often outside of protected areas, our risk mapping helps to prioritize the location of investments for mitigation. Our study can also lead to greater institutional capacity to address HWC, and the conception of a larger strategic conservation and research framework for local DFOs, one that includes engaging in broader conservation planning for mitigation of HLC, the capture of leopards for study and relocation, and the monitoring of wild and domestic animals and their behavior (Acharya et al. 2016). Although financial compensation itself is not a long-term solution to HLC, the use of community-based relief funds as part of an insurance scheme, and its integration alongside effective mitigation strategies as for other species in Nepal (e.g., Neupane et al. 2017), is highly recommended.

Finally, in and around protected areas across Nepal, community-based anti-poaching units have been successful in controlling some illegal activities (Lamichhane et al. 2020). We believe these models should be replicated outside of the protected area network and adapted to mitigate conflict in working landscapes, possibly through financial investments made from community-based ecotourism initiatives. Livestock depredation can further be reduced by improving corral structure and animal husbandry practices (Shalu et al. 2023). The reduction of anthropogenic causes of local habitat fragmentation, and the implementation of local climate change adaptation initiatives, could lead to the restoration of more habitat connectivity, and/or greater ecological resilience. Further outreach of local people regarding basic, low cost HLC mitigation methods, and livestock husbandry practices that can reduce conflict might also yield positive results. For leopards however, long-term monitoring in areas with robust HLC mitigation planning, as compared with those yet to adopt such an approach, would yield important information on the efficacy of the former in the context of local leopard population status.

Acknowledgments

We thank NORHED SURNEM project, Institute of Forestry, Kathmandu for providing financial support fieldwork and IDEA WILD for instrumental support. We acknowledge the Gandaki Province Ministry and Divisional Forest Office of province for granting study permission and sharing data. We would like to thank field assistants as well as division forest staff of Gandaki Province districts who helped in data collection and field verifications. Also, we would like to thank and acknowledge Dr. Dinesh Neupane for his input in English editing and reviewing the manuscript.

Authors Contributions

SL: Conceptualization, writing original draft, data Curation and analysis; AT: Conceptualization, input in drafting, data analysis, reviewing, and editing; MT: Helped in field investigation and resources; SP: Review and editing; AG: English editing and reviewing.

Ethics Declaration

Availability of Data/Materials: Data will be made available from the corresponding author on reasonable request.

Conflicts of Interest: The authors declare no competing interests.

Electronic Supplementary Material

Supplementary material (Appendixes 1-4) is available in the online version of this article at https://doi.org/10.1007/s11629-023-8007-8.

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