Management of habitat, its connectivity, and human-large carnivore conflict in Western Terai Arc Landscape (TAL)

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in

Wildlife Science

by

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to

Saurashtra University, Rajkot -360005 (Gujarat)

Under the supervision of

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DECLARATION

I, Nishant Verma, declare that the thesis entitled **"Management of habitat, its connectivity, and human-large carnivore conflict in Western Terai Arc Landscape (TAL)"** has been prepared by me under the supervision of **Dr. Bivash Pandav**, Scientist – G, Wildlife Institute of India, and co-supervision of **Dr. Samrat Mondol**, Scientist – F, Wildlife Institute of India. No part of this thesis has formed the basis for the award of any degree or fellowship previously.

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CERTIFICATE

This is to certify that the thesis of **Mr. Nishant Verma** titled **"Management of habitat, its connectivity, and human-large carnivore conflict in Western Terai Arc Landscape (TAL)"** is an original piece of work submitted to the Saurashtra University, Rajkot, for the award of the **Doctor of Philosophy** in **Wildlife Science**.

Mr. Nishant Verma has put more than six terms of research work embodied in this thesis under my guidance and supervision. He has published 1 original research paper from this thesis and presented the outcomes at 2 international conferences. The work presented in this thesis has not been submitted for any degree to any other University or Institution.

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I certify that the research work was appreciated by all who were present, and the comments made by the faculty and researchers have been appropriately included in the thesis.

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DEDICATION

This thesis is dedicated to my beloved parents, my father, Shri Ravindra Singh, and my mother, Late Smt. Geeta Singh, whose recent passing away has left an immeasurable void, but whose guidance continues to inspire me. I also dedicate this work to my wife, Alpana Verma, and my children, Nitya and Anant Verma, for their constant support, patience, and love throughout my academic journey. Thank you for making me see this adventure through to the end.

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"We are not self-made. We are shaped by the people who nurtured us, guided us, and believed in us." ***— Barack Obama***

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ABSTRACT

A wildlife corridor is an area of habitat that connects wildlife populations otherwise separated by human pressures such as roads, development, or logging. Functionally, corridors allow for the exchange of individuals between populations, reducing the negative effects of inbreeding and loss of genetic diversity that often occur in isolated populations.

The western part of the Terai Arc Landscape (TAL), a region listed among the 200 globally important ecoregions for its rich assemblage of large mammals. Over time, land modification for agriculture and anthropogenic disturbances disrupted these connections. Despite this, the TAL retains immense conservation value, sustaining two Level I Tiger Conservation Units — Rajaji–Corbett and Chitwan–Parsa–Valmiki — alongside several Level II units. Recent assessments estimate that about 20,800 km² of tiger habitat remains on the Indian side of the TAL.

The study area of this doctoral research spans the western Terai Arc Landscape (TAL) and centres around Rajaji National Park (RNP), encompassing connected forest divisions in Uttarakhand and Uttar Pradesh, where it aims at (1) evaluating corridor use by wildlife in Rajaji National Park and adjoining divisions**,** (2) assessing the extent and severity of human–large carnivore conflict in the western TAL**,** and (3) evaluating existing management practices for large carnivore conservation, based on the following research questions:

1. How functional are the corridors for wildlife movement in western TAL?
2. What ecological and environmental factors predict conflict, and how can they guide mitigation strategies?
3. How effective are existing management practices in conserving large carnivores and their habitats?

Towards evaluating the activity of wildlife and for assessing corridor functionality, systematic sign surveys were carried out in 2022–2023 to identify suitable sampling sites across all corridors, prior to camera-trapping. Transects were walked to record signs such as dung, pugmarks, hoof marks, and scrapes of large mammals. Further, a total of 87 camera traps were deployed in 2022 and 2025, yielding a total of 9,670 trap nights. Sign surveys revealed that leopards and elephants were the most frequently encountered species across both eastern and western corridors. Chillawali–Shiwalik showed extensive elephant signs, confirming its role as an elephant movement pathway. Camera traps recorded 17 species in the forest areas and nine in the corridors, with the highest species richness being recorded in Chillawali-Shiwalik, followed by Chilla-Motichur and Laltappar, and Teenpani. Chillawali-Shiwalik had the highest Relative Abundance Index (RAI) for chital (269.53), followed by Teenpani for wild pig (227.2) and sambar (123.31), whereas Chilla-Motichur and Laltappar exhibited lower RAIs for most species. In contrast, adjacent forest areas exhibited higher RAIs across all species, indicating a preference for less-disturbed habitats. Species exhibited distinct activity patterns between corridors and forest areas. Leopards were uniformly active throughout the day in the forest but showed slightly reduced daytime activity in corridors ($\Delta = 0.71$). Elephants exhibited contrasting activity patterns, with a daytime activity peak in forest ranges and a nighttime peak in corridors ($\Delta = 0.48$). These results highlight both the functionality and challenges of four key wildlife corridors in RNP in maintaining connectivity for species within fragmented habitats.

Details of human-wildlife conflict incidents were collected from each of the Forest Divisions of the study area for 12 years (2012-2024). Of this, incident details of attacks on humans were available from 2018 to 2024, while livestock depredation incidents were available from 2003 to 2024. Of the collected data, large carnivore conflict incidents were compiled on the basis of the species of carnivore involved, and the incidents were categorised into attacks on humans and livestock depredation. Species-wise conflict points were extracted, and for each of the species, 5000 random points were then generated in QGIS to act as absence points in the study area. 65 incidents of attacks on humans were due to large carnivores – including tigers (n=29), leopards (n=19), and bears (n=17) (2018 to 2024), and 3,258 incidents of livestock depredation were attributed to large carnivores – including tigers (n=615) and leopards (n=2,635) (2003 to 2024). Human population densities were significantly different for locations of bear and tiger attacks on people and random points, whereas livestock population density was significantly different at locations of human-leopard conflict as compared to random locations. Similarly human population densities significantly varied between locations of livestock depredation by tigers & random non-conflict locations, while both human & livestock population densities were significantly different at locations of livestock depredation by leopards and random locations. Elevation gradient ($p<0.01$) in the study area was one of the major drivers of human conflict with bears and leopards on humans. Distance to linear infrastructure ($p<0.01$) and Human Footprint Index ($p<0.05$) majorly drive leopard attacks on people. Additionally, livestock and human population densities ($p<0.05$) influence bear and tiger

attacks on people. Tiger attacks on humans were also driven by distances to linear infrastructure & Protected Area ($p<0.01$), and nightlight ($p<0.01$). Annual precipitation, terrain ruggedness & elevation, distances to linear infrastructure & water, human population density, and Human Footprint Index ($p<0.001$) are some of the factors that drive livestock depredation by leopards & tigers. The results of this study highlight the variations in trends and drivers of conflict with each large carnivore in the study area, with severe socio-economic and ecological consequences.

The evaluation of management practices in the Western Terai Arc Landscape (TAL) was carried out using the Management Effectiveness Evaluation (MEE) framework developed by the International Union for Conservation of Nature (IUCN), that have been adapted for the Indian tiger reserves. This framework assesses management performance across six broad elements: context, planning, inputs, processes, outputs, and outcomes, and provides a structured mechanism to identify strengths and gaps in conservation practice. Data was collected from (a) working plans and Tiger Conservation Plans, (b) field records and secondary data, and (c) primary evaluation and scoring. The site-specific scores were aggregated to generate comparative rankings across divisions, and grouped under five major elements (context, planning, input, process, and output). Selected critical indicators were examined individually to highlight specific areas of weakness. Additional parameters relating to habitat degradation, encroachment, invasive species status, and habitat recovery were also scored qualitatively. Scores ranged narrowly from 66.41 (Kalsi) to 68.97 (Dehradun), with Lansdowne (68.75), Rajaji (67.19), and Shivalik (67.17) occupying intermediate positions, indicating moderate but consistent levels of management. Disaggregated analysis revealed variation across the five evaluation elements. Planning (68.52) and Inputs (68.75) received relatively higher scores, reflecting the availability of documented management plans, budget allocations, and staffing provisions (Figure 4.2). By contrast, Processes (65.17) and Outputs (62.92) scored lower, indicating weaknesses in implementation and outcome delivery. Indicator-level analysis pointed to specific areas of weakness, specifically indicators related to control of biotic pressures, stakeholder participation, and conflict mitigation consistently received low scores. These findings reveal that management effectiveness in the western TAL is functional but fragile, characterized by strong planning frameworks but weaker implementation and ecological outcomes.

The Western Terai Arc Landscape (TAL) represents one of India’s most critical conservation frontiers where ecological connectivity, large mammal persistence, and human livelihoods intersect. This thesis generates crucial understanding of the interdependence between habitat connectivity, conflict mitigation, and management effectiveness. Fragmentation of corridors intensifies edge effects and human intrusion, which in turn elevates conflict frequency, further complicating management efforts. This study provides several actionable insights for strengthening conservation outcomes in the western TAL, including landscape integration, corridor restoration, conflict mitigation, participatory management, monitoring, and policy mainstreaming.

CHAPTER 1: INTRODUCTION AND OBJECTIVES

INTRODUCTION

A wildlife corridor is an area of habitat that connects wildlife populations otherwise separated by human pressures such as roads, development, or logging. Functionally, corridors allow for the exchange of individuals between populations, reducing the negative effects of inbreeding and loss of genetic diversity that often occur in isolated populations. They also facilitate recolonisation after local extinctions caused by random events such as fires or disease, thereby buffering some of the most detrimental consequences of habitat fragmentation. When urbanisation and agricultural expansion split habitats into smaller patches, corridors become crucial to maintaining connectivity and enabling species to access essential resources for survival (Holderegger & Di Giulio, 2010; Burkart et al., 2016).

The western part of the Terai Arc Landscape (TAL), a region listed among the 200 globally important ecoregions for its rich assemblage of large mammals (Olson & Dinerstein, 1998). Historically, the TAL supported a continuous stretch of forests that harboured tigers, elephants, and their prey. Johnsingh et al. (2004) identified nine Tiger Habitat Blocks (THBs) within this landscape, which were formerly connected by 13 narrow corridors. Over time, land modification for agriculture and anthropogenic disturbances disrupted these connections. Despite this, the TAL retains immense conservation value, sustaining two Level I Tiger Conservation Units — Rajaji–Corbett and Chitwan–Parsa–Valmiki — alongside several Level II units (Wikramanayake et al., 1998). Recent assessments estimate that about 20,800 km^2 of tiger habitat remains on the Indian side of the TAL (Qureshi et al., 2006).

The western and eastern portions of the TAL between the Yamuna and the Kho rivers are characterised by the bhabar tract, which maintains approximately 36% forest cover (Johnsingh et al., 2004). Rajaji and Corbett Tiger Reserves are the main Protected Areas in this region. The Shivalik foothills host a mix of floral elements from both peninsular India and the temperate Himalayas. Moist deciduous forests dominated by sal (*Shorea robusta*) typify the bhabar tract, while the terai plains support woodland–grassland–wetland mosaics dominated by species such as *Saccharum narenga*, *Sclerostachya*, *Imperata*, and *Typha* sp. (Mathur, 2000).

The faunal diversity of this landscape is high. It supports ungulates, including chital (*Axis axis*), sambar (*Rusa unicolor*), barking deer (*Muntiacus muntjak*), nilgai (*Boselaphus tragocamelus*), goral (*Naemorhedus goral*), serow (*Capricornis thar*), and wild pig (*Sus scrofa*). Megaherbivores such as the Asian elephant (*Elephas maximus*) occur here alongside large carnivores like the leopard (*Panthera pardus*), tiger (*Panthera tigris*), hyena (*Hyaena hyaena*), Asiatic black bear (*Ursus thibetanus*), and sloth bear (*Melursus ursinus*). Avifaunal diversity is equally remarkable, with more than 549 species reported from Corbett and 312 species from Rajaji National Park (Pandey et al., 1994).

Given the pace of infrastructure development, land-use change, and increasing human population pressure, the western TAL faces acute challenges of habitat fragmentation and conflict. Yet it remains a critical link for sustaining tiger and elephant populations in northwestern India. Assessing corridor functionality, identifying conflict hotspots, and evaluating management practices are therefore essential to guide conservation interventions and ensure long-term ecological connectivity in this landscape.

LITERATURE REVIEW

Vegetation and Habitat Studies in Terai Arc Landscape (TAL)

Vegetation studies in the TAL have historically concentrated on grasses and grasslands (Singh, 1982; Chaturvedi & Mishra, 1985; Rodgers et al., 1990; Rawat et al., 1997) and woody vegetation (Joshi et al., 1986; Singh et al., 1995; Agni et al., 2000). Pant and Chavan (2000) used satellite data to map vegetation types and land-use patterns in Corbett National Park, highlighting the heterogeneity of habitats in the region. Grasslands in particular are of ecological significance, providing forage for ungulates and shaping predator–prey dynamics. The bhabar and terai tracts differ in vegetation structure, influencing the distribution and abundance of large herbivores and carnivores (Mathur, 2000). These foundational vegetation studies set the stage for subsequent work on wildlife–habitat relationships.

Avifauna and Ungulate Research in TAL

Despite the high avifaunal diversity of the TAL, detailed ornithological studies remain limited. Research has focused on a few threatened species such as the Bengal florican, *Hubaropsis bengalensis* (Rahmani et al., 1989), swamp francolin, *Francolinus gularis* (Javed et al., 1999), and raptors (Naoroji, 1997a, 1997b, 1999). Pandey et al. (1994)

compiled a comprehensive bird list for Rajaji National Park, documenting 312 species, while Sharma et al. (unpublished) reported over 549 species in Corbett Tiger Reserve.

Ungulate research has similarly been patchy, despite their role as primary prey for large carnivores. Studies have documented goral (*Naemorhedus goral*) group sizes and behaviour (Pendharkar & Goyal, 1995; Johnsingh, 2001), brief assessments of hog deer (*Axis porcinus*) (Tak & Lamba, 1981), and chital (*Axis axis*) in Corbett and Rajaji (De & Spillet, 1966; Bhat & Rawat, 1995, 1999). Swamp deer (*Cervus duvauceli duvauceli*) studies have primarily focused on conservation status (Holloway, 1973; Schaaf & Singh, 1976; Singh, 1978; Sankaran, 1990). Historical records indicate a wider distribution of rhinos (*Rhinoceros unicornis*), with sightings near Kotdwara in the late 18th century (Rookmaaker, 1999), while reintroduction efforts in Dudhwa National Park have been highlighted by Sale (1986), Sale & Singh (1987), and Mishra (1989).

Elephant Ecology and Corridors

Elephants (*Elephas maximus*) have received the most sustained research attention in the TAL. Singh (1969a, 1978, 1989) provided early assessments of their status in Uttar Pradesh. Subsequent studies underscored the importance of corridors for elephant movement, particularly the Chilla–Motichur and Rajaji–Corbett linkages (Johnsingh et al., 1990, 2002; Johnsingh & Joshua, 1994). Joshua & Johnsingh (1995) documented elephant-ranging patterns, emphasizing the need for corridor protection in reserve design. Sunderraj et al. (1995) evaluated elephant use of the Rajaji–Corbett corridor, while Javed (1996) reported on elephants in Dudhwa. More recently, Williams et al. (2001) quantified human–elephant conflict in Rajaji, underscoring the challenges of coexistence in multi-use landscapes.

Tigers and Other Large Carnivores

Early tiger research in the region (Singh, 1969b) focused on distribution and status. Harihar et al. (2009) later demonstrated that the removal of anthropogenic pressures led to positive responses from both tigers and their prey in Rajaji National Park. More recent work indicates rising populations of tigers (~800 individuals) and leopards (~1000 individuals) across the TAL (Qureshi et al., 2023, 2024). Tigers remain largely confined to forested areas, whereas leopards occur widely, including outside Protected Areas (Malviya & Ramesh, 2015). Competition between the two felids often results in the displacement of leopards, although they coexist in complex terrain such as the Shivalik. The leopard diet includes both wild prey and livestock, with a broader dietary niche than tigers (Ranjan et al., 2024). This adaptability increases interactions with people, reinforcing perceptions of leopards as more intrusive (Chauhan et al., 2001; Naha et al., 2018; Yadav et al., 2020).

Bear species also occur in the TAL, with Asiatic black bears (*Ursus thibetanus*) overlapping with sloth bears (*Melursus ursinus*) in Uttarakhand (Bargali, 2012; Pigeon et al., 2019). While bears do not generally prey on livestock, they are prone to aggressive defensive encounters with humans, leading to conflict (Rajpurohit & Krausman, 2000; Pokharel et al., 2022). Community tolerance for bears is typically low due to frequent human attacks (Can et al., 2014; Lamb et al., 2020).

Corridor Functionality and Infrastructure Impacts

Habitat loss and fragmentation are widely recognised as key drivers of biodiversity decline (Haddad et al., 2015). Roads, railways, agriculture, and urbanisation disrupt wildlife movement, impede ecological processes, and increase the likelihood of human–wildlife conflict (Laurance et al., 2014; van der Ree et al., 2015). Within this context, the TAL represents both a conservation stronghold and a hotspot of challenges, making it a focal region for research on connectivity, conflict, and management.

Corridors are essential for maintaining gene flow and population viability in fragmented landscapes (Holderegger & Di Giulio, 2010). They provide safe passage between habitat patches and mitigate the effects of habitat loss (Burkart et al., 2016). In the TAL, critical corridors include Kansrao–Barkot, Barkot–Motichur, Chilla–Motichur, and Chillawali–Shiwalik, which connect Rajaji with adjoining divisions (Johnsingh et al., 2004). The Chilla–Motichur corridor, a 3 km by 1 km stretch across the Ganges, is the sole functional link between the eastern and western parts of Rajaji. However, roads and railways create severe barriers to animal movement, particularly for elephants (Carvalho et al., 2017; Gilhooly et al., 2019). Recent mitigation efforts include the construction of underpasses at Chilla–Motichur, Teenpani, and Laltappar in 2021 to restore connectivity (Nigam et al., 2022). The Chillawali–Shiwalik corridor further extends connectivity westward to Kalesar Wildlife Sanctuary in Haryana.

Human–Wildlife Conflict in TAL

Large carnivores require extensive areas to survive (Thapa et al., 2015). Although capable of living in multi-use landscapes (Thapa et al., 2021), their proximity to human settlements leads to competition and conflict. In TAL, retaliatory killings of carnivores and negative attitudes toward conservation are common outcomes of livestock depredation and human attacks (Naha et al., 2020). Conflict is widespread across Uttarakhand, where tigers, leopards, and bears coexist with dense human populations (Chanchani et al., 2014). Leopards account for nearly 30% of all human deaths and injuries in the past five years (Qureshi et al., 2024; Uttarakhand Forest Department, 2024). Livestock depredation by both tigers and leopards is also frequent, particularly in fragmented patches outside Protected Areas (Malviya & Ramesh, 2015; Ahmed & Bargali, 2018). Increases in tiger numbers have coincided with declines in leopard abundance in some regions, highlighting interspecific competition (Qureshi et al., 2024).

Bears, though less frequently involved in depredation, are prone to aggressive defensive behaviour when startled, resulting in human injuries (Bargali, 2012; Pokharel et al., 2022). With growing anthropogenic pressures on forest habitats (Dobhal et al., 2011; Badola et al., 2021), incidents of conflict are projected to rise. Despite multiple studies on conflict drivers, there remains a gap in comprehensive analyses across all large carnivore species in Uttarakhand (Malviya & Ramesh, 2015; Naha et al., 2020). This gap underscores the need for integrated approaches to understanding conflict dynamics.

Management Practices and Effectiveness

Globally, frameworks such as the IUCN Management Effectiveness Evaluation (MEE) and the World Commission on Protected Areas (WCPA) emphasise adaptive management, stakeholder engagement, and monitoring (Chen et al., 2022; Hoffmann, 2021). In India, landscape-scale planning has been highlighted as crucial for large carnivore conservation (Kumar et al., 2020; Reddy et al., 2017; Rodrigues & Cazalis, 2020). Research has shown that Protected Areas are particularly effective for tigers and leopards, while buffer zones play a role in supporting herbivores and less threatened species (Somaraj, 2025). Persistent challenges in the TAL include invasive species such as Lantana camara, forest fires, and human–wildlife conflict (Srivathsa et al., 2023; Das, 2024).

In Rajaji, management interventions include resettlement of pastoralist communities, fire management, and restoration of key corridors (Geldmann et al., 2019; Karanth & Nepal, 2012). Such measures have improved prey availability and facilitated tiger recovery, though threats from fragmentation and encroachment persist (Kumar et al., 2020; Shah et al., 2021). The NTCA's MEE framework provides structured evaluations of tiger reserve management, identifying strengths in core protection but weaknesses in corridor management and community engagement (Shah et al., 2021; Das, 2024). While the MEE has prompted adaptive recommendations, implementation remains inconsistent.

The body of literature on the TAL highlights significant progress in documenting vegetation, ungulate populations, elephant ecology, and tiger recovery. Long-term studies have underscored the importance of corridors such as Chilla–Motichur for maintaining connectivity. At the same time, emerging challenges from infrastructure development and escalating human–wildlife conflict reveal the complexity of conserving this landscape. Key research gaps include comprehensive studies on bear conflict, integrated multi-species conflict analyses, and the translation of management recommendations into sustained practice. Addressing these gaps is essential for guiding conservation strategies in the western TAL, ensuring the persistence of its large mammal populations, and maintaining ecological connectivity in the Himalayan foothills.

STUDY AREA

The study area of this doctoral research spans the western Terai Arc Landscape (TAL) and centres around Rajaji National Park (RNP), encompassing connected forest divisions in Uttarakhand and Uttar Pradesh (Figure 1.1). Geographically, it encompasses Rajaji National Park and Tiger Reserve, as well as the SC Kalsi, Dehradun, Haridwar, Lansdowne, and Shivalik Forest Divisions, collectively covering approximately 5,660 km² (Rajaji NP-820 km², SC Kalsi- 427.19 km², Dehradun- 849.5 km², Haridwar- 1960.69 km², Lansdowne- 1270.66 km², Shivalik- 332 km²). Together with the National Park, this forms a substantial forested block of the western TAL. While all other ranges fall under the Uttarakhand state, the Shivalik Forest Division is administratively under Uttar Pradesh. All the divisions are ecologically and functionally connected to Rajaji National Park.

Topographically, the area is divided into two ecological zones. The bhabar, forming the Shivalik foothills, is characterised by dissected ridges and coarse alluvial deposits. It supports largely sal-dominated deciduous forests interspersed with scrubland and rocky outcrops. Elevations range between 300 and 1,400 m. The terai, forming the low-lying alluvial plains, supports a mosaic of tall grasslands, wetlands, and sal forests. The faunal richness of this area underscores its conservation significance. Rajaji and its adjoining divisions form the northwestern limit of tiger and Asian elephant distribution in India. The western TAL block, which includes RNP and surrounding forests, is estimated at nearly 1,800 km², and is a critical but vulnerable segment of the larger TAL connectivity network

(Harihar et al., 2009). These characteristics make the study area both ecologically rich and essential for maintaining connectivity between larger habitat patches in the Himalayan foothills. Once home to species like the one-horned rhinoceros (*Rhinoceros unicornis*) and wild dog (*Cuon alpinus*), the area now faces high rates of habitat loss, fragmentation, and human–wildlife conflict.

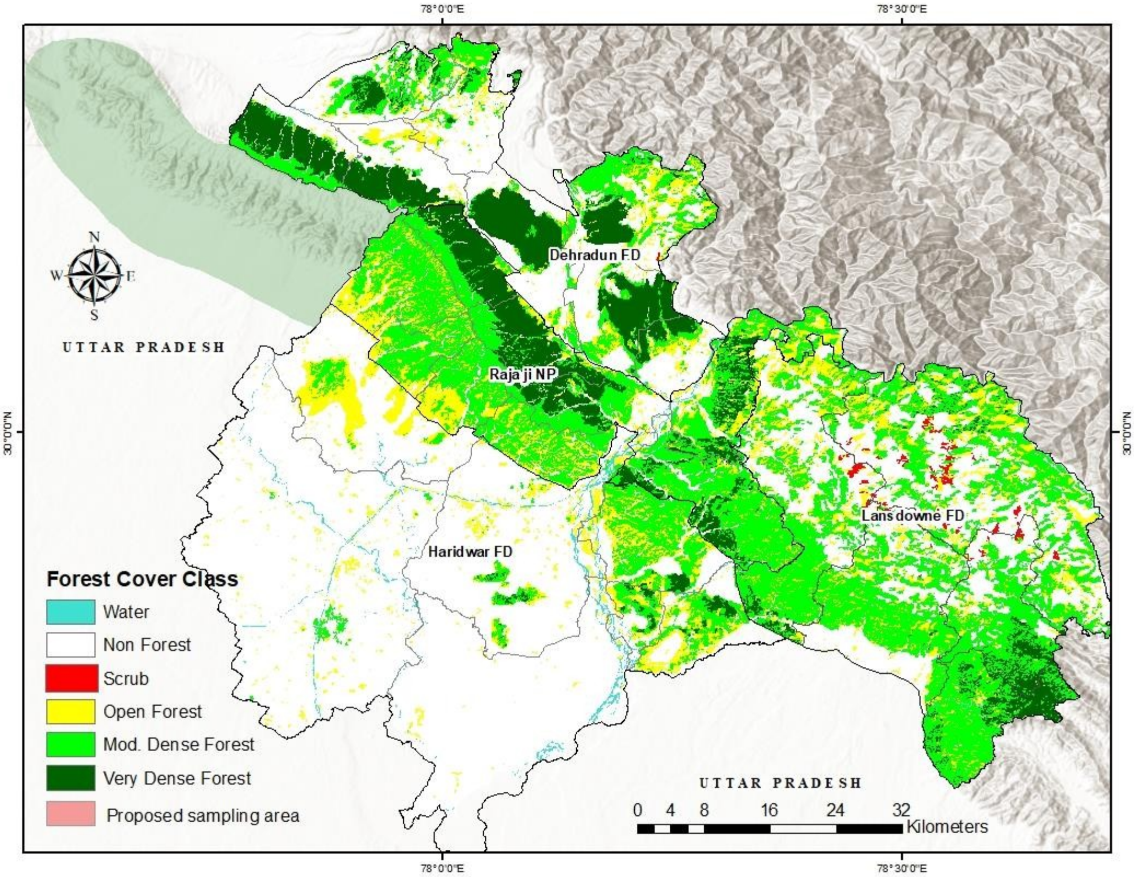

Figure 1.1. The study area includes Rajaji National Park, Dehradun, Haridwar, Lansdowne, and SC Kalsi Forest Divisions of Uttarakhand and Shivalik Forest Division of Uttar Pradesh, connected to Rajaji National Park.

OBJECTIVES

This research focuses on three interlinked objectives:

Objective 1: Evaluating corridor use by wildlife in Rajaji National Park and adjoining divisions.

Assess critical corridors such as Kansrao–Barkot, Barkot–Motichur, Chilla–Motichur, and Chillawali–Shivalik.

Use sign surveys and camera trapping to document species presence and activity.

Compare corridor activity patterns with those in nearby forests and examine overlap with human activity.

Objective 2: Assessing the extent and severity of human–large carnivore conflict in the western TAL.

Compile conflict records (human casualties, livestock depredation, crop loss) from compensation data with the forest department.

Identify conflict hotspots and predictors using statistical analyses.

Develop species- and site-specific recommendations for conflict mitigation and community engagement.

Objective 3: Evaluating existing management practices for large carnivore conservation.

Review the management and working plans of Rajaji Tiger Reserve and adjoining divisions.

Assess habitat restoration, invasive species removal, fire management, and species-specific subplans.

Identify gaps and recommend strategies using NTCA's Management Effectiveness Evaluation Protocol.

Research Questions

1. How functional are the corridors for wildlife movement in western TAL?
2. What ecological and environmental factors predict conflict, and how can they guide mitigation strategies?
3. How effective are existing management practices in conserving large carnivores and their habitats?

ORGANISATION OF THE THESIS

This thesis is organised into four chapters:

Chapter 1: Introduction and objectives.

Chapter 2: Evaluating wildlife activity and corridor functionality: A study of underpasses in and around Rajaji National Park, India.

Chapter 3: Extent and severity of human–large carnivore conflict in the western Terai Arc Landscape, with recommendations for mitigation.

Chapter 4: Evaluation of existing management practices for large mammal conservation in Rajaji National Park and the surrounding landscape.

Chapter 5. Synthesis and conclusion.

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CHAPTER 2: EVALUATING WILDLIFE ACTIVITY AND CORRIDOR FUNCTIONALITY: A STUDY OF UNDERPASSES IN AND AROUND RAJAJI NATIONAL PARK, INDIA

INTRODUCTION

The rapid expansion of human activities has led to significant changes in natural landscapes. Habitat loss and fragmentation are among the main drivers of biodiversity decline (Haddad et al., 2015). Conversion of natural areas for human activities such as agriculture, horticulture, infrastructure development, and urban expansion causes anthropogenic habitat loss. Roads, railways, and urban expansion fragment once-continuous landscapes, impeding wildlife movement, disrupting ecological processes, and increasing the risk of local extinctions (Laurance et al., 2014; van der Ree et al., 2015). These processes reduce habitat connectivity, which is essential for the movement, dispersal, and genetic exchange of wildlife populations (Callens et al., 2011; Napolitano et al., 2015). Such disruptions can have profound consequences, including population decline and loss of ecosystem functionality. Therefore, connecting natural habitats through ecological corridors is crucial for maintaining gene flow and population viability in the wild (Holderegger & Di Giulio, 2010).

Wildlife corridors, typically composed of native vegetation, link larger habitat patches and enable the safe movement of animals across fragmented landscapes (Burkart et al., 2016). By mitigating the effects of habitat loss and fragmentation, these corridors help sustain healthy animal populations and preserve biodiversity. In human-dominated landscapes, corridors are particularly important as they allow animals to navigate altered environments, reduce the risk of population isolation, and help maintain biodiversity.

The Terai Arc Landscape (TAL), spanning the Himalayan foothills in India and Nepal, is among the world's 200 globally significant ecoregions (Olson & Dinerstein, 1998). The TAL supports large mammals such as the Royal Bengal Tiger (*Panthera tigris*) and the Asiatic Elephant (*Elephas maximus*), which require extensive connected habitats for their survival (Jhala et al., 2015). However, the TAL is also a heavily human-impacted landscape, facing significant challenges from expanding settlements, agriculture, and transportation infrastructure (Harihar & Pandav, 2012). Corridors within this landscape are vital for maintaining connectivity between protected areas, but many face degradation from anthropogenic pressures.

Rajaji National Park (RNP), covering 820 km² within the western TAL, is a crucial protected area for tigers, elephants, and other large mammals. This park is bifurcated into eastern and western sections by the Ganges River (Johnsingh et al., 2004). Additionally, highways and railway lines connecting Haridwar and Dehradun, two of Uttarakhand's most populated cities, create significant movement barriers for wildlife between protected areas and surrounding patches of reserve forests. Particularly, the connectivity between the Barkot range of the territorial forest and the Kansrao range of RNP is critical for elephant movement in this landscape (Johnsingh et al., 2004). Historically, the erstwhile Chilla-Motichur corridor played a crucial role in facilitating wildlife movement across both banks of the Ganges. This 3 km long and 1 km wide stretch of forest land, which connects the Chilla Forest range on the eastern part of the Ganga to the Motichur range on the west bank, is the only functional link between the eastern and western parts of RNP. While roads, railways, irrigation channels, etc., hinder wildlife movement, roads pose the greatest barrier due to a continuous traffic flow. To address these challenges, three wildlife underpasses—Chilla-Motichur, Teenpani, and Laltappar—were constructed on the highway to provide connectivity between forested habitats within and around the park in 2021 (Nigam et al., 2022).

In addition to these eastern corridors, another important linkage exists on the western edge of RNP: the Chillawali–Shiwalik corridor, approximately 15 km long, which connects RNP to the Shiwalik Forest Division of Uttar Pradesh, and further west to the Kalesar Wildlife Sanctuary in Haryana. This corridor forms the westernmost connection of RNP with adjoining landscapes and is of high strategic value for large mammal movement, particularly elephants and tigers.

In this chapter, I evaluated the current functionality of these four corridors – Chilla–Motichur, Teenpani, Laltappar, and Chillawali–Shiwalik – in facilitating wildlife movement. Using sign surveys and camera-trap data, I compared the activity patterns of key species — Leopard (*Panthera pardus*), Asiatic Elephant, Spotted Deer or Chital (*Axis axis*), Sambar (*Rusa unicolor*), and Wild Pig (*Sus scrofa*)—within the corridors and nearby forest ranges. I also examined how human activities influence wildlife behaviour and corridor usage. By assessing corridor effectiveness, this chapter provides data-driven insights for enhancing connectivity and informing conservation planning in RNP and the broader TAL.

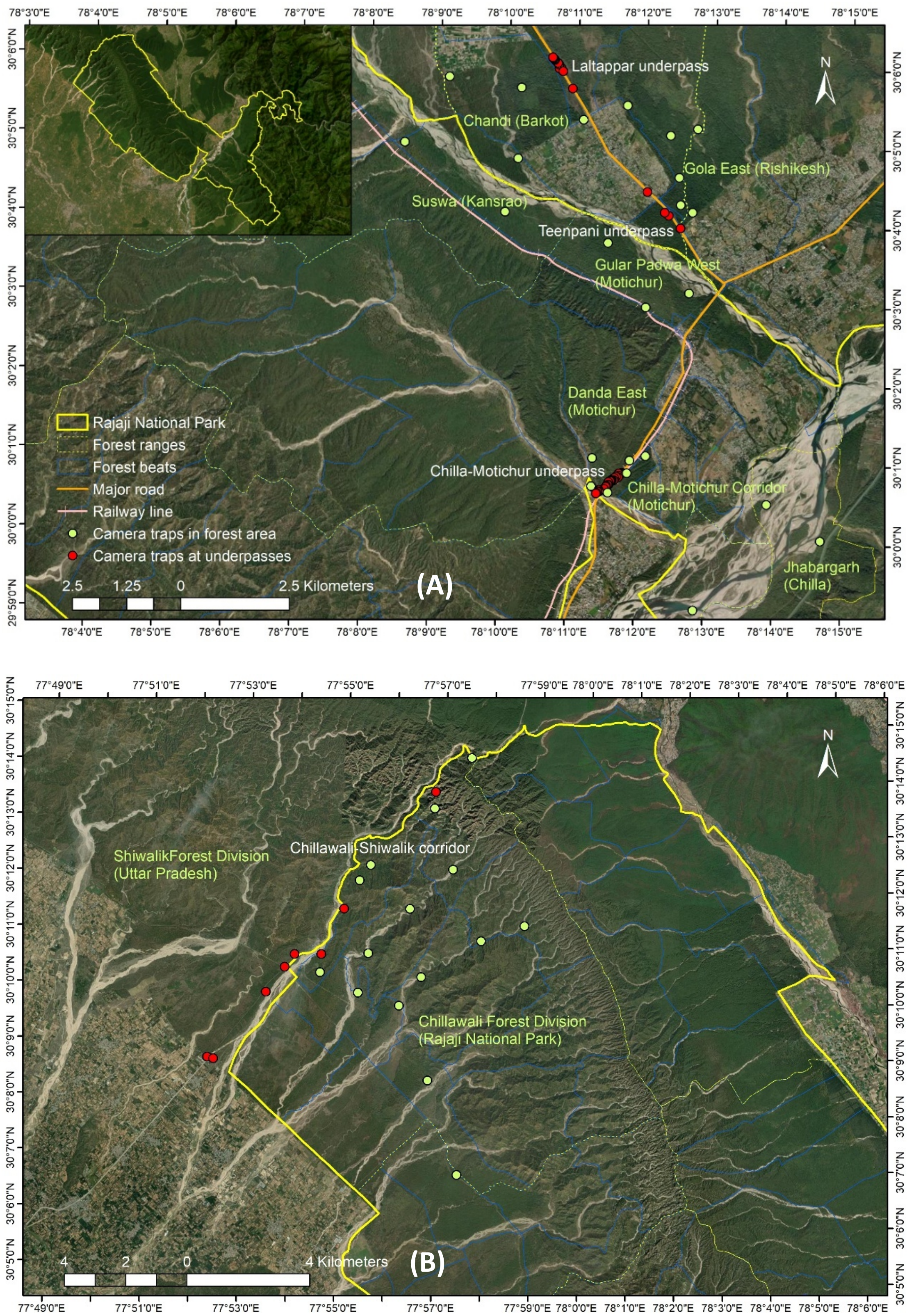


Figure 2.1. Location of the four corridors – (A) Laltappar, Teenpani, and Chilla-Motichur – in the east, and (B) Chillawali-Shiwalik – in the west at the boundary of the western Rajaji National Park. All corridors are traversed by road, and wildlife underpasses are built on all three roads. Sampled forest beats are mentioned in green text.

STUDY AREA

The study was conducted in the western part of Rajaji National Park (RNP), situated in Uttarakhand, India (29°15' to 30°31' North Latitude, 77°52' to 78°22' East Longitude), within the Terai Arc Landscape (TAL). The study focused on four wildlife corridors – Chilla-Motichur, Teenpani, Laltappar, and Chillawali-Shiwalik – which have been established to connect fragmented forest patches of the Chilla, Motichur and Kansrao ranges of RNP with Barkot and Rishikesh ranges of the Dehradun Forest Division on the eastern side, and Chillawali range of RNP Shiwalik in Uttar Pradesh (Figure 2.1). These corridors are intersected by major highways and railways, with underpasses designed to mitigate barriers to wildlife movement. The Chilla-Motichur underpass is 900 meters long, while the Teenpani and Laltappar underpasses are each approximately 500 meters in length. These underpasses provide critical connectivity between forested habitats in the park and adjacent territorial forests (Nigam et al., 2022). Chillawali-Shiwali is ~15 km forested corridor forming the westernmost linkage of RNP, and recently an overpass of 12 km is constructed on the Delhi Dehradun highway to enhance forest connectivity.

The vegetation of RNP is primarily tropical moist and dry deciduous forest (Champion & Seth, 1968), dominated by Sal (*Shorea robusta*). Riverine forests and scrublands are also present. The region supports diverse wildlife, including flagship species such as the Tiger, Asiatic Elephant, and Leopard. It also harbours a rich diversity of avifauna and herpetofauna.

METHODOLOGY

Sign Surveys

Prior to camera-trapping, systematic sign surveys were carried out in 2022–2023 to identify suitable sampling sites across all corridors (Table 2.1). Transects were walked to record signs such as dung, pugmarks, hoof marks, and scrapes of large mammals.

Camera-Trapping

Camera traps were deployed between April and November 2022 across the three eastern corridors, and between January and March 2025 in Chillawali–Shiwalik (Table 2.2). A total of 87 motion-triggered digital cameras (Cuddeback Model C1) were installed, yielding a total of 9,670 trap nights. Cameras were single-sided and mounted approximately 30–40 cm above ground level. The Chilla-Motichur corridor was monitored by 24 cameras, whereas the Teenpani, Laltappar, and Chillawali-Shiwalik corridors each had 8 cameras. Six adjacent forest ranges of RNP and the Dehradun Forest Division were sampled to understand the presence of wildlife. Three camera traps were deployed in each of the beats, except six cameras in the Chandi beat of Barkot range and 15 cameras in Chillawali range, as these were relatively larger (Figure 2.1, Table 2.2). Camera traps were strategically placed along trails, riverbanks, and other linear features to maximise the detection of medium- and large-sized mammals, which commonly use these pathways (Jhala et al. 2015). All the camera traps were active 24 hrs and monitored every fortnight to check the battery status and retrieve the data.

Table 2.1. Sign surveys were conducted in and around the corridors on the boundary of the western Rajaji National Park (RTR) during 2022-2023 prior to conducting camera trapping.

Site	**Start Date**	**End Date**	**Total Km Surveyed**
Three corridors surveyed in the eastern part of the western RTR			
Lal Tappar	21-01-2022	24-01-2022	20.82
Teen Pani	21-01-2022	27-01-2022	34.61
Chilla-Motichur	21-01-2022	27-01-2022	73.66
Ranges surveyed around the Chillawali-Shiwalik corridor in the western part of the western RTR			
Chillawali	04-03-2023	27-03-2023	67.56
Mohand	02-03-2023	04-03-2023	45.50
Badkala	02-03-2023	04-03-2023	105.00

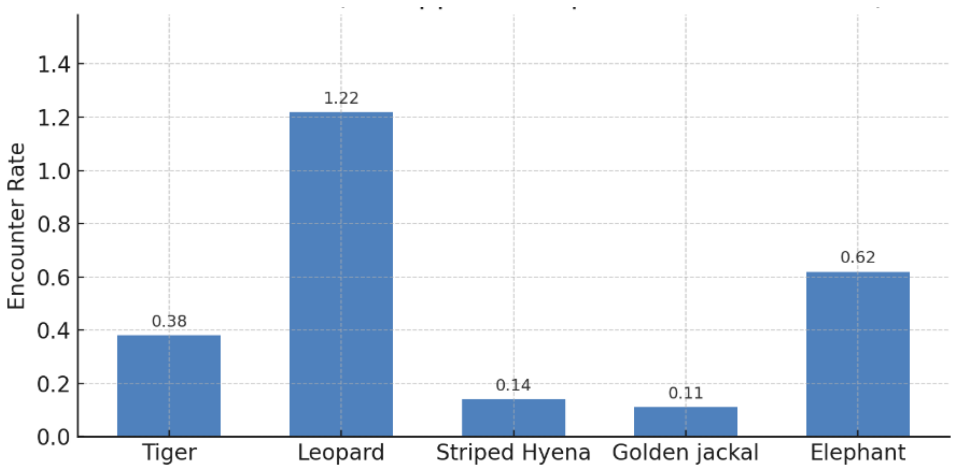
Table 2.2. Details of the survey effort during camera trapping at the corridors and adjacent forest ranges in and around the western Rajaji National Park.

Sites	**Start Date**	**End Date**	**Total Cameras**	**Total Trap Nights**	**Sampling coverage**
Corridors					**Length (meter)**
Laltappar	12-04-2022	05-11-2022	8	1656	500
Teenpani	10-06-2022	05-11-2022	8	1184	500
Chilla-Motichur	25-04-2022	26-11-2022	24	4485	900
Chillawali-Shiwalik	15-01-2025	20-03-2025	8	512	~15000

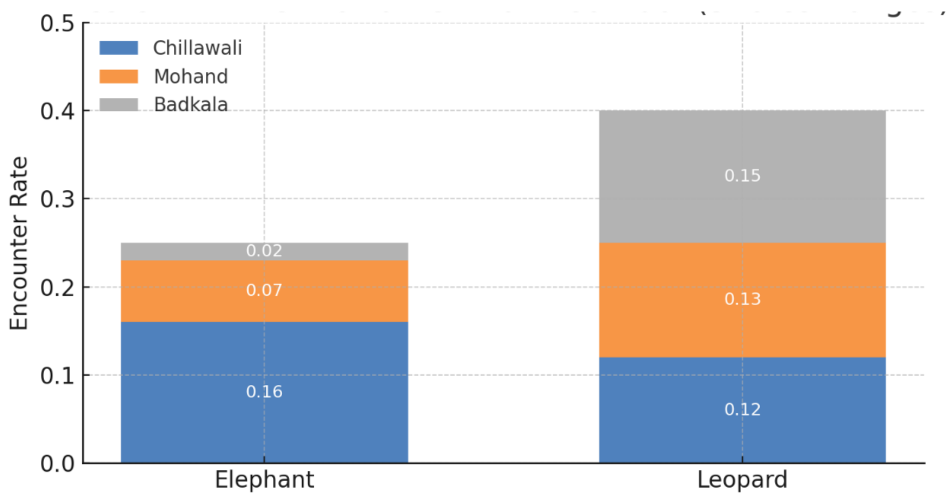
Sites	Start Date	End Date	Total Cameras	Total Trap Nights	Sampling coverage
Forest beats (ranges)					**Area (Sq. Km.)**
Chandi (Barkot)	04-03-2022	21-04-2022	6	288	14.83
Jhabargarh (Chilla)	13-03-2022	16-04-2022	3	102	11.60
Suswa (Kansrow)	19-03-2022	04-05-2022	3	138	6.14
Gola East (Rishikesh)	13-03-2022	22-04-2022	3	120	10.57
Chilla-Motichur Corridor (Motichur)	01-04-2022	18-04-2022	3	54	2.20
Danda East (Motichur)	16-03-2022	19-04-2022	3	102	6.12
Gular Parwa West (Motichur)	16-03-2022	08-04-2022	3	69	6.40
Chillawali Range	15-01-2025	20-03-2025	15	960	50.47

Data Analyses

Species identification was conducted manually for each photograph by a single observer and verified by a second observer. The date and time of each photograph were recorded from the image metadata, maintaining a time interval of 1 minute for independent capture events. Wildlife presence in the connected forest areas and corridor underpasses was quantified using the Relative Abundance Index (RAI), defined as the number of independent detections per 1,000 trap nights (O'Brien, 2011). Comparative analyses of species activity patterns in forests and corridors, as well as their temporal overlap with humans, were conducted using the camtrapR package (version 2.3.0; Niedballa et al., 2016) in R (version 4.4.0; R Core Team, 2024). Temporal overlap was estimated by the overlap coefficient Δ, which ranges from 0 (no overlap) to 1 (complete overlap) and is calculated using kernel density functions fitted to the time data of capture incidents of two species (Ridout & Linkie, 2009).



(A)



(B)

Figure 2.2. Sign encounter rate for major species close to A) Laltappar, Teenpani, and Chilla-Motichur, and D) Chillawali-Shiwalik corridors in the western Rajaji National Park.

RESULTS

Sign surveys revealed that leopards and elephants were the most frequently encountered species across both eastern and western corridors (Figure 2.2). Chillawali–Shiwalik showed extensive elephant signs, confirming its role as an elephant movement pathway. Over 9,670 trap nights, camera traps recorded 17 species in the forest areas and nine in the corridors (Figure 2.3, Tables 2.3 & 2.4). Among the corridors, Chillawali-Shiwali recorded the highest species richness (8 species), followed by Chilla-Motichur and Laltappar (7 species each), while Teenpani recorded 6 species (Table 2.3). Chillawali-Shiwalik had the highest Relative Abundance Index (RAI) for chital (269.53), followed by Teenpani for wild pig (227.2) and sambar (123.31), whereas Chilla-Motichur and Laltappar exhibited lower RAIs for most species (Tables 2.3 & 2.4). In contrast, adjacent forest areas exhibited higher RAIs across all species, indicating a preference for less-disturbed habitats (Wilcoxon test: V= 0, p<0.001).

Figure 2.3. Some of the wildlife species captured by camera traps at the corridors- Top left to right: Asiatic elephant, Sambar, Spotted Deer or Chital, and Barking Deer; Bottom left to right: Leopard, Striped Hyena, and Wild Pig.

Table 2.3. Relative Abundance index (per 1000 trap nights) of the wildlife species, livestock and humans captured at three corridors and adjacent forest areas in and around the eastern part of the western Rajaji National Park.

Species	**Laltappar**	**Teenpani**	**Chilla-Motichur**	**Forest area**
Barking Deer (*Muntiacus muntjak*)	0.6	-	0.22	12.9
Chital (*Axis axis*)	50.12	-	8.03	1363.44
Sambar (*Rusa unicolor*)	99.64	123.31	7.8	993.55
Nilgai (*Boselaphus tragocamelus*)	-	-	-	15.05

Species	**Laltappar**	**Teenpani**	**Chilla-Motichur**	**Forest area**
Asiatic Elephant (*Elephas maximus*)	19.93	2.53	0.89	172.04
Wild pig (*Sus scrofa*)	13.89	227.2	22.07	223.66
Rhesus Macaque (*Macaca mulatta*)	1.81	-	1.34	43.01
Langur (*Semnopithecus entellus*)	-	0.84	-	25.81
Indian Hare (*Lepus nigricollis*)	-	-	-	49.46
Indian Crested Porcupine (*Hystrix indica*)	-	3.38	-	49.46
Indian Peafowl (*Pavo cristatus*)	-	-	-	329.03
Indian Pangolin (*Manis crassicaudata*)	-	-	-	4.3
Leopard (*Panthera pardus*)	12.08	15.2	4.01	215.05
Tiger (*Panthera tigris*)	-	-	-	4.3
Striped Hyena (*Hyaena hyaena*)	-	-	-	21.51
Golden Jackal (*Canis aureus*)	-	-	-	4.3
Small Indian Civet (*Viverricula indica*)	-	-	-	17.2
Livestock	397.34	333.61	108.58	531.18
Human	752.42	26094.59	2360.98	206.45

Table 2.4. Relative Abundance index (per 1000 trap nights) of the wildlife species, livestock, and humans captured at Chillawali-Shiwalik corridor and adjacent forest areas around it in the western part of the western Rajaji National Park.

Species	**Chillawali-Shivalik Corridor**	**Chillawali Forest area**
Barking Deer (*Muntiacus muntjak*)	-	3.91
Chital (*Axis axis*)	269.53	273.44
Sambar (*Rusa unicolor*)	82.03	347.66
Nilgai (*Boselaphus tragocamelus*)	13.67	7.81
Asiatic Elephant (*Elephas maximus*)	3.91	21.48

Species	Chillawali-Shivalik Corridor	Chillawali Forest area
Wild pig (*Sus scrofa*)	21.48	52.73
Indian Hare (*Lepus nigricollis*)	3.91	-
Indian Crested Porcupine (*Hystrix indica*)	19.53	21.48
Indian Peafowl (*Pavo cristatus*)	15.63	1.95
Indian Pangolin (*Manis crassicaudata*)	-	1.95
Leopard (*Panthera pardus*)	3.91	13.67
Tiger (*Panthera tigris*)	-	1.95
Small Indian Civet (*Viverricula indica*)	1.95	-

Species exhibited distinct activity patterns between corridors and forest areas (Figure 2.4). Chital, the only diurnal species, exhibited activity throughout 24 hours in corridors, whereas it displayed a distinct early-morning peak inside the forest ($\Delta = 0.68$). Leopards were uniformly active throughout the day in the forest but showed slightly reduced daytime activity in corridors ($\Delta = 0.71$). Elephants exhibited contrasting activity patterns, with a daytime activity peak in forest ranges and a nighttime peak in corridors ($\Delta = 0.48$). Sambar displayed an early-morning activity peak in corridors, avoiding the daytime, while in the forest, it maintained activity throughout the day with increased movement during morning and evening hours ($\Delta = 0.55$).

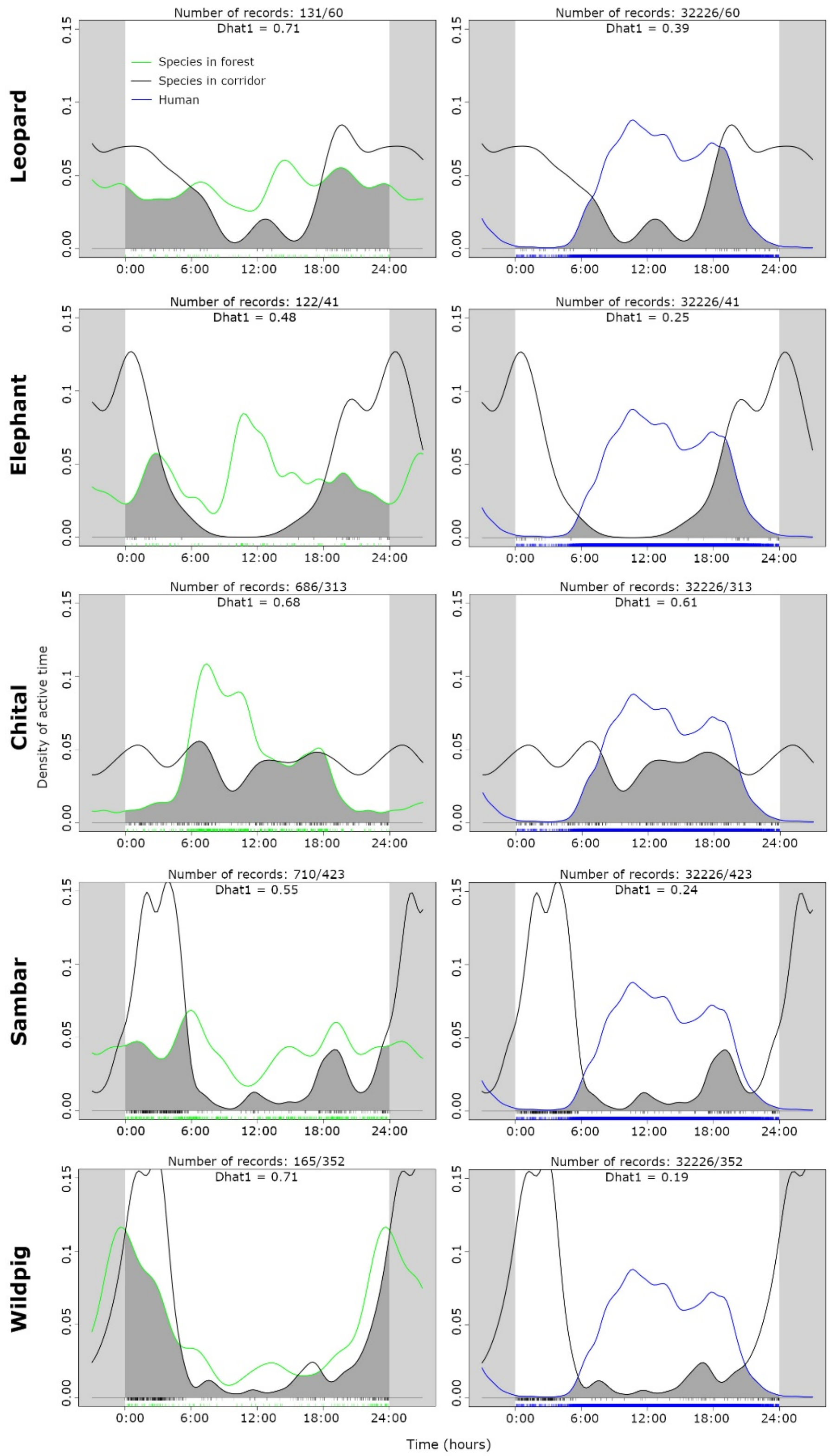


Figure 2.4. Comparison of the activity time of the five species frequently captured at the corridors around the western Rajaji National Park. Left- activity time of the species within the corridor and the forest ranges; Right- activity overlap of the species with humans in the corridor. Dhat value represents the overlap coefficient.

Wild Pig activity remained consistent across both habitats, with peaks at night and reduced activity during the day (Δ = 0.71). Human activity occurred exclusively during the daytime across all corridors, significantly overlapping with Chital (Δ = 0.61, Figure 2.4). Other species avoided times of peak human activity. However, the Leopard (Δ = 0.39) and the Elephant (Δ = 0.25), both species frequently involved in negative human-wildlife interactions, showed increased overlap with human activity in the evening hours.

DISCUSSION

This study highlights both the functionality and challenges of four key wildlife corridors in RNP in maintaining connectivity for species within fragmented habitats. The addition of the Chillawali–Shiwalik corridor extends the understanding of connectivity to the park's western boundary. The lower species richness observed in corridors compared to forested areas (9 vs 17 species) reflects the impact of disturbance and habitat fragmentation in human-dominated landscapes, a pattern consistent with global studies (Benítez-López et al., 2010; van der Ree et al., 2015).

Chital and sambar dominated captures in Chillawali–Shiwalik, indicating its importance for ungulate movement. Though elephant and leopard records were relatively low in number, sign surveys showed high elephant use, suggesting that camera-trapping underestimated their frequency. Thus, Chillawali–Shiwalik remains a critical route for wide-ranging species, especially elephants, confirming its role as a functional linkage to the Shiwalik FD and further to Kalesar WLS.

Species activity patterns exhibited significant shifts within corridors compared to forest areas (Figure 2.4). Chital exhibited continuous activity throughout the daytime in corridors, whereas in forests, its activity peaked during the early morning hours. Chital is primarily a diurnal species, with peak activity occurring at dawn and dusk. They spend most of their time feeding, followed by resting and social activities. This diurnal pattern is consistent across various habitats, including those with high human activity, where they may alter their behaviour to avoid disturbances (Rajawat & Chandra, 2020; Dahya et al. 2023; Kumar et al., 2023). Leopards, known for their cathemeral activity (Palei et al., 2021; Dahya et al., 2023), exhibited uniform activity in forests but reduced daytime activity in corridors, possibly avoiding human activity (Palei et al., 2021). Elephants shifted their activity from a daytime peak in forests to a nocturnal peak in corridors, demonstrating their adaptability to avoid human encounters (Chakraborty et al., 2021). Sambar, predominantly nocturnal in other studies (Kumar et al., 2023), showed early-morning peaks in corridors, likely due to lower human presence at that time. Wild Pigs maintained their nocturnal peaks across both habitats, consistent with findings from Dahya et al. (2023).

Human activity in corridors was predominantly diurnal, significantly overlapping with Chital activity, while other species mostly avoided peak human activity times. The overlap of Leopards and Elephants with human activity during evening hours is concerning, given the elevated risk of human-wildlife encounters (Figure 2.4). Such patterns, particularly involving species known to cause damage or pose danger in shared spaces, highlight the need for targeted management strategies.

The study also underscores the importance of infrastructure like underpasses in enhancing corridor functionality. Although highway underpasses support wildlife movement, parallel railway lines may act as significant barriers, particularly for Elephants, necessitating targeted mitigation measures (Carvalho et al., 2017; Gilhooly et al., 2019). Additionally, debris from underpass construction, garbage dumping, and the use of old roads below the flyover at Teenpani, and now Chillawali-Shiwalik, exacerbate habitat degradation (Oro et al., 2013; Katlam et al., 2018). Habitat restoration, particularly in the Chilla-Motichur corridor, and increasing forested cover are crucial for improving corridor effectiveness (e.g. Dutta et al., 2018).

In 2022, a male Tiger was photo-captured in camera traps moving from the Chilla range in the east to the Motichur range in the western Rajaji using the reclaimed corridor under the Chilla-Motichur flyover. This observation signifies the successful restoration of historical connectivity between the eastern and western RNP. Furthermore, it highlights the critical role of the Chilla-Motichur corridor in Tiger conservation in this landscape. The corridor, however, is yet to be fully restored as an existing ammunition depot of the Indian army cuts through it, leaving little space for unrestricted movement of wild animals.

The translocation of four Tigers from Corbett Tiger Reserve to western Rajaji National Park (2021–2024) reinforces the importance of maintaining functional corridors (Times of India, 2024). The data in this study has been recorded of tiger movement close to Chillawali-Shiwalik corridor. Since the road that earlier bisected Chillawali to Shiwalik connectivity is not converted to a flyover, tigers are expected to reclaim their historical connectivity upto Kalesar WLS in the west. As Tigers recolonise the western TAL, maintaining and monitoring these corridors will be vital for their survival and genetic exchange.

The current study was limited in scope due to a smaller sample size, a lack of a more systematic sampling design, and coverage of only limited areas around the flyovers. Using more camera traps in a grid design could yield more information on the spatial use and abundance of wildlife populations in the landscape. Therefore, I restricted my analyses to RAI as an indicator of site use intensity. Interpreting RAI as abundance may be incorrect as the number of captures may be affected by habitat quality, disturbances, individual behaviour and camera placement (O'Brien, 2011). Temporal activity may also be affected by similar biases in captures. Therefore, I did not analyse the temporal patterns of all the captured species but focused only on the species with sufficient captures across the camera traps.

Nonetheless, this study provides valuable insights into the effectiveness of highway underpasses and the challenges of maintaining corridor functionality in human-dominated landscapes. Active measures are essential to enhance corridor utility, including habitat restoration to increase forest cover, shifting of the army's ammunition depot to fully restore the corridor, restricting human activity during critical wildlife movement times, ensuring proper disposal of construction debris and garbage, and implementing effective mitigation strategies for railways to facilitate safe crossings such as advance alert systems, improved braking systems in the trains, regular patrolling and crossing infrastructures (Carvalho et al., 2017). Continuous monitoring of corridor use is crucial, particularly with the recent reintroduction of tigers, to support the long-term conservation of these apex predators and elephants in the region.

The findings from this study offer broader conservation implications for wildlife corridors in other parts of the Terai Arc Landscape and similarly fragmented habitats across India. The observed shifts in wildlife activity patterns and the influence of human presence highlight the urgent need for integrated infrastructure planning, including road and rail barriers, in preserving corridor functionality. These results can inform national-level policy on corridor identification, underpass design, and mitigation strategies, especially under frameworks such as India's Wildlife Action Plan (2017–2031), which prioritises connectivity conservation (MOECCF, 2017). Furthermore, the study underscores the importance of long-term monitoring, offering a replicable approach for assessing corridor functionality in other tiger and elephant landscapes.

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CHAPTER 3: EXTENT AND SEVERITY OF HUMAN–LARGE CARNIVORE CONFLICT IN THE WESTERN TERAI ARC LANDSCAPE, WITH RECOMMENDATIONS FOR MITIGATION

INTRODUCTION

Biodiversity is the cornerstone of sustained ecosystem processes and functions. This, in turn, is essential for livelihood security and overall well-being of human societies (Ministry of Environment, Forests & Climate Change, 2021). Conservation of biodiversity is essential in India, not only because the resulting loss of ecosystem functioning & lack of ecosystem services is detrimental to the general health and welfare of communities, but also to preserve the cultural heritage of the country, where coexistence has been the natural way of living (Ministry of Environment, Forests & Climate Change, 2021).

India is a tropical, megadiverse nation (Mathur & Sinha, 2008). It is also a developing country with the largest human population in the world (United Nations Fund for Population Activities, Communications and Strategic Partnerships, 2023). Thus, increasing demand on existing natural resources has intensified competition between people & wildlife for limited resources. This, in turn, has led to the exaggeration of human-wildlife conflict (HWC) situations across the nation. This has been attributed to the exploitation of limited resources and increased developmental activities leading to the degradation & destruction of natural habitats of wildlife (Karanth & Vanamamalai 2020).

Unlike the conservation paradigms of other large countries like the USA, China and Brazil, Protected Areas (PAs) in India are situated in a matrix of human-modified landscapes (Ghosh-Harihar et al., 2019). In India, where human settlements are often situated adjacent to PAs, spillover of wildlife from the protected habitat patches into the surrounding human-dominated landscapes (HDLs) increases the interface between people and wildlife (Treves & Karanth, 2003; Ghosh-Harihar et al., 2019). It has been observed that higher intensity of negative interactions tends to be concentrated in areas where a wide range of species co-occur with extensive human settlements, thereby increasing the interface between humans and large mammals (Anand & Radhakrishna, 2017).

In India, millions of people reside within PAs, and more live in close proximity to them (Ghosh-Harihar et al., 2019). Due to direct dependence on natural resources for their livelihoods, conflict more intensively affects rural populations in India (Anand & Radhakrishna, 2017). Negative interactions are also seen to be more intense where livestock holdings and agriculture are an important part of rural livelihoods (Distefano, 2005). Attacks on humans – resulting in injury or death – is the most severe consequences of HWC, with dire costs (Gulati et al., 2021). Livestock depredation and damage to crops also result in extensive economic losses (Karanth & Vanamamalai, 2020). Such conditions often lead to increased antagonism in local communities towards continued conservation efforts. Retaliatory killing of wild animals is a serious outcome of such conflict situations, frequently leading to local declines in populations of the affected species.

Certain characteristics like large body size leading to higher energy requirements, specialised niche and dietary requirements, low population densities and complex social behaviour are inherent to large mammals (Karanth et al., 2012). This makes them particularly vulnerable to habitat losses and environmental changes (Terborgh, 1974). In India, large carnivores like tigers (*Panthera tigris*), leopards (*Panthera pardus*), and bears (*Ursus* spp.), as well as herbivores including elephants (*Elephas maximus*) and wild boar (*Sus scrofa*) are most infamously involved in conflict (Karanth, 2002; Treves & Karanth, 2003). The pattern of cause and effect of conflict with herbivores and carnivores varies due to their habits, habitats, trophic placements, and ecology (Karanth, 2002; Gureja et al., 2019).

Often, large felids like tigers and leopards end up in conflict situations with humans due to loss of habitat and natural prey base, resulting in livestock depredation or attacks on humans (WWF, 2011). Megaherbivores like elephants, on the other hand, require large home ranges often spanning multiple landscapes, and thus, are one of the first species to suffer the adverse outcomes of habitat loss and fragmentation (Uttarakhand Forest Department, 2015). This results in individuals wandering out into agricultural lands adjoining forest patches in search of food, leading to incidents of crop raiding, damage to infrastructure and sometimes even attacks on people (WWF, 2011; Singh, 2016). Omnivorous species like bears often come into conflict with humans due to their dietary flexibility and opportunistic behaviour, leading them to forage near human settlements (Kumar et al., 2022).

Large carnivores exert a significant top-down cascade effect on any ecosystem, and are vital to its continued functioning (Schmitz et al., 2000). While large carnivores are being extirpated from vast stretches of their global range, there are increases in local populations in PAs across India resulting from focused conservation efforts (Karanth & Chellam, 2009).

However, the PAs of the country are often not large enough to sustain these increased numbers, resulting in individuals spilling out into the surrounding HDLs where there are increased chances of encounters with people (Naha et al., 2020).

Tiger, leopard, and bear attacks on people, resulting in injury/death has been reported from most habitat range states across the country, and even accounted for a large portion of conflict between people and large carnivores (Karanth, 2002; Bargali, 2012; Sathyakumar et al., 2012). Attacks on humans are the consequence of a conflict that most antagonises local residents towards continued large carnivore conservation. Meanwhile, large carnivores have been known to substitute livestock in their diets (Naha et al., 2020). Consequent depredation by tigers & leopards is economically extremely costly for rural communities. Such incidents of conflict have been increasingly reported from the Terai Arc Landscape (TAL) spanning India and Nepal (Kala & Kothari, 2013).

The Terai Arc Landscape (TAL) is one of the globally important eco-regions and a critical tiger conservation unit (TCU) (Wikramanayake et al., 2004; Semwal, 2005). The TAL encompasses the Shivalik hills and the Terai floodplains, running parallel to the outer Himalayas (Harihar et al., 2009). It includes around 15 PAs of India and Nepal (Chanchani et al., 2014). The landscape has one of the highest human population densities (~550 individuals per km^2) in the country as a result of its high productivity (Johnsingh et al., 2004; Malviya & Ramesh, 2015). This has resulted in high levels of fragmentation of natural habitats due to anthropogenic activities. Consequently, there is poor or no connectivity between the different PAs in the region (Harihar et al., 2009). The continuing loss of natural habitat in this landscape poses daunting challenges for wildlife conservation efforts. This is compounded by the increasing reports of conflict incidents from the region, leading to antagonism among the local resident communities. Conservation within shared landscapes is, thus, a complex issue where the safety of human lives, property, livelihood and well-being need to be preserved while considering the socio-political circumstances of the region.

LITERATURE REVIEW

Large carnivores require large areas to sustain themselves (Thapa et al., 2015). There is increasing evidence that these carnivores are capable of thriving in multi-use landscapes outside PAs (Thapa et al., 2021). The quality of the larger landscapes, including the suitability of habitat, abundance of wild prey, extent of anthropogenic disturbance, and tolerance by the local communities, is vital to the continued survival of these species in multi-use regions (Naha et al., 2020). However, their existence in close proximity to humans in areas outside PAs often results in competition for shared resources, leading to an increase in large carnivore related conflict in recent years (Qureshi et al., 2024). Such regions of increased conflict are prone to retaliatory killing of these animals and antagonism of locals towards continued carnivore conservation (Naha et al., 2020).

The TAL is inhabited by sizeable populations of tigers (~800), leopards (~1000) & bears, with evidence suggesting an increase in numbers of large felids (Qureshi et al., 2023; 2024). Tigers often restrict themselves to the forest patches and adjoining areas in the Terai region of the landscape, sporadically using anthropogenically disturbed regions (Warrier et al., 2020). Meanwhile, leopards are observed to be near-ubiquitous across most of the area (Malviya & Ramesh, 2015). Interference competition leading to the displacement of the smaller predator has been widely observed in this region, with up to 65% of the leopard population here existing outside PAs (Qureshi et al., 2024). However, with greater terrain complexity – such as can be observed in the Shivalik region – leopards tend to coexist with tigers (Malviya and Ramesh, 2015). Meanwhile, Asiatic black bears are found to co-occur alongside sloth bears in the state of Uttarakhand, India, while in Bhutan and Nepal, the two bear species occur exclusive of each other (Pigeon et al., 2019).

Tigers and leopards are the two largest sympatric felids inhabiting large portions of the Indian forests (Ranjan et al., 2024). Effective conservation measures have led to an increase in predator numbers in the PAs of TAL. High densities of tigers and leopards within the PAs of the landscape have resulted in individuals dispersing and spilling outside the PA boundaries (Malviya & Ramesh, 2015). A transboundary study by Chanchani et al. (2014) posits that prey density was notably lower in the PAs in India as compared to Nepal. The study additionally states that certain sites in the landscape face severe grazing pressures by livestock. Several studies from the parts of TAL have looked at livestock depredation by the two big cats (Malviya & Ramesh, 2015; Ahmed & Bargali, 2018). Ranjan et al. (2024) note that while the large felids were observed to largely consume wild prey species, a significant portion of the diet was observed to consist of livestock in wildlife corridors outside PAs of TAL. The same study notes that the leopard was found to exhibit a broader dietary niche as compared to tigers in parts of TAL. Leopards are known to be able to survive in fringe habitats, often in close proximity to human settlements (Naha et al., 2018; Yadav et al., 2020). This often leads to interactions between the felid and people. Thus, local communities in parts of TAL have been known to consider leopards as more intrusive due to their generalist and adaptable natures (Chauhan et al., 2001; Malviya & Ramesh, 2015).

On the other hand, bear species in India do not actively hunt or substitute livestock in their diets. Any encounters between livestock and bears are usually accidental in nature. However, several species of bears in the New World are known to exploit human subsidised food resources (Can et al., 2014; Lamb et al., 2020). Can et al. (2014) emphasise that the community tolerance for sloth bears is low since attacks on people are much more common than other species of bears. Pokharel et al. (2022) hypothesise that species like sloth bears have developed aggressive behaviours as a protective adaptation for co-occurring with large and seemingly dangerous animals like the Asiatic elephant, tigers, one-horned rhinoceros, and leopards. Additionally, due to their physiologies, bears are easily startled by human presence in close proximity and, thus, prone to defending themselves by mauling people (Rajpurohit & Krausman, 2000). This has earned the bears a reputation for being aggressive animals. However, there are few studies focusing on bear conflict in the TAL, which creates a significant information gap in the region.

Terai is simultaneously a biodiverse region supporting many species of plants and animals, and also home to dense human settlements heavily dependent on agriculture and industry (Chanchani et al., 2014). This creates a unique circumstance of sharing of limited resources by high densities of people & wildlife. Being a landscape with high densities of large carnivores, pockets of the TAL have been noted to experience frequent conflict incidents where the animals inhabit multi-use regions outside PAs (Chanchani et al., 2014). All three large carnivores have been involved in attacks on humans, while the large cats have been involved in livestock depredation.

The state of Uttarakhand – part of the western TAL – has witnessed a notable increase in tiger population in the past few years (Qureshi et al., 2023). Regions with a steep increase in tiger numbers saw a slight decline in leopard populations (Qureshi et al., 2024). A study by Bargali (2012) reported that a good population of black bears (>300) existed in various parts of the state, while other parts supported a significant number of sloth bears, and both the species overlapped in certain regions of the state. However, the forest habitats of the state are simultaneously facing high levels of anthropogenic pressures (Dobhal et al., 2011; Badola et al., 2021). Subsequently, utilisation of fragmented patches of forests outside the boundaries of PAs by most species of large mammals has increased, leading to higher severity of conflict situations in various parts of the state (Nath et al., 2020; Natarajan et al., 2021). About 30% of all human death and injury cases were caused by leopards in the past 5 years (Qureshi et al., 2024; Uttarakhand Forest Department, 2024). Much higher numbers have been quoted for livestock depredation incidents by both tigers and leopards. Increasing reports of negative interactions with large felids from inside and outside PAs in the state indicate a serious issue of large carnivore conflict. Occasional incidents of attacks on people or livestock by bears have been reported from outside PAs in the state, whereas the numbers are quite low from within PAs (Bargali, 2012).

Multiple studies have attempted to understand the drivers of various types of large carnivore conflict (Malviya & Ramesh, 2015; Ahmed & Bargali, 2018; Naha et al., 2020). However, there appears to be a lacuna in a comprehensive as well as comparative investigation of the trends and factors influencing the conflict due to all species of large carnivores in the state of Uttarakhand. This study, thus, aims to address this gap by looking at the spatial distribution of conflict incidents and delineating the relationship between the incidents of conflict and the biogeographic variables of the region.

STUDY AREA

The transboundary Terai Arc Landscape comprises of three distinct geographical zones (Johnsingh et al., 2004): (i) *Shivaliks* are the southernmost range of the Himalaya. They run parallel to the southern edges of the lesser Himalayan ranges, sometimes indistinguishable from them. (ii) *Bhabar* is characterised by a low gradient terrain, with mixed vegetation communities. Such areas are associated with the lesser Himalayan ranges and the lower slopes of the Shivaliks. (iii) *Terai* is characterised by a mosaic of tall grasslands, wetlands and mixed deciduous forests, containing predominantly Sal (*Shorea robusta*) trees. These habitats are present along the floodplains of many streams and rivers originating in the Himalayas. These regions have been particularly listed among the 200 ecoregions of global importance.

Geographically, Uttarakhand is situated in northern India, in the Gangetic basin and can be divided based on physiographical characteristics into the Himalayas, the Shivalik and the Terai regions (Bargali, 2012). The state lies between the latitudes 28º 43’ and 31º 27’N, and longitudes 77º 34’ and 81º 02’ E and shares an international boundary with China in the north and Nepal in the east, while Himachal Pradesh and Uttar Pradesh share its western and southern borders, respectively (Bargali, 2012; India State Forest Report, 2019). The state is administratively divisible into 37 Forest Divisions (FDs) (Bargali, 2012; Figure 3.1).

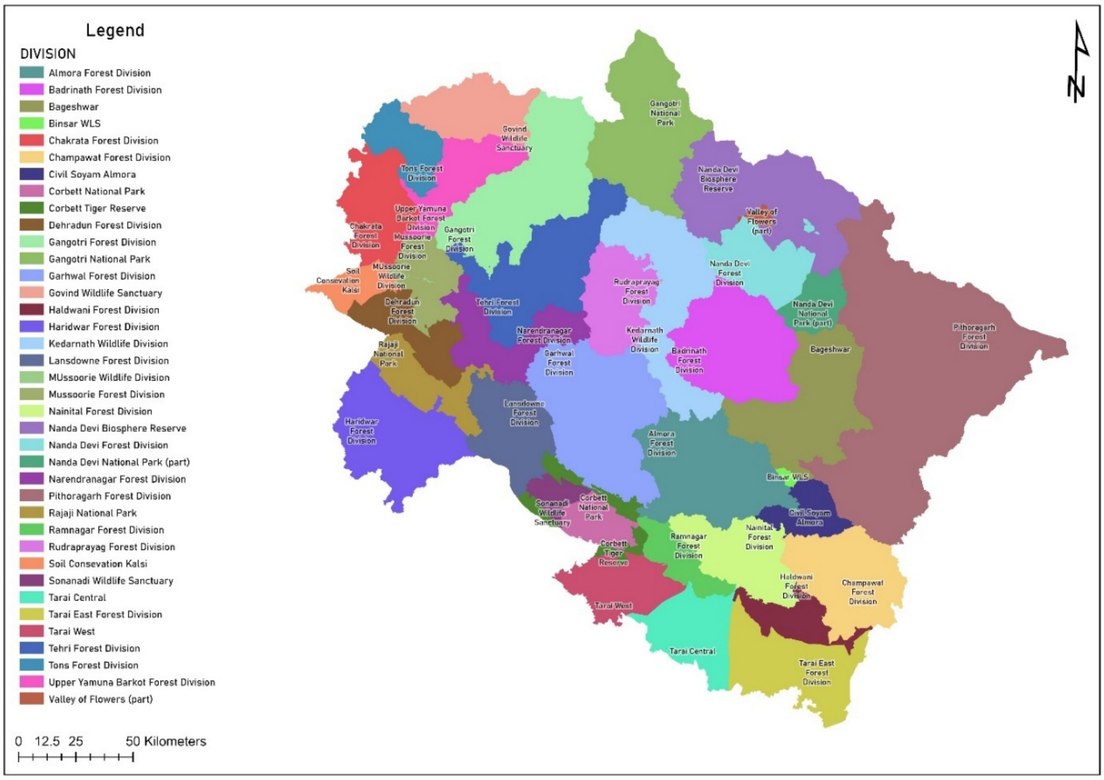


Figure 3.1. Map illustrating the division boundaries in the state of Uttarakhand

The state is spread over an area of 53,483 sq. km with approximately 63% land under forested areas (Dobhal et al., 2011; India State Forest Report, 2019). The state has an extensive system of perennial and seasonal streams, and is resource rich (Dobhal et al., 2011). Uttarakhand is very rich in biodiversity (Semwal, 2005). The state is dotted with multiple PAs (~12), which act as refuge for multiple species of large mammals that resides within them (Dobhal et al., 2011). Three species of bear (Asiatic black, Himalayan brown, and sloth bears), 2 species of large felid (tigers and leopards), as well as elephant populations have been reported from Uttarakhand (Sathyakumar et al., 2012; Jhala et al., 2018; Badola et al., 2021). It is also home to over 1.01 crore people, which makes up 0.83% of India's population (Census of India, 2011). Such simultaneously high populations lead to high interface between people and large carnivores and, consequently, increased intensity of conflict.

The Rajaji-Corbett complex has been identified as a Level I Tiger Conservation Unit, with the highest large carnivore numbers in the state (Dinerstein et al., 1997). Given the conservation importance of this stretch of the state for large carnivores, this study focuses on the Forest Divisions surrounding the Rajaji-Corbett complex *viz.*, Soil Conservation Kalsi, Dehradun, Haridwar, and Lansdowne Forest Divisions, along with Rajaji and Corbett Tiger Reserves (Figure 3.2).

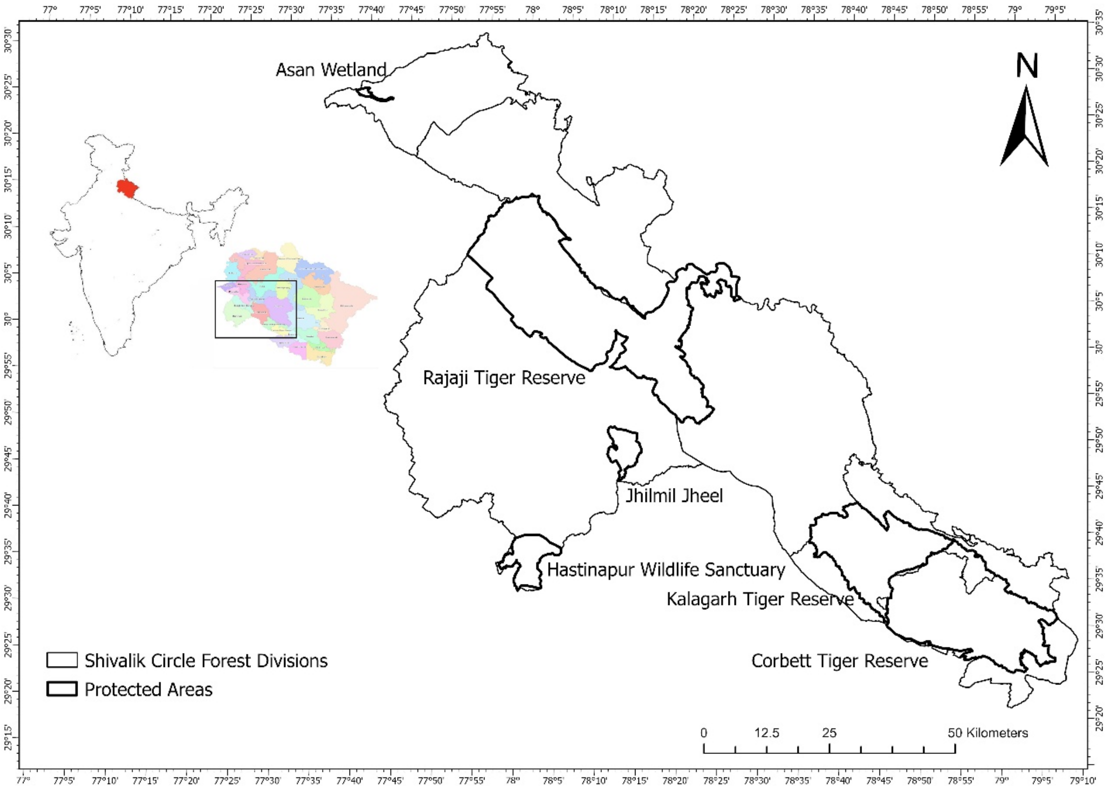


Figure 3.2. Map depicting the study area, including Forest Divisions where conflict data was analysed

METHODOLOGY

Data collection

Details of human-wildlife conflict incidents were collected from each of the Forest Divisions of the study area for 12 years (2012-2024). Of this, incident details of attacks on humans were available from 2018 to 2024, while livestock depredation incidents were available from 2003 to 2024. The details included date and location of incidents, name of person attacked (in case of attack on human)/name of owner (in case of livestock depredation), details of person attacked – including age and sex – or details of livestock – including species, age and sex – and amount of compensation paid. Large carnivore conflict incidents were compiled on the basis of the species of carnivore involved. The incidents were then categorised based on the victim of the conflict incidents viz., humans and livestock.

Data verification

The GPS location details of the incidents were verified for their accuracy. The incidents where location details were erroneous – i.e., the locations did not match the specified range – were discarded. Only the incidents where the GPS locations could be verified were utilised for further analyses.

Species-wise conflict points were extracted using QGIS (version 3.28) viz., tiger, leopard and bear. For each of the species, 5000 random points were then generated in QGIS to act as absence points in the study area.

Covariate extraction

Relevant covariates were obtained or generated for the study area in the form of raster files. The covariates were categorised as:

Bioclimatic – annual mean temperature and annual precipitation (https://www.worldclim.org/data/bioclim.html)

Habitat characteristics – DEM (Digital Elevation Model), distance to linear infrastructure (https://earthworks.stanford.edu), distance to Protected Area, distance to water (https://earthworks.stanford.edu), terrain ruggedness, terrain slope, and LULC (land use/land cover) (Biodiversity Information System)

Anthropogenic – HFP (Human Footprint Index) (https://gis.earthdata.nasa.gov), livestock population density (Gilbert et al., 2018), human population density (https://gis.earthdata.nasa.gov), and nightlight (https://www.earthdata.nasa.gov/topics/human-dimensions/nighttime-lights).

These covariates were then extracted for the conflict presence and absence points of each large carnivore species. The abbreviations of each covariate, as used in analysis, are given in Table 3.1.

Table 3.1. Covariates used (with their abbreviations) as drivers of carnivore conflict for regression analyses.

Covariate abbreviation	**Covariate name**	**Covariate abbreviation**	**Covariate name**
bio1	Mean annual temperature	slope	terrain slope
bio12	Annual precipitation	lulc	Land use/Land cover
distlin	Distance to linear infrastructure	hfp	Human Footprint Index
distpa	Distance to Protected Area	livestock	livestock population density
distwater	distance to water	popden	human population density
ruggedness	terrain ruggedness	nite	nightlight

Exploratory analysis

Boxplots were created using "*ggplot*" package in R version 4.3.1 for the presence (conflict) and absence (non-conflict) points for each of the extracted covariates to visualise and understand the differences in the drivers of conflict vs non-conflict locations in the landscape.

Pearson's correlation matrix was generated using "*corrplot*" package in R for the extracted covariates. Following correlation analysis, redundant correlated variables (≥0.8) were omitted from further analyses.

Regression analysis

Generalised linear modelling (GLM) was done using '*MuMIN*' package in R to understand the linear relationship between large carnivore conflict and its drivers in the study area. Binomial family was used since the dependent variable was the presence (1) or absence (0) of conflict. The package modelled the different combinations of covariates that best explained the presence of conflict at the presence locations in the study area. Akaike Information Criteria (AIC) values were used to assess the best-fit model. Model-averaging was done where the differences of model AICs were less than 2 (ΔAIC<2), implying that the models are not significantly different in their ability to explain the relationships (Burnham & Anderson, 1998).

Predictive modelling

The output of the regression analysis was used to predict the relationship between a significant covariate and the occurrence of conflict in the region. This prediction was then used to generate graphs using "*ggplot*" package in R to understand the relationship between each of the significant covariates and their impact on conflict.

RESULTS

A total of 114 incidents of attacks on humans were verified from the Forest Divisions of the study area. Out of these, 65 incidents were due to large carnivores – including tigers (n=29), leopards (n=19), and bears (n=17) (2018 to 2024). 3,277 incidents of livestock depredation were verified, out of which 3,258 incidents were attributed to large carnivores – including tigers (n=615), leopards (n=2,635), and bears (n=8) (2003 to 2024). However, since bears do not predate on livestock, these incidents were assumed to be random accidental encounters and excluded from further analyses.

Exploratory analyses suggest significant differences in human population density, annual precipitation and terrain slope between background and conflict locations of bear attacks on people. Distance to linear infrastructure, livestock population density, and Human Footprint Index values were significantly different for locations with leopard attacks on people and random locations. Human population densities of the locations with tiger attacks on people varied significantly from those of the randomly selected background locations (Supplementary S1 & S2).

Human and livestock population density, Human Footprint Index, nightlight, terrain slope, and elevation levels were considerably different for locations of livestock depredation by leopards as compared to the non-conflict locations, while human population density and elevation were significantly different for livestock depredation locations by tigers as compared to those of background locations.

The number of models averaged ($\Delta AIC<2$) for conflict with each species varied, with 16 models averaged for bear attacks on humans, 14 models for leopard attacks on humans, and 7 models for tiger attacks on people. Meanwhile, two models were averaged for livestock depredation by leopards, and four models were averaged for livestock depredation by tigers.

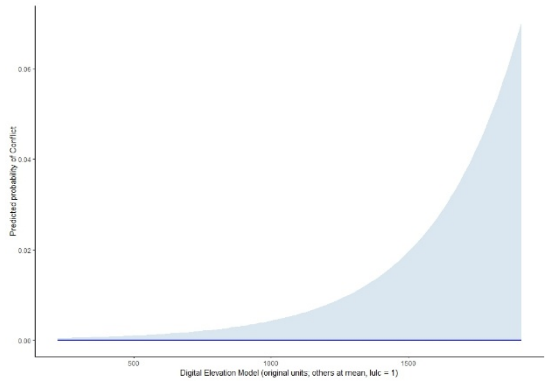
Table 3.2. Best-fit models with ΔAIC<2 for bear attacks on humans in the study area

Component models	df	logLik	AICc	delta	weight
dem + livestock + popden	4	-84.89	177.79	0.00	0.11
dem + livestock + nite + popden	5	-83.99	177.99	0.20	0.10
dem + distlin + livestock + nite + popden	6	-83.09	178.19	0.41	0.09
dem + livestock + popden + ruggedness	5	-84.15	178.31	0.52	0.09
dem + livestock + nite + popden + ruggedness	6	-83.24	178.50	0.72	0.08
dem + distlin + livestock + nite + popden + ruggedness	7	-82.31	178.63	0.85	0.07
bio12 + distpa + livestock + nite + popden	6	-83.50	179.02	1.24	0.06
bio12 + distlin + distpa + livestock + nite + popden	7	-82.69	179.40	1.62	0.05
dem + distpa + livestock + nite + popden	6	-83.74	179.51	1.72	0.05
dem + distlin + livestock + popden	5	-84.75	179.51	1.72	0.05
dem + distpa + livestock + popden	5	-84.80	179.60	1.82	0.05
dem + hfp + livestock + nite + popden	6	-83.84	179.70	1.91	0.04
bio12 + dem + livestock + popden	5	-84.86	179.74	1.95	0.04
dem + distwater + livestock + popden	5	-84.87	179.76	1.98	0.04
dem + distwater + livestock + nite + popden	6	-83.87	179.77	1.98	0.04
dem + livestock + popden + slope	5	-84.88	179.78	1.99	0.04

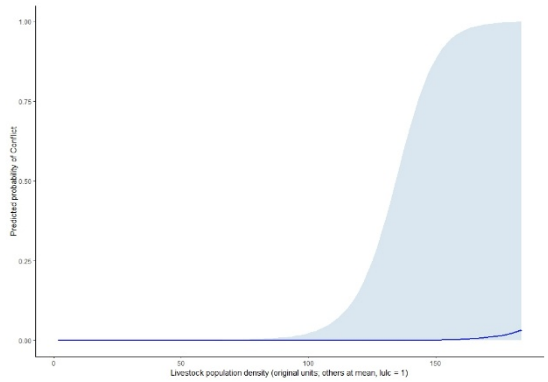
Regression analysis results (Tables 3.2 to 3.10) give the best-fit models used to generate the averaged model. Elevation ($p<0.01$), livestock ($p<0.05$) and human population densities ($p<0.05$) are significant factors for understanding the patterns of bear attacks on people (Tables 3.2 & 3.3). While elevation does not have a strong negative or positive relationship with incidents of conflict, an increase in livestock population density relates to an increase in conflict incidents, while a decrease in human population density causes a significant increase in conflict (Figure 3.3). Elevation ($p<0.01$) also significantly influences leopard attacks on people, along with distance to linear infrastructure ($p<0.01$) and Human Footprint Index ($p<0.05$) (Tables 3.4 & 3.5). Elevation and Human Footprint Index are not strongly correlated to the incidence of conflict, while an increase in distance from linear infrastructure leads to a decrease in probability of conflict (Figure 3.4). Tiger attacks on humans were driven by human population density ($p<0.001$), along with distance to linear infrastructure ($p<0.01$) and Protected Area ($p<0.01$), nightlight ($p<0.01$), and livestock population density ($p<0.05$) (Table 3.6 & 3.7). An increase in human population density resulted in a significant decrease in the probability of conflict, while an increase in nightlight and livestock population density led to an increased probability of conflict occurring (Figure 3.5). Distances to linear infrastructure and PAs were inversely correlated to the occurrence of conflict (Figure 3.5).

Table 3.3. Conditional averaged summary of the best-fit model for bear attacks on humans in the study area

	Estimate	**Std. Error**	**Adjusted SE**	**z value**	**Pr(>|z|)**	
(Intercept)	-14.85404	4.17445	4.17542	3.557	0.000374	***
dem	0.76676	0.25681	0.25686	2.985	0.002835	**
livestock	4.32908	1.98927	1.98970	2.176	0.029574	*
popden	-10.64990	4.40472	4.40575	2.417	0.015637	*
nite	-1.83474	1.35412	1.35442	1.355	0.175534	
distlin	-0.30213	0.27462	0.27468	1.100	0.271363	
ruggedness	0.31219	0.25579	0.25586	1.220	0.222394	
bio12	0.90082	0.76736	0.76748	1.174	0.240503	
distpa	0.41627	0.35212	0.35217	1.182	0.237203	
hfp	0.29249	0.52761	0.52774	0.554	0.579426	
distwater	-0.07797	0.24809	0.24815	0.314	0.753379	
slope	0.82584	5.96747	5.96891	0.138	0.889958	



(a)



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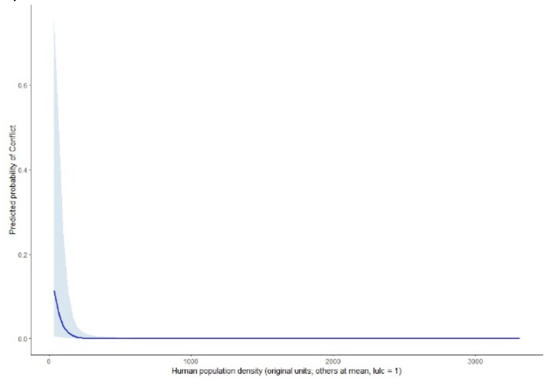


(c)

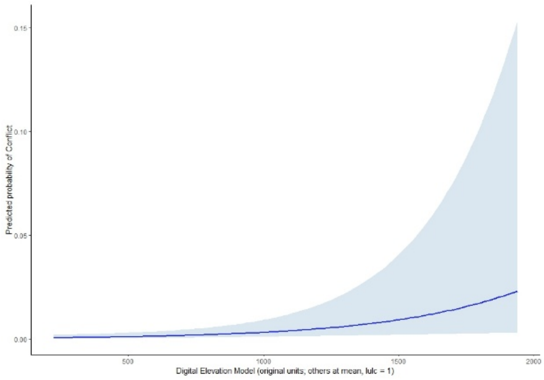
Figure 3.3. Predictive graphs showing the relationship between conflict locations and (a) Digital Elevation Model, (b) livestock population density, and (c) human population density for bear attacks on people in the study area

Table 3.4. Best-fit models with ΔAIC<2 for leopard attacks on humans in the study area

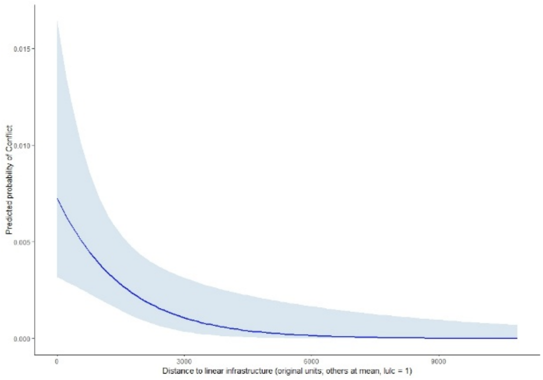
Component models	**df**	**logLik**	**AICc**	**delta**	**weight**
dem + distlin + hfp	4	-109.45	226.91	0.00	0.12
dem + distlin + hfp + livestock	5	-108.48	226.97	0.06	0.12
dem + distlin + hfp + nite	5	-108.68	227.37	0.46	0.10
bio12 + dem + distlin + hfp + livestock	6	-107.69	227.40	0.49	0.10
dem + distlin + hfp + livestock + nite	6	-107.88	227.77	0.86	0.08
dem + distlin + distpa + hfp	5	-108.94	227.89	0.98	0.08
dem + distlin + hfp + slope	5	-109.18	228.37	1.46	0.06
dem + distlin + hfp + popden	5	-109.22	228.45	1.54	0.06
bio12 + dem + distlin + hfp + livestock + nite	7	-107.33	228.69	1.78	0.05
dem + distlin + distpa + hfp + nite	6	-108.35	228.71	1.80	0.05
bio12 + dem + distlin + distpa	5	-109.40	228.80	1.89	0.05
dem + distlin + distpa + livestock + popden	6	-108.43	228.87	1.96	0.05
dem + distlin + distpa + ruggedness	5	-109.44	228.89	1.98	0.05
dem + distlin + distpa + livestock + slope	6	-108.44	228.90	1.99	0.05

Table 3.5. Conditional averaged summary of best-fit model for leopard attacks on humans in the study area

	Estimate	**Std. Error**	**Adjusted SE**	**z value**	**Pr(>|z|)**	
(Intercept)	-6.65638	0.49509	0.49521	13.442	< 2e-16	***
dem	0.65108	0.22725	0.22730	2.864	0.00418	**
distlin	-1.42325	0.53196	0.53208	2.675	0.00748	**
hfp	0.51891	0.25779	0.25784	2.013	0.04416	*
livestock	-0.55773	0.42024	0.42034	1.327	0.18455	
nite	-0.34085	0.32106	0.32114	1.061	0.28851	
bio12	-0.44834	0.49887	0.49897	0.899	0.36890	
distpa	-0.24906	0.27652	0.27659	0.900	0.36788	
slope	1.20951	2.22730	2.22783	0.543	0.58719	
popden	-0.15956	0.31754	0.31762	0.502	0.61540	
ruggedness	0.04234	0.25691	0.25697	0.165	0.86913	



(a)



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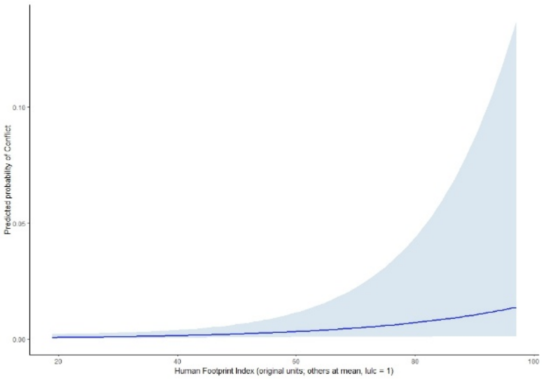


(c)

Figure 3.4. Predictive graphs showing relationship between conflict locations and (a) Digital Elevation Model, (b) distance to linear infrastructure, and (c) Human Footprint Index for leopard attacks on people in the study area

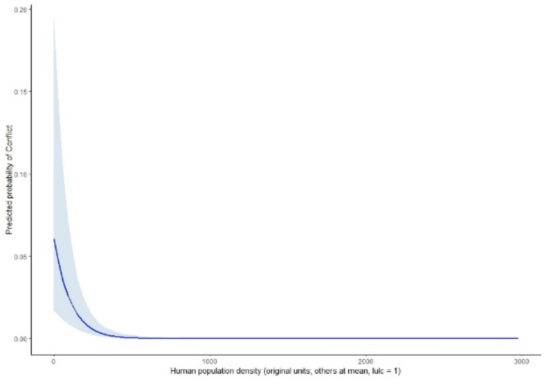
Table 3.6. Best-fit models with ΔAIC<2 for tiger attacks on humans in the study area

Component models	**df**	**logLik**	**AICc**	**delta**	**weight**
dem + distlin + distpa + hfp + livestock + nite + popden	8	-134.53	285.10	0.00	0.27
dem + distlin + distpa + livestock + nite + popden	7	-136.06	286.14	1.05	0.16
bio12 + distlin + distpa + hfp + livestock + nite + popden	8	-135.25	286.54	1.44	0.13
dem + distlin + distpa + hfp + livestock + nite + popden + ruggedness	9	-134.33	286.69	1.59	0.12
bio12 + dem + distlin + distpa + hfp + livestock + nite + popden	9	-134.37	286.78	1.68	0.12
dem + distlin + distpa + distwater + hfp + livestock + nite + popden	9	-134.47	286.98	1.88	0.10
dem + distlin + distpa + hfp + livestock + nite + popden + slope	9	-134.52	287.08	1.98	0.10

Table 3.7. Conditional averaged summary of best-fit model for tiger attacks on humans in the study area

	Estimate	**Std. Error**	**Adjusted SE**	**z value**	**Pr(>|z|)**	
(Intercept)	-8.88269	0.99376	0.99399	8.936	< 2e-16	***
dem	-0.77293	0.40881	0.40891	1.890	0.05873	.
distlin	-0.69812	0.26634	0.26640	2.621	0.00878	**
distpa	-1.72508	0.57507	0.57520	2.999	0.00271	**
hfp	-0.61936	0.36223	0.36232	1.709	0.08737	.
livestock	1.47220	0.58763	0.58777	2.505	0.01225	*
nite	1.39422	0.46387	0.46396	3.005	0.00266	**
popden	-4.81678	1.08206	1.08230	4.451	8.6e-06	***
bio12	-0.65892	0.64525	0.64538	1.021	0.30726	
ruggedness	-0.13187	0.20383	0.20388	0.647	0.51776	
distwater	-0.08058	0.22977	0.22982	0.351	0.72588	
slope	0.05213	0.50669	0.50682	0.103	0.91808	

Annual precipitation, terrain ruggedness and elevation, distance to linear infrastructure, Protected Area and water, human population density, Human Footprint Index and nightlight, and LULC ($p<0.001$) significantly influence livestock depredation by leopards in the study area (Table 3.8 & 3.9). Of these, annual precipitation, distances to linear infrastructure, PAs and water, HFI, nightlight and human population density negatively influence incidents of conflict, while elevation and ruggedness were directly proportional to the occurrence of conflict (Figure 3.6). Annual precipitation, terrain elevation & ruggedness, distance to linear infrastructure & water, human & livestock population densities, and Human Footprint Index are the important drivers influencing livestock depredation incidents by tigers (Table 3.10 & 3.11). Increase in annual precipitation, elevation& ruggedness, distances to linear infrastructure and water, HFI, and human population density led to a decrease in conflict probability, with human population density having the strongest relationship (Figure 3.7). Meanwhile, livestock population density was directly proportional to the occurrence of conflict (Figure 3.7).



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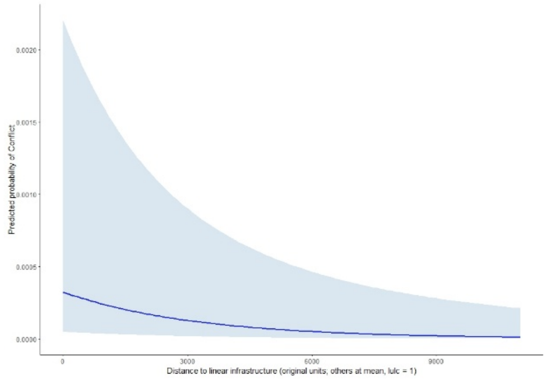

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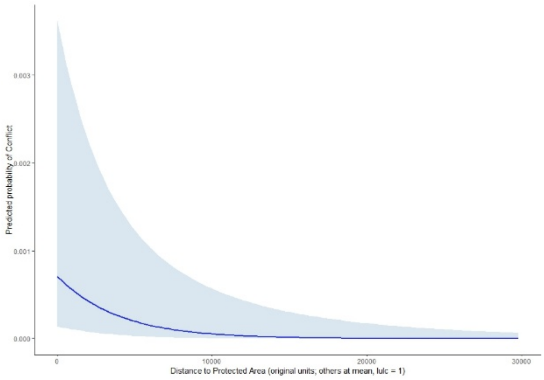

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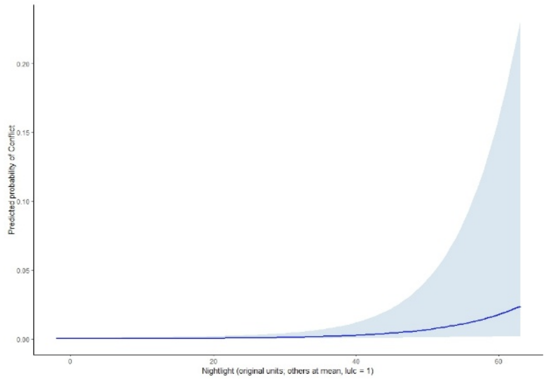

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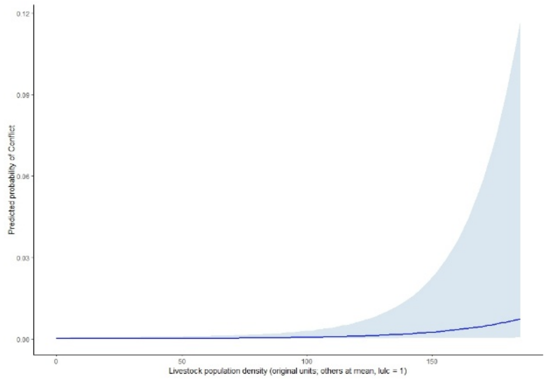

(e)

Figure 3.5. Predictive graphs showing the relationship between conflict locations and (a) human population density, (b) distance to linear infrastructure, (c) distance to Protected Area, (d) nightlight, and (e) livestock population density for tiger attacks on people in the study area

Table 3.8. Best-fit models with ΔAIC<2 for livestock depredation by leopards in the study area

Component models	df	logLik	AICc	delta	weight
bio12 + dem + distlin + distpa + distwater + hfp + livestock + lulc + nite + popden + ruggedness + slope	17	-2523.93	5081.94	0.00	0.69
bio12 + dem + distlin + distpa + distwater + hfp + lulc + nite + popden + ruggedness + slope	16	-2525.74	5083.55	1.61	0.31

Table 3.9. Conditional averaged summary of the best-fit model for livestock depredation by leopards in the study area

	Estimate	Std. Error	Adjusted SE	z value	Pr(>|z|)	
(Intercept)	-0.79370	0.53741	0.53750	1.477	0.139766	
bio12	-1.46689	0.11897	0.11899	12.328	< 2e-16	***
dem	1.37143	0.08529	0.08530	16.078	< 2e-16	***
distlin	-0.28811	0.04107	0.04108	7.014	< 2e-16	***
distpa	-0.65255	0.06953	0.06954	9.384	< 2e-16	***
distwater	-0.40431	0.04312	0.04313	9.375	< 2e-16	***
hfp	-0.42320	0.08647	0.08649	4.893	9.90e-07	***
livestock	0.30740	0.16303	0.16306	1.885	0.059396	.
lulc_2	-1.24085	0.53036	0.53045	2.339	0.019322	*
lulc_3	-2.48671	0.52796	0.52804	4.709	2.49e-06	***
lulc_4	-2.29489	0.53517	0.53525	4.287	1.81e-05	***
lulc_5	-1.87245	0.55508	0.55517	3.373	0.000744	***
lulc_6	-2.61182	0.55030	0.55039	4.745	2.08e-06	***
nite	-0.90109	0.18878	0.18881	4.773	1.82e-06	***
popden	-3.44662	0.27554	0.27557	12.507	< 2e-16	***
ruggedness	0.62649	0.04284	0.04284	14.623	< 2e-16	***
slope	0.93012	0.44083	0.44090	2.110	0.034892	*

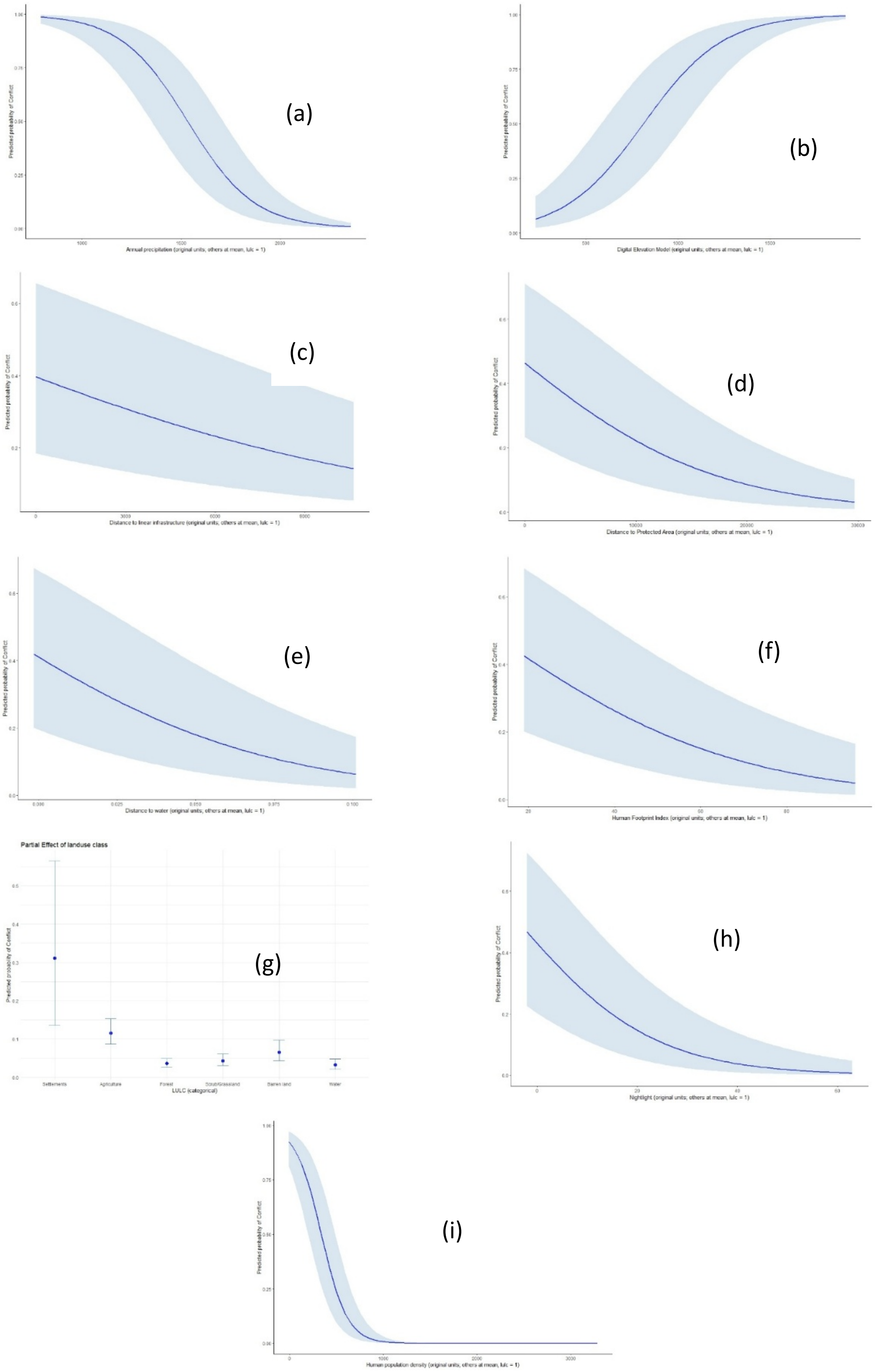

Figure 3.6. Predictive graphs showing relationship between conflict locations and (a) annual precipitation, (b) Digital Elevation Model, (c) distance to linear infrastructure, (d) distance to Protected Area, (e) distance to water, (f) Human Footprint Index, (g) Land Use/Land Cover, (h) nightlight, and (i) human population density for livestock depredation by leopards in the study area

Table 3.10. Best-fit models with ΔAIC<2 for livestock depredation by tigers in the study area

Component models	df	logLik	AICc	delta	weight
bio12 + dem + distlin + distpa + distwater + hfp + livestock + lulc + nite + popden + ruggedness + slope	18	-1071.30	2178.72	0.00	0.28
bio12 + dem + distlin + distwater + hfp + livestock + lulc + popden + ruggedness + slope	16	-1073.33	2178.77	0.04	0.27
bio12 + dem + distlin + distwater + hfp + livestock + lulc + nite + popden + ruggedness + slope	17	-1072.40	2178.90	0.18	0.25
bio12 + dem + distlin + distpa + distwater + hfp + livestock + lulc + popden + ruggedness + slope	17	-1072.66	2179.43	0.70	0.20

Table 3.11. Conditional averaged summary of the best-fit model for livestock depredation by tigers in the study area

	Estimate	Std. Error	Adjusted SE	z value	Pr(>|z|)	
(Intercept)	-8.17641	1.20583	1.20609	6.779	< 2e-16	***
bio12	-2.45664	0.27466	0.27472	8.942	< 2e-16	***
dem	-1.54599	0.14370	0.14372	10.757	< 2e-16	***
distlin	-0.41234	0.06325	0.06326	6.518	< 2e-16	***
distpa	0.15546	0.11606	0.11609	1.339	0.1805	
distwater	-0.30153	0.06987	0.06988	4.315	1.60e-05	***
hfp	-0.49619	0.11956	0.11959	4.149	3.34e-05	***
livestock	1.36208	0.20030	0.20034	6.799	< 2e-16	***
lulc_2	1.43618	1.16260	1.16285	1.235	0.2168	
lulc_3	1.39312	1.16331	1.16356	1.197	0.2312	
lulc_4	2.37574	1.17153	1.17178	2.027	0.0426	*
lulc_5	1.84640	1.18768	1.18794	1.554	0.1201	
lulc_6	-1.58671	1.28747	1.28774	1.232	0.2179	
lulc_7	-2.02981	324.74621	324.81644	0.006	0.9950	
nite	-0.25421	0.17311	0.17315	1.468	0.1421	
popden	-7.17547	0.42725	0.42734	16.791	< 2e-16	***
ruggedness	-0.29885	0.06299	0.06300	4.744	2.10e-06	***
slope	0.70541	0.32050	0.32057	2.201	0.0278	*

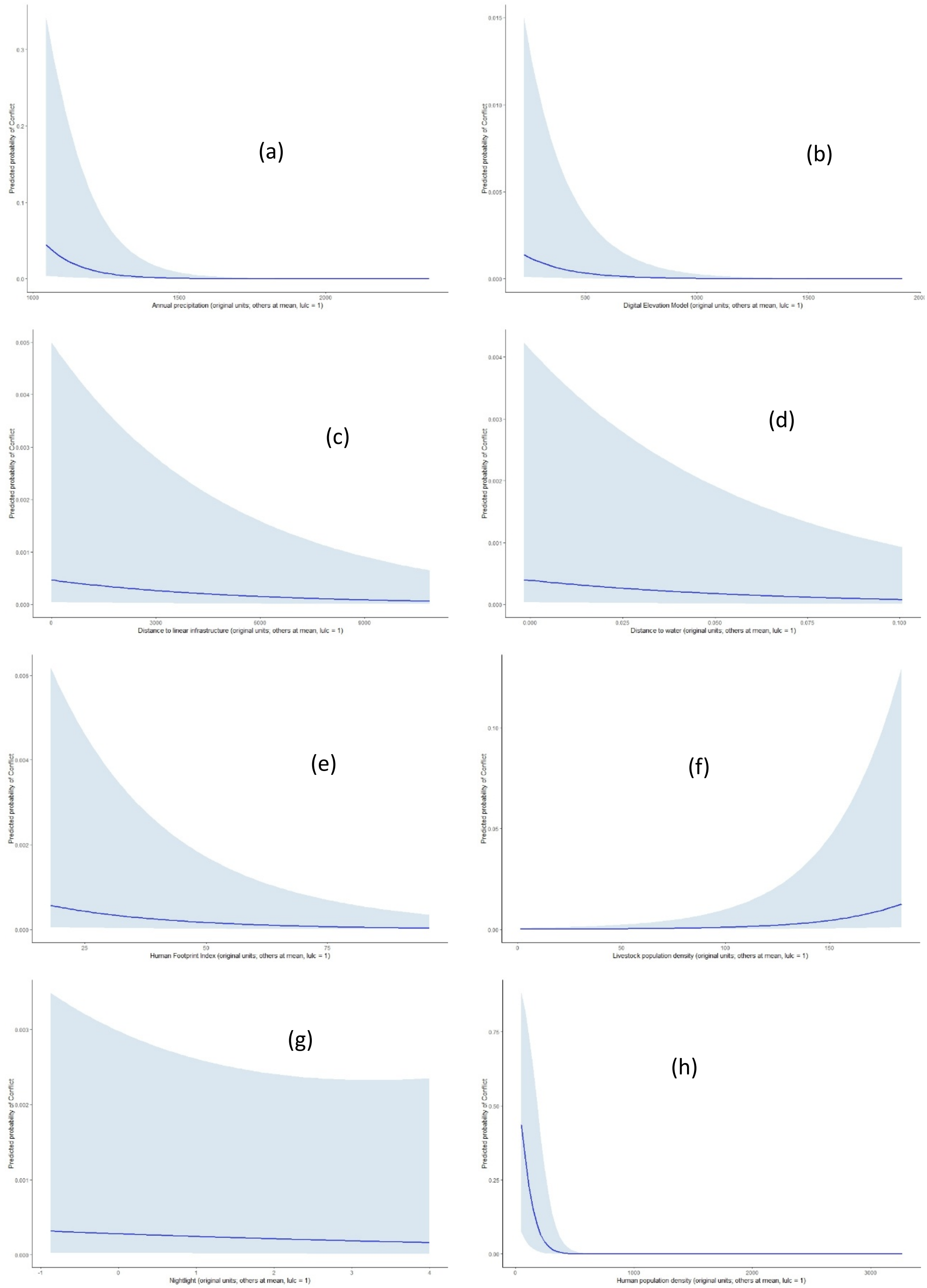

Figure 3.7. Predictive graphs showing relationship between conflict locations and (a) annual precipitation, (b) Digital Elevation Model, (c) distance to linear infrastructure, (d) distance to water, (e) Human Footprint Index, (f) livestock population density, (g) nightlight, and (h) human population density for livestock depredation by tigers in the study area

DISCUSSION

The state of Uttarakhand – as part of the larger Terai Arc Landscape – has witnessed local increases in the populations of large carnivores, especially large cats viz., tigers and leopards (Qureshi et al., 2023; Qureshi et al., 2024). This has occurred with a simultaneous rise in human populations, leading to increased interface between people and large predators. The result has been a surge in the reports of conflict incidents from various parts of the state.

The maximum incidents of attacks on humans reported in recent years were due to tigers (~45%), followed by leopards (~29%) and bears (~26%). Meanwhile the number of livestock depredation incidents were more due to leopards (~81%) than tigers (~19%).

Elevation gradient in the study area was one of the major drivers of human conflict with bears in the study area. Bears are prone to persisting around human settlements at higher elevations where natural food resources may be scarce and anthropogenic food subsidies would play a significant role (Lamb et al., 2020; Pokharel et al., 2022). Increase in livestock population densities and decreasing human population densities lead to increased probability of bear attacks on people. This is expected since human population densities decrease with increasing elevation (Takahata et al., 2013; Pokharel et al., 2022).

More than 30% of the human injuries and deaths in the state of Uttarakhand in the past 5 years have been due to leopards, despite a decline in their population (Qureshi et al., 2024). Similar to the findings of Naha et al. (2018), our study identified elevation as a significant driver of leopard attacks on people. The chance of encounter between people and leopards decreases away from linear infrastructure, leading to a decrease in conflict probability with increased distance from linear infrastructure (Sondhi et al., 2016). Despite being considered an intrusive predator, anthropogenic factors did not significantly influence the probability of leopard attacks on people (Malviya & Ramesh, 2015).

On the other hand, with their propensity to avoid anthropogenic disturbances, an increase in human population density led to a decrease in the probability of tiger attacks on people (Kanagaraj et al., 2011). However, increased nightlight & livestock population density led to an increase in the chances of attacks by tigers (Chatterjee et al., 2022). As observed by Chatterjee et al. (2022) in Dudhwa and Pilibhit Tiger Reserves, the probability of attacks increased significantly as the distance from PAs decreased. Additionally, our study identified distance from linear infrastructure as a significant driver, with increased distance from roads and railway decreasing the probability of attack.

Livestock depredation by leopards was significantly influenced by 9 of the 12 covariates. A study by Sondhi et al. (2016), highlighted the importance of local perception, where the majority of the respondents felt there had been an increase in conflict with leopards in recent years. This study finds the significance of habitat types, including forest, scrubland, barren land, and waterbodies, similar to our study, which finds the importance of LULC in influencing conflict. These results vary from the study by Naha et al. (2020) where it was found that landscape variables were not significant drivers of livestock depredation by leopards in the Himalayan region. Anthropogenic variables have a negative relationship with livestock depredation, indicating that while leopards are highly adaptable and able to survive proximal to human settlements, increased anthropogenic disturbance is not conducive to hunting, as has been found in leopard habitats across the country (Miller et al., 2015; Yadav et al., 2024). Higher terrain elevation and ruggedness in the study area have a higher probability of depredation by leopards, since more livestock availability in higher altitudes (Kotru, 2011). PAs and water sources contain common resources for both predator and livestock, whereas linear infrastructure represents shared spaces for the two. Thus, depredation was more likely to occur closer to shared resources, unlike the results from Pauri Garhwal given in Naha et al. (2020).

Preferred habitat factors for tigers include low human disturbance (Karanth & Sunquist, 2000). Thus, the probability of overlap between predators and livestock is low in areas with high anthropogenic disturbances. However, as expected, increased livestock population densities lead to an increased possibility of depredation by tigers. The possibility of livestock depredation is also higher in close proximity to linear infrastructure and water sources; however, our study did not identify distance to PA as a significant driver of depredation by tigers, as have been identified by studies from various tiger habitat states (Ramesh et al., 2020; Malviya & Ramesh, 2022). Unlike leopards, livestock depredation by tigers was higher in low elevation and less rugged terrain, which might be because tiger presence is high in the PAs in low elevational regions of the state.

The results of our study highlight the variations in trends and drivers of conflict with each large carnivore in the study area. These surges in conflict incidents have severe socio-economic and ecological consequences. It has, thus, become increasingly essential to understand the trends and drivers of large carnivore conflict in the state in order to develop effective and sustainable mitigation strategies to counteract the effects of large carnivore conflict.

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CHAPTER 4: EVALUATION OF EXISTING MANAGEMENT PRACTICES FOR LARGE MAMMAL CONSERVATION IN RAJAJI NATIONAL PARK AND THE SURROUNDING LANDSCAPE

INTRODUCTION

Effective conservation in today's complex landscapes demands more than legal protection; it requires adaptive management, systematic monitoring, and the active involvement of local communities. Globally, frameworks such as the IUCN's Management Effectiveness Evaluation (MEE) and guidance from the World Commission on Protected Areas (WCPA) emphasise these principles, highlighting the need to link scientific evidence with institutional practice and to iteratively refine management strategies based on observed outcomes (Chen et al., 2022; Hoffmann, 2021). In India, where large carnivores such as tigers and leopards require extensive territories, protected areas alone are insufficient. Landscape-scale planning (beyond protected areas), ecological connectivity, and the coordinated management of adjoining territorial divisions have become central to maintaining viable populations and resilient ecosystems (Kumar et al., 2020; Reddy et al., 2017; Rodrigues & Cazalis, 2020).

The Terai Arc Landscape (TAL), stretching across northern India and Nepal, exemplifies these challenges. It is a mosaic of Protected Areas, reserve forests, corridors, and human-dominated landscapes, supporting diverse assemblages of large mammals, herbivores, and avifauna. Rajaji Forest Division, one of the key sites in the western TAL, has been the focus of sustained conservation interventions aimed at restoring ecological integrity. Initiatives such as the resettlement of pastoralist communities, habitat restoration, systematic fire management, and the revival of critical corridors like Chilla–Motichur have contributed to improvements in prey populations and the gradual recovery of tiger populations (Geldmann et al., 2019; Karanth & Nepal, 2012). These measures reflect a broader recognition that the persistence of apex predators is intricately linked to the health of the wider landscape and the functioning of ecological networks.

Despite these interventions, the western TAL continues to face significant ecological and socio-political pressures. Habitat fragmentation due to infrastructure development, encroachment, invasive species such as *Lantana camara*, and intensifying human–wildlife conflict challenge the long-term effectiveness of management actions

(Srivathsa et al., 2023; Das, 2024). Human communities living within and adjacent to forested areas are both affected by and influential in shaping conservation outcomes, underscoring the need for participatory approaches that integrate local knowledge, address conflict, and foster co-existence. These dynamics highlight that even well-planned interventions require sustained monitoring, flexible adaptation, and effective coordination between Protected Area authorities and territorial forest divisions.

In this context, structured evaluation tools such as the National Tiger Conservation Authority's MEE framework provide a critical lens to assess management performance. By evaluating planning, inputs, processes, and outputs, MEE highlights both strengths and areas needing improvement, offering actionable recommendations for adaptive management. These assessments, when integrated with ecological research and analyses, provide a nuanced understanding of conservation effectiveness, moving beyond simple measures of population recovery to consider broader ecosystem integrity and human dimensions. Research from the TAL reinforces the importance of corridors, ecosystem connectivity, and proactive conflict mitigation, revealing that conservation success depends on strategies that are both site-specific and landscape-oriented.

This chapter presents a comprehensive evaluation of management effectiveness in Rajaji Forest Division and its adjoining territorial divisions within the western TAL. Drawing on MEE assessments and ecological studies, it examines patterns of performance, identifies persistent challenges, and highlights opportunities to strengthen conservation outcomes. The discussion emphasises the need to move beyond generic management prescriptions, advocating for adaptive, evidence-driven strategies that integrate scientific research, stakeholder participation, and institutional strengthening. In doing so, it lays the foundation for understanding how conservation in the western TAL can be sustained over the long term, ensuring the persistence of large mammal populations, ecological connectivity, and the resilience of this critical landscape.

METHODOLOGY

Study Framework

The evaluation of management practices in the Western Terai Arc Landscape (TAL) was carried out using the Management Effectiveness Evaluation (MEE) framework developed by the International Union for Conservation of Nature (IUCN) and adapted by the National Tiger Conservation Authority (NTCA) and the Wildlife Institute of India (WII) for Indian tiger reserves (Yadav et al., 2022). The framework assesses management performance across six broad elements: context, planning, inputs, processes, outputs, and outcomes and provides a structured mechanism to identify strengths and gaps in conservation practice.

While the MEE methodology was designed primarily for Tiger Reserves, it was applied here to assess adjoining territorial divisions to facilitate comparative evaluation across the western TAL. This introduces certain methodological limitations, as these divisions are managed under the legal status of Protected Forests or Reserved Forests**,** with differing administrative mandates, budgetary priorities, and management objectives compared to Tiger Reserves. Consequently, not all parameters of the NTCA's MEE framework, such as tourism management, staff welfare schemes, or core-buffer delineation, were directly applicable. Despite these constraints, using a standardised framework allowed for a consistent, comparative assessment of management effectiveness across the landscape.

Additionally, the scoring process relied partly on available management records and field observations, which may introduce subjectivity in certain indicators. To minimise this, cross-verification of data was undertaken wherever possible, and scores were moderated.

Data Collection

The MEE exercise was conducted for Rajaji Forest Division and adjoining territorial divisions (Dehradun, Lansdowne, Kalsi, Shivalik, Haridwar) that form critical components of the Western TAL (Supplementary S3). Data were collected from three main sources:

1. **Working Plans and Tiger Conservation Plans–** Forest Department working plans and tiger conservation plans (TCPs) were reviewed to extract information on management objectives, prescriptions, staffing patterns, and budget allocations.
2. **Field Records and Secondary Data–** Records of human–wildlife conflict, fire incidents, invasive species removal, and corridor restoration efforts were obtained and analysed.

3. **Primary Evaluation and Scoring**– Each MEE element was scored based on structured indicators using NTCA's standard evaluation protocol. Scores were assigned for individual indicators across divisions and normalised against maximum possible scores to derive element-wise and site-level percentages.

Analytical Approach

- **Scoring and Ranking:** Site-specific scores were aggregated to generate comparative rankings across divisions. A "descending order" analysis was prepared to identify the best and worst performing divisions.
- **Element-wise Analysis:** Scores were grouped under five major elements (context, planning, input, process, and output). This allowed identification of management components that performed relatively strongly (e.g., planning, input) versus those that lagged (e.g., process, output).
- **Indicator-wise Analysis:** Selected critical indicators—such as stakeholder participation, management of biotic pressures, habitat restoration, and conflict mitigation—were examined individually to highlight specific areas of weakness.
- **Additional Criteria:** To supplement the NTCA framework, additional parameters relating to habitat degradation, encroachment, invasive species status, and habitat recovery were also scored qualitatively (rated as *poor, fair, or good*). These provided a broader ecological perspective to complement institutional performance.

Data Handling and Visualisation

All data were compiled and analysed in Microsoft Excel 2021 for basic descriptive statistics and visualisation. Comparative charts and ranking tables were prepared to highlight variation in management effectiveness across divisions.

RESULTS AND DISCUSSION

Division-wise MEE Scores

The MEE exercise across Rajaji Forest Division and adjoining territorial divisions (Dehradun, Lansdowne, Kalsi, Shivalik, Haridwar) revealed moderate but consistent levels of management effectiveness. Scores ranged narrowly from 66.41 (Kalsi) to 68.97 (Dehradun), with Lansdowne (68.75), Rajaji (67.19), and Shivalik (67.17) occupying intermediate positions. The average MEE score across all sites was 67.70%, indicating a generally stable management performance across the landscape. Notably, Rajaji Tiger Reserve achieved a score of 68.94% in the national MEE of Tiger Reserves conducted in 2022, underscoring the consistency of findings between the present assessment and the official NTCA–WII evaluation.

The clustering of scores in the mid-60s suggests that while fundamental management systems are in place, none of the sites are achieving high levels of effectiveness. This aligns with national MEE reports, which often rate Protected Areas in India as “fair” or “good” but highlight significant scope for improvement (Shah et al., 2021). As shown in Figure 4.1**,** Dehradun and Lansdowne divisions recorded the highest management effectiveness scores, while Kalsi lagged behind.

A detailed breakdown of element-wise performance across divisions is presented in Table 4.1, which highlights variations in specific management components such as planning, input allocation, and process implementation. This comparative matrix illustrates that while planning and input scores remain relatively strong, process and output elements continue to constrain overall management effectiveness in several divisions.

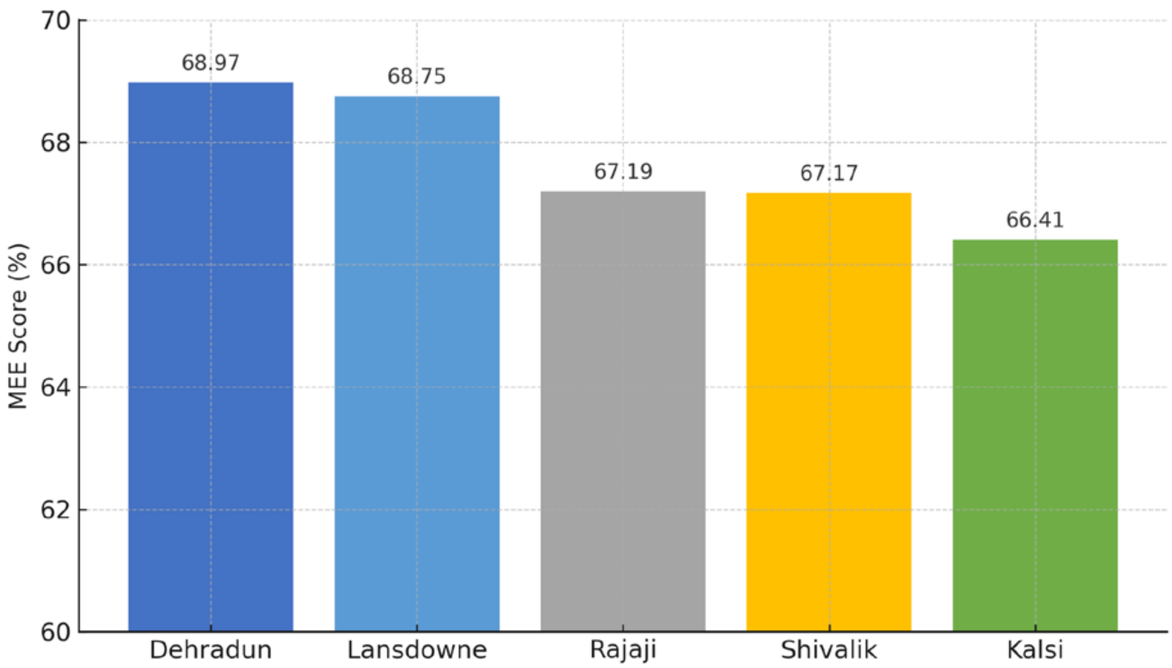

Figure 4.1. Division-wise Management Effectiveness Evaluation (MEE) Scores across Rajaji Forest Division and adjoining divisions.

Table 4.1. Element-wise MEE Scores across Divisions

Elements	Kalsi	Lansdowne	Rajaji	Shivalik	Haridwar	Dehradun
Context	6.67	6.67	7.5	5.0	7.5	5.83
Planning	7.78	8.06	6.39	6.79	6.39	7.22
Input	5.83	6.25	7.08	7.92	7.5	6.67
Process	5.5	6.0	6.0	8.0	6.0	8.13
Output	7.5	6.88	5.63	5.63	5.63	6.67
Outcome	6.0	6.5	8.0	7.0	6.0	6.25

Overall element-wise performance

Disaggregated analysis revealed variation across the five evaluation elements. Planning (68.52) and Inputs (68.75) received relatively higher scores, reflecting the availability of documented management plans, budget allocations, and staffing provisions. By contrast, Processes (65.17) and Outputs (62.92) scored lower, indicating weaknesses in implementation and outcome delivery. For example, while invasive species removal and fire management are included in management plans, monitoring and post-treatment follow-up remain inconsistent, limiting ecological recovery. These findings mirror global critiques of Protected Area management, where planning often outpaces implementation (Geldmann et al., 2019). Figure 4.2 illustrates that planning and input elements performed better than processes and outputs, indicating strong institutional frameworks but weaker implementation mechanisms. This gap suggests that while planning structures are robust, the translation of strategies into measurable field outcomes remains limited.

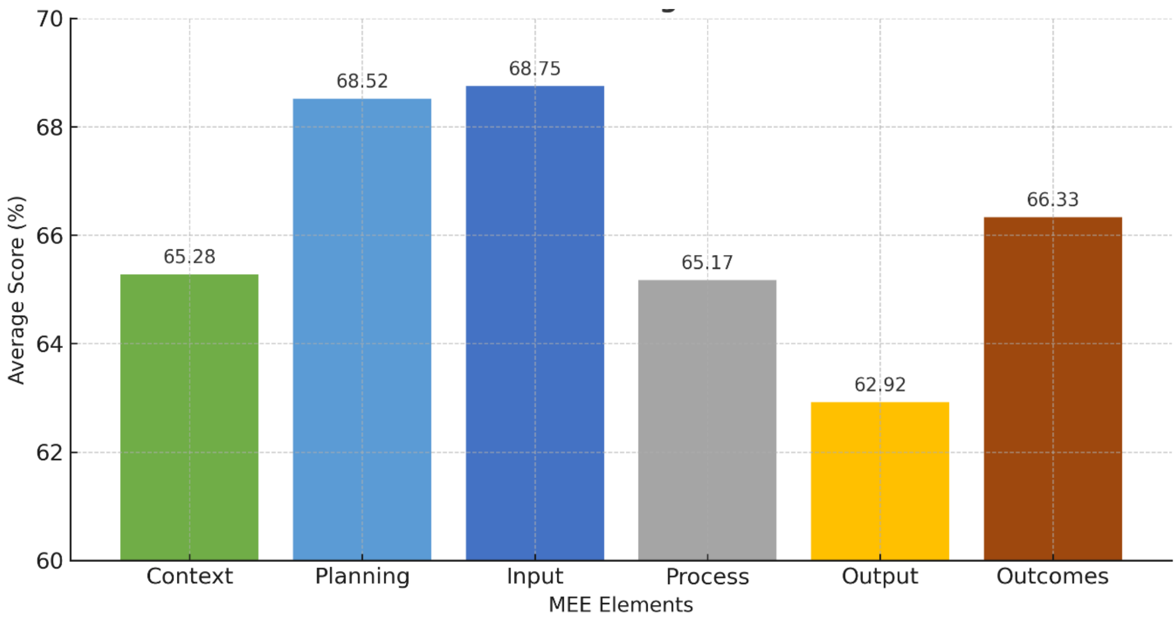

Figure 4.2. Overall element-wise average MEE scores highlight variation in management performance across planning, inputs, processes, and outputs.

Indicator-wise Insights

Indicator-level analysis pointed to specific areas of weakness. Indicators related to control of biotic pressures, stakeholder participation, and conflict mitigation consistently received low scores. In particular, stakeholder engagement mechanisms were poorly developed across divisions, confirming earlier observations that community participation in TAL remains limited to consultation rather than genuine co-management (Reddy et al., 2017; Das, 2024). By contrast, indicators linked to documentation of site values and law enforcement capacity scored comparatively higher, suggesting that baseline ecological knowledge and patrolling systems are relatively robust. The comparative scores and their distribution across elements are illustrated in Figures 4.1 and 4.2. These visual patterns highlight the consistency of moderate performance across divisions while revealing clear deficiencies in process and output indicators.

Additional Criteria: Habitat and Threats

Supplementary evaluation criteria provided further ecological insights. Habitat degradation was generally rated “fair,” with invasive species infestations widespread across grasslands and forest edges. Encroachment and settlement pressures were reported as “poor” to “fair” in divisions such as Shivalik and Dehradun, where expanding villages and cultivation continue to erode habitat quality. Fire management and recovery status varied, with Dehradun performing relatively better due to recent fire-prevention initiatives. These patterns underscore that while protection in core areas is relatively effective, peripheral habitats and corridors remain vulnerable to anthropogenic pressures.

Linking Results to Broader Literature

The findings corroborate regional studies that identify corridor disruption, invasive species, and conflict as the dominant challenges in the western TAL (Srivathsa et al., 2023; Kumar et al., 2020). The relatively high planning scores contrast with persistent gaps in outputs, echoing critiques of NTCA's MEE framework that emphasise strong prescriptions but weak follow-through (Shah et al., 2021). Similarly, low stakeholder participation aligns with global evidence that participatory management remains underutilised in South Asia despite its proven effectiveness in other landscapes (Oldekop et al., 2016).

Discussion of Key Trends

Overall, the MEE results suggest that management effectiveness in the western TAL is functional but fragile. The presence of well-documented plans and resource inputs demonstrates institutional commitment, yet ecological outcomes are compromised by weak processes, limited community involvement, and inadequate corridor management. The narrow score range across divisions implies systemic constraints rather than isolated failures, pointing to governance-level issues that cut across both Protected Areas and territorial divisions. These findings reinforce the need for integrated, adaptive approaches that combine ecological restoration with institutional strengthening and community partnerships.

KEY MANAGEMENT GAPS AND CHALLENGES

The results of the MEE exercise highlight a number of persistent gaps that constrain conservation effectiveness in the western TAL. While legal protection, management planning, and the allocation of resources are largely in place, several systemic and ecological challenges continue to undermine outcomes. These challenges are both structural, arising from institutional arrangements and governance, and ecological, linked to habitat quality and species interactions.

Habitat Degradation and Fragmentation

Across divisions, habitat degradation was consistently rated “fair,” with evidence of invasive species such as *Lantana camara, Parthenium hysterophorus,* and *Chromolaena odorata* limiting natural regeneration. Fragmentation from linear infrastructure, including highways, railways, and canals, further disrupts habitat integrity and impedes species movement. Although Rajaji and its adjoining divisions have initiated corridor restoration efforts, MEE scores indicate that these interventions remain partial and inconsistent.

Encroachment and Settlements

Encroachment and illegal settlement pressures were assessed as “poor” to “fair” in several divisions, particularly Shivalik and Dehradun. Human habitation, grazing, and fuelwood collection within forest areas continue to erode habitat quality and exacerbate human–wildlife conflict. The relocation of Van Gujjar pastoralist communities from Rajaji has reduced some direct pressures, but incomplete resettlement and new encroachments persist.

Invasive Species and Fire Regimes

Invasive species infestation was generally rated as “fair,” indicating widespread but uneven management attention. Fire management strategies exist but are often reactive rather than preventive, with prescribed burning and post-fire monitoring inadequately implemented. These issues contribute to recurring habitat degradation, particularly in grassland ecosystems crucial for ungulates.

Weaknesses in Process and Output Indicators

The element-wise breakdown revealed that while planning and inputs are relatively strong, processes (65.17) and outputs (62.92) lag behind. This suggests that working plans and TCPs are not being translated into measurable ecological outcomes. For example, while conflict mitigation programs are mentioned in plans, on-ground implementation remains limited, with compensation systems slow and community engagement mechanisms weak.

Human–Wildlife Conflict

Conflict incidents, particularly livestock depredation by leopards and crop damage by elephants, remain one of the most pressing challenges. While the forest department maintains records of such cases, the absence of a unified monitoring and rapid response system undermines timely action. Public perception surveys and MEE indicator scores further reveal low levels of stakeholder participation in decision-making, limiting trust and cooperation between local communities and management authorities.

Institutional and Governance Constraints

Management overlaps between territorial divisions and Protected Areas create inconsistencies in implementation. While tiger reserve areas benefit from NTCA monitoring and funding, adjoining territorial forests face resource constraints despite playing critical roles as buffer and corridor habitats. MEE scores for Dehradun and Lansdowne demonstrate better performance where institutional capacity is stronger, but gaps persist across divisions due to limited staff training, funding shortfalls, and fragmented coordination.

Taken together, these gaps underscore the need for site-specific, adaptive strategies that not only address ecological restoration but also strengthen institutional processes and local participation. Unless these challenges are systematically addressed, the potential of the western TAL to sustain viable populations of tigers, elephants, and other large mammals will remain compromised.

MANAGEMENT IMPLICATIONS

1. Rajaji Forest Division

- **Corridor Restoration:** Fully restore the Chilla–Motichur corridor by relocating remaining settlements and the ammunition dump, removing debris, and regulating vehicular movement through flyovers.
- **Species-specific Management:** Strengthen post-translocation monitoring of tigers through MSTrIPES and camera traps; secure elephant corridors with mitigation against road/rail mortality.

- **Habitat Recovery:** Undertake systematic *Lantana camara* removal, coupled with multi-year grassland and native forest restoration.
- **Conflict Mitigation:** Restrict evening human activity in high-risk zones and strengthen primary response teams to reduce overlaps with elephant and leopard movement.

2. Dehradun Division

- **Encroachment Control:** Address expansion of settlements and agricultural edges near forests through strict anti-encroachment measures.
- **Corridor Integration:** Secure corridors linking Dehradun with Rajaji and Mussoorie Wildlife Sanctuary by reducing fragmentation from highways and canals.
- **Fire Management:** Build on relatively strong fire-prevention programs by scaling prescribed burning and involving local communities in early warning.
- **Conflict Response:** Develop a rapid-response mechanism for elephant crop raids, including early warning systems and community patrolling.

3. Lansdowne Division

- **Connectivity Strengthening:** Prioritise corridors linking Lansdowne with Rajaji and Corbett, given its central role in landscape connectivity.
- **Community Partnerships:** Promote eco-tourism and livelihood alternatives (handicrafts, honey, eco-guides) to reduce grazing and NTFP pressures.
- **Invasive Management:** Expand invasive species removal from key grasslands, followed by long-term monitoring to ensure recovery.
- **Capacity Building:** Train frontline staff in conflict mitigation and corridor monitoring, strengthening the division’s role as a buffer for Rajaji.

4. Kalsi Division

- **Habitat Restoration:** Kalsi scored lowest in MEE; priority must be invasive control, erosion prevention, and riparian habitat restoration.
- **Corridor Security:** Protect corridors linking Kalsi with Shivalik and Rajaji to maintain genetic exchange for large carnivores.

- **Community Involvement:** Launch awareness programs targeting livestock owners to minimise predation risk and improve compensation uptake.
- **Monitoring:** Establish a systematic database of conflict cases and habitat interventions to improve adaptive management.

5. Shivalik Division

- **Encroachment Reduction:** Encroachment and grazing remain acute; targeted relocation and stricter enforcement are essential.
- **Corridor Protection:** Secure the Chillawali–Shivalik corridor by regulating human use and strengthening patrolling.
- **Conflict Mitigation:** Develop local "conflict response teams" modelled on Tadoba's Primary Response Teams to improve community trust.
- **Invasive and Fire Control:** Implement integrated fire management and invasive species programs, linking them with employment for local youth.

6. Haridwar Division

- **Conflict Hotspots:** Prioritise conflict mitigation in crop depredation zones near villages adjoining the Ganga and Suswa corridors.
- **Riverine Corridor Protection:** Strengthen the ecological health of river corridors that are vital for elephants and ungulates.
- **Urban Pressure Management:** Haridwar faces unique pressures from pilgrimage and urban expansion; collaboration with local municipalities is critical to manage waste, traffic, and habitat disturbance.
- **Eco-tourism Potential:** Harness religious tourism to promote conservation-linked awareness programs, positioning Haridwar as a model for urban–forest coexistence.

A synthesis of division-specific gaps and corresponding management recommendations is presented in Table 4.2.

Table 4.2. Summary of key gaps and management implications for Rajaji Forest Division and adjoining divisions.

Division / Reserve	Key Gaps Identified	Management Implications
Rajaji Forest Division	Corridor disruption (Chilla–Motichur), invasive species, conflict overlaps, weak post-translocation monitoring	Restore corridor (relocation, debris clearance, regulate vehicles), strengthen tiger & elephant monitoring, systematic invasive removal with long-term recovery, restrict evening human activity, primary response teams for conflict
Dehradun Division	Encroachment, corridor fragmentation, recurring fire, elephant crop raids	Anti-encroachment drives, secure Rajaji–Mussoorie corridors, expand fire-prevention & community early warning, rapid-response teams for elephant raids
Lansdowne Division	Corridor vulnerability, grazing pressure, invasive spread, limited staff capacity	Strengthen Rajaji–Corbett connectivity, promote eco-tourism & alternative livelihoods, expand invasive removal & monitoring, staff training for conflict mitigation
Kalsi Division	Lowest MEE score, habitat degradation, corridor insecurity, weak conflict records	Habitat & riparian restoration, protect Kalsi–Rajaji–Shivalik corridors, livestock depredation awareness + fast compensation, build conflict & habitat intervention database
Shivalik Division	High encroachment & grazing, weak corridor protection, recurring conflict, invasive/fire pressures	Relocation/strict enforcement, protect Chillawali–Shivalik corridor, community-led conflict response teams, integrated fire + invasive control with youth employment
Haridwar Division	Conflict hotspots (crop raids), corridor disturbance (Ganga, Suswa), urban/ pilgrimage pressures, weak eco-tourism linkages	Target high-risk conflict zones, strengthen riverine corridors, collaborate with municipalities for waste & traffic management, eco-tourism & conservation awareness linked to religious tourism

WAY FORWARD

- **Landscape-Level Management**
  - The five territorial divisions adjoining Rajaji—Dehradun, Lansdowne, Kalsi, Shivalik, and Haridwar—form one continuous ecological landscape.
  - They should be managed as a single functional unit rather than fragmented administrative entities.
  - Implementing a common MEE framework across these adjoining divisions will facilitate standardised evaluation, cross-learning, and consistent performance tracking.
- **Interlinked Working Plans**
  - Divisional working plans must be interconnected, mutually dependent, and designed to inform one another.
  - This will ensure consistency in habitat management, corridor restoration, and conflict mitigation across the western TAL.
- **Internalised MEE Exercises**
  - The MEE framework should evolve from being an externally driven five-year cycle to internal, continuous evaluations by divisions themselves.
  - Regular use of MEE-style indicators at the divisional level can enhance adaptive learning and accountability.
- **Revenue and NTFP Dimensions**
  - Territorial forests generate revenue from timber, tourism, and related activities, yet this aspect is not assessed in current MEE exercises.
  - Future evaluations must integrate revenue generation and its influence on conservation priorities.
  - Sustainable **non-timber forest product (NTFP) collection** should be explicitly incorporated into management plans, recognising its importance for local livelihoods and forest-based economies.
- **Rajaji Forest Division**

- Consolidate the gains from tiger translocation by fully restoring the Chilla–Motichur corridor (relocating settlements and ammunition dumps, removing debris, regulating vehicular traffic through flyovers).
- Strengthen post-release monitoring of tigers using MSTrIPES and camera traps.
- Enhance elephant corridor security against road and railway mortality.
- Undertake systematic removal of *Lantana camara* and other invasives, with multi-year native vegetation restoration.
- Restrict evening human activity in high-risk elephant and leopard movement zones.
- Expand conflict mitigation through Primary Response Teams.

- **Territorial Divisions (Dehradun, Lansdowne, Kalsi, Shivalik, Haridwar)**
    - Align working plans with wildlife conservation and corridor needs, not just timber objectives.
    - Strengthen community engagement through eco-tourism, benefit-sharing, and fast-track compensation systems.
    - Establish preventive fire regimes (prescribed burning, community early-warning systems).
    - Expand invasive species management from ad-hoc removal to long-term monitoring.
    - Institutionalise division-level MEE assessments for continuous monitoring.
- **Elephant Reserves and Corridors**
    - Address rail and road collisions, especially along the Dehradun–Haridwar line, through underpasses, sensor-based alert systems, and speed regulations.
    - Protect the Song, Suswa, and Ganga corridors through anti-encroachment measures and habitat restoration.

- Pilot conflict management tools—early warning systems, grain banks, and coordinated night patrolling—in high-conflict villages.
- Mainstream elephant reserve management into state forest planning**,** ensuring funding is not restricted to tiger-centric programs.

- **Cross-Cutting Strategies for the Western TAL**
  - **Species- and site-specific planning:** Move beyond generic prescriptions; prepare micro-plans for high-risk zones and flagship species.
  - **Institutional strengthening:** Build capacity of frontline staff in conflict response, habitat restoration, and use of technology.
  - **Community partnerships:** Develop trust through livelihood programs (honey production, handicrafts, eco-tourism) to reduce forest dependence.
  - **Integrated governance:** Foster coordination between Protected Area managers, territorial divisions, and development agencies (MoRTH, Railways, Irrigation).
  - **Climate resilience:** Incorporate climate-adaptive restoration anticipating shifts in rainfall, fire frequency, and crop depredation patterns.

In summary, the findings from the MEE exercise reveal that management effectiveness in the western TAL is functional but fragile, characterised by strong planning frameworks but weaker implementation and ecological outcomes. The discussion underscores that addressing systemic issues requires a transition from generic, protection-centric approaches to adaptive, evidence-driven strategies that integrate ecological science, community participation, and institutional strengthening. The management implications and way forward outlined above provide a pathway to secure connectivity, reduce conflict, and balance biodiversity conservation with human well-being, ensuring the long-term resilience of this critical Himalayan foothill landscape.

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CHAPTER 5: SYNTHESIS AND CONCLUSION

The Western Terai Arc Landscape (TAL) represents one of India's most critical conservation frontiers where ecological connectivity, large mammal persistence, and human livelihoods intersect. Across its mosaic of Protected Areas, territorial divisions, and human-dominated zones, conservation outcomes are shaped by the interplay between habitat continuity, species ecology, and governance mechanisms. This thesis, structured around four interlinked components, provides an integrative assessment of habitat connectivity, wildlife corridor functionality, human–large carnivore conflict, and management effectiveness in and around Rajaji National Park (RNP). This chapter discusses the major findings from each chapter within the broader ecological and management context of the Terai Arc Landscape.

LANDSCAPE CONNECTIVITY AND WILDLIFE MOVEMENT

The analysis of corridors (Chapter 2) reaffirmed the pivotal role of ecological linkages in sustaining viable populations of wide-ranging species such as elephants and tigers within the Western TAL. Camera-trap and sign survey data from four key corridors – Chilla–Motichur, Teenpani, Laltappar, and Chillawali–Shiwalik – demonstrated that wildlife continues to use these linear habitats, albeit under increasing anthropogenic pressure. While species richness was lower in corridors compared to adjoining forests (9 vs. 17 species), relative abundance indices (RAI) indicated continued use of these linkages by leopards, elephants, chital, and sambar. The Chillawali–Shiwalik corridor emerged as a critical western linkage connecting Rajaji to the Shiwalik Forest Division of Uttar Pradesh and onward to Kalesar Wildlife Sanctuary in Haryana, underscoring its strategic value for long-term gene flow (see Chapter 2).

Temporal activity analyses revealed behavioural adaptations by species to human presence, with elephants exhibiting nocturnal shifts in corridors and leopards reducing daytime activity to avoid human overlap. Such patterns mirror findings from other fragmented landscapes (Benítez-López et al., 2010; Chakraborty et al., 2021) and emphasise that infrastructural mitigation, while beneficial, cannot fully substitute for natural connectivity. The successful movement of a tiger through the newly constructed Chilla–Motichur underpass highlights both the success of recent mitigation infrastructure and the necessity of maintaining these structures through consistent monitoring and restoration (Nigam et al., 2022).

Together, these results demonstrate that while wildlife crossings improve local permeability, ecological connectivity at the landscape scale remains contingent on habitat quality, disturbance regulation, and long-term management commitment. The integration of underpass design with ecological restoration, as emphasised by Holderegger & Di Giulio (2010) and van der Ree et al. (2015), should therefore form the foundation of future connectivity planning in the TAL.

HUMAN–CARNIVORE CONFLICT DYNAMICS

Chapter 3 examined the extent and drivers of human–large carnivore conflict across Uttarakhand, focusing on Rajaji and adjacent divisions. Using twelve years of verified compensation data (2012–2024) and spatial covariates, the study identified species-specific and landscape-level predictors of conflict. The results indicated that tigers, leopards, and bears together accounted for 65 human injury/death cases and over 3,200 livestock depredation incidents during the period of study. While tigers were responsible for most human attacks (~45%), leopards caused the majority of livestock losses (~81%), a pattern consistent with their broader dietary niche and tolerance of human-modified habitats (Ranjan et al., 2024; Naha et al., 2020).

Elevation, proximity to linear infrastructure, and human population density emerged as the key predictors of conflict, though their influence varied by species. Bear attacks were more frequent in higher altitudes with low human density and high livestock presence, reflecting seasonal foraging near settlements (Pokharel et al., 2022). Leopard attacks on humans were associated with proximity to roads and moderate human footprint, suggesting behavioural habituation to peri-urban environments (Malviya & Ramesh, 2015). Tiger attacks, in contrast, were concentrated near Protected Area boundaries and areas of high livestock density. The findings support earlier observations from the western TAL that landscape attributes – particularly terrain, human density, and infrastructure proximity – strongly mediate conflict patterns (Harihar et al., 2009; Naha et al., 2020).

Predictive modelling also indicated that livestock depredation by leopards was highest in elevated, rugged terrains and near water bodies, while for tigers it was concentrated in flatter, low-elevation zones adjacent to forests. These species-specific gradients of conflict emphasise the need for differentiated mitigation strategies: reinforcing livestock corralling and night patrolling in tiger-prone areas, and targeted awareness and deterrent programs in leopard-affected settlements. More broadly, the study highlighted that conflict is both an ecological and governance issue, reflecting the permeability of human-dominated landscapes to wildlife and the uneven implementation of compensation and prevention systems.

MANAGEMENT EFFECTIVENESS AND GOVERNANCE GAPS

Chapter 4 evaluated management practices in Rajaji Tiger Reserve and adjoining territorial divisions using the NTCA's Management Effectiveness Evaluation (MEE) framework. The results revealed moderate performance across all divisions, with scores ranging between 66 to 69%. Planning and input components – such as the existence of management plans, staffing, and financial allocations – scored highest, while process and output indicators, which reflect implementation and ecological outcomes, lagged significantly. These findings are consistent with national MEE trends that identify strong planning frameworks but weak adaptive follow-through (Shah et al., 2021).

Persistent ecological challenges included invasive species spread (notably Lantana camara), encroachment, inadequate fire management, and incomplete corridor restoration. The Chilla–Motichur corridor, despite recent underpass construction, remains partially functional due to unresolved land-use conflicts and waste accumulation (see Chapter 2). Low scores in stakeholder participation confirmed that community engagement remains primarily consultative, echoing broader critiques of participatory management in South Asia (Oldekop et al., 2016). Yet, positive signs include improved patrolling and documentation systems, successful tiger reintroduction in western Rajaji, and growing emphasis on habitat restoration in working plans.

The division-wise comparison suggested that systemic rather than site-specific constraints undermine conservation effectiveness. Dehradun and Lansdowne divisions performed marginally better due to stronger institutional capacity and active fire prevention initiatives, while Kalsi lagged due to resource limitations and weaker corridor protection. Addressing these disparities requires integrating territorial and Protected Area management under a unified landscape governance framework – an approach advocated for large mammal landscapes globally (Geldmann et al., 2019; Srivathsa et al., 2023).

CONNECTIVITY, CONFLICT, AND MANAGEMENT

The combined findings of this research underscore the interdependence between habitat connectivity, conflict mitigation, and management effectiveness. Fragmentation of corridors intensifies edge effects and human intrusion, which in turn elevates conflict frequency, further complicating management efforts. Conversely, effective landscape governance and community involvement can reduce both ecological fragmentation and social antagonism.

In Rajaji and the western TAL, wildlife corridors serve as both ecological lifelines and social fault lines. The Chilla–Motichur and Chillawali–Shiwalik corridors exemplify this duality: they sustain animal movement but are simultaneously subject to infrastructural disruption and human encroachment. The observed nocturnal shifts in elephant activity and diurnal avoidance by leopards illustrate adaptive behavioural responses to human pressures, but such plasticity has limits. Without proactive management and spatial planning, these behavioural adjustments may evolve into long-term displacement, reducing gene flow and increasing population isolation.

The conflict analysis further revealed that ecological processes and human socio-economic realities are inseparable. High conflict zones often coincide with high conservation value areas, near water sources, forest edges, and corridors, highlighting the paradox that the very landscapes essential for wildlife are those most contested by people. Thus, future management must integrate predictive conflict modelling (Chapter 3) into corridor design and restoration priorities (Chapter 2). For example, areas of high leopard depredation risk should inform livestock compensation and rapid-response teams, while elephant movement corridors should be aligned with railway mitigation designs (Carvalho et al., 2017; Gilhooly et al., 2019).

The MEE-based evaluation demonstrated that planning alone cannot ensure effective conservation; implementation mechanisms, inter-divisional coordination, and community trust are equally crucial. The consistent mid-range performance across divisions suggests the need for adaptive co-management frameworks that embed learning, monitoring, and accountability into regular practice (Reddy et al., 2017; Das, 2024). Furthermore, the findings emphasise that Protected Areas like Rajaji cannot function in isolation. The surrounding territorial forests are integral extensions of its ecological network, necessitating joint management, shared databases, and synchronised working plans.

FUTURE DIRECTIONS AND POLICY IMPLICATIONS

This thesis provides several actionable insights for strengthening conservation outcomes in the western TAL:

1. **Landscape Integration:** Management of Rajaji Tiger Reserve and adjoining divisions should shift from administrative segmentation to an integrated landscape governance model. This would facilitate coordinated corridor management, harmonised fire and invasive species control, and shared conflict mitigation protocols.

2. **Corridor Restoration:** Complete the restoration of the Chilla–Motichur and Chillawali–Shiwalik corridors by relocating remaining settlements, clearing debris, and regulating human use. Restoration should be guided by ecological monitoring and adaptive management cycles (Dutta et al., 2018).

3. **Conflict Mitigation:** Institutionalise predictive modelling of conflict risk into management plans. Integrate early warning systems, improved livestock compensation, and non-lethal deterrents to reduce retaliation and improve coexistence (Can et al., 2014; Naha et al., 2020).

4. **Participatory Management:** Strengthen community participation through co-management committees, benefit-sharing, and eco-tourism initiatives that align livelihood security with conservation goals (Karanth & Nepal, 2012).

5. **Monitoring and Technology:** Leverage remote sensing, camera-trap networks, and AI-based tools for real-time monitoring of species movement and conflict reporting. Continuous data-driven evaluation will enable adaptive decision-making.

6. **Policy Mainstreaming:** Integrate corridor and conflict management into state forest and infrastructure planning. Align these initiatives with India's National Wildlife Action Plan (2017–2031) and the Global Biodiversity Framework to ensure sustainable financing and accountability.

CONCLUSION

The Western Terai Arc Landscape remains one of India's most vital yet vulnerable ecological regions. This research demonstrates that sustaining its biodiversity requires a multifaceted strategy combining ecological science, spatial planning, and participatory governance. The study of corridor functionality established the continued, though constrained, movement of wildlife across infrastructural barriers. The analysis of human–carnivore conflict illuminated how ecological and social systems intersect to shape coexistence outcomes. Finally, the evaluation of management effectiveness revealed both institutional strengths and systemic weaknesses that determine conservation success.

In synthesis, the resilience of large mammal populations in the western TAL hinges on restoring connectivity, reducing conflict, and fostering adaptive management that bridges administrative and ecological boundaries. By integrating empirical research with management frameworks, this thesis contributes a holistic understanding of the challenges and opportunities for conserving one of India's most significant transboundary ecosystems. The lessons derived here have broader relevance for similar landscapes across South and Southeast Asia, where the future of large mammals will depend not only on Protected Area management but on our collective capacity to reweave the ecological and social fabric of shared landscapes.

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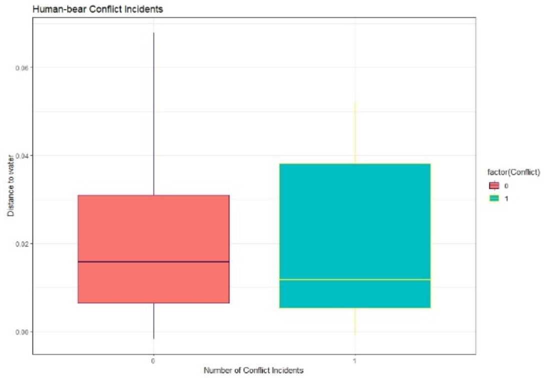
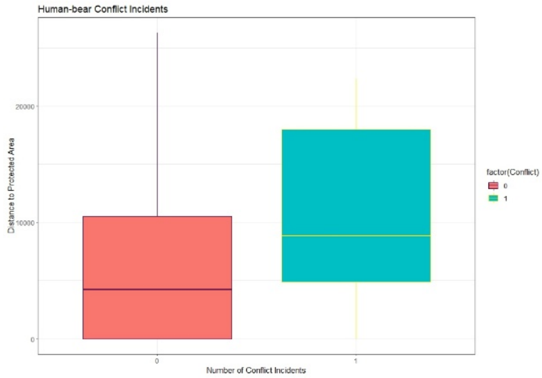
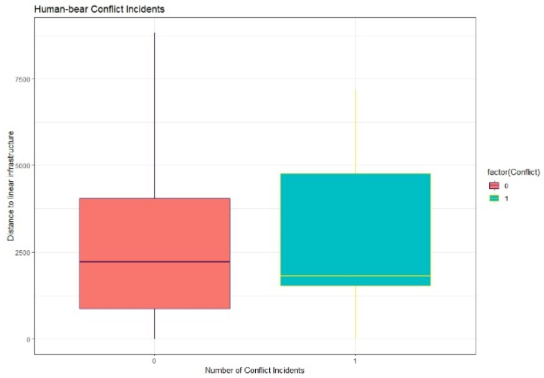
SUPPLEMENTARY FILES

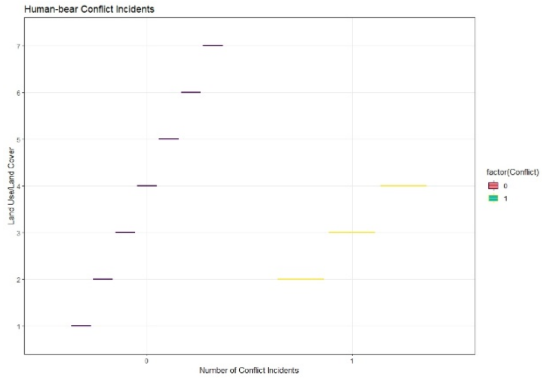
S1 – Large carnivore attacks on humans

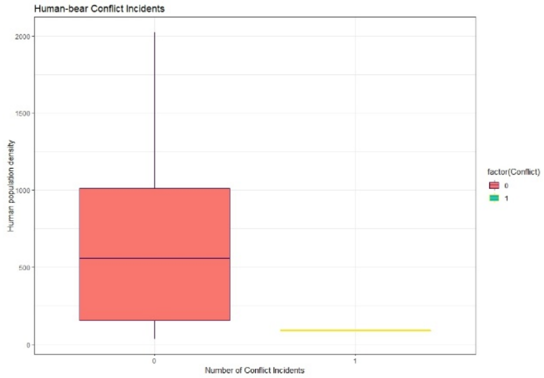
Bear attacks on humans

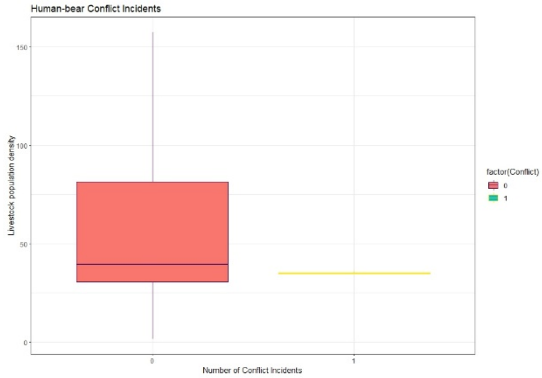


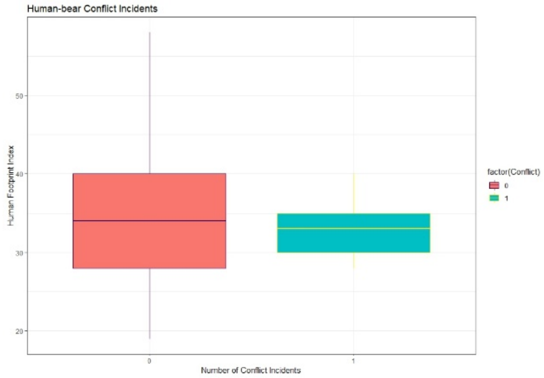


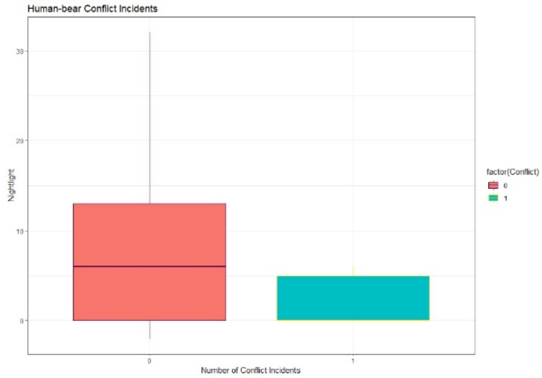


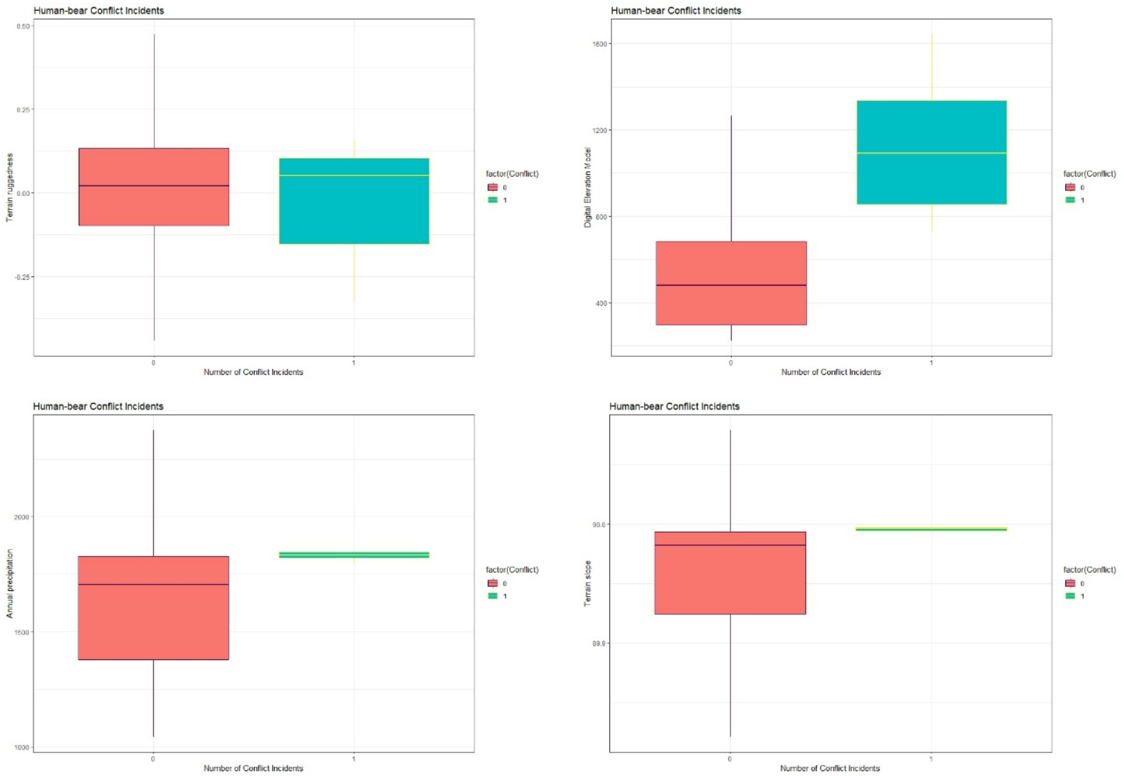




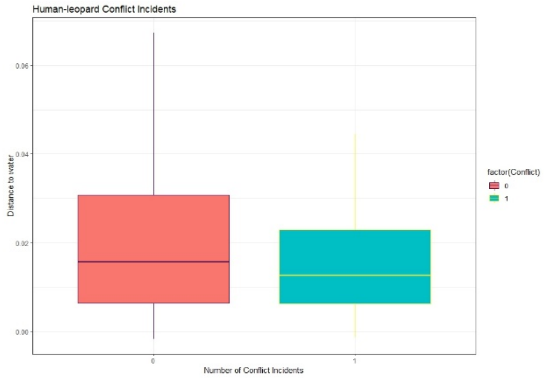


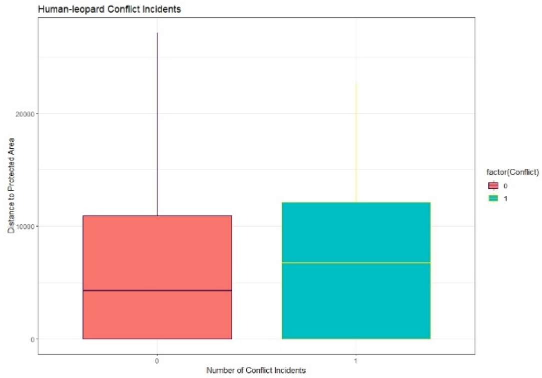


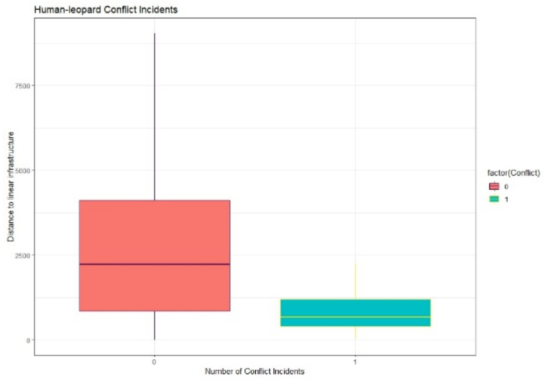


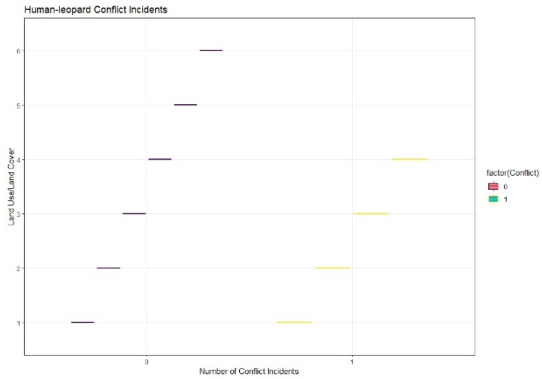

Human-bear Conflict Incidents
Terrain ruggedness
Number of Conflict Incidents
factor(Conflict)
Human-bear Conflict Incidents
Digital Elevation Model
Number of Conflict Incidents
factor(Conflict)
Human-bear Conflict Incidents
Annual precipitation
Number of Conflict Incidents
factor(Conflict)
Human-bear Conflict Incidents
Terrain slope
Number of Conflict Incidents
factor(Conflict)

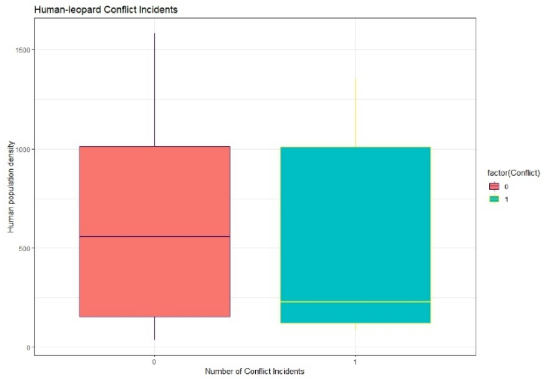
Leopard attacks on humans

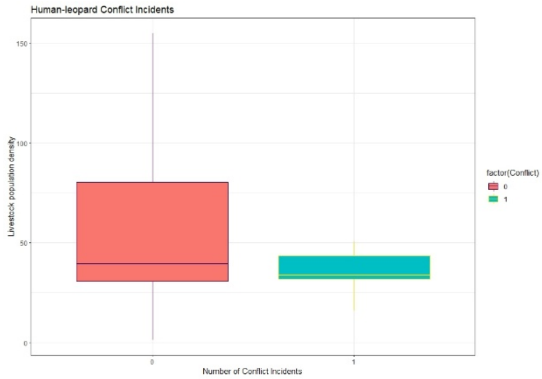


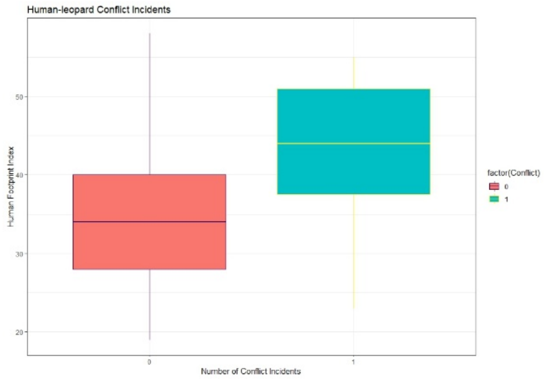


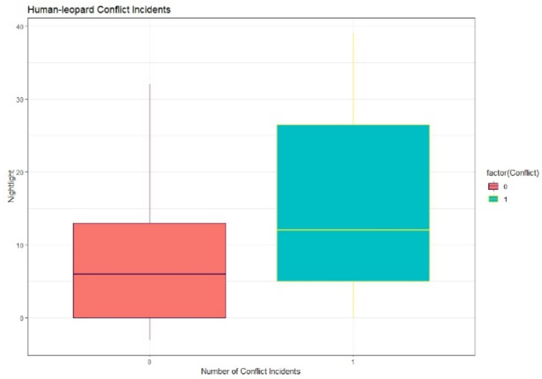


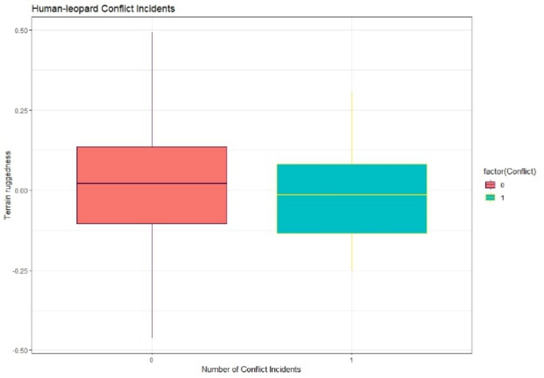











Human-leopard Conflict Incidents
Terrain ruggedness
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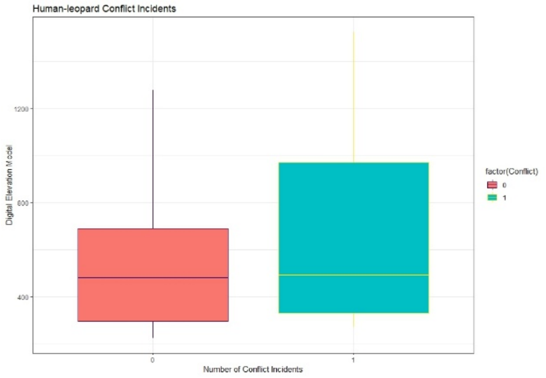
0.25
0.00
-0.25
-0.50
0
1
Number of Conflict Incidents
factor(Conflict)
0
1


Human-leopard Conflict Incidents
Digital Elevation Model
1200
800
400
0
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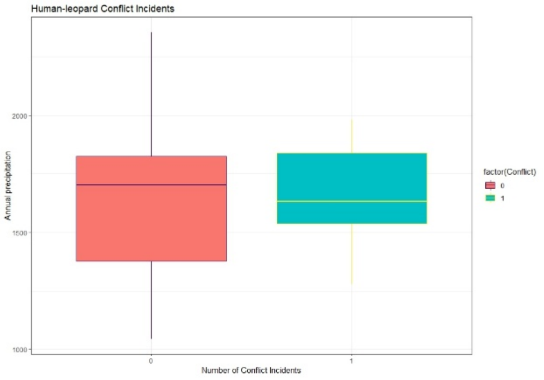
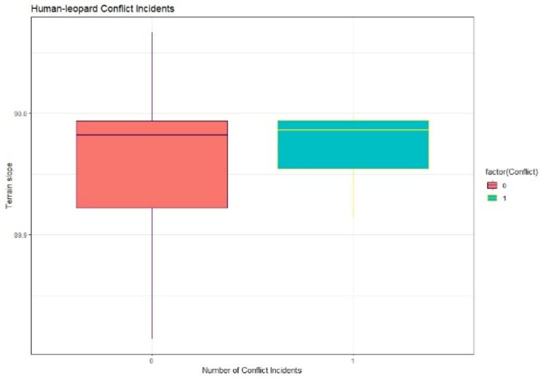
Number of Conflict Incidents
factor(Conflict)
0
1


Human-leopard Conflict Incidents
Annual precipitation
2000
1500
1000
0
1
Number of Conflict Incidents
factor(Conflict)
0
1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Terrain slope
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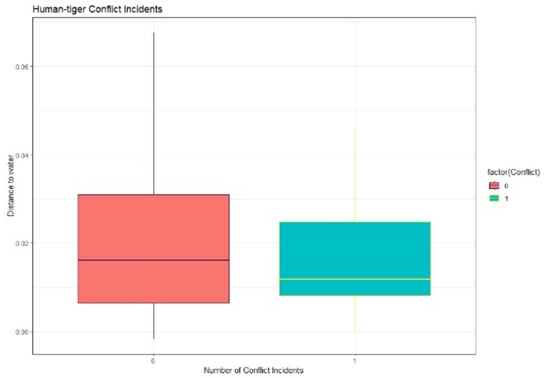
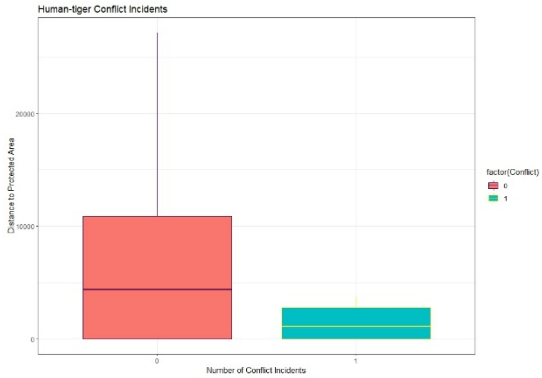
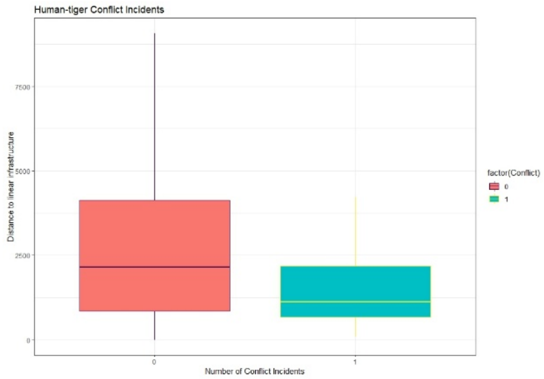
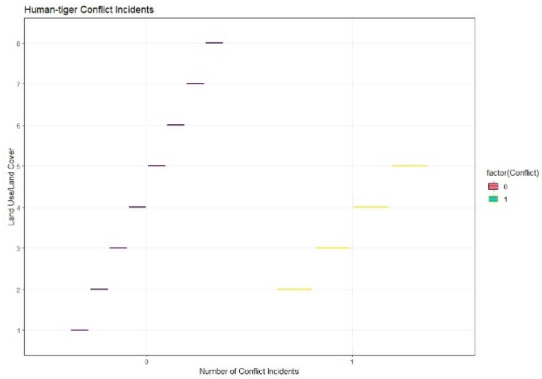
89.9
0
1
Number of Conflict Incidents
factor(Conflict)
0
1

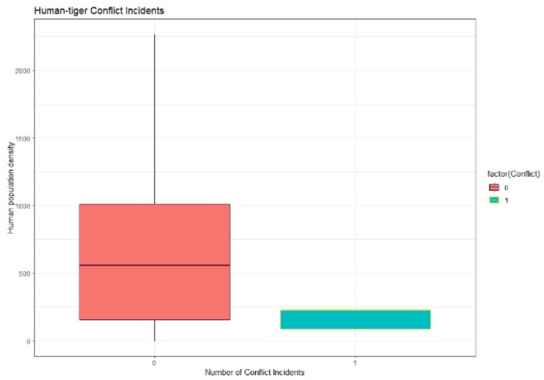
Tiger attacks on humans

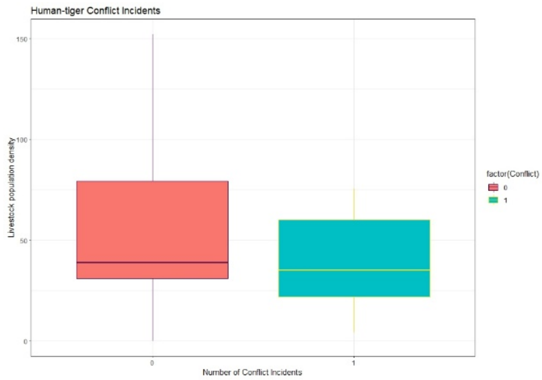


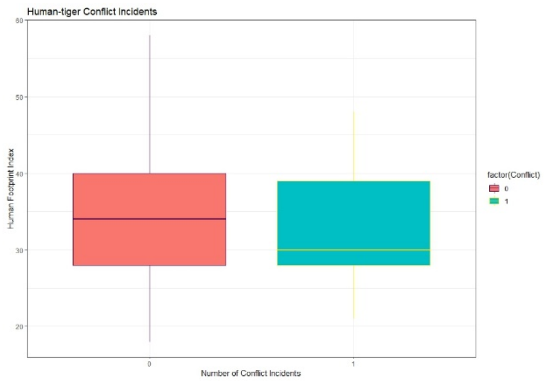


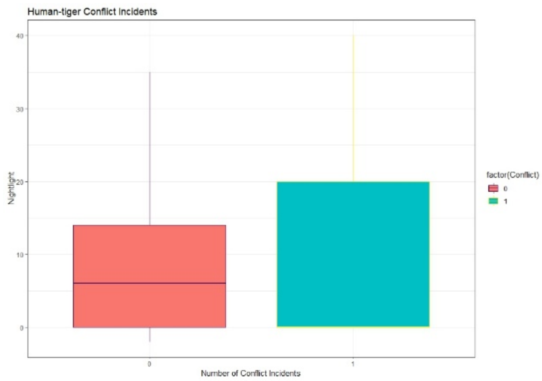


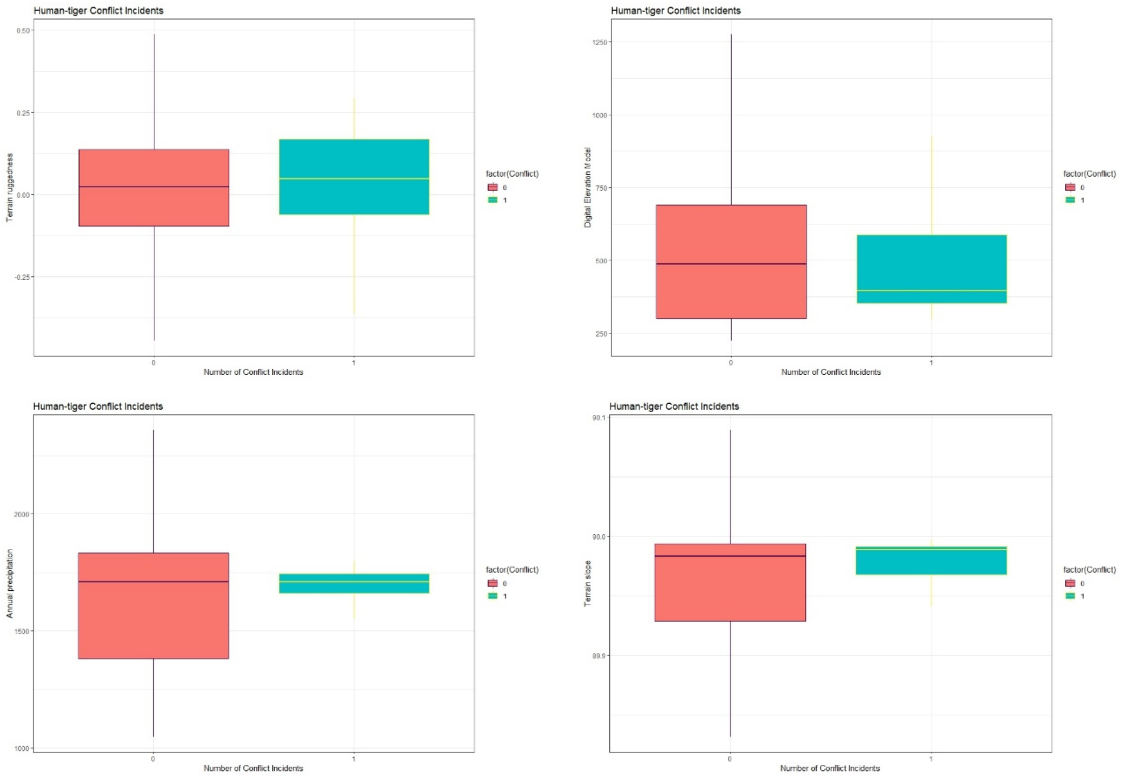






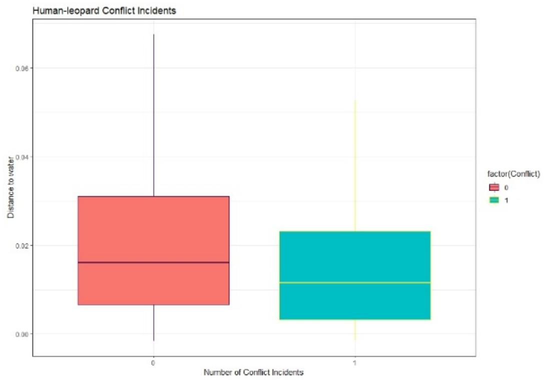


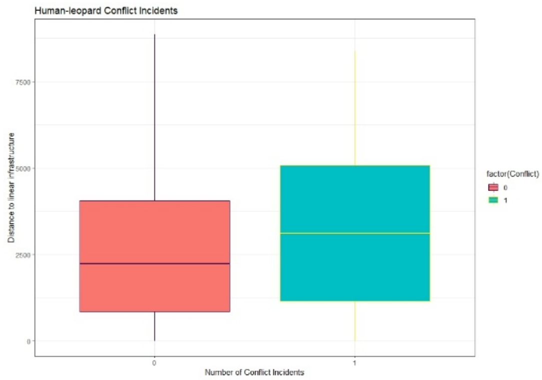


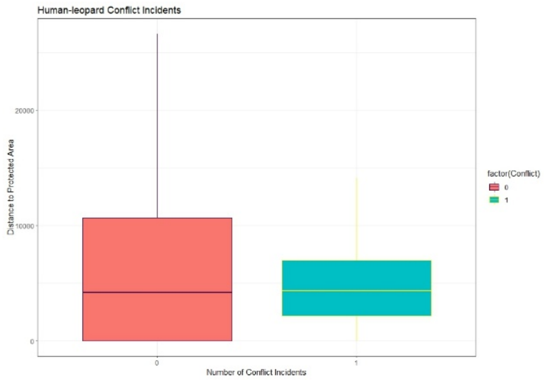

Human-tiger Conflict Incidents
Terrain ruggedness
Number of Conflict Incidents
factor(Conflict)
Human-tiger Conflict Incidents
Digital Elevation Model
Number of Conflict Incidents
factor(Conflict)
Human-tiger Conflict Incidents
Annual precipitation
Number of Conflict Incidents
factor(Conflict)
Human-tiger Conflict Incidents
Terrain slope
Number of Conflict Incidents
factor(Conflict)

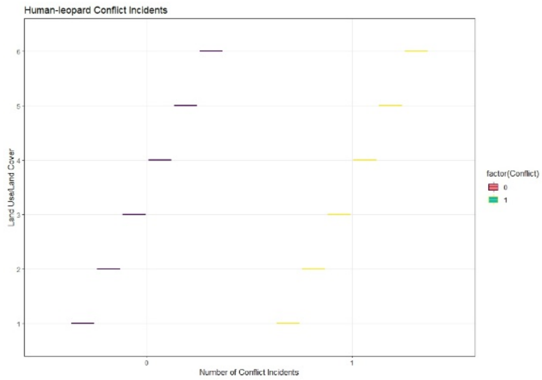
S2 – Livestock depredation by large carnivores

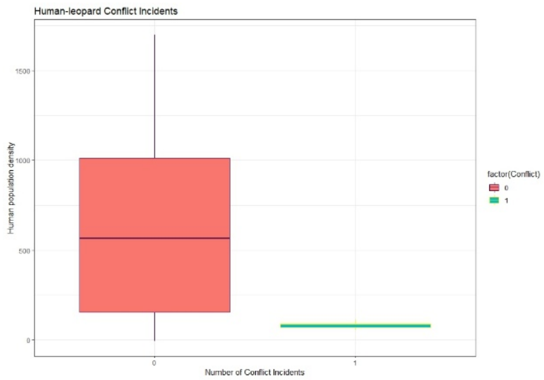
Livestock depredation by leopards

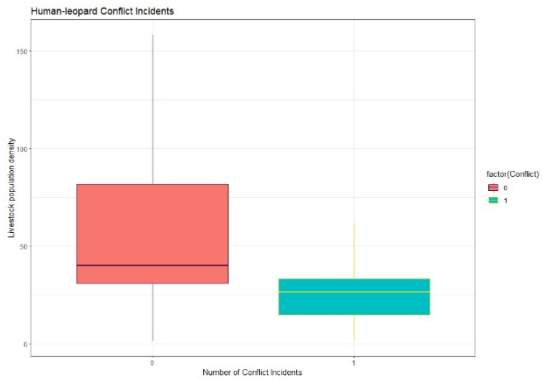


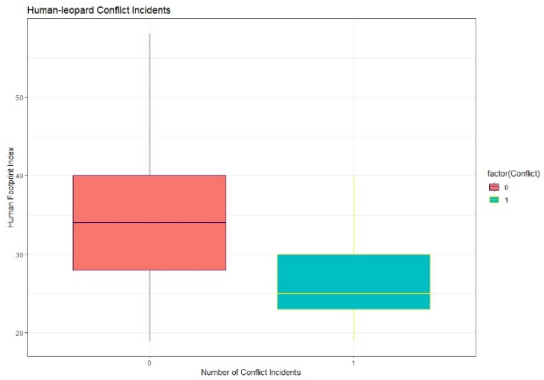


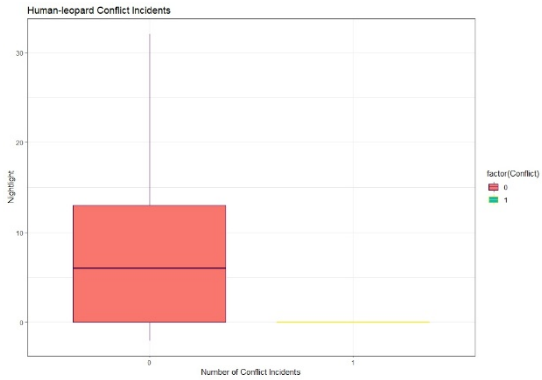


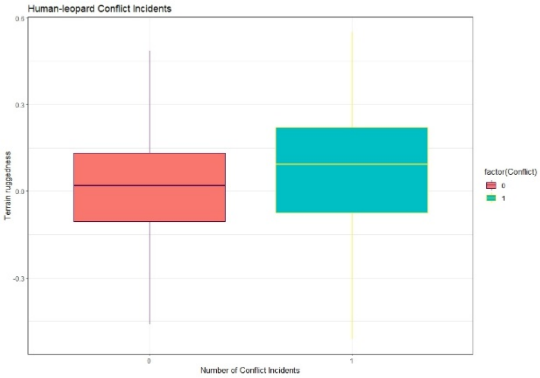











Human-leopard Conflict Incidents
Terrain ruggedness
Number of Conflict Incidents
factor(Conflict)
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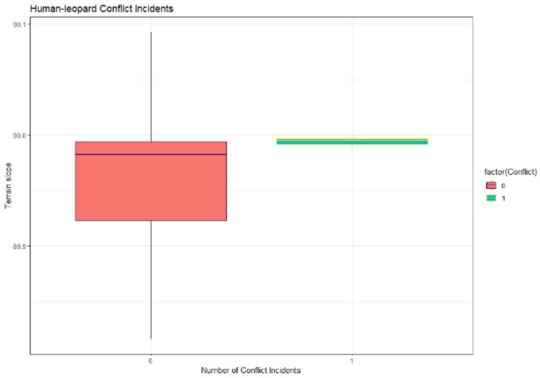
Human-leopard Conflict Incidents
Terrain slope
Number of Conflict Incidents
factor(Conflict)
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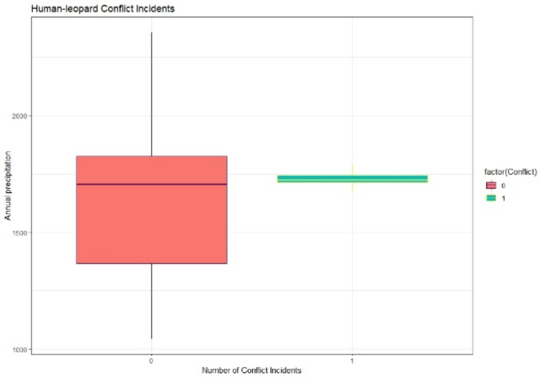
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Annual precipitation
Number of Conflict Incidents
factor(Conflict)
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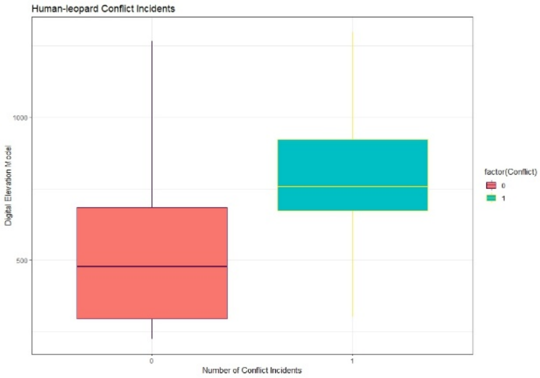
Human-leopard Conflict Incidents
Digital Elevation Model
Number of Conflict Incidents
factor(Conflict)
0
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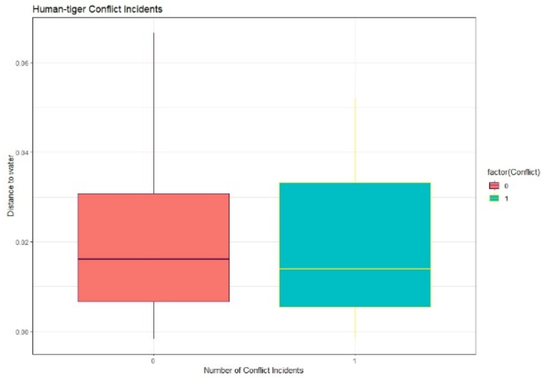
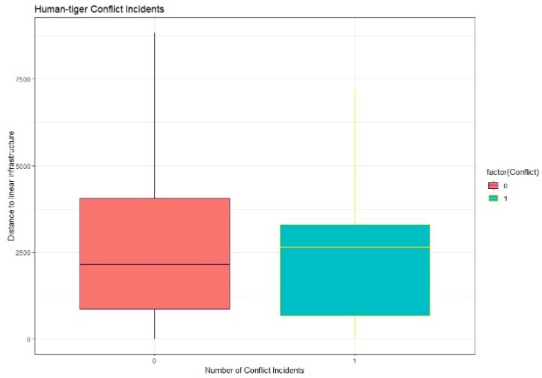
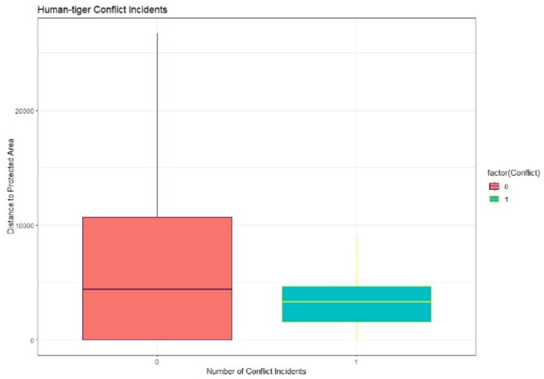
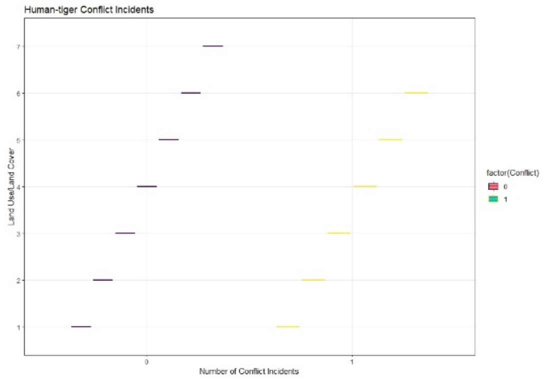
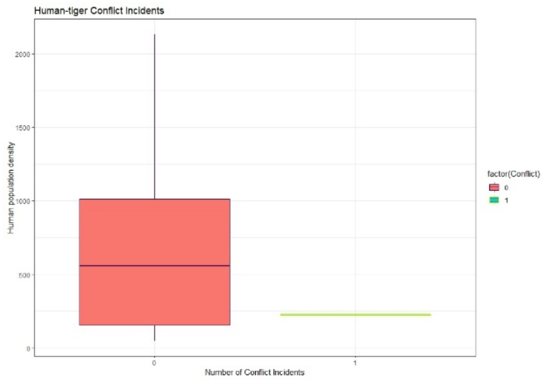
Livestock depredation by tigers

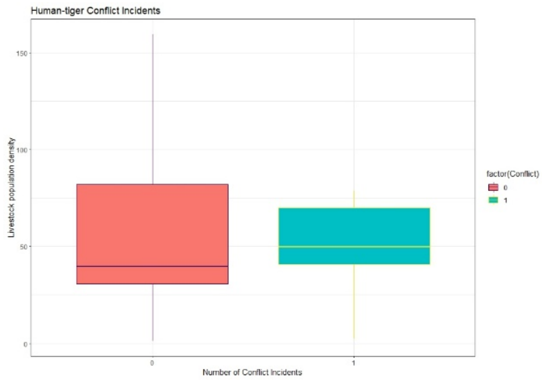


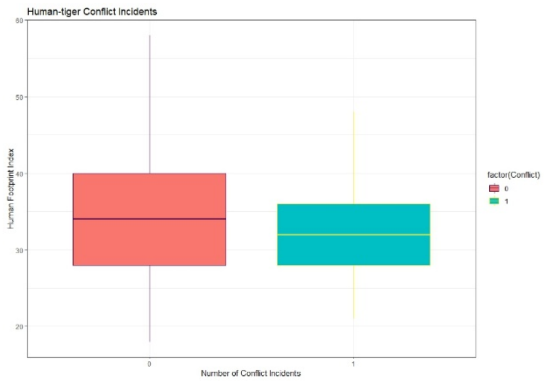


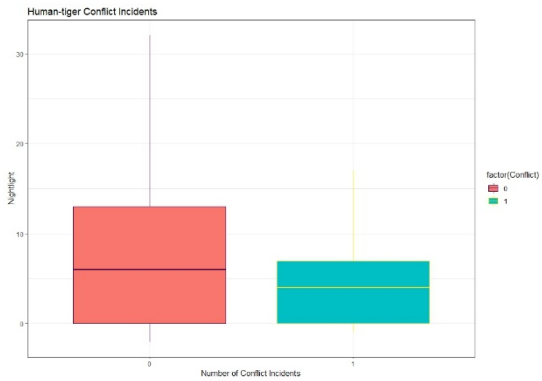


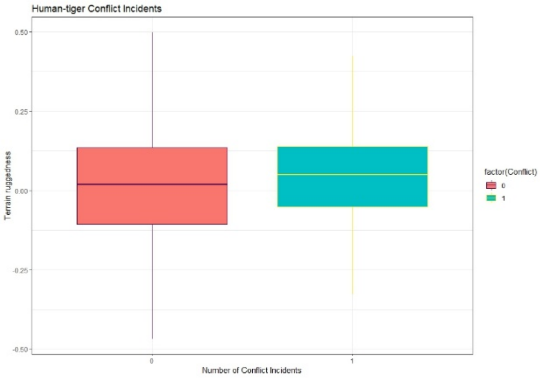











Human-tiger Conflict Incidents
Terrain ruggedness
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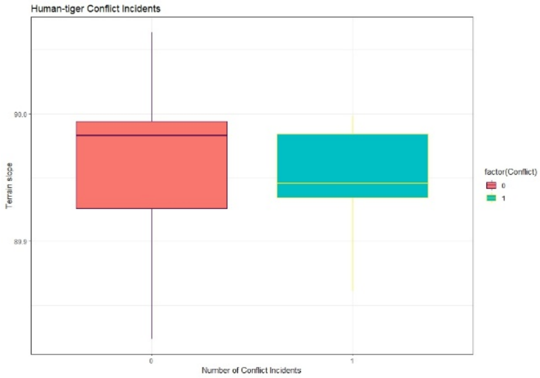
0.25
0.00
-0.25
-0.50
0
1
Number of Conflict Incidents
factor(Conflict)
0
1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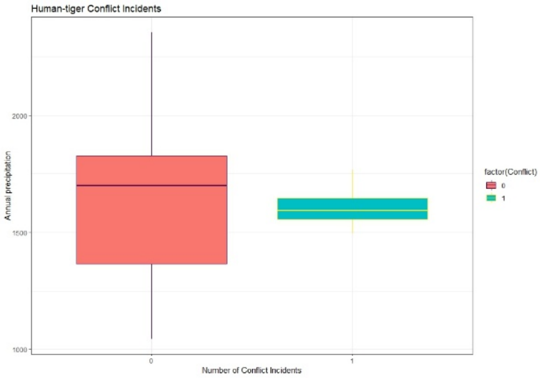
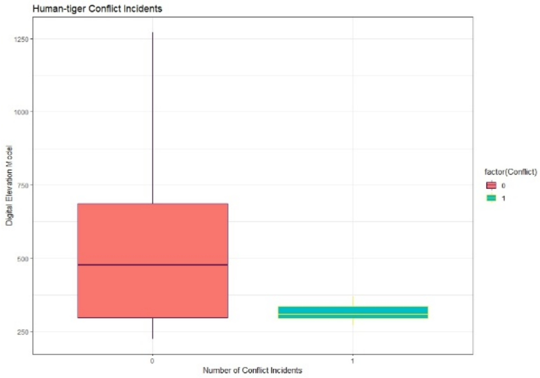
Terrain slope
90.0
89.9
0
1
Number of Conflict Incidents
factor(Conflict)
0
1


Human-tiger Conflict Incidents
Annual precipitation
2000
1500
1000
0
1
Number of Conflict Incidents
factor(Conflict)
0
1


Human-tiger Conflict Incidents
Digital Elevation Model
1250
1000
750
500
250
0
1
Number of Conflict Incidents
factor(Conflict)
0
1

S3 – Management Effectiveness Evaluation (MEE) – Questionnaire Form

Adopted from the MEE protocol for the Tiger Reserve

All the questions required a response in categorised rubric scale of 0-10: Poor (2.5), Fair (5), Good (7.5), Very good (10).

Context

1.1 Are the values of the Tiger Reserves (TR) well documented, assessed and monitored?

1.2 Are the threats to TR values well documented and assessed?

1.3 Is the 'Core Area' of TR free from human and biotic interference and the "Buffer Area" under unified control?

1.4 Has the TR complied with the four Statutory+ Requirements (SR) along with Tripartite MoU and three Standard Operation Procedures (SOP)?

1.5 Has the Action Points of Previous MEE been Addressed Substantially?

Planning

2.1 Status of Tiger Conservation Plan (TCP)?

2.2 Does the TR safeguard the threatened biodiversity values?

2.3 Are stakeholders given an opportunity to participate in planning process?

2.4 Are habitat management programmes systematically planned, relevant and monitored, and contribute effectively to tiger and other endangered species conservation?

2.5 Does the TR have an effective Protection Strategy (PS)* and Security Plan and Security Audit (SA) in place?

2.6 Has the TR been effective in the mitigation of human-wildlife conflicts?

2.7 Is the TR integrated into a wider ecological network/ landscape following the principles of the ecosystem approach?

2.8 Is the TR being consciously managed to prevent carbon loss and to encourage further carbon capture/ climate change mitigation?

Input

3.1 Are personnel adequate, well organized and deployed with access to adequate resources in the Tiger Reserve (TR)*?

3.2 Are resources (vehicle, equipment, building etc.) adequate, well organized and managed with desired access?

3.3 Are financial resources other than those of the state linked to priority actions and are funds adequate, released timely and utilized?

3.4 Are financial resources from the state linked to priority action and funds adequate, timely released and utilized for the management of Tiger Reserve?

3.5 What level of resources are provided by donors other than government sources?

Process

4.1 Does the TR have manpower resources trained in wildlife conservation for effective TR management?

4.2 Is TR staff management performance linked to achievement of management objectives?

4.3 Is there effective public participation in TR management+ and does it show in making a difference?

4.4 Is there a responsive system for handling complaints and comments+ about TR management?

4.5 Does TR management address the livelihood issues+ of resource dependent communities, especially of women?

4.6 Has the TR planned and implemented creation of inviolate zone by means of voluntary Village Relocation and phasing out of tourism from the Core/ Critical Tiger Habitat (CTH)?

Output

5.1 Is adequate information on TR management publicly available?

5.2 Are visitor services and facilities appropriate and adequate?

5.3 Are research/ monitoring related trends systematically evaluated and routinely reported and used to improve management?

5.4 Is there a systematic maintenance schedule and funds in place for management of infrastructure/assets?

Outcome

6.1 Are populations of threatened species declining, stable or increasing?

6.2 Is the population of tigers showing a declining, stable or increasing trend?

6.3 Have the threats+ to the TR being reduced/ minimized? Or is there an increase?

6.4 Are the expectations of visitors+ generally met or exceeded?

6.5 Are local communities supportive of TR management?

Additional Criteria

1. Habitat degradation and fragmentation status
2. Area encroachment and illegal settlement status
3. Invasive species infestation status
4. Habitat recovery status

LIST OF PUBLICATIONS

Conferences Presentations

1. Verma, N. (2025). Assessing wildlife activity and corridor functionality: A case study of highway underpasses in Rajaji National Park. Ind: *Seminar on Current Environmental Issues for Sustainable Circular Economic Strategies and Fisheries Development for a Greener Tomorrow.* Indian Academy of Environmental Science, Haridwar *and* Department of Zoology and Environmental Science, Gurukula Kangari sam Vishwavidyala, Haridwar. 28-29 January, 2025.
2. Verma, N. (2023). Assessing the extent, and severity of human-large carnivore conflict in Western Terai Arc Landscape. In: *International Conference "Wildlife Conservation: Emerging Scenario and Way forward."* Kanha Tiger Reserve, Madhya Pradesh, India. 27-29 April, 2023.

Research Paper

1. Verma, N., S. Badola & S. Mondol (2025). Evaluating wildlife activity and corridor functionality: a study of underpasses in and around Rajaji National Park, India. *Journal of Threatened Taxa* 17(4): 26780–26788. https://doi.org/10.11609/jott.9621.17.4.26780-26788

Indian Academy of Environmental Sciences, Haridwar

in collaboration with

Department of Zoology and Environmental Sciences

Gurukula Kangari sam Vishwavidyalya, Haridwar

Certificate of Participation in

International Seminar On

Current Environmental Issues for Sustainable Circular Economic Strategies and Fisheries Development for a Greener Tomorrow

This is to certify that Prof. /Dr. / Mr./ Ms.........Nishant Verma..

from...

attended the above mentioned seminar organized by the Indian Academy of Environmental Sciences Haridwar in collaboration with Department of Zoology and Environmental Science, Gurukula Kangari sam Vishwavidyalya, Haridwar , during 28-29 January, 2025.

Prof./Dr./Mr./Ms...delivered the Key note lecture / an invited lecture / chaired/ co-chaired / an academic session/presented a research paper/oral/ poster in the international seminar.

Date : 29 January 2025
Place : Haridwar

(Prof. Namita Joshi)
Head, Dept. of Zool. & Env. Sciences

(Prof. B. D. Joshi)
President-IAES

Diamond Jubilee Year
(1963-2023)

CERTIFICATE of PARTICIPATION

__NISHANT VERMA,______Wildlife Institute of India, Dehradun
(CCF/Director NDBR, Uttarakhand)

Successfully participated in the

International Conference

"Wildlife Conservation: Emerging Scenario and Way forward"

Kanha Tiger Reserve, Madhya Pradesh, India

April 27th – 29th, 2023

Amitabh Agnihotri, IFS Principal Chief Conservator of Forests & Director State Forest Research Institute, Jabalpur, M.P.	**Jasbir Singh Chauhan,** IFS Principal Chief Conservator of Forests & Chief Wildlife Warden M.P., Bhopal	**Ramesh Kumar Gupta,** IFS Principal Chief Conservator of Forests & Head of Forest Force M.P., Bhopal

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continued on the back inside cover

Cover: Nilgiri Large Burrowing Spider *Haploclastus nilgirinus*. Acrylic on canvas. © Aakanksha Komanduri.

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ARTICLE

Evaluating wildlife activity and corridor functionality: a study of underpasses in and around Rajaji National Park, India

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Abstract: Habitat fragmentation threatens biodiversity, making wildlife corridors vital for maintaining ecological connectivity. This study evaluated the functionality of three corridors—Chilla-Motichur, Teenpani, and Laltappar—in and around Rajaji National Park, Uttarakhand, India. We deployed camera traps at these corridors and surrounding forest areas for 8,198 trap nights to monitor the wildlife use of the corridors. We recorded 17 species of wild animals in the connected forested area and nine within the corridors. The Wild Pig *Sus scrofa* and Sambar *Rusa unicolor* were the most frequently captured species, with the highest Relative Abundance Index (RAI) in the Teenpani corridor. Activity patterns of wild species showed changes in the corridor compared to forest areas. Chital *Axis axis* exhibited continuous activity in corridors but an early-morning peak in forests (Δ = 0.68). Asiatic Elephant *Elephas maximus* shifted from daytime activity in forests to nocturnal peaks in corridors, likely avoiding human presence (Δ = 0.48). Sambar avoided daytime activity in the corridor compared to activity in the forest (Δ = 0.55), while Wild Pig maintained nocturnal peaks across both habitats (Δ = 0.71). Human activity, primarily diurnal, overlapped with Chital (Δ = 0.61) and increased potential encounters with Elephants and Leopards during evening hours (Δ = 0.25 and 0.39, respectively). Mitigation measures, such as habitat restoration and managing anthropogenic activities, are crucial for strengthening corridor functionality. The recent reintroduction of tigers in western Rajaji underscores the importance of these corridors for species connectivity and genetic exchange. This study provides valuable insights into managing wildlife corridors in human-dominated landscapes, highlighting their role in biodiversity conservation.

Keywords: Asiatic Elephant, camera trapping, conservation monitoring, habitat connectivity, human disturbance, infrastructure mitigation, species activity patterns.

Editor: Anonymity requested.

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Funding: All the equipment and logistics were supported by the Uttarakhand Forest Department.

Competing interests: The authors declare no competing interests.

Author details and **Author contributions:** Nishant Verma (APCCF, Uttarakhand Forest Department) conceptualised the study, conducted fieldwork, analysed data, and wrote the first draft. Saket Badola (former director, Rajaji Tiger Reserve) assisted with data collection and manuscript preparation. Samrat Mondol (scientist, Wildlife Institute of India) contributed to the study design and reviewed the manuscript.

Acknowledgements: We sincerely thank the Director, Rajaji Tiger Reserve, the Divisional Forest Officer, Dehradun Forest Division, and Dr. Samir Sinha, former Chief Wildlife Warden, Uttarakhand, for providing field logistics and the necessary permissions to conduct this research. We are grateful to Dr. Bivash Pandav, Wildlife Institute of India, for his invaluable guidance in planning and carrying out the study. Dr. Shivam Shrotriya is acknowledged for his guidance in data analysis and writing. We also extend our appreciation to the field staff for their dedication and support in carrying out the work.

भारतीय वन्यजीव संस्थान Wildlife Institute of India

उत्तराखण्ड वन विभाग

INTRODUCTION

The rapid expansion of human activities has led to significant alterations in natural landscapes. Habitat loss and fragmentation are two main contributors to biodiversity decline (Haddad et al. 2015). Anthropogenic habitat loss occurs when natural areas are converted for human activities such as agriculture, horticulture, infrastructure development, and urban expansion. Roads, railways, and urban expansion fragment once-continuous landscapes, thus impeding wildlife movement, disrupting ecological processes, and increasing the risk of local extinctions (Laurance et al. 2014; van der Ree et al. 2015). These processes disrupt habitat connectivity, impacting the movement, dispersal, and genetic exchange of wildlife populations (e.g., Callens et al. 2011; Napolitano et al. 2015). Such disruptions can have profound consequences, including population decline and loss of ecosystem functionality. Therefore, connecting natural habitats through ecological corridors is crucial for maintaining gene flow and population viability in the wild (Holderegger & Di Giulio 2010).

Wildlife corridors, composed of native vegetation, link larger habitat patches and facilitate animal movement (Burkart et al. 2016). By mitigating the effects of habitat loss and fragmentation, these corridors help sustain healthy animal populations and preserve biodiversity. In human-dominated landscapes, corridors are essential conservation tools, enabling wildlife to navigate fragmented habitats and reducing the risks of isolation and local extinctions.

The Terai Arc Landscape (TAL), spanning the Himalayan foothills in India and Nepal, is among the world's 200 globally significant ecoregions (Olson & Dinerstein 1998). This landscape harbours flagship species such as the Royal Bengal Tiger *Panthera tigris* and the Asiatic Elephant *Elephas maximus*, which require large, connected habitats for survival (Jhala et al. 2015). TAL is also a human-dominated landscape, facing significant challenges from expanding settlements, agriculture, and transportation infrastructure (Harihar & Pandav 2012). Corridors within this landscape are critical for maintaining connectivity between protected areas, yet many have become degraded due to anthropogenic pressures.

Rajaji National Park (RNP), spanning 820 km² within the western TAL, is a key protected area for Tigers, elephants, and other large mammals. This park is bifurcated into eastern and western sections by the Ganges River (Johnsingh et al. 2004). Additionally, highways and railway lines connecting Haridwar and Dehradun, two of Uttarakhand's most populated cities, create significant movement barriers for wildlife between protected areas and surrounding patches of reserve forests. Particularly, the connectivity between the Barkot Range of the territorial forest and the Kansrao Range of RNP is critical for elephant movement in this landscape (Johnsingh et al. 2004). Historically, the erstwhile Chilla-Motichur corridor played a crucial role in facilitating wildlife movement across both banks of the Ganges. This 3-km long and 1-km wide stretch of forest land that connects the Chilla Forest range on the eastern part of the Ganga to the Motichur Range on the west bank, is the only functional link between the eastern and western parts of RNP. While roads, railways, and irrigation channels hinder wildlife movement, roads pose the greatest barrier due to a continuous traffic flow. To address these challenges, three wildlife underpasses—Chilla-Motichur, Teenpani, and Laltappar—were constructed on the highway to provide connectivity between forested habitats within and around the park in 2021 (Nigam et al. 2022).

In this study, the current functionality of these three corridors were accessed in facilitating wildlife movement. Using camera-trap data, the activity patterns of key species — Leopard *Panthera pardus*, Asiatic Elephant, Spotted Deer or Chital *Axis axis*, Sambar *Rusa unicolor*, and Wild Boar *Sus scrofa*—were compared within the corridors and nearby forest ranges. It was also examined how human activities influence wildlife behaviour and corridor usage. By assessing corridor effectiveness, this study provides data-driven insights for enhancing connectivity and informing conservation planning in RNP and the broader TAL.

MATERIAL AND METHODS

Study Area

The study was conducted in the western part of Rajaji National Park (RNP), situated in Uttarakhand, India (30.248–29.850 ^{0}N & 77.878–78.444 ^{0}E), within the Terai Arc Landscape (TAL). The study focused on three wildlife corridors—Chilla-Motichur, Teenpani, and Laltappar—which have been established to connect fragmented forest patches of the Chilla, Motichur, & Kansrao ranges of RNP, and Barkot & Rishikesh ranges of the Dehradun Forest Division (Image 1). These corridors are intersected by major highways and railways, with underpasses designed to mitigate barriers to wildlife movement. The Chilla-Motichur underpass is 900 m

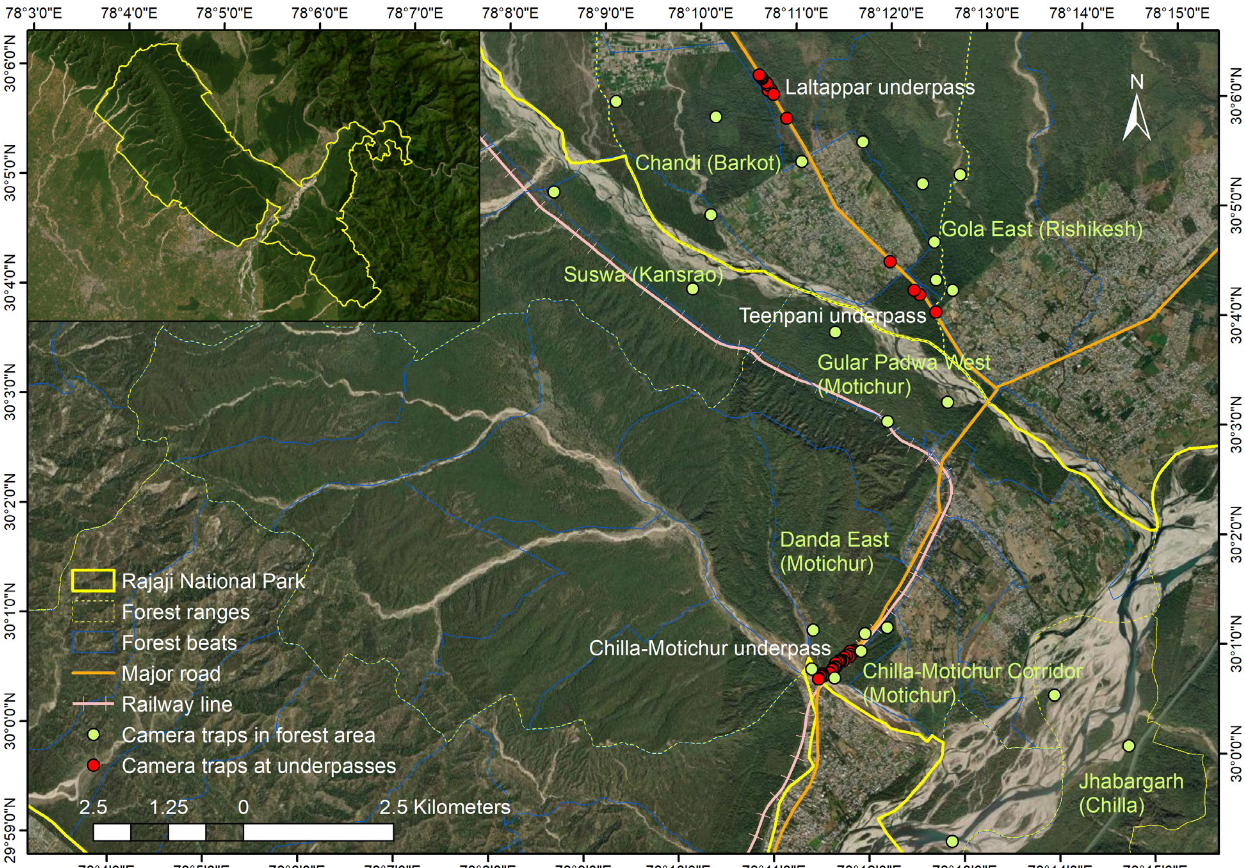

Image 1. Location of the three corridors — Laltappar, Teenpani, and Chilla-Motichur — at the boundary of the western Rajaji National Park. All three corridors are traversed by road, and wildlife underpasses are built on all three roads. Sampled forest beats are mentioned in green text.

long, while the Teenpani and Laltappar underpasses are each approximately 500 m in length. These underpasses provide critical connectivity between forested habitats in the park and adjacent territorial forests (Nigam et al. 2022).

The vegetation of RNP is primarily tropical moist and dry deciduous forests (Champion & Seth 1968), dominated by Sal *Shorea robusta*. Riverine forests and scrublands are also present. The region supports diverse wildlife, including flagship species such as the Tiger, Asiatic Elephant, and Leopard. It also harbours a rich diversity of avifauna and herpetofauna.

Camera-trapping

Camera traps were deployed between April and November 2022 across the corridors and adjacent forest ranges (Table 1). Sixty-four motion-triggered digital cameras (Cuddeback Model C1) were installed, yielding a total of 8,198 trap nights. Cameras were single-sided and mounted approximately 30–40 cm above ground level. Under the flyovers, the cameras were placed at a minimum of 25 m to a maximum of 100 m distance from each other along the flyover, so that any animal crossing the flyover would not be missed out. The Chilla-Motichur corridor was monitored by 24 cameras, whereas the Teenpani and Laltappar corridors each had eight cameras. Eight adjacent forest beats in five ranges of RNP and the Dehradun Forest division were sampled to understand the presence of wildlife. Three camera traps were deployed in each of the beats, except for six cameras in the Chandi beat of Barkot Range as it was relatively larger (Image 1, Table 1). Camera traps were strategically placed along trails, riverbanks, and other linear features to maximize the detection of medium- and large-sized mammals, which commonly use these pathways (Jhala et al. 2015). All the camera traps were active 24 h and monitored every fortnight to check the battery status and retrieve the data.

Data analyses

Species identification was conducted manually for each photograph by a single observer and verified by a

Table 1. Details of the survey effort during camera trapping at the corridors and adjacent forest ranges in and around the western Rajaji National Park.

Sites	Start date	End date	Total cameras	Total trap nights	Sampling coverage
Corridors					**Length (m)**
Laltappar	12.iv.2022	05.xi.2022	8	1656	500
Teenpani	10.vi.2022	05.xi.2022	8	1184	500
Chilla-Motichur	25.iv.2022	26.xi.2022	24	4485	900
Forest beats (ranges)					**Area (Km^2)**
Chandi (Barkot)	04.iii.2022	21.iv.2022	6	288	14.83
Jhabargarh (Chilla)	13.iii.2022	16.iv.2022	3	102	11.60
Suswa (Kansrow)	19.iii.2022	04.v.2022	3	138	6.14
Gola East (Rishikesh)	13.iii.2022	22.iv.2022	3	120	10.57
Chilla-Motichur Corridor (Motichur)	01.iv.2022	18.iv.2022	3	54	2.20
Danda East (Motichur)	16.iii.2022	19.iv.2022	3	102	6.12
Gular Parwa West (Motichur)	16.iii.2022	08.iv.2022	3	69	6.40

second observer. The date and time of each photograph were recorded from the image metadata, maintaining a time interval of 1 min for independent capture events. Wildlife presence in the connected forest areas and corridor underpasses was quantified using the relative abundance index (RAI), defined as the number of independent detections per 1,000 trap nights (O'Brien 2011). Comparative analyses of species activity patterns in forests and corridors, as well as their temporal overlap with humans, were conducted using the camtrapR package (version 2.3.0; Niedballa et al. 2016) in R (version 4.4.0; R Core Team 2024). Temporal overlap was estimated by the overlap coefficient Δ, which ranges from 0 (no overlap) to 1 (complete overlap) and is calculated using kernel density functions fitted to the time data of capture incidents of two species (Ridout & Linkie 2009).

RESULTS

Over 8,198 trap nights, camera traps recorded 17 species in the forest areas and nine in the corridors. Among the corridors, Chilla-Motichur and Laltappar had the highest species richness (seven species each), while Teenpani recorded six species (Image 2, Table 2). Teenpani had the highest relative abundance index (RAI) for Wild Boar (227.2) and Sambar (123.31) among the corridors, whereas Chilla-Motichur and Laltappar exhibited lower RAIs for most species (Table 2). In contrast, adjacent forest areas exhibited higher RAIs across all species, indicating a preference for less-disturbed habitats (Wilcoxon test: $V = 0$, $p < 0.001$).

Species exhibited distinct activity patterns between corridors and forest areas (Figure 1). Chital, the only diurnal species, exhibited activity throughout the 24-hour period in corridors, whereas it displayed a distinct early-morning peak inside the forest (Δ = 0.68). Leopards were uniformly active throughout the day in the forest but showed slightly reduced daytime activity in corridors (Δ = 0.71). Elephants exhibited contrasting activity patterns, with a daytime activity peak in forest ranges and a night-time peak in corridors (Δ = 0.48). Sambar displayed an early-morning activity peak in corridors, avoiding the daytime, while in the forest, it maintained activity throughout the day with increased movement during morning and evening hours (Δ = 0.55). Wild Pig activity remained consistent across both habitats, with peaks at night and reduced activity during the day (Δ = 0.71).

Human activity occurred exclusively during the daytime across all corridors, significantly overlapping with Chital (Δ = 0.61, Figure 1). Other species avoided times of peak human activity. The Leopard (Δ = 0.39) and the elephant (Δ = 0.25), both species frequently involved in negative human-wildlife interactions, showed increased overlap with human activity in the evening hours.

Image 2. Some of the wildlife species captured by camera traps at the corridors; top left to right: Asiatic Elephant, Sambar, Chital, and Barking Deer; bottom left to right: Leopard, Striped Hyena, and Wild Boar. © Uttarakhand Forest Deparment.

DISCUSSION

This study highlights both the significance and challenges of wildlife corridors in maintaining connectivity for species within fragmented habitats. The lower species richness observed in corridors (nine species) compared to forested areas (17 species) reflects the impact of disturbance and habitat fragmentation in human-dominated landscapes, a pattern consistent with global studies (Benítez-López et al. 2010; van der Ree et al. 2015).

Species activity patterns exhibited significant shifts within corridors compared to forest areas (Figure 1). Chital exhibited continuous activity throughout the daytime in corridors, whereas, in forests, its activity peaked during the early morning hours. Chital is primarily a diurnal species, with peak activity occurring at dawn and dusk. They spend most of their time feeding, followed by resting and social activities. This diurnal pattern is consistent across various habitats, including those with high human activity, where they may alter their behaviour to avoid disturbances (Rajawat & Chandra 2020; Dahya et al. 2023; Kumar et al. 2023). Leopards, known for their cathemeral activity (Palei et al. 2021; Dahya et al. 2023), exhibited uniform activity in forests but reduced daytime activity in corridors, possibly avoiding human activity. Elephants shifted their activity from a daytime peak in forests to a nocturnal peak in corridors, demonstrating their adaptability to avoid human encounters (Chakraborty et al. 2021). Sambar, predominantly nocturnal in other studies (Kumar et al. 2023), showed early-morning peaks in corridors, likely due to lower human presence at that time. Wild Boars maintained their nocturnal peaks across both habitats, consistent with findings from Dahya et al. (2023).

Human activity in corridors was predominantly diurnal, significantly overlapping with Chital activity, while other species mostly avoided peak human activity times. The overlap of Leopards and Elephants with human activity during evening hours is concerning, given

Table 2. Relative abundance index (per 1,000 trap nights) of the wildlife species, livestock, and humans captured at three corridors and adjacent forest areas in and around the western Rajaji National Park.

Species	Laltappar	Teenpani	Chilla-Motichur	Forest area
Barking Deer *Muntiacus muntjak*	0.6	-	0.22	12.9
Chital *Axis axis*	50.12	-	8.03	1363.44
Sambar *Rusa unicolor*	99.64	123.31	7.8	993.55
Nilgai *Boselaphus tragocamelus*	-	-	-	15.05
Asiatic Elephant *Elephas maximus*	19.93	2.53	0.89	172.04
Wild Boar *Sus scrofa*	13.89	227.2	22.07	223.66
Rhesus Macaque *Macaca mulatta*	1.81	-	1.34	43.01
Central Indian Langur *Semnopithecus entellus*	-	0.84	-	25.81
Indian Hare *Lepus nigricollis*	-	-	-	49.46
Indian Crested Porcupine *Hystrix indica*	-	3.38	-	49.46
Indian Peafowl *Pavo cristatus*	-	-	-	329.03
Indian Pangolin *Manis crassicaudata*	-	-	-	4.3
Leopard *Panthera pardus*	12.08	15.2	4.01	215.05
Tiger *Panthera tigris*	-	-	-	4.3
Striped Hyena *Hyaena hyaena*	-	-	-	21.51
Golden Jackal *Canis aureus*	-	-	-	4.3
Small Indian Civet *Viverricula indica*	-	-	-	17.2
Livestock	397.34	333.61	108.58	531.18
Human	752.42	26094.59	2360.98	206.45

the elevated risk of human-wildlife encounters (Figure 1). Such patterns, particularly involving species known to cause damage or pose danger in shared spaces, highlight the need for targeted management strategies.

The study also underscores the importance of infrastructure like underpasses in enhancing corridor functionality. Although highway underpasses support wildlife movement, parallel railway lines may act as significant barriers, particularly for elephants, necessitating targeted mitigation measures (Carvalho et al. 2017; Gilhooly et al. 2019). Additionally, debris from underpass construction, garbage dumping, and the use of old roads below the flyover at Teenpani exacerbate habitat degradation (Oro et al. 2013; Katlam et al. 2018). Habitat restoration, particularly in the Chilla-Motichur corridor, and increasing forested cover are crucial for improving corridor effectiveness (Dutta et al. 2018).

The translocation of four Tigers from Corbett Tiger Reserve to western Rajaji National Park (2021–2024) reinforces the importance of maintaining functional corridors (Times of India 2024, director, Rajaji Tiger Reserve pers. comm. 20.iii.2025). In 2022, a male Tiger was photo-captured in camera traps moving from the Chilla Range in the east to the Motichur Range in the western Rajaji using the reclaimed corridor under the Chilla-Motichur flyover. This observation signifies the successful restoration of historical connectivity between the eastern and western RNP. Furthermore, it highlights the critical role of the Chilla-Motichur corridor in Tiger conservation in this landscape. As Tigers recolonise the western TAL, maintaining and monitoring these corridors will be vital for their survival and genetic exchange. The corridor, is yet to be fully restored as an existing ammunition depot of the Indian army cuts through it leaving little space for unrestricted movement of wild animals.

The current study was limited in scope due to a smaller sample size, a lack of a more systematic sampling design, and coverage of only limited areas around the flyovers. Using more camera traps in a grid design could yield more information on the spatial use and abundance of wildlife populations in the landscape. Therefore, the analyses were restricted to RAI as an indicator of site use intensity. Interpreting RAI as abundance may be incorrect as the number of captures may be affected by habitat quality, disturbances, individual behaviour and camera placement (O'Brien 2011). Temporal activity may also be affected by similar biases in captures. Therefore,

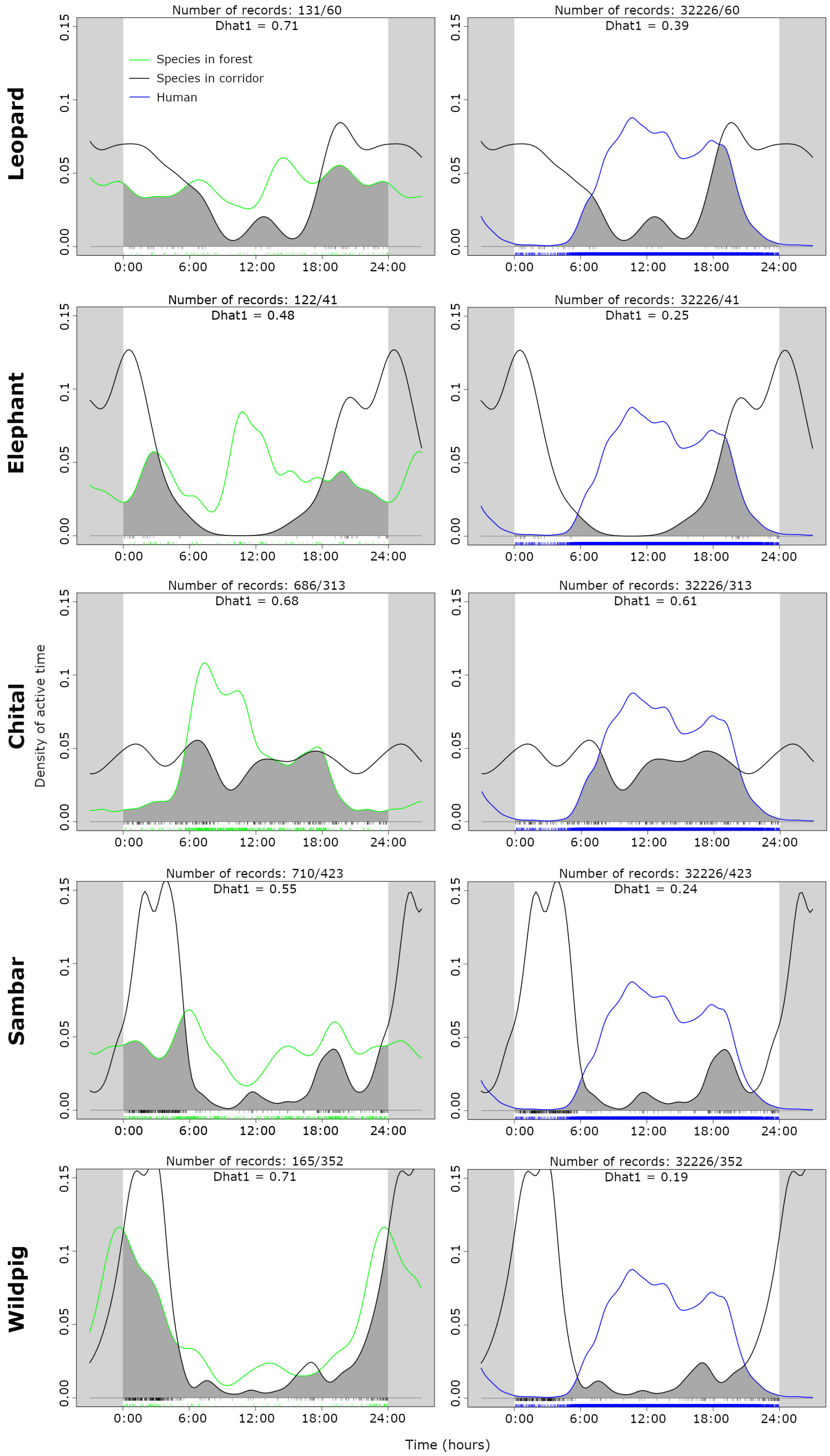

Figure 1. Comparison of the activity time of the five species frequently captured at the corridors around the western Rajaji National Park: Left—activity time of the species within the corridor and the forest ranges | right—activity overlap of the species with humans in the corridor. Dhat value represents the overlap coefficient.

temporal patterns were not analysed for all the captured species but focused only on the species with sufficient captures across the camera traps.

Nonetheless, this study provides valuable insights into the effectiveness of highway underpasses and the challenges of maintaining corridor functionality in human-dominated landscapes. Active measures are essential to enhance corridor utility, including habitat restoration to increase forest cover, shifting of the army's ammunition depot to fully restore the corridor, restricting human activity during critical wildlife movement times, ensuring proper disposal of construction debris and garbage, and implementing effective mitigation strategies for railways to facilitate safe crossings such as advance alert systems, improved braking systems in the trains, regular patrolling and crossing infrastructures (Carvalho et al. 2017). Continuous monitoring of corridor use is crucial, particularly with the recent reintroduction of Tigers, to support the long-term conservation of these apex predators and Elephants in the region.

The findings from this study offer broader conservation implications for wildlife corridors in other parts of the TAL and similarly fragmented habitats across India. The observed shifts in wildlife activity patterns and the influence of human presence highlight the urgent need for integrated infrastructure planning including road and rail barriers in preserving corridor functionality. These results can inform national-level policy on corridor identification, underpass design, and mitigation strategies, especially under frameworks such as India's Wildlife Action Plan (2017–2031), which prioritises connectivity conservation (MOECCF 2017). Furthermore, the study underscores the importance of long-term monitoring, offering a replicable approach for assessing corridor functionality in other Tiger and elephant landscapes.

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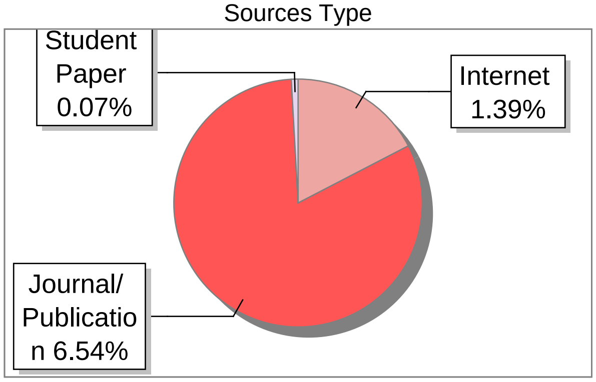

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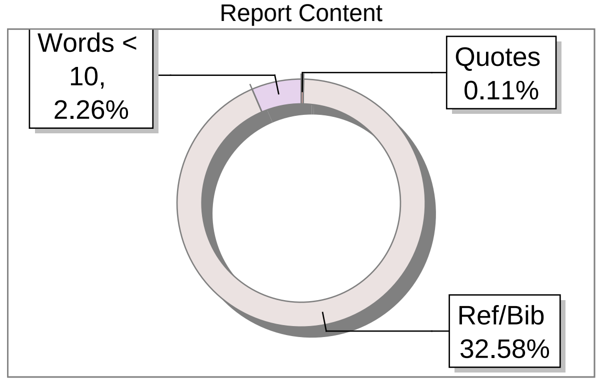

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