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The sacred and the wild: Unpacking human-wildlife interaction in Indian part of Kailash Sacred Landscape

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Abstract

The negative interaction between humans and wildlife in the Indian Himalayas has increased in recent decades. Studies on human-wildlife negative interactions have primarily focused on protected areas. However, research on such interactions is limited in regions like the Indian part of Kailash Sacred Landscape (KSL), where wildlife and humans share a common space. This study examined the patterns of crop damage, livestock depredation, human fatalities, seasonal and temporal variations, location-specific factors, and critical variables contributing to negative human-wildlife interactions in KSL India. We examined 574 incidences of livestock depredation, 123 incidences of human injury/death between 1984-2016, and 560 crop damage incidences between 2002-2017. Most incidences of human injury/death and livestock depredation were by common leopards, followed by Asiatic black bears. Maize was the highest raided crop (n=202), followed by wheat (n=190) and paddy (n=168). Maximum incidences of crop loss were reported in 2017 (n=76), and the lowest was in 2002 (n=5). The hotspot maps of crop damage and livestock depredation revealed that the negative interaction between humans and wildlife was highest in the southern part of the landscape. The result predicted 195 villages as hotspots in the Indian part of KSL. Villages were identified at the forest range level. We found that 11 villages in Askot, 12 in Munshiyari, 17 in Beringag, 15 in Dharchula, 36 in Didihat, 61 in Gangolihat, and 43 in Pithoragarh forest ranges are severely affected by negative interaction with wildlife.

Keywords: Crop damage, livestock depredation, negative interaction, seasonal and temporal interaction.

Introduction

Human-wildlife conflict (HWC) is a growing global concern, particularly as human populations expand and natural habitats shrink (Ma *et al.* 2024). This conflict arises when wild animals enter human settlements or agricultural lands, leading to negative interactions that can damage crops, livestock, and even human life. Rapid urbanization, deforestation, and agricultural expansion have fragmented ecosystems, forcing wildlife to adapt to human-dominated landscapes (Thapa *et al.* 2024). Across the globe, this has escalated tensions between local communities and wildlife, particularly in regions that border protected areas or biodiversity hotspots (Zhang *et al.* 2024). The consequences are often more severe, affecting not only the livelihoods and safety of rural communities of mountainous landscapes but also threatening species conservation.

In recent decades, conflicts or negative interactions between humans and wildlife in the Indian Himalayan Region (IHR) have intensified (Sylvia & Sharma, 2023), conspicuously involving common leopards (*Panthera pardus*), Asiatic black bears (*Ursus thibetanus*), wild pigs (*Sus scrofa*), and rhesus macaques (*Macaca mulatta*) (Mishra 1996; Chauhan, 2009; Meena *et al.* 2021; Hussain *et al.* 2018; Hussain *et al.* 2022). These species are reported to cause extensive property loss, such as livestock kill, human injury/death, property damage, and crop damage (Hussain *et al.* 2018, 2022). The rise in human-wildlife conflict in recent years has been attributed to anthropogenic pressures, which have led to habitat degradation and fragmentation. Rangelands and grassy slopes have been extensively grazed by livestock (Mishra 1996; Ogra 2008), which leads to competition with wildlife for resources and reduces the tolerance levels among humans towards native wildlife in the landscape (Ogra & Badola 2008; Bargali & Ahmad 2018; Hussain *et al.* 2018).

Most negative interaction incidents with wildlife in the Himalayas are reported from areas adjacent to forests (Ogra 2008; Hussain *et al.* 2018), involving crop and property damage, livestock depredation, as well as human deaths and injuries (Negi 1996; Naha *et al.* 2018; Hussain *et al.* 2022). Besides economic loss, the aftermath of these negative interactions includes psychological stress, fear of travelling through roads and trails adjacent to forested areas, the pressure of guarding crops, and reduced human activities (Ogra 2008). These factors contribute to negative attitudes among locals towards wildlife and local community conservation initiatives (Ogra 2008; Hussain *et al.*, 2022). Incidents of HWC, such as the death of humans or livestock and damage to crops or property, evoke severe backlash from people and pose setbacks for wildlife conservation (Ogra & Badola 2008; Agarwal *et al.*, 2011). Understanding these interactions is crucial for addressing complex conservation problems (Pradhan 2018), and a thorough understanding of these conflicts is essential for minimizing them (Ogra & Badola 2008; Farooque *et al.*, 2004). One contributing factor, which increases negative interaction with wildlife in the IHR, is human out-migration due to a lack of opportunities and good education for children, leading to abandoned villages and agricultural land (Pathak *et al.*, 2017). This also reduces traditional techniques for minimizing conflict, as fewer people guard, chase, and protect livestock and crops (Hussain *et al.*, 2022).

Studies on HWC have primarily focused on adjoining protected areas (Bargali & Ahmad 2018). However, research on such interactions is limited within the IHR, where abundant forest cover and resources mean that the natural habitats of wild animals often extend beyond government-designated protected areas. Additionally, human settlements in the IHR are patchy and dispersed. The population density of the IHR is also significantly lower than that of peninsular India. The Kailash Sacred Landscape (KSL) is one of the important Himalayan landscapes, and wildlife and humans share the same space (Hussain *et al.* 2018, 2022). There is scarcely any baseline data on HWC from the Indian part of KSL. Large-ranging wild mammals involved in HWC in the Himalayas are found in almost all the districts and villages in the region (Hussain *et al.* 2018). Considering the rising cases of negative interactions with wildlife, including crop loss, livestock loss, and human death or injury, this study aimed to assess the patterns of human-wildlife negative interaction in the Indian part of KSL. Furthermore, the Indian KSL holds both cultural and ecological sensitivity, raising the stakes where traditional livelihoods and biodiversity conservation meet.

The primary objectives of this study are (1) to investigate the patterns and factors contributing to HWC in the Indian part of the KSL, a unique landscape where community and wildlife share a common space, and (2) to identify human-wildlife conflict hotspots focusing four major wild animals.

This research offers two key contributions to the field. First, it investigates HWC in the Indian part of the KSL, which is a distinctive area where wildlife coexists with humans outside of protected zones. Thus, this study fills a gap in the existing literature on HWC, which is primarily concentrated on regions adjacent to protected area. Second, the study identifies specific villages as hotspots for negative interactions. This identification facilitates the development of targeted conservation strategies at a regional scale and allows for more effective resource allocation to mitigate human-wildlife conflicts within these communities.

Materials and method

Study area

KSL is an important transboundary landscape comprising portions of the southwestern Tibetan Autonomous Region of Poeople's Republic of China, adjacent portions of northern India and northwestern Nepal (Zomer & Oli, 2011). The landscape is mountainous and remote, with steep topography, high spatial heterogeneity, and difficult access. The total area of KSL extends over 31,000 km^2 area, and in the Indian part, it covers the Pithoragarh district in Uttarakhand state (Figure 1), with a geographical area of 7,120 km^2 lying between 29° 20'-30° 55'N latitude and 79° 50'- 81° 0'E longitude. The district has seven forest ranges, *viz.* Askot, Berinag, Dharchula, Pithoragarh, Didihat, Munshiyari, and Gangolihat. The forest types range from moist subtropical broadleaf to temperate oak forests, sub-alpine conifers, high-altitude birch forests, alpine meadows, and grasslands. The forests in this landscape fall under protected areas (PA) and non-protected areas. Askot Wildlife Sanctuary is the lone legally designated PA. However, the non-PA category of forests includes reserve forests under the control of the state forest department and community forests or Van Panchayat, protected by the local community body called panchayat. Among all the seven ranges, density of human settlement is very high in the Pithoragarh range, which encompases the district headquarters. Nearly 80% of the villages are connected with roads in the study area. About 63% of people in the study area depend on agriculture and livestock farming (Zomer & Oli 2011; Hussain *et al.* 2018). Nearly 53% of the agricultural land shares its boundary with forest and 90% of the farming land is rain-fed. Numerous rivers, tributaries, and springs are spread across the landscape. The study area shows wide altitude variation ranging from < 350 m asl to peaks ranging > 7000 m asl (Zomer & Oli 2011; Hussain *et al.* 2018).

Compiling conflict data and field visits

To understand the nature of human-wildlife conflict, we compiled records of human injuries and fatalities, livestock depredation, compensation, and crop losses collected and records maintained by the Pithoragarh forest department from 1984 to 2017. The data collected from the forest department included information on the location of conflict incidence, households affected, species causing the problem, date and time, and compensation amount paid (Bargali & Ahmad 2018). Using records of repeated conflict incidents from 1984 to 2017 and data on compensation paid to victims, we determined the most conflicted regions encompassing seven forest ranges in KSL-India. The area was subdivided into 2 km^2 grids for systematic sampling, with each grid visited for a household survey (Figure 1). A total of 584 individuals from the survey region were interviewed to gather information on human-wildlife interactions and to validate data obtained from the forest department (Hussain *et al.* 2018; Naha *et al.* 2018). During the interviews, all the respondents were asked about the details of conflict incidents and their companions, as well as more information on age, time, month of the attack, and activity during the attack (demographic details of the respondents in Supplementary Table S1). All the conflict locations collected from the field and the forest department records were marked and mapped using GPS locations in ArcGIS 10.3.

Predicting HWC Hotspot

Using presence data with possible influencing factors, we predicted the conflict hotspots of the common leopard (n = 151), Asiatic black bear (n = 76), wild pig (n = 631), and rhesus macaque (n = 278). The spatial distributions of these locations are provided in the Supplementary Figure S1. We identified two main categories related to conflict distribution, namely abiotic factors (elevation, slope, aspect, land use land cover- LULC, and

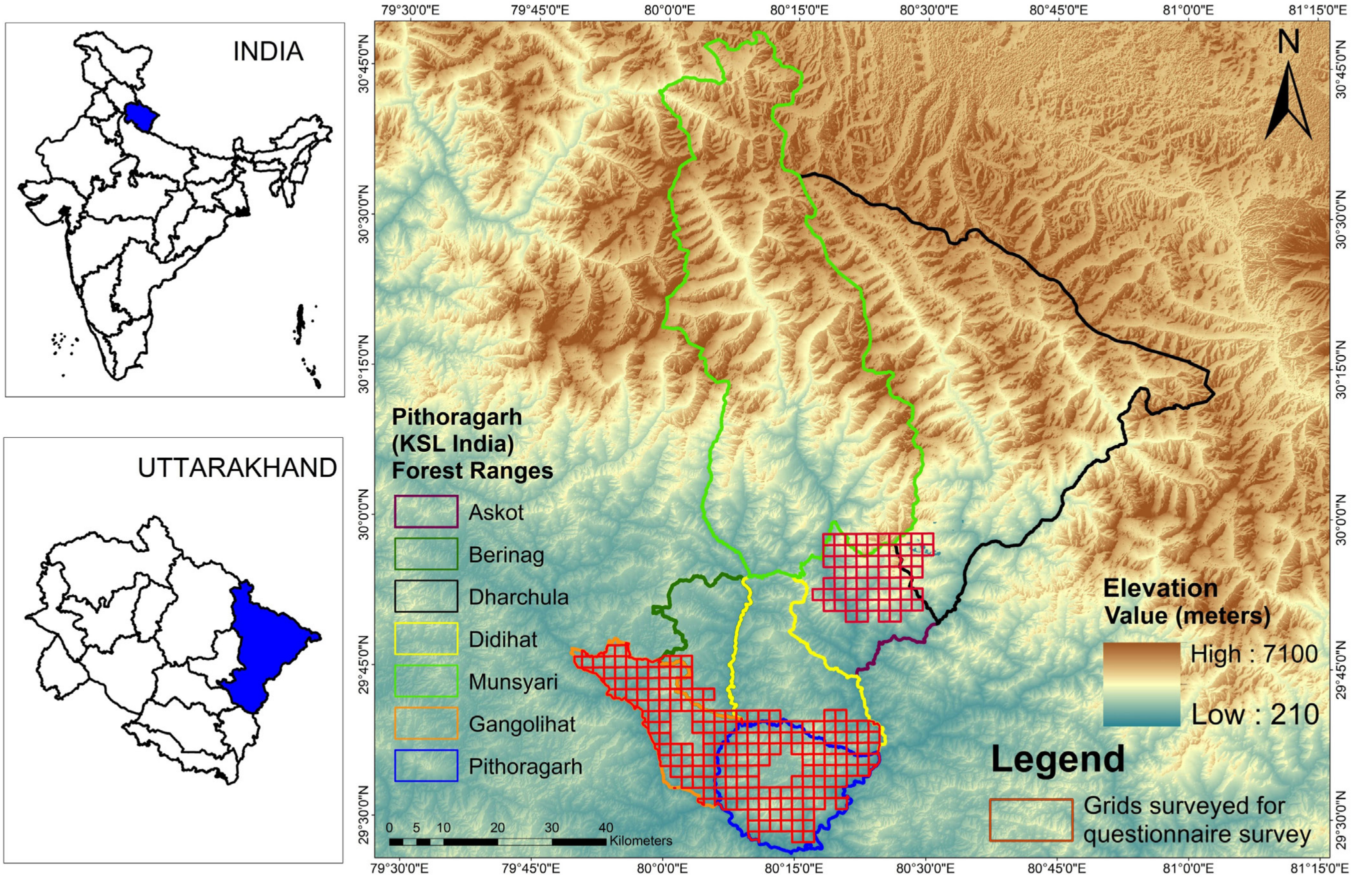

Figure 1: Map of the Indian part of KSL, showing the questionnaire survey area, determined based on villages that experienced repeated conflict incidents from 1984 to 2017 and where the Forest Department compensated affected communities. The survey area covered seven forest ranges of the region. This area was divided into 2 km^2 grids, with at least one household surveyed per grid.

Table 1. Hypotheses for selecting various independent variables to model the human-wildlife conflict hotspots using MaxEnt in Kailash Sacred Landscape, India

Influencing Factors	**The Rationale of Selecting Influencing Factors**	**Source**
Human Density (Individuals/ km^2)	Higher human density can increase the likelihood of encounters between humans and wildlife, as more people in a given area can lead to greater land use and resource competition (Pithoragarh District - Population 2011).	2011 Census data (https://www.census2011.co.in/census/district/580-pithoragarh.html)
Livestock Density (Individuals/ km^2)	Areas with high livestock density are often targets for predation by wildlife, leading to increased conflict. Understanding livestock distribution helps predict where conflicts are likely to occur (Livestock Demography of Pithoragarh 2011).	LPDAC (https://ahd.uk.gov.in/pages/display/107-livestock-demography)
Land use land cover (LULC)	Different land use types influence wildlife behavior and movement. Understanding LULC can help identify areas where wildlife may intrude into human-dominated landscapes (Zeller *et al.* 2017).	Landsat - 8 (USGS) (https://earthexplorer.usgs.gov/)
Distance from agriculture	Proximity to agricultural land can indicate areas of potential crop raiding by wildlife. Measuring distance helps in understanding how far wildlife will travel to access food resources (Mamo *et al.* 2021).	LULC Generated from using Landsat images
Euclidean distance from road	Roads can serve as barriers or corridors for wildlife movement. Analyzing the distance from roads can help identify how road infrastructure impacts wildlife behavior and potential conflict zones (Mulero *et al.* 2022).	LULC Generated from using Landsat -8 images
Euclidean distance from settlement	Closer proximity to human settlements increases the risk of wildlife encounters. Understanding this distance can help identify vulnerable areas where conflicts are more likely (Mekonen 2020).	LULC Generated from using Landsat -8 images

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Euclidean distance from water bodies	Water sources are critical for both wildlife and livestock. Analyzing distances from water bodies can help predict where wildlife might congregate, increasing the likelihood of conflict (Naha *et al.* 2018)	LULC Generated from using Landsat -8 images
Euclidean distance form forest	Forests often provide habitat for wildlife. Distance from forest edges can indicate how likely wildlife is to venture into human-dominated areas (Bargali & Ahmed 2018)	LULC Generated from using Landsat -8 images
Digital elevation model (DEM)	Elevation data helps in understanding the topography of the area, which is essential for modeling wildlife movement and habitat preferences, as well as human land use patterns (Naha *et al.* 2018).	ASTER (https://www.earthdata.nasa.gov/news/new-version-aster-gdem)
Slope	The slope of the terrain can influence wildlife movement patterns. Steeper slopes may limit wildlife access to certain areas, affecting their interaction with human settlements (Naha *et al.* 2018)	Generated from DEM
Aspect	The orientation of the land (aspect) can influence vegetation growth and microclimate conditions, which in turn can affect wildlife distribution and behavior (Naha *et al.* 2018)	Generated from DEM
NDVI (Normalized Difference Vegetation Index)	NDVI is a measure of vegetation health and density. Healthier vegetation may attract wildlife, and monitoring NDVI can provide insights into wildlife habitats and foraging areas (Xiaoxu 2014).	Satellite Image/Landsat (USGS) (https://earthexplorer.usgs.gov/)
Annual Temperature	Temperature influences wildlife behavior, reproduction, and habitat use. Changes in temperature can impact the distribution of both wildlife and human activities, affecting conflict dynamics (Naha *et al.* 2018).	WorldClim (www.worldclim.org)
Annual Precipitation	Precipitation patterns can affect vegetation growth and water availability, influencing both wildlife habitats and agricultural practices. Understanding precipitation trends helps in predicting resource competition between humans and wildlife (Naha *et al.* 2018)	WorldClim (www.worldclim.org)

Table 2. The per cent contribution of different variables and AUC values for predicting conflict distribution of rhesus macaque, wild pig, common leopard, and Asiatic black bear in Kailash Sacred Landscape, India.

Variables	**Variables Contributions (%)**			
	Rhesus Macaque	**Wild Pig**	**Common Leopard**	**Asiatic Black Bear**
AUC Value	0.93	0.94	0.95	0.97
Annual Mean Temperature (bio_1)	6.2	7.3	5.7	3.2
Annual precipitation (bio_12)	7.2	4.5	10.3	2.3
Livestock Density	NA	NA	53	60.9
Distance to Agriculture	51.2	39.6	NA	NA
NDVI	2	1.9	2.9	1.8
Distance to Road	11.5	10.2	0.8	2
Distance to Settlement	9.3	18.5	3.3	7.6
Distance to Water Body	4.5	4.6	0.1	2.2
Distance to Forest	1.3	4.5	5.6	4.3
DEM (Elevation)	2.3	4.2	7.9	8.5
Slope	1.1	2.1	4.3	2.1
Aspect	3.4	2.6	6.1	5.1

distance factors) and bioclimatic and biotic factors (livestock density, anthropogenic factors) (Phillips *et al.* 2006; Sarkar *et al.* 2018). We selected elevation, slope, aspect, Normalized Difference Vegetation Index (NDVI), and bioclimatic factors for landscape-level analysis. Details of all 14 predictor variables are provided in Table 1. In ArcMAP 10.3, elevation, aspect, and slope were generated using a digital elevation model (DEM) layer, with all variables clipped to our study areas. Land use and land cover were classified using LANDSAT 8 imagery. All predictor variables were re-scale to 1 km^2 spatial resolution, and we performed pairwise calculations of Pearson's correlation coefficient (Supplementary Table S2) among the influencing factors, confirming that the correlation coefficient remained within the range of ±0.75 for any combination of variable pairs (Tehrany *et al.*, 2019). Based on Pearson's correlation coefficient, we excluded human density and LULC from the list of influencing factors, retaining 12 variables for further analysis (Table 2, Supplementary Figures S2-S13).

To address spatial sampling biases and spatial autocorrelation challenges for the location data of four prominent conflicting animals, *viz.*, common leopard, Asiatic black bear, wild pig, and rhesus macaque, we employed a bootstrapping approach using the spThin package in R (Aiello-Lammens *et al.*, 2019) for each species separately. To achieve a 1 km^2 spatial resolution for the modeling exercise, we conducted 50 iterations of bootstrapping using a minimum thinning distance of 1 km. This process resulted in obtaining 138, 72, 628, and 259 unique locations of common leopard, Asiatic black bear, wild pig, and rhesus macaque, respectively. This approach effectively minimized the removal of records while significantly mitigating sampling bias (Aiello-Lammens *et al.*, 2015).

We used the maximum entropy model (MaxEnt) (Phillips *et al.* 2006; Naha *et al.* 2018; Sarkar *et al.* 2018) to predict the distribution of conflict in the study area under the present scenario. We input all biotic and abiotic variables and presence locations into MaxEnt version 3.4.1. We ran the model through twenty-five bootstrap resampling runs with 75% training data and 25% for model validation. Jackknife and sensitivity analyses were carried out to determine the contribution of variables (Naha *et al.* 2018). Area under the receiver operator characteristic curve (AUC) was used to assess model accuracy (Phillips *et al.* 2006; Sarkar *et al.* 2018). The results were interpreted as conflict hotspots. We used logistic probability, and the gradient map was reclassified in ArcMap 10.3 to show conflict distribution for common leopards, Asiatic black bears, wild pigs, and rhesus macaques, each separately categorized as low (0.0–0.14), moderate (0.14–0.42), and high (0.42–1.0). Hotspot areas with < 0.8 values were extracted from the final shape files of all four conflict hotspot maps and merged all the clip shape flies of the final hotspot.

Results

Human-wildlife conflict in KSL India

A total of 560 crop damage incidences were recorded between 2002 and 2017 from seven forest ranges of KSL India (Figure 2), and 574 livestock depredation and 123 incidences of human injuries and deaths were recorded between 1984 and 2016 (Figure 3). Most human injuries and deaths were associated with the common leopard (75.29%), followed by the Asiatic black bear (24.51%) (Figure 3A). Likewise, the maximum incidences of livestock depredation were also by common leopards (83.62%) followed by Asiatic black bears (16.2%) (Figure 3B). Maximum incidences of human injury/death (n=12) were recorded in 2011, and no incidences were recorded in 2003, 2006 and 2007 (Figure 3A). Maximum livestock depredation (n = 38) was recorded in 2012, and minimum (n = 3) in 2010 (Figure 3B). Maize was the most commonly raid crop (n = 202), followed by wheat (n = 190) and paddy (n =168) (Figure 2). Wild pigs (n = 301) were responsible for most of the incidences of crop raiding, followed by rhesus macaques (n = 259) (Figure 2). Maximum incidences of crop loss were reported in 2017 (n=76), and the lowest number was in 2002 (n = 5) (Figure 2). Common leopards mainly preyed on goats (50.98%), followed by cattle (43.30%), horses (3.54%), and mules (2.16%). For the Asiatic black bear, a similar trend was noted; the primary victims were goats (65.07%), followed by cattle (15.87%), mules (14.28%), and horses (4.76%).

Seasonal and temporal variation of leopard and bear attacks in KSL India

Common leopard caused more incidences of livestock depredation and human attacks than Asiatic black bear (Figure 4A). Moreover, the livestock depredation was highest in the winter season (47.23%), followed by the monsoon (29.27%) and the summer season (23.5%) (Figure 4B). During the monsoon season, common leopards accounted for 75.55% of the depredation incidents, while Asiatic black bears accounted for 24%. In the winter season, the proportion of incidents involving common leopards rose to 83.43%, compared to 16.57% for black bears (Figure 4B). The record of the forest department and informal interactions with the victim's family members revealed that 36.59% of victims were attacked in villages near the forest, 30.89% of victims were attacked inside the forest, 22.76% of victims were attacked in agricultural fields, and 9.76% of victim's were attacked near nallah or streams (Figure 5A). About 56% of attacks occurred in the evening between 16:00 h and 20:00 h, 29.27% of the attacks occurred between 21:00h and 24:00h, 10.57% of attacks occurred between 06:00h and 15:00h, and 4.07% of attacks happened between 01:00h and 05:00h (Figure 5B). Among the age groups, the analysis revealed that 43% of victims of the common leopard and black bear attack in the Kailash landscape were between 31-45 years in age, followed by 33.33% between 16-30 years age group, 12.20% between the 0-15 years age group and 11.38% above 45 years of age (Figure 5C). Compensation paid by the forest department to the community members in terms of human injury/death and livestock depredation by common leopard and Asiatic black bear was ₹17,51,300 ($20,866) between 2004 - 2016. The data collected from the forest department shows that the compensation amount is gradually increasing at the study site (Figure 5D).

Predictor variables and human-wildlife conflict risk zones in KSL India

We selected 12 independent and ecologically significant variables to predict conflict distribution and hotspots in KSL (Table 2). The AUC values of best performing MaxEnt models for wild pig, rhesus macaque, black bear and common leopard were 0.92, 0.93, 0.97 and 0.95, respectively (Table 2). All the ROC curves predicting conflict hotspots for wild pig, rhesus macaque, black bear, and common leopard are provided in Supplementary Figure S15. The analysis revealed hotspots of wild pig conflict near forested areas or fringes of the forest, particularly in the lower part of the study site, along the forest edges and towards agriculture fields near forest patches and near the water body. In the analyses of conflict hotspots for wild pigs and rhesus macaques, Euclidean distance to agriculture was identified as the primary factor. This variable accounted for 51.2% of the prediction for rhesus macaques and 39.6% for wild pigs. Additionally, distance to settlement emerged as the second most significant factor, contributing 9.3% to the prediction for rhesus macaques and 18.5% for wild pigs (Table 2). However, distance to the forest contributed the lowest, followed by annual temperature and precipitation.

The response curves of Euclidian distance to agriculture demonstrated a high risk of conflict with wild pigs and rhesus macaques closer to agricultural fields, with the conflict probability falling drastically after 100 - 500 meters. MaxEnt fitted the response curve unexplainably at short distances, possibly implying overfit. The response curve for annual average precipitation increased the risk of conflict in areas with higher annual rainfall. The analysis also predicted high risk in areas with very high annual average precipitation, fitting a U-shaped response to the variable. Most models predicted areas with NDVI of 0.4–0.8 having the highest risk of conflict. In the models, the conflict of crop raiding risk rose in areas with relatively low human settlement and high agricultural regions. The models fitted response showing crop raiding by macaques and pigs being more likely in areas between 600 and 3000 m asl. The model response predicted the highest risk for conflict in close vicinity of water sources, decreasing with distance and increasing between 0 to 100 m distance.

Livestock density was overall the most crucial variable in human-bear conflict models, contributing 60.9%, followed by the contribution from elevation at 8.5%, and Euclidean distance to settlement at 7.6%. The least essential variables were the Euclidean distance to the road, slope, annual mean precipitation and temperature (Table 2). In the case of common leopard, the most important variables impacting the distribution of human-leopard conflicts were livestock density contributing 53 %, annual mean precipitation 10.3%, and elevation, contributing 7.%. The models predicted a high risk of conflict with common leopards and black bears in areas with a high density of cattle and human settlements closer to forested areas.

All the species involved in conflict preferred forested edges/ patches near agriculture and human habitation areas. Moderately dense areas dominated by shrubs were preferred by wild pigs, common leopards, and rhesus macaque. Wild pigs, common leopards, and Asiatic black bears avoid areas with dense human settlements. Asiatic black bears preferred middle elevations and dense forest patches. In terms of climatic factors, the rhesus macaque, common leopard, and wild pig avoided low winter temperatures. Asiatic black bears, common leopards, wild pigs, and rhesus macaques avoided areas >3000 m asl, which are severely cold during winter (Supplementary Figure S14). The factors influencing the distribution of conflict by all species included NDVI, Euclidean distance to agriculture, livestock density, and Euclidean distance to settlements. Rhesus macaque, wild pigs and common leopards use near to moderately dense forests near human settlements between 0 to 1000 meters, and Asiatic black bears prefer dense forests near human settlements between 0 to 2000 meters from the forest (Supplementary Figure S14).

The hotspot distribution maps indicated that for the common leopard, hotspots were located in the southern area and much of the central region of the study site (Figure 6A). Whereas conflict hotspots for the wild pig, rhesus macaque, and Asiatic black bear were found concentrated in the southern part and smaller areas of the central region (Figures 6B–6D). It was found that 195 villages come under HWC hotspots in the Indian part of KSL (Figure 7). Villages were identified at the forest range level. It is found that 11 villages in Askot, 12 in Munshiyari, 17 in Berinag, 15 in Dharchula, 36 in Didihat, 61 in Gangolihat, and 43 in Pithoragarh forest ranges are severely affected by HWC. It was found that 112 villages were affected by common leopards, 89 were affected by Asiatic black bears, 135 were affected by wild pigs, and 157 were affected by rhesus macaque, respectively. For effective prevention and mitigation plans for HWC, we identified the severely affected villages. Out of 195 villages, 87 villages faced conflict with all four species (Figure 7).

Discussion and Conclusion:

This study provides crucial information on human-wildlife conflict within the Indian region of the KSL, where wildlife and human communities coexist beyond the boundaries of designated protected areas. Unlike previous studies focused primarily on regions adjacent to protected areas (Bargali & Ahmed, 2018; Naha *et al.*, 2018), this research addresses an underexplored context, examining HWC dynamics in large multi-use landscapes with limited conservation oversight. By identifying specific villages as high-risk hotspots, this study not only deepens our understanding of spatial and temporal patterns in HWC but also provides a baseline for targeted conservation strategies at a community level. These contributions are essential for informing resource allocation and developing tailored interventions that enhance coexistence and mitigate socio-economic impacts in this culturally and ecologically significant landscape.

Common leopard and Asiatic black bear were the major predators in the Indian part of KSL, as most of the cases of human injury/death and predation on livestock were associated with these two predators. While leopard conflicts have been documented in areas adjacent to protected areas (Naha *et al.*, 2018), this study reveals a significant increase in conflict incidences involving leopards and Asiatic black bears far from designated protected areas in the study region between 1984 and 2016. This poses an urgent challenge for the forest department to strategize future conservation efforts, mitigate human-wildlife conflict, and protect both wildlife and local communities within this shared-resource landscape. Most of the conflict incidences by common leopards and Asiatic black bears were recorded during the winter season. A similar pattern of conflict incidents during winter has been reported by other studies in the western Himalayan landscape (Naha *et al.*, 2018; Sharma *et al.*, 2020). This may be due to increased fodder collection and livestock grazing in the forest after the monsoon season, which heightens human-wildlife interactions in the study area. Most of the livestock and humans killed by leopards and bears were reported at the fringes of the forest. For human victims, age between 31 and 45 was the most vulnerable. This might be because of the involvement of this age group mostly in activities like agricultural farming, grazing cattle fodder, and fuel wood collection. A similar pattern was observed in several other studies in the western Himalayas (Agarwal *et al.* 2011; Chetri *et al.* 2019; Naha *et al.* 2018; Hussain *et al.* 2018). Conflict incidents of all types were concentrated in the mid to lower elevation areas of the landscape, a trend consistent with findings from both the western (Agarwal *et al.*, 2016) and eastern (Sharma *et al.*, 2020) Himalayan regions. One contributing factor may be the greater degree of forest fragmentation in these low and mid elevation zones, which, as Sharma *et al.* (2020) suggest, disrupts natural habitats and forces wildlife closer to human settlements. This proximity increases the likelihood of encounters and conflict between local communities and wildlife.

Our study finds an increase in crop raiding cases by macaques and wild pigs from 2002 to 2017. The rhesus macaques are fearless against humans in the entire KSL, because in many temples and sacred grooves, the devotees feed rhesus macaques, making them habituate with humans and, with time, become fearless. When macaques did not find food in temples, the entire macaque troops entered villages, attacked houses and agricultural fields and started conflict (Hussain *et al.* 2022). The finding of the study reveals that most of the attacks by black bears on humans and livestock occurred in villages involved in apiculture farming, this might be because honey attracts bears as stated by several studies in the Himalayas (Charoo *et al.* 2009; Agarwal *et al.* 2016; Hussain *et al.* 2022).

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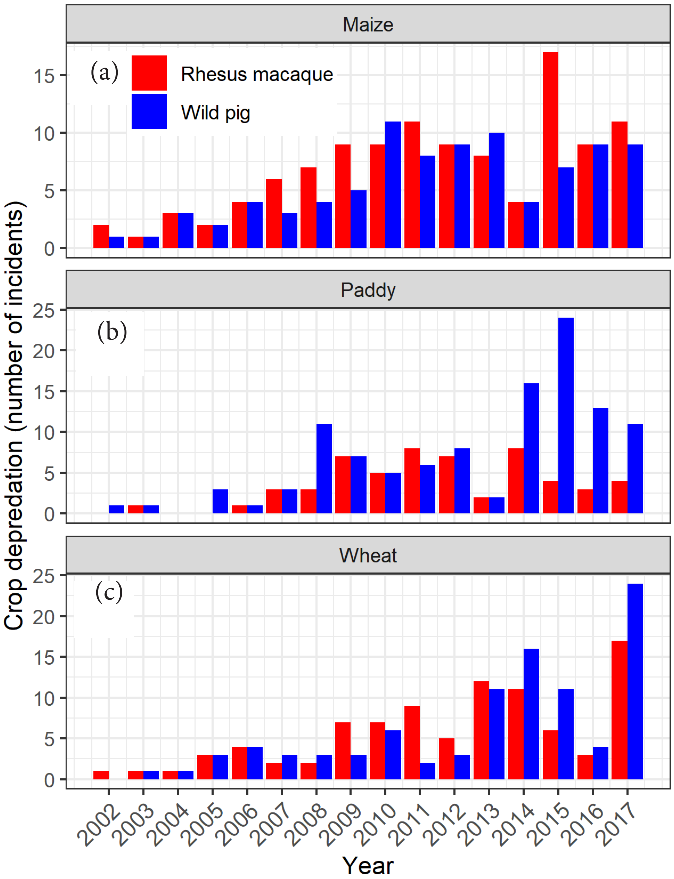

Figure 2: Crop depredation incidents by wild pig and rhesus macaque from 2002 to 2017 in Kailash Sacred Landscape, for different crops (a) Maize, (b) Paddy, and (c) Wheat.

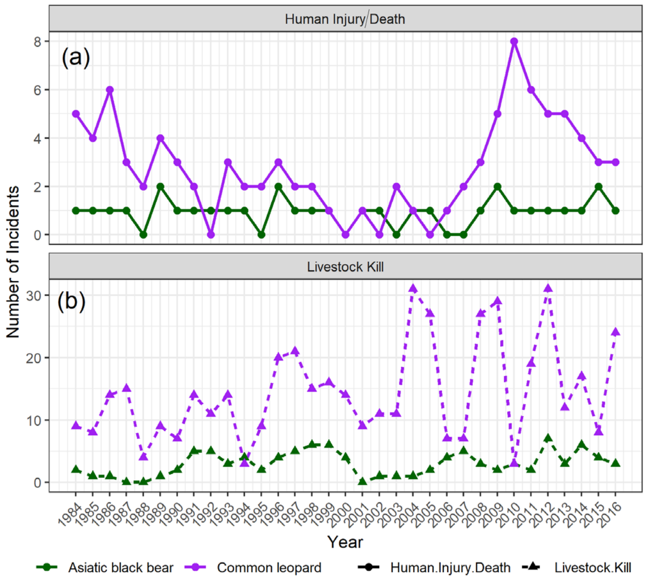

Figure 3: Trends in livestock kills and human injuries/deaths caused by Asiatic Black Bear and Common Leopard from 1984 to 2016 in Kailash Sacred Landscape. The line plot illustrates the number of incidents per year, with separate panels for each incident type (a) Human Injury/ Death and (b) Livestock Kills.

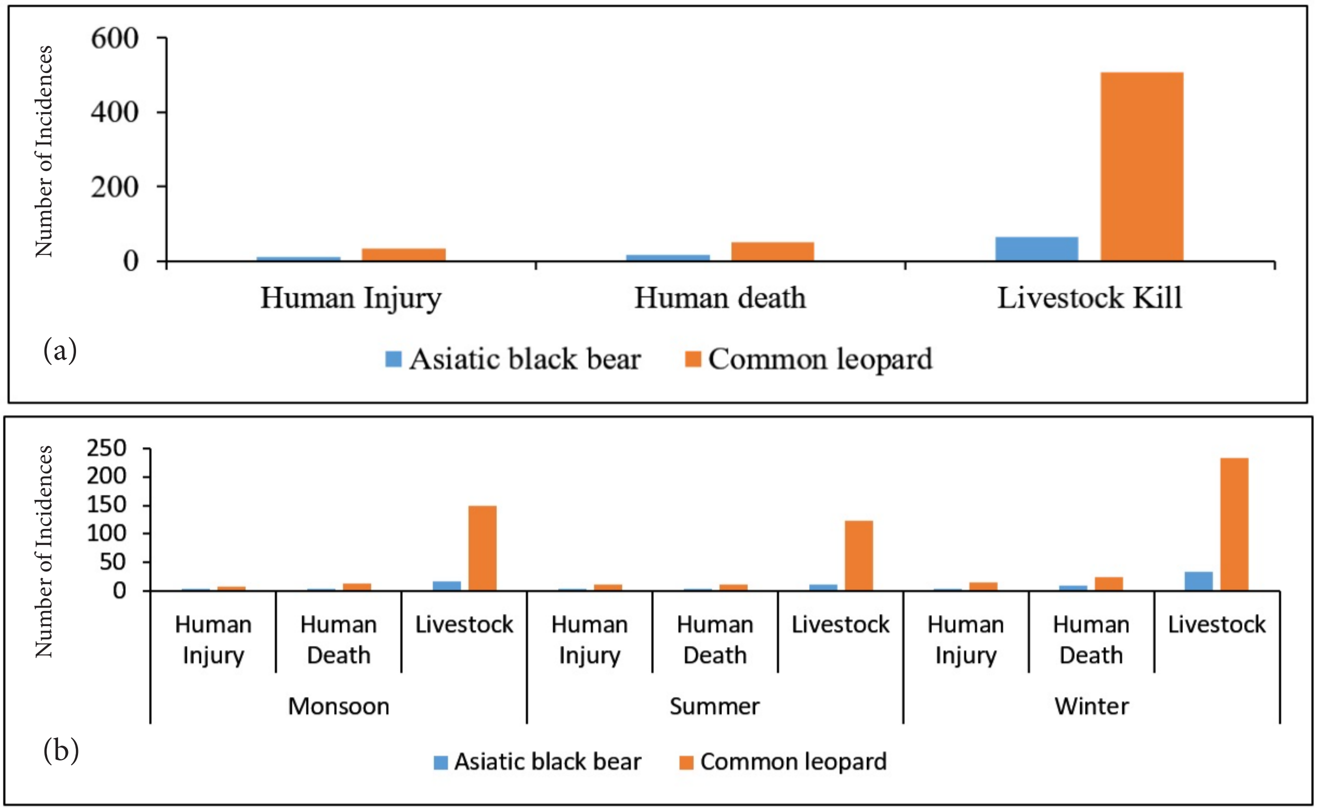

Figure 4: (a) human injury/death, livestock kill by common leopard and Asiatic black bear b) seasonal variation in livestock kill, human injury/death by common leopards, and Asiatic black bear from 1984 to 2016 in Kailash Sacred Landscape India.

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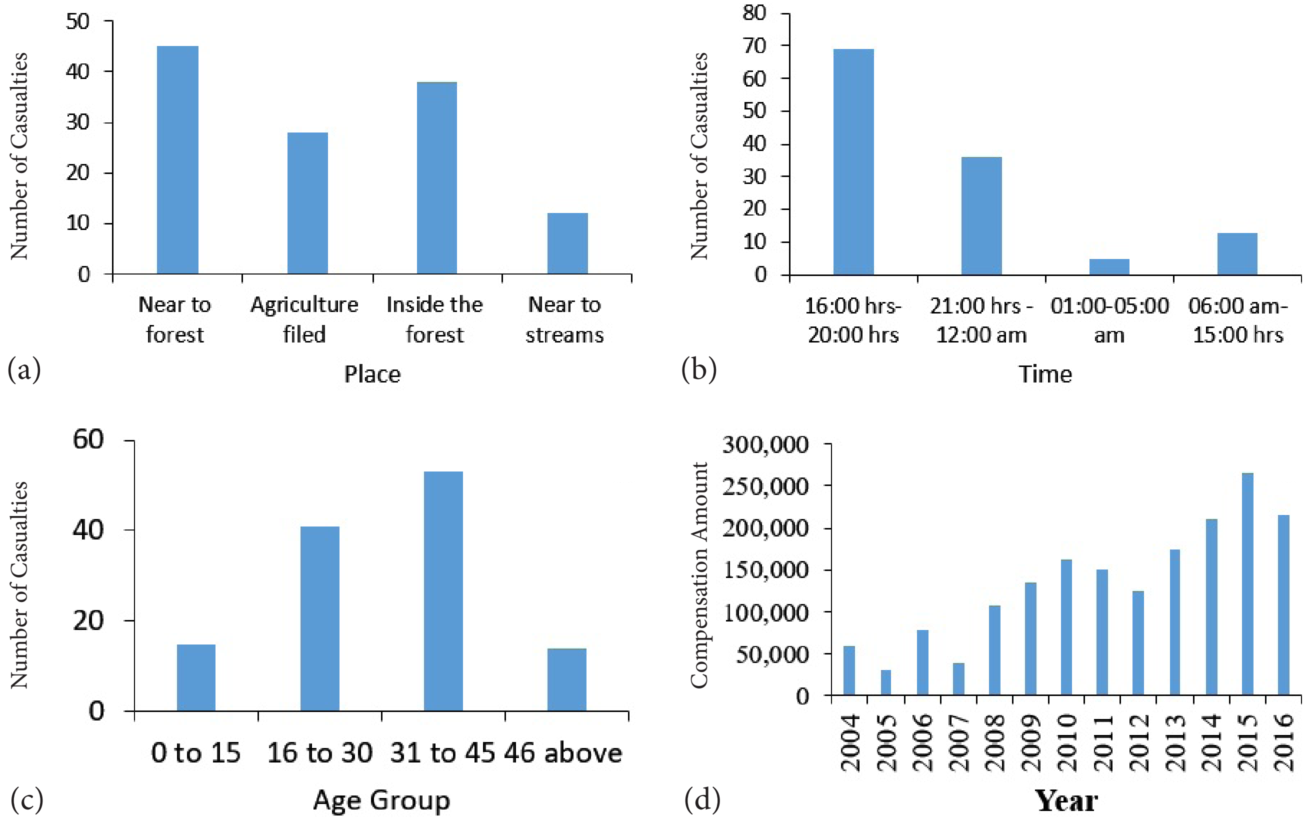

Figure 5: Details of (a) site characteristics of human casualties by leopard and bear reported, (b) time of human casualties happen by leopard and bear, (c) age group of human casualties, and (d) trend of compensation amount distributed from 2004 to 2016 in Kailash Sacred Landscape, India.

We found small scrub patches of Eupatorium spp in the entire study region, near villages, along trails and roads, and agricultural areas, which are not a source of food for wildlife and livestock, but these serve as a daytime refuge for wildlife species involved in HWC, such as wild pigs, porcupines, and common leopard. Villages surrounded by patches of Eupatorium spp. experience higher rates of crop and livestock loss than villages without such vegetation. Hussain *et al.* (2022) found similar results in their study within the same landscape: after removing Eupatorium spp. patches from two villages, both showed a reduction in crop loss incidents. This suggests that clearing Eupatorium patches, which provide daytime refuge for wildlife near human settlements and agricultural areas, may help mitigate HWC.

The differences in variable contributions across species for predicting conflict distribution in KSL India reflects each species' distinct ecological needs, behaviors, and habitat preferences. Distance to agriculture (51.2%) was the strongest predictor of conflict for rhesus macaques, as they frequently forage in agricultural fields. Distance to roads (11.5%) and distance to settlement (9.3%) suggest their adaptability to human presence. Wild pigs also rely heavily on agricultural areas (distance to agriculture, 39.6%) and often approach settlements (18.5%) to forage, with annual mean temperature (7.3%) and distance to forest (4.5%) also influencing their conflict patterns due to temperature and natural cover needs. In contrast, common leopards are most influenced by livestock density (53%), which focuses on areas with high livestock availability, leading to livestock predation. They also show sensitivity to elevation (7.9%) and aspect (6.1%), as these terrain features support hunting and shelter preferences. For Asiatic black bears, livestock density (60.9%) was a primary conflict predictor, as livestock attracts them when they descend from higher elevations, while elevation (8.5%) and distance to settlement (7.6%) suggest their general avoidance of low-elevation settlements unless food scarcity prompts otherwise. These variable contributions reveal how each species' unique foraging behavior, habitat requirement, and tolerance for human proximity shape conflict patterns across the KSL. In general, among variables used for predicting HWC hotspots, we found that distance from agricultural areas, distance from the forest, livestock density, and distance from human settlements are the four prominent predictor variables that contributed highly to identifying conflict hotspots for all conflict-causing animals. Similar patterns were also observed in the other studies by Rao *et al.* (2002), Bargali & Ahmad (2018) and Hussain *et al.* (2018). This is logical since wildlife's main habitat is forest, and forests near agricultural areas and human settlements make it easy for wildlife to raid crops, attack humans and kill livestock.

The analysis of hotspot mapping predicted 195 hotspot conflict villages in KSL India, 85 of which suffered conflict from all four species. Since areas like KSL have limited resources to minimize HWC, it is important to identify villages involved in conflict. Further, forest officials should monitor the identified villages, and possible mitigation measures should be introduced to minimize HWC.

During our field survey, we found that most agricultural fields are located close to forested areas, typically within 50 to 400 meters from the forest edge, where they experience significant crop loss due to wildlife. Beyond 400 meters, the risk of crop loss declines sharply. Additionally, villages near forests with

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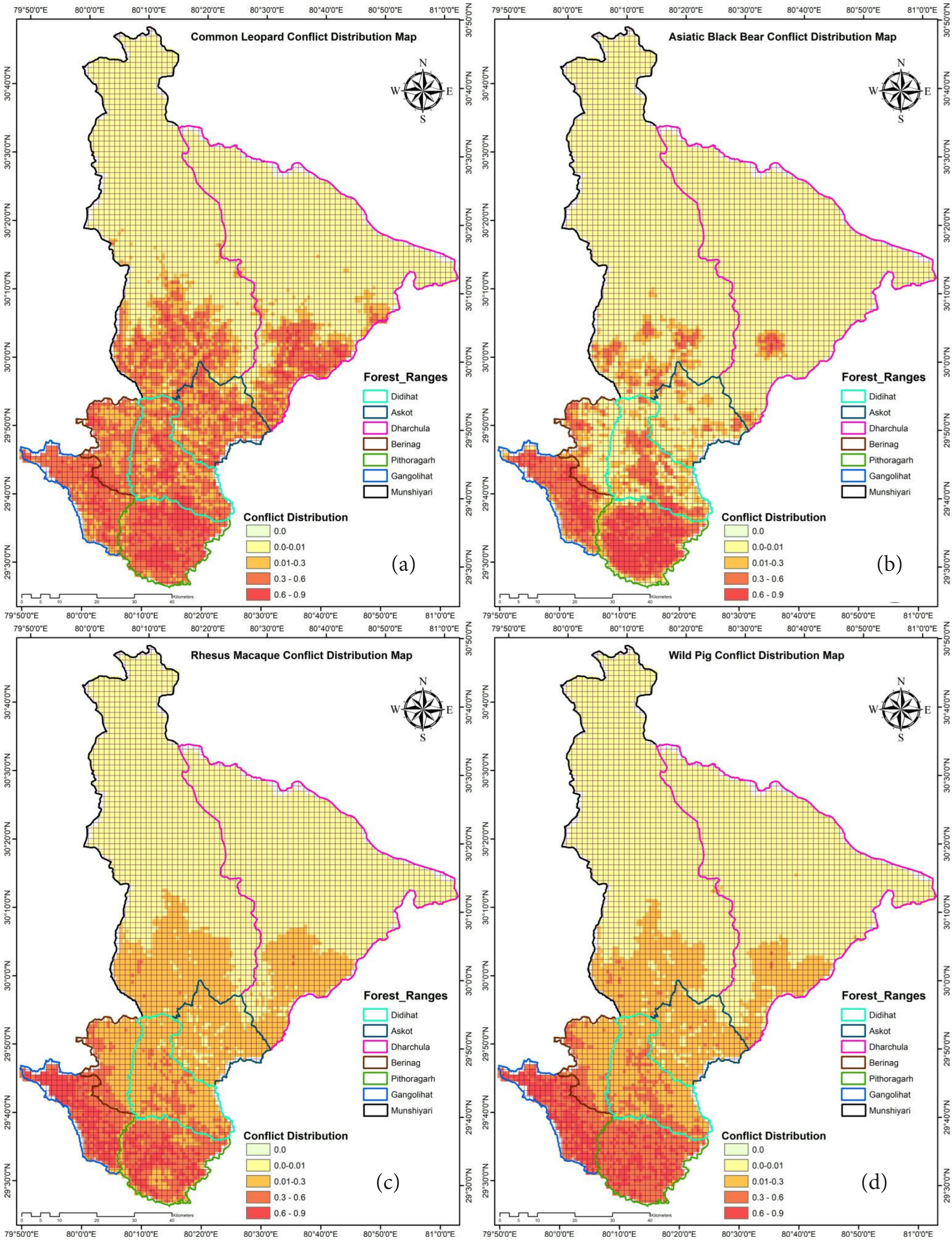

Figure 6: Human-wildlife conflict predictive risk map of a) Common leopard, b) Asiatic black bear, C) Rhesus macaque, and d) Wild pig.

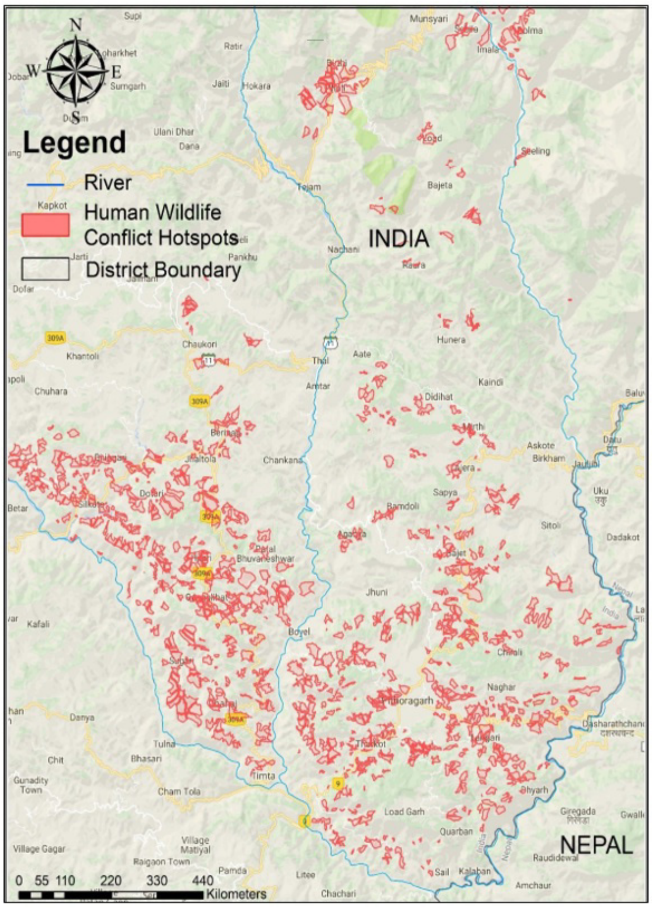

Figure 7: The location of identified 195 conflict hotspot villages in Kailash Sacred Landscape, India.

high livestock densities experience more livestock losses than those farther from forested areas. The final probability risk map identifies three forest ranges in the southern part of the landscape as high-conflict zones, two in the central part as medium-conflict zones, and one in the upper region as a low-conflict zone. This distribution aligns with the southern part's extensive agricultural areas, high livestock densities, and greater human presence compared to other forested areas in the landscape.

To mitigate HWC in the Indian KSL region, targeted interventions should focus on high-risk villages and hotspot zones, particularly in the southern forest ranges where conflict is high due to dense agricultural land, livestock, and human activity. Strengthening conservation efforts in these multi-use landscapes, which lack formal protection, is essential to safeguard vulnerable communities. Species-specific strategies, such as regulating livestock density near forests and building livestock enclosures, can address conflict behaviors of primary predators like common leopards and Asiatic black bears. Removing Eupatorium spp. patches through a community participatory approach near villages can also help prevent HWC. Educational programs discouraging feeding rhesus macaques at temples could reduce their habituation to humans, while barriers around apiaries in bear-prone areas can protect against bear incursions. Conflict-prone areas within 400 meters of forest edges would benefit from buffer zones or deterrents to reduce crop and livestock losses. Finally, an integrated policy framework is essential at the landscape level, involving collaboration across various sectors—such as forestry, agriculture, wildlife, and rural development—to enhance monitoring and allocate resources effectively in high-risk areas. This cross-sectoral approach can ensure that all stakeholders contribute to a proactive HWC management strategy. By coordinating efforts among departments and local communities, the framework can address the complex, overlapping factors that drive HWC, such as habitat encroachment, livestock density, and agricultural expansion. Such a unified strategy would also enable adaptive responses to conflict hotspots, fostering sustainable coexistence and protecting both livelihoods and biodiversity in this culturally and ecologically significant region.

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CONFLICT OF INTEREST

The authors have no competing interests to declare that are relevant to the content of this article.

DATA AVAILABILITY

Data available from the corresponding author on request.

AUTHOR CONTRIBUTIONS

Conceptualization, fundraising and editing: Ajaz Hussain, Mriganka Shekhar Sarkar, G. S. Rawat, B. S. Adhikari, and S. Sathyakumar.
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