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Climate Change and Wildlife Ecology in the Indian Himalayan Region:
Biodiversity Responses, Ecological Vulnerability, and Conservation Imperatives for Sustainable Mountain Development

Dr Neetu Rani

Assistant Professor

Department of Zoology

Dhanauri PG. College, Dhanauri, Haridwar, Uttarakhand

Abstract

The Indian Himalayan mountain ecosystem extend cover approximately 3,500 km area. This ecosystem is known for its unique biodiversity and climatic conditions. This region encompass different altitudinal gradients from tropical foothills, forest, alpine meadow to large snowfields mountains. The climate change is exerting pressure on Himalayan wildlife, which leads to the altitudinal range shifts, phenological mismatches, and local extinction of species. This review paper will synthesises evidence from 2000– 2024 to critically evaluate how climate change and anthropogenic land-use intensification collectively affecting Himalayan ecology. The indicator species, snow leopard (*Panthera uncia*), Himalayan brown bear (*Ursus arctos isabellinus*), high-altitude amphibians, were integrate with climate variables to demographic outcomes. This paper propose a vulnerability-sensitivity-exposure (VSE) assessment matrix for Himalayan wildlife which is helpful in conservation policies. This paper identify critical research gap in long-term faunal diversity datasets above 4,500 m.

Keywords: Biodiversity; climate vulnerability; *Panthera uncia*; phenological mismatch, wildlife conservation

Corresponding author email: nandugarg2010@gmail.com

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Introduction

The Himalayan mountain ecosystems globally comprises approximately 25% of terrestrial biodiversity of total land surface on Earth. The Hindu Kush-Himalayan (HKH) region known as the most important centre of high-altitude endemism apart from polar regions (Wester, P. et al., 2019). The Palaearctic and Oriental biogeographic realms connected with Himalayan biological bridge which results (Schickhoff, U. 2005; Wester, P., 2019)

The Himalayas act as a biological bridge between the Palaearctic and Oriental biogeographic realms, resulting in a variety of geographical regions. Tibetan plateau fauna with tropical forest species across elevational continua that span less than 150 horizontal kilometres (Schickhoff, U. 2005). This structural uniqueness renders Himalayan wildlife communities both ecologically irreplaceable and acutely sensitive to externally imposed perturbations-particularly the accelerated warming trajectory documented by the Intergovernmental Panel on Climate Change (IPCC AR6, 2022) and regionally validated by the Hindu Kush Himalaya Assessment of the International Centre for Integrated Mountain Development (ICIMOD, 2019).

The greater Himalaya, facing elevation-dependent warming (EDW), due to which the rate of surface temperature increasing 1.5-2.0. The increasing temperature leads to decrease snow cover, so exposing surface absorb higher solar energy (Wester, P. et al., 2019). Global warming increase ecological instability in Himalayan region. Erratic monsoon, and decreased snow cover amplifying radiative forces in Himalayas are increasing day by day. Several modelling studies suggested that precipitation increase 10-40% and prolonged dry period during inter-monsoon season. These erratic events disturb hydrological regimes that regulated the breeding behaviour, foraging behaviours, and migratory pattern of different fauna (Vanak, 2014).

Since 1980, the Hindu Kush Himalaya facing glacial retreat losing mass which altering thermal profile and seasonal flow of glaciers fed streams. These stressor affect aquatic biodiversity and riparian food webs.

Although scientific concerns are increasing, but Himalayan wildlife ecology needed more integrated regional sustainable development policies frameworks in this sensitive ecosystem. The Sustainable Development Goals, specially SDG 13 (Climate Action), and SDG 15 (Life on Land) provide baseline anchors, but their implementation in Himalayan contexts require species-specific vulnerability data. This review paper address knowledge gap by: (i) synthesis existing documentation of faunal responses to climatic and anthropogenic pressures; (ii) Suggesting a

Vulnerability Sensitivity Exposure (VSE) assessment matrix adapted for faunal diversity of Himalaya; and (iii) Integrating evidence-based proposal for climate-adaptive conservation within sustainable mountain Himalayan development.

2. Himalayan Wildlife: Structural Diversity and Biogeographic Context

2.1 Elevational Zonation and Faunal Assemblages

The Himalayan elevational gradient constitutes one of ecology's most powerful natural experiments, compressing multiple biomes within a single continuous landscape (Chettri et al., 2008). Faunal communities are conventionally partitioned into four broad elevational zones: (i) the Sub-Himalayan Siwaliks (200–1,200 m), dominated by tropical and subtropical fauna including the Bengal tiger (Panthera tigris tigris), Asian elephant (Elephas maximus), and Indian rhinoceros (Rhinoceros unicornis); (ii) the Lesser Himalayan zone (1,200–3,000 m), characterised by temperate forest assemblages including barking deer (Muntiacus muntjak), Himalayan black bear (Ursus thibetanus), and a rich avifauna exceeding 300 resident species; (iii) the Greater Himalayan zone (3,000–5,000 m), supporting charismatic megafauna such as the snow leopard, Himalayan brown bear, bharal (Pseudois nayaur), and Asiatic ibex (Capra sibirica); and (iv) the TransHimalayan cold deserts (>5,000 m), home to highly specialised assemblages including the Tibetan wolf (Canis lupus filchneri), kiang (Equus kiang), and Himalayan griffon (Gyps himalayensis) (Chettri et al., 2008).

Invertebrate diversity along this gradient is comparably extraordinary but far less systematically documented. Alpine insect communities—including bumblebees (Bombus spp.), noctuid moths, and high-altitude Coleoptera—serve critical pollination and decomposition functions that underpin plant community composition (Thuiller, W.,et al., 2005). and, by extension, vertebrate habitat structure. The effective conservation cannot be achieved by targeting individual species in isolation, so effort should be focus on the protection of entire mountain range because flora and fauna in this region are interconnected.

2.2 Endemism and Conservation Status

High endemism rates present in the Himalayas relative which occurs nowhere else on the earth i.e. approximately 33% of amphibian species, 12% of mammalian species, and 18% of plant species (Thuiller, W. et al., 2005). According to IUCN Red List (2023), 76 Himalayan vertebrate species are threatened and comes under Vulnerable, Endangered, or Critically Endangered categories. In this region, the snow leopard (Vulnerable), Ganges river dolphin (Endangered), and

Kashmir stag or hangul (Critically Endangered) are demanding specific conservation focus. Endemic amphibian genera such as Nanorana and Scutiger are bio-indicator of disturbing climate driven habitat due to their sensitivity to temperature and moisture.

3. Climate Change Drivers Affecting Himalayan Fauna

3.1 Elevation-Dependent Warming and Its Biological Consequences

Elevation-dependent warming (EDW) affect the entire mountain ecosystem of Himalaya. The scientific records from 1901 to 2020 reveal that temperatures above 3,500 m have increased approximately twice as the global mean surface temperature around the same period. These mechanism directly affect ectothermic animals particularly amphibians, lizards, and invertebrates (Pound et al., 2006). Theses taxa facing compressing viable thermal niches upslope, and species already occupying summit elevations, remove refugia entirely (Rangwala, I., & Miller, J.R. 2012).

Endothermic mammals face subtler but equally consequential challenges: altered snowpack phenology disrupts den emergence timing in hibernating species, while changing vegetation phenology—driven by earlier spring warming—can generate trophic mismatches in which herbivore nutritional requirements peak outside the window of maximum forage productivity (Rangwala, I., & Miller, J.R. 2012).

3.2 Glacial Retreat and Hydrological Disruption

Himalayan glaciers collectively store approximately 40% of global freshwater excluding polar ice caps and supply seasonal baseflow to ten major river systems supporting 1.3 billion people. Beyond their human-use significance, glaciers regulate aquatic thermal regimes critical to cold-stenothermic fauna including snow trout (*Schizothorax spp*.), mahseer (*Tor spp*.), and glacier-dependent macroinvertebrate communities. Glacial retreat is advancing the 'peak water' inflection point—the juncture at which glacier meltwater contribution to river discharge begins declining—sooner than projected, threatening to collapse population viability for species whose reproductive cycles are temporally anchored to meltwater-driven flow pulses. Postpeak-water scenarios also project increased inter-annual discharge variability, which is ecologically disruptive for obligate riverine vertebrates with low plasticity in reproductive habitat selection.

3.3 Altered Monsoon Dynamics and Precipitation Extremes

The South Asian monsoon, the dominant climatic driver of summer ecology across the central and eastern Himalayas, is exhibiting intensification in peak intensity concurrent with greater inter-annual variability. For wildlife populations, the consequences are asymmetric: prolonged dry pre-monsoon periods reduce standing water availability in alpine meadows critical to breeding amphibians (Pound et al., 2006) and insectivorous birds (Biber et al., 2020), while intense post-monsoon flooding events erode riverbank nesting habitat for species such as the river lapwing (*Vanellus duvaucelii*) (Biber et al., 2020), and gharial (*Gavialis gangeticus*). Crucially, altered monsoon timing disrupts the synchrony between arthropod prey peaks and the nestling growth phases of passerine birds-a phenological mismatch dynamic extensively documented in temperate European systems but requiring systematic investigation in Himalayan contexts.

4. Documented Faunal Responses to Climate Change

4.1 Altitudinal Range Shifts

Altitudinal range shifts-the upslope displacement of species' distributional limits in response to warming—represent the most extensively documented wildlife response to climate change in mountain systems globally (Körner, C. 2007). In the Himalayas, systematic evidence derives from a growing body of resurvey studies, camera-trap analyses, and citizen science databases. Shrestha et al. (2012) documented upslope advances of 29 bird species in Nepal over a 20-year period, with an average shift of approximately 11 m per year. More recently, occupancy modelling of snow leopard habitat suitability across the Tibetan Plateau and Himalayan arc projects a net reduction of 22–30% in climatically suitable area under RCP 4.5 scenarios by 2050, with the highest-quality remaining habitat concentrated in increasingly fragmented trans-boundary zones (Xu, J., 2009).

A critical but underappreciated dimension of altitudinal range shifts is the 'summit trap' phenomenon: species occupying the highest elevational niches cannot shift upslope indefinitely, and for Himalayan specialists such as the chiru (Pantholops hodgsonii) or high-altitude Nanorana frogs, the summit constitutes an absolute biological ceiling beyond which no suitable habitat exists. Populations encountering upper mountain facing geographic footprint in viable range area lead to near-total habitat loss within decades under continued warming.

4.2 Phenological Disruption and Trophic Cascades

Phenological shifts—alterations in the seasonal timing of biological events such as breeding, migration, and dormancy—represent a second major axis of climate-driven ecological reorganisation. In Himalayan systems, spring advancement driven by warming means that plant flowering, insect emergence, and snowmelt now occur in altered temporal relationships. For migratory waterfowl staging in high-altitude wetlands such as Tsomoriri and Pangong in Ladakh, earlier ice-melt affects stopover habitat availability and food web composition during critical pre-breeding fattening periods. Himalayan snowcock (Tetraogallus himalayensis) breeding success has been negatively correlated with late-season snowfall anomalies that reduce chick survival through hypothermia and insect prey reduction—a relationship that, given projected increases in precipitation variability, presages declining population trajectories in multiple high-altitude galliforms.

4.3 Interspecific Interactions Under Climate Stress

Climate change not only affects species individually but reshapes competitive, predatory, and mutualistic relationships in ways that can propagate through food webs with amplifying effects (Shrestha et al., 2012). Upslope expansion of common leopards (Panthera pardus) into former snow leopard territory (Forrest, J.L., 2012) driven by prey availability shifts and reduced deepsnow barriers -creates novel competitive overlap that disadvantages the ecologically specialised and territorially subordinate snow leopard in disturbed areas (Forrest, et al., 2012). Similarly, the northward and upward advance of generalist ungulates such as domestic livestock, facilitated by reduced winter severity, increases grazing competition with wild bharal and markhor (Capra falconeri) on alpine pastures (Mishra, et al., 2006,) simultaneously exposing native fauna to novel pathogen exposure from domestic animals.

5. A Novel Vulnerability–Sensitivity–Exposure (VSE) Assessment Matrix for Himalayan Fauna

Existing climate vulnerability frameworks—such as the IUCN Climate Change Vulnerability Assessment (CCVA) and Trait-Based Climate Exposure models— provide valuable generic tools but inadequately capture the specific ecological architecture of mountain fauna, particularly the interaction between elevational niche breadth, seasonal migration distances, and thermal tolerance plasticity(Sandhu, H.S. et al., 2017). We propose a contextually calibrated VSE matrix that integrates three orthogonal axes of climate risk:

- Vulnerability (V): The intrinsic biological capacity of a taxon to adapt the climatic stressors, and assessed through physiological tolerance ranges reproductive success rate, and genetic diversity.

- Sensitivity (S): The fitness parameters (survival, reproduction, range occupancy) of taxa are quantitatively linked to mountain climatic parameters i.e. temperature, precipitation, snowpack depth, or stream discharge. These parameters estimated through species distribution modelling with the help of demographic analysis (Sandhu, H.S. et al., 2017).

• Exposure (E): The size and rate of climatic change within a taxon's current and future range are differentiated by elevational zone and RCP scenario, with explicit treatment of spatial variability govern by topographic shielding and aspect-mediated microclimate heterogeneity.

Table 1. VSE Assessment Summary for Selected Himalayan Indicator Taxa

Indicator Taxon	VSE Risk Category and Key Determinant
Snow leopard (Panthera uncia)	HIGH — Low reproductive rate (V), strong prey-climate linkage (S), summit-trap compression (E)
Himalayan brown bear (Ursus arctos isabellinus)	MODERATE-HIGH — Omnivory confers sensitivity buffer (V), hibernation phenology disrupted (S), range fragmentation (E)
High-altitude amphibians (Nanorana spp.)	CRITICAL — Narrow thermal tolerance (V), direct moisture dependence (S), severe EDW exposure (E)
Alpine bumblebees (Bombus spp.)	HIGH — Thermoregulation costly at elevated temps (V), floral synchrony disrupted (S), upslope compression (E)
Snow trout (Schizothorax spp.)	HIGH — Cold stenothermic (V), glacial baseflow decline (S), peak-water timeline (E)
Himalayan griffon (Gyps himalayensis)	MODERATE — Wide thermal tolerance (V), scavenging flexibility (S), livestock carcass availability shift (E)

The VSE matrix is act as a scoring instrument which is capable of producing spatially explicit risk maps when combined with multidimensional regional climatic and satellite-derived land-cover change data (Sandhu, H.S. et al., 2017). The VSE matrix have three innovative methodologies: i) The climatic indices derived from incorporation of microclimatic heterogeneity via digital elevation model, ii) The species assemblage model proposed integration of biotic interaction with competitive displacement and prey switching method, iii) The temporal dynamism component support the VSE risk categories which shift under various emission.

6. Sustainable Mountain Development: Reconciling Conservation and Human Welfare

6.1 The Tension Between Development Imperatives and Biodiversity Conservation

The Himalayan region support million people whose livelihoods are fundamentally shaped by ecosystem services i.e. water supply, pasture productivity, timber, medicinal plants, and climate regulation. The HKH river systems is facing development pressure of hydropower infrastructure expansion. Around 400 dams are planned or under construction in HKH river system. The linear road construction through sensitive altitudinal transition zones, tourism growth in fragile area, and agricultural expansion are major anthropogenic pressures. These anthropogenic pressures interacts with climate change synergistically. As a result mountain species facing risk of decline and extinction due to isolation driven by climate change.

6.2 Conservation Corridors as Climate Adaptation Infrastructure

Climate change is forcing shift in animal distribution and at the same time extensive infrastructure causing wildlife restriction (Palomo, 2017). So transboundary conservation corridors act as ecological linkages that allow wildlife to move freely across different countries and wide range of elevation gradient (Nogués-Bravo, D. et al., 2007). These movement maintain genetic diversity among populations so it is most suitable strategy for tackling habitat fragmentation or isolation caused by climate change (Palomo, 2017). There are some corridors i.e. Kanchenjunga - Terai Arc-Chitwan landscape, the Karakoram-Pamir-Hindu Kush landscape, and proposed connectivity zones linking India's Gangotri National Park with Tibet's Qomolangma National Nature Reserve corridors with huge potential to sustain metapopulation viability under warming scenarios. At the same time proper functioning of these corridors depend on land-use planning with minimum infrastructure to elevational gradients. This approach of corridors design maintain natural riparian vegetation, and depends upon species-specific behavioural ecology. The corridor width and habitat characteristics vary with animal preference.

6.3 Indigenous and Local Community Knowledge as Conservation Resource

Indigenous communities tribes, pastoral groups, and mountain farming communities have rich traditional knowledge of land management and biodiversity conservation (Datta., 2008). These communities maintain mountain ecology, habitat heterogeneity and balanced hunting pressure in mountain areas. But in modern scientific discourse undervalued the role of indigenous knowledge in Himalayan conservation (Xu, J., 2009). The phenological knowledge in agriculture, pastoral movement according to seasonal resource along the elevational zones, and community-based forest management and wildlife protection through sacred groove are prime example of ecological intelligence. Climate adaptation protocol for Himalayan wildlife will be more suitable when local knowledge (Datta., 2008) can combine with contemporary conservation monitoring programmes.

7. Critical Research Gap and Future Directions

This review paper synthesize and identify the following research gaps in climate change and its impact on wildlife:

- The Long-term monitoring of faunal diversity above 4,500 m through Camera-trap, acoustic monitoring, and transect surveys are unbalanced due to logistical hurdles in high elevation zone. The zone between 4,500 and 5,500 m, not well sampled due to harsh terrain and its extreme climatic. This zone is now a critical blind spot for the conservation of wildlife.

- The baseline thermal tolerance data of invertebrates in Himalayan ecosystem are largely unavailable. In alpine ecosystem, the Critical thermal maximum and minimum data of insects is present less than 5%, assessment of sensitivity in this zone remain impossible.

- The Demographic modelling with climate change and anthrogenic pressure: Most distribution models for Himalayan species consider climate and land-use change as independent factors rather than treating them as interacting drivers. This synergistic effects underestimate on population viability for wide-ranging carnivores in Himalayas.

- Disease ecology and climate change: The altitudinal range shifts of hosts and their pathogens under global warming, including chytridiomycosis fungal strains and tick-borne encephalitis vectors are poorly characterised risks. Global warming (Bhatt, U.S., 2013) could precipitate disease-mediated population in naive host populations and trigger encountering pathogens.

- Socio-ecological integration: The feedback loops in mountain communities, inadequately modelled between wildlife population changes and human adaptive behaviour, limit the accuracy of projections used to sustainable development.

8. Conclusions

The Himalayan ecosystem facing rapid acceleration of climate change with anthropogenic pressure, reshaping wildlife of this sensitive zone. This review paper highlight that how Himalayan fauna responding with altitudinal range shifts in different taxonomic groups. The interspecific interactions, and demographic decline of endemic species measure along the altitudinal gradient. The VSE matrix demonstrate a novel instrument for conservation strategies and policy- risk assessments.

The sustainable development in the Himalayas is not only socioeconomic but it is inherently ecological. Socio-economic development is dependent on biodiversity supported ecosystem in this region, that cannot be maintained if habitat fragmentation, species range shift, and trophic levels are not checked. Climate modelling with field ecology fulfil the conservation goal. The transboundary governance policy extend conservation beyond national park boundaries and partnership with the indigenous communities. This review highlights that traditional knowledge is inseparable irreplaceable component of long term conservation strategy

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