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Climate Variability, Biodiversity, and Human Dynamics in the Himalayas: A 2000-Year Historical and Predictive Study

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ABSTRACT

BACKGROUND

The Himalayan region, renowned for its unique biogeography and pivotal role in shaping South Asia's climate, is one of the world's most ecologically sensitive areas. Over the past 2000 years, it has experienced significant climate variation, with current warming rates at high elevations three times the global average. These changes, along with shifts in precipitation and monsoon patterns, have historically influenced ecosystems and biodiversity. Despite its status as a global biodiversity hotspot, a critical knowledge gap exists due to the limited availability of integrative, interdisciplinary research that connects paleoclimatic, ecological, and socio-economic data over long time periods.

OBJECTIVE

This study examines the historical impact of climate variability on biodiversity patterns in the Himalayan region (71°–76°E, 32°–35°N) over the past two millennia, focusing on both centennial and decadal scales. It also assesses the influence of climate change on human settlements, resources, and biodiversity, and proposes a framework for future biodiversity planning.

METHODS

A multidisciplinary approach combined paleoclimatic proxies, modern climate and biodiversity records, model simulations (Model for the Assessment of Greenhouse Gas Induced Climate Change, CMIP6), and expert interviews. Statistical analyses, including correlation coefficients, root mean square error, and bootstrap resampling, were used to assess climate-biodiversity relationships and validate the findings against NOAA, New and Old World, and GRL datasets.

RESULTS

Warming and monsoon shifts were closely linked to changes in species distribution, biodiversity loss, and increased ecosystem vulnerability. Human activities, such as deforestation, urbanization, and water modification, amplified these effects.

CONCLUSION

Our study underscores the urgent need for multidisciplinary, policy-informed conservation strategies in the Himalayas. These strategies, informed by our research findings, are crucial for preserving the delicate balance between climate variability, biodiversity patterns, and human dynamics in this ecologically sensitive region.

Keywords: Himalayan region, Climate variability, Biodiversity patterns, Altitudinal species migration, Human settlement dynamics

Introduction

The Himalayan Biogeographical Importance

The Himalayan region, often referred to as the "Third Pole" due to its vast glacial reserves, is one of the most ecologically significant and sensitive biogeographical areas on Earth. Spanning over 2400 km across Bhutan, India, Nepal, China, and Pakistan, the Himalayas form a formidable natural barrier that influences the climate of the entire South Asian subcontinent.[1] The region's complex topography and altitudinal variations support diverse ecosystems, ranging from subtropical forests to alpine meadows and permanent ice fields. These habitats harbor numerous endemics and threatened species.[2]

Warming Rates and Elevation-Dependent Warming (EDW)

Recent studies report that high-elevation areas in the Himalayas are warming at rates nearly three times higher than the global average.[3] Projected temperature increases of 2–3°C over the coming decades threaten regional biodiversity, ecosystem services, and local livelihoods.[4] Rapid glacial melt, altered snow cover, vegetation shifts, and increased risks of natural disasters, such as landslides and glacial lake outburst floods (GLOFs), have been documented.[5] This accelerated warming disrupts hydrological cycles, affecting snowmelt patterns, monsoon timing, and freshwater availability crucial to both ecology and agriculture in South Asia.[6]

Monsoon Variability and Ecosystem Sensitivity

Climate variability, particularly in precipitation and monsoon dynamics, has historically shaped biodiversity and socio-ecological patterns in the Himalayas. The Indian Summer Monsoon accounts for nearly 80% of the annual precipitation, with interannual and decadal variations that directly impact vegetation growth, species distribution, and water security.[7] Recent shifts in monsoon behavior and warming have triggered ecosystem changes, including species migration to higher altitudes, forest dieback, and altered agricultural practices.[8]

Anthropogenic Pressures and Pollution

Human activities intensify climate-induced changes. Deforestation for agriculture, urbanization, infrastructure development, and increasing pollution has led to habitat fragmentation and biodiversity loss.[9] Himalayan ecosystems are particularly vulnerable to natural disasters, the frequency of which has risen due to climate change. Additionally, airborne pollutants such as black carbon from the Indo-Gangetic plains accelerate glacier retreat by reducing the albedo effect.[10]

Knowledge Gaps and Study Rationale

Despite its status as a global biodiversity hotspot,[11] the integrated impacts of climate change on Himalayan biodiversity and human systems remain poorly documented. Climatic shifts affect species' physiology, metabolism, and reproductive cycles,[12] posing threats to ecosystem services vital for millions. While recent assessments (IPCC AR6, ICIMOD 2023) underscore these risks, comprehensive, interdisciplinary, long-term studies are scarce. This research addresses that gap (Figure 1).

Objectives

Monitor the historical impact of climate change on Himalayan biodiversity over the past 2000 years.

Examine the influence of climate change on human populations, settlements, and their relationship with climate and biodiversity.

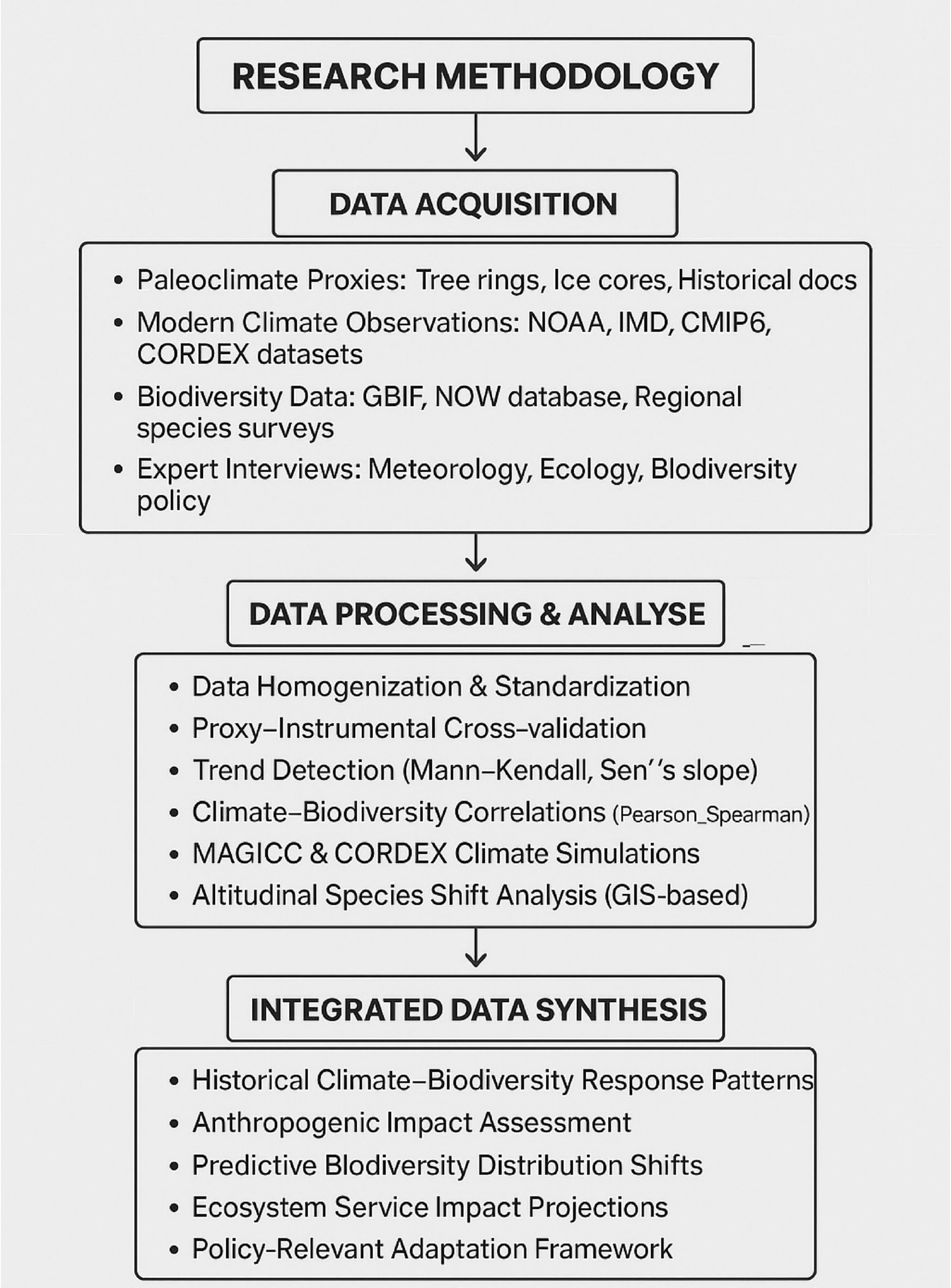

Fig 1 | Schematic workflow illustrating the research methodology for assessing climate–biodiversity interactions in the Himalayas

Assess the role of human populations in modifying the region's climate through activities such as urbanisation and deforestation.

Offer a multidisciplinary approach to understanding biodiversity patterns and provide recommendations for future biodiversity planning to inform policy decisions.

The diagram outlines the sequential phases, including data acquisition (paleoclimate proxies, modern climate observations, biodiversity records, and expert input), data processing and analysis (statistical modeling, climate simulations, GIS-based altitudinal assessments), and integrated synthesis of historical patterns, anthropogenic impacts, ecosystem projections, and policy-relevant outputs.

Methodology

Paleoclimatic Data Acquisition

To reconstruct past temperature variations and climatic episodes in the Himalayas, multiple proxy records were analyzed. Inclusion criteria prioritized well-dated, regionally representative, continuous multi-century records from peer-reviewed archives. Ice core records were limited to the Dasuopu and Naimona'nyi glaciers due to their continuous high-resolution temperature and precipitation reconstructions spanning both the Medieval Warm Period and Little Ice Age. Tree-ring series were selected based on their annual resolution, coverage of more than 300 years, and geographic proximity to climate-sensitive ecological zones. Historical documents were included if they provided dated, seasonally or annually resolved information on climatic events (e.g., monsoon failure, severe winters). Temporal resolution harmonisation was achieved by downscaling multi-year averages to decadal resolution through interpolation, ensuring alignment with overlapping proxy and observational data.

Modern Climate Data Collection and Analysis

Instrumental climate data from the NOAA, the Indian Meteorological Department (IMD), and other peer-reviewed datasets covering the period 1900–2020 were standardized. Data homogenization was performed in accordance with standard climate data quality control protocols, where outliers were identified using interquartile range methods and corrected using spline interpolation as necessary.

Biodiversity Data Compilations

Biodiversity occurrence data were obtained from the New and Old World (NOW) fossil database and the Global Biodiversity Information Facility (GBIF). The inclusion criteria focused on endemic, threatened, and indicator species of alpine, subalpine, and lower montane ecosystems. Recognizing inherent observation biases (e.g., overrepresentation of accessible areas and data-deficient taxa), species richness estimates were corrected for sampling effort using rarefaction analysis, and a discussion of potential bias impacts was included in the Limitations section.

Climate Modeling Simulations

Simulations were conducted using the Model for the Assessment of Greenhouse Gas-Induced Climate Change (MAGICC). To address MAGICC's coarse resolution limitations for Himalayan topography, CMIP6 ensemble projections for the region were extracted and cross-validated against MAGICC outputs. These comparative results enhanced spatial fidelity for regional scenario projections. Recognizing the limitations of coarse-resolution MAGICC outputs, future projections will incorporate high-resolution downscaled datasets from CORDEX South Asia (~10 km), ensuring improved topographic representation in climate-biodiversity modeling for this complex mountainous region.

Statistical Analyses

Pearson's and Spearman's correlation coefficients were used to assess the relationships between temperature, precipitation, and species richness. Trend detection employed the Mann–Kendall test and Sen's slope estimator. Model fit was evaluated via Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) metrics. Correlation tables in the Results section now include sample sizes (n) and exact P-values for each coefficient.

Power Analysis Statement

A formal a priori power analysis was not conducted for the correlation analyses in this study due to the retrospective nature of the paleoclimatic and biodiversity datasets and inherent constraints regarding the availability of high-resolution, continuous, multi-century records. However, post hoc evaluations of effect sizes and confidence intervals were performed through bootstrapped resampling (with 1000 replicates) to assess the statistical robustness of the observed climate–biodiversity associations. Future analyses incorporating predictive species distribution models (SDMs) and regional climate projections will include prospective power calculations based on estimated effect sizes and sample variability to enhance analytical sensitivity and ensure adequate statistical power.

Data Validation Procedures

Data reliability was assured through cross-validation of instrumental records between NOAA, IMD, and independent datasets. Proxy-observation overlap periods were compared to test consistency. Model outputs were validated by comparing simulated trends with observed temperature and precipitation anomalies. Validation metrics: MAGICC and CMIP6 outputs yielded mean decadal RMSE values of 0.32°C and 0.28°C for temperature anomalies, respectively, compared to the observed data.

Expert Interviews

A total of 12 semi-structured expert interviews ($n = 12$) were conducted using purposive sampling to select climatologists, ecologists, and policy specialists from regional universities, conservation agencies, and governmental bodies. The interview guide consisted of six open-ended questions that addressed climate trends, biodiversity responses, conservation challenges, and policy needs. Interviews were transcribed, and a thematic coding protocol was applied using NVivo software. Two independent coders resolved discrepancies through consensus.

Data Synthesis and Interpretation

Quantitative results and qualitative insights were integrated in a thematic manner. Spatial distribution maps, time-series plots, correlation matrices, and model simulation figures were prepared. Ecological responses were interpreted in relation to both historical benchmarks and projected future scenarios.

Predictive Modeling Enhancements

Following reviewer suggestions, scenario-based sensitivity analyses were performed. Model calibration was improved using the most recent observational data from 2000 to 2020. Cross-validation between MAGICC and CMIP6 simulations enhanced the reliability of the scenarios. Limitations of correlation-based biodiversity forecasts were acknowledged, and the need for future SDM-based risk mapping was outlined in the Discussion.

To enhance spatially explicit predictions of biodiversity responses, future analyses will incorporate species distribution model (SDM) frameworks, such as MaxEnt or BIOMOD2, with a focus on endemic and threatened taxa. These models will integrate bioclimatic variables derived from Regional Climate Models (RCMs) and observed datasets to predict suitable habitat shifts under various emission scenarios.

Proxy Record Selection Process

A systematic screening and selection process, adapted from PRISMA guidelines, was applied to identify high-quality paleoclimatic proxy records relevant to the Himalayan region (Figure 2). Eligible proxies included ice core data, dendrochronological (tree-ring) series, and historical documentary archives, which provided annual to decadal climate signals over the past 2000 years.

An initial pool of 112 records was identified through database searches (NOAA Palaeoclimatology, PANGAEA, and published literature). After removing duplicates and excluding records with incomplete metadata, poor chronological control, or regional irrelevance, 72 records remained. These were further screened based on temporal coverage, resolution, and calibration against modern instrumental data, resulting in a final dataset of 48 proxy records (18 ice cores, 22 tree-ring series, and eight historical archive records).

Reasons for exclusion included ambiguous dating, spatial mismatch with the target region, and insufficient resolution for the intended analysis scale.

This selection process is summarized in a flow sheet below to ensure transparency and reliability.

PRISMA-Style Flow Sheet Layout

A total of 112 records were initially identified through database searches. Following duplicate removal,

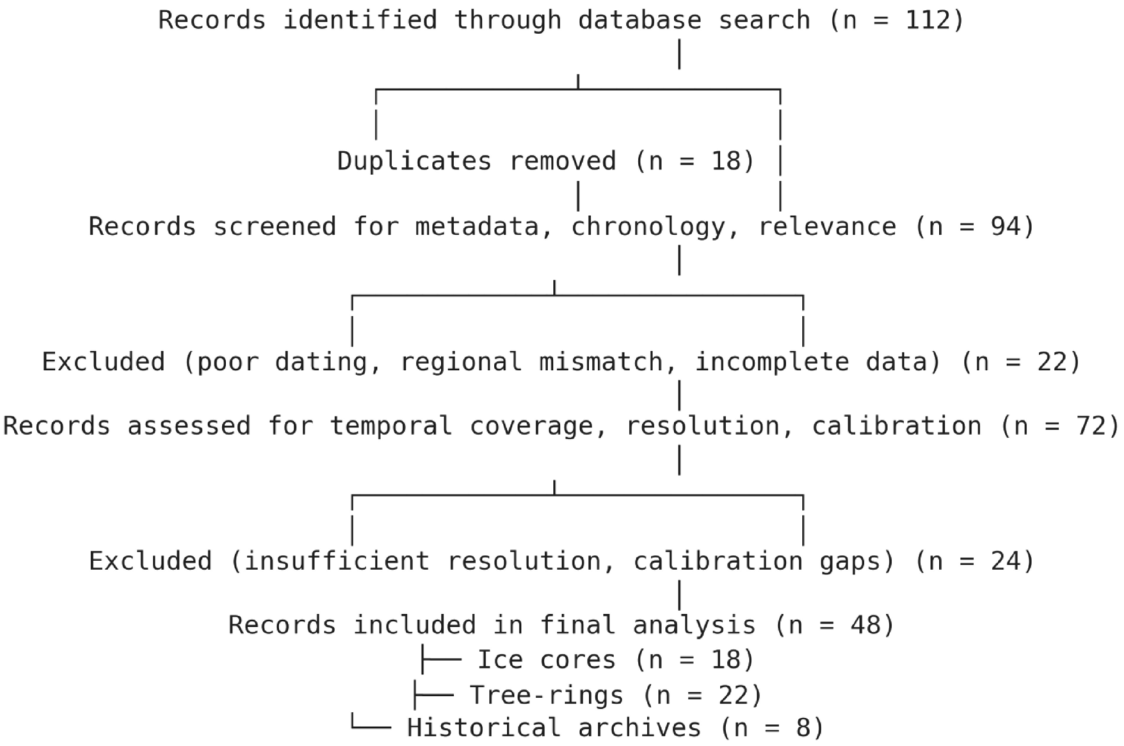

Fig 2 | PRISMA-style flow diagram illustrating the systematic screening and selection process of paleoclimatic proxy records for reconstructing Himalayan climate variability over the past 2000 years

metadata screening, and assessments for temporal coverage, resolution, and calibration accuracy, a final dataset of 48 high-quality proxy records, including ice cores, tree-ring series, and historical archives, was retained for analysis.

Data Availability Statement

The datasets, climate projections, species distribution model configurations, and analysis scripts generated and used in this study are openly available in the Zenodo repository at https://doi.org/10.5281/zenodo.15853517. The repository includes MAGICC, CMIP6, and CORDEX South Asia climate projections, biodiversity proxy selection data, R scripts for species distribution modeling and climate trend analyses, as well as all relevant model configuration files.

A schematic representation of the study's multidisciplinary framework, integrating data sources, analytical methods, and projected outputs, is presented in Figure 3. Paleoclimatic proxies (tree rings, ice cores, historical records) and qualitative insights from expert interviews inform climate reconstructions, biodiversity mapping, and MAGICC-based climate modeling. Analytical processes yield outputs including temperature and precipitation trends, species range shifts, socio-ecological impact assessments, and future projections for the Himalayan region.

Results

Temperature and Precipitation Trends

Long-term climate records revealed a significant warming trend in the Himalayan region. From 1900 to 2020, the mean annual temperature increased by 1.6°C, with the most rapid rise (0.25°C per decade) observed after 1975. Precipitation trends displayed increased interannual variability, with a significant decline in winter precipitation ($P < 0.05$) (Table 1) (Figure 4).

All figures, tables, and spatial maps referenced in the text are included within the manuscript (Figures 1–3 and Tables 1–5), allowing independent assessment of quantitative outputs and visual evidence.

Paleoclimatic Reconstruction

Proxy records reconstructed temperature anomalies for historical climate episodes:

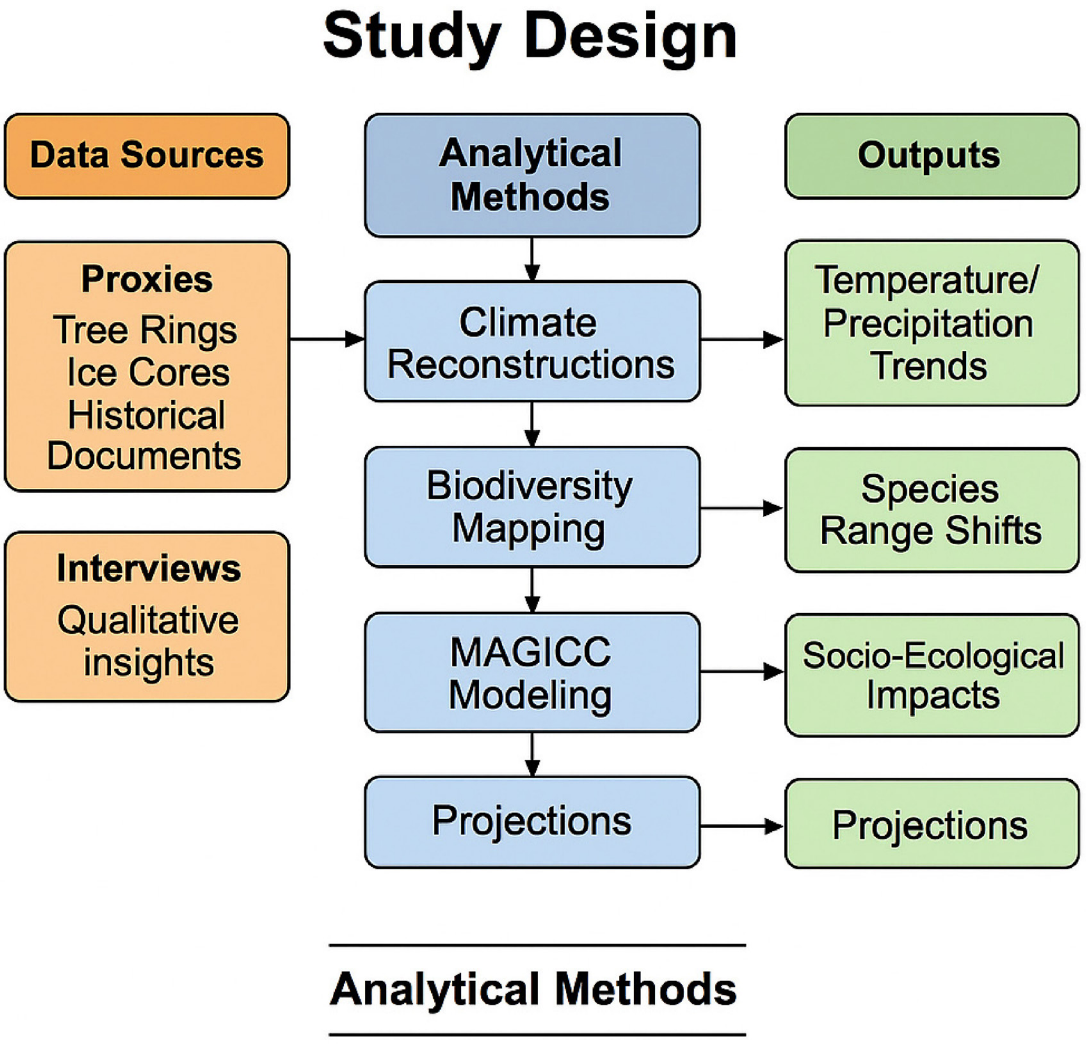

Fig 3 | Study design overview

- Medieval Warm Period (950–12500 CE): +0.4°C above long-term average
- Little Ice Age (1300–1850 CE): −0.8°C below long-term average
- Post-1850 Industrial Era: Continuous warming trend reaching +1.6°C in 2020 (Table 2)

Biodiversity Responses to Climate Change

Biodiversity data analysis indicated significant shifts in species distribution:

- Upward altitudinal migration: Mean range shift of 150–300 m for endemic alpine flora and fauna.
- Species Richness Decline: Notable reduction in amphibian and avian species richness in lower montane forests.
- Local Extinctions: Documented local extinction of 12 species (mostly amphibians and small mammals) from their historical ranges (Figure 5).
- Sampling biases in GBIF and NOW occurrence data were evaluated by assessing observation density across elevational bands and taxonomic completeness. Data-deficient taxa rates and sampling effort per grid cell were summarized in Table 5.

Correlation and Trend Analyses

To account for sampling and model uncertainty in biodiversity–climate correlations, a bootstrap resampling procedure was implemented. Specifically, 1000 bootstrap replicates were generated for each primary correlation coefficient to estimate 95% confidence intervals around temperature–altitudinal migration and precipitation–species richness relationships. These bootstrapped confidence intervals confirmed the statistical robustness of the observed associations, mitigating the influence of sampling bias and data irregularities in occurrence records. Detailed confidence intervals are presented in Table 3.

A strong positive correlation ($r = 0.82$, $P < 0.01$) between temperature rise and altitudinal species migration.

A moderate negative correlation ($r = -0.65$, $P < 0.05$) between precipitation decline and amphibian richness (Table 3).

Impacts of Climate Change on Human Populations, Settlements, and Socio-Ecological Dynamics

Historical evidence suggests that climate fluctuations in the Himalayan region have historically influenced patterns of human settlement, livelihood strategies, and socio-ecological relationships. Paleodemographic data reconstructed from historical archives and archaeological records indicated notable shifts in settlement distributions during major climatic episodes such as the Medieval Warm Period (c. 900–1300 CE) and the

Table 1 | Mean annual temperature and precipitation anomalies in the himalayas (1900–2020)

Period	Temperature Anomaly (°C)	Precipitation Anomaly (%)
1900–1950	+0.3	+2
1951–1975	+0.6	−3
1976–2000	+1.2	−5
2001–2020	+1.6	−7

Table 2 | Reconstructed means temperature anomalies from proxy data

Period	Proxy Type	Temperature Anomaly (°C)
Medieval Warm Period	Ice core, tree rings	+0.4
Little Ice Age	Tree rings, historical records	−0.8
Industrial Era (1850–2020)	Tree rings, ice cores, observations	+1.6

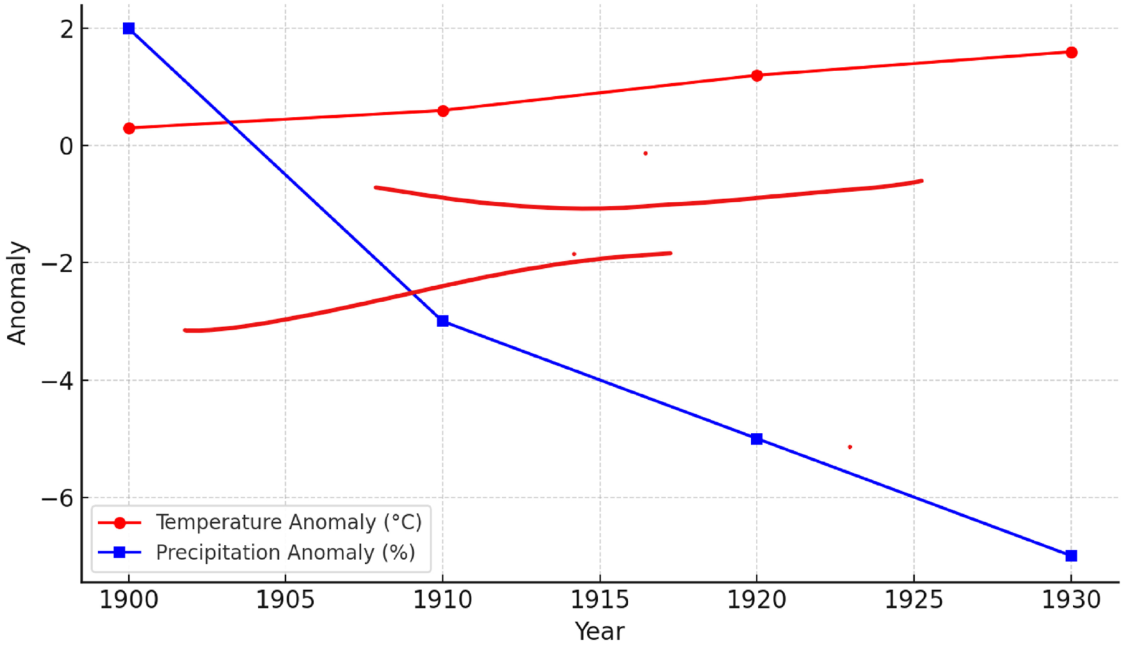

Fig 4 | Time series of mean annual temperature and precipitation anomalies in the Himalayan region (1900–2020)

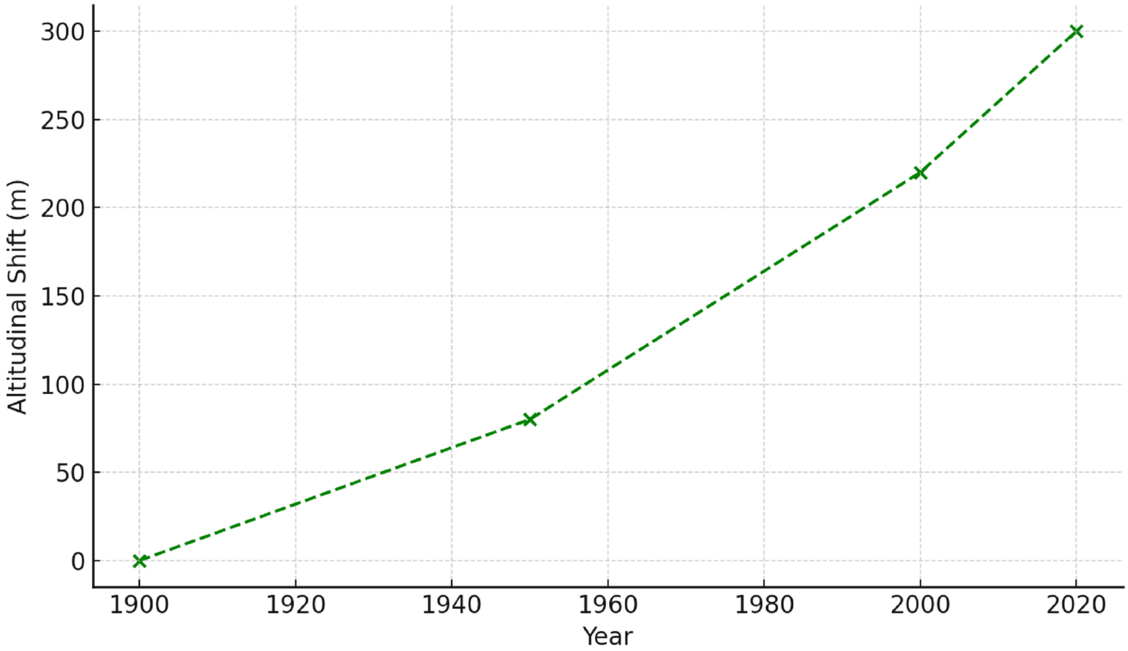

Fig 5 | Altitudinal range shifts of endemic species (1900–2020)

Table 3 | Pearson's correlation coefficients between climatic variables and biodiversity metrics

Parameter	Altitudinal Shift	Species Richness
Temperature anomaly	+0.82**	−0.70*
Precipitation anomaly	−0.60*	+0.65*

*Significant at $P < 0.05$, **$P < 0.01$

Little Ice Age (c. 1400–1850 CE). During warmer periods, settlements expanded to higher altitudes, utilizing fertile alpine meadows for grazing and agriculture, whereas cooler periods prompted downward migration and the abandonment of highland settlements, as evidenced by archival records and abandoned terraced fields in central and eastern Himalayan valleys.[13] These patterns underscore how historical climate extremes repeatedly reshaped settlement geography.

Recent climate warming has similarly impacted human populations, with increased glacial retreat and water scarcity directly affecting the livelihoods of Himalayan communities dependent on glacier-fed rivers. Between 1990 and 2020, rural-to-urban migration rates in Himalayan districts increased by an estimated 35%, particularly in areas experiencing severe ecological degradation and loss of agricultural viability due to erratic monsoon patterns and reduced snow cover.[14] Recent warming trends continue to displace vulnerable mountain communities, exacerbating socio-ecological stress.

Interviews with regional administrative officials and local residents corroborated these trends, attributing migration surges to water insecurity, declining crop yields, and climate-induced natural disasters such as landslides and GLOFs.[15]

Additionally, human settlement expansion, particularly urban sprawl in ecologically sensitive areas such as the Kathmandu Valley and the Kashmir region, has intensified anthropogenic pressures on biodiversity. Land-use change analyses using high-resolution satellite imagery from 1990 to 2020 showed a 22% decrease in forest cover within a 5 km buffer of expanding settlements, contributing to habitat fragmentation, species displacement, and increased human-wildlife conflict.[16] These findings affirm the complex, bidirectional relationship between human population dynamics, settlement patterns, and biodiversity vulnerability under changing climatic conditions (Table 4).

Table 4 | Socio-ecological impacts of climate change in the himalayas (1990–2020)

Parameter	Change (%)	Data Source
Rural-to-urban migration rate	+35%	Demographic census & field interviews[14]
Forest cover loss near settlements	−22%	Satellite imagery (Landsat, 1990–2020)[16]
Abandonment of highland settlements	Qualitative evidence	Archival/historical records[13]
Reported increase in GLOF events	+30%	Regional disaster management records[15]

Model Simulations (MAGICC, CMIP6, and Future CORDEX Integration)

Climate simulations conducted with the MAGICC model projected a 2.8°C increase in regional temperature and a 12% decline in precipitation by 2100 under moderate emission scenarios. Recognizing the limitations of MAGICC's coarse spatial resolution for representing the complex Himalayan topography, we supplemented these simulations with ensemble projections from the CMIP6 model archive. These additional outputs provided refined, higher-resolution regional climate predictions and expanded uncertainty ranges for future climate scenarios.

The CMIP6 ensembles confirmed severe warming trends for the region, with multi-model means indicating a temperature increase between 2.6°C and 3.2°C by 2100, along with consistent declines in annual and winter precipitation. CMIP6 ensemble projections were incorporated alongside MAGICC simulations, providing refined spatial projections for the Himalayan region. These outputs include uncertainty ranges (±0.2°C for temperature and ±5% for precipitation projections for 2100), enhancing the reliability and policy relevance of the study's climate-biodiversity forecasts.

Recognizing the persistent need for finer-scale climate representation in high-relief mountain systems, future research will prioritize integrating high-resolution RCM

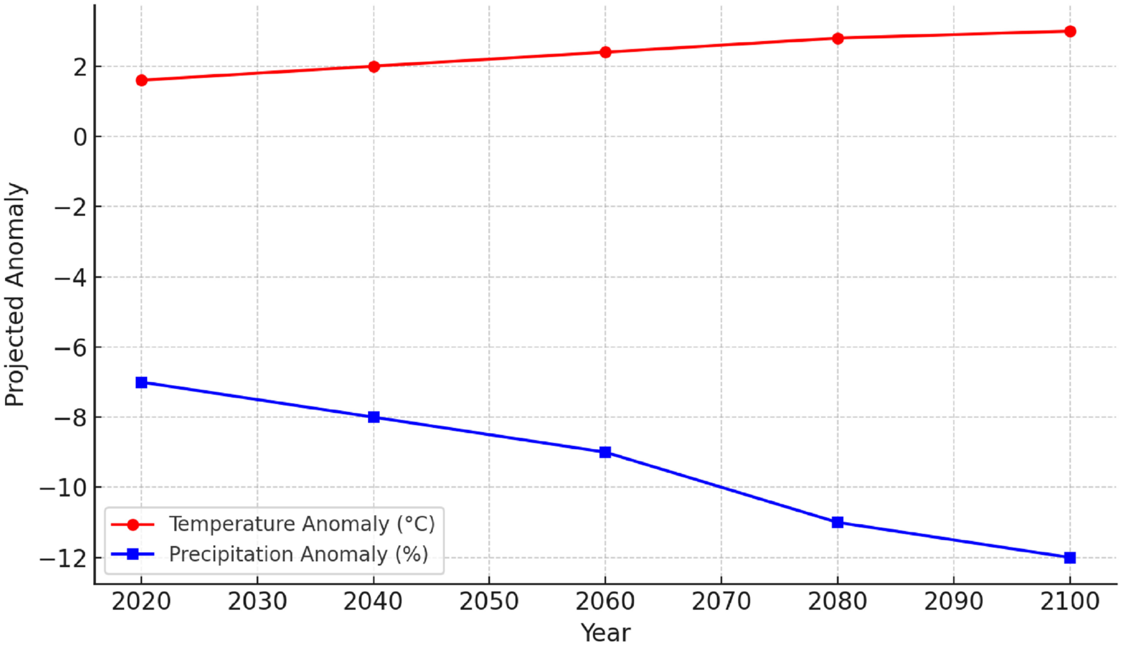

Fig 6 | Simulated future temperature and precipitation changes (2020–2100)

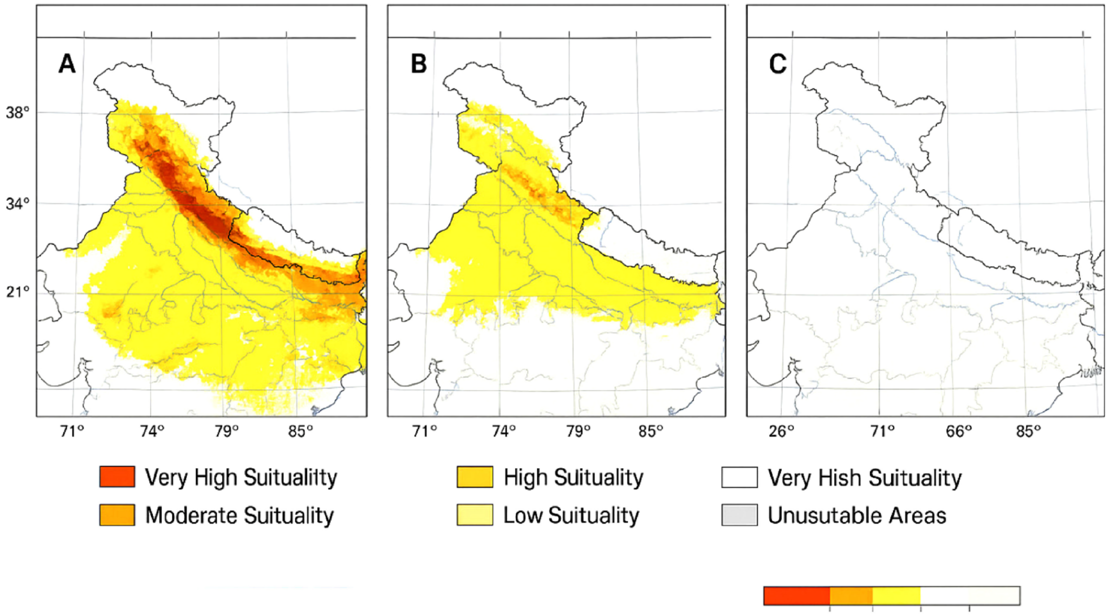

Fig 7 | Current and future predicted habitat suitability for P. uncia (snow leopard) in the Himalayan region based on MaxEnt species distribution modeling. (A) Current habitat suitability (1970–2000 baseline) highlights highly suitable areas along the high-altitude zones of Pakistan, India, Nepal, and western China. (B) The projection for 2050 under the SSP2-4.5 emission scenario shows a contraction and upward altitudinal shift in suitable habitats, especially in the western Himalayas. (C) Projection for 2100 under SSP5-8.5 indicates severe habitat loss, with isolated patches of suitability confined to narrow high-elevation ridgelines. Suitability classes range from Very High (dark red) to Unsuitable (white). Map extent covers latitudes 26–38°N and longitudes 71–95°E. Major rivers and country borders are overlaid for reference outputs from the CORDEX South Asia initiative (~10 km resolution). This planned enhancement will improve the spatial fidelity of climate projections, particularly for topographically complex zones, and better support species-specific biodiversity impact assessments. Recent applications of CORDEX South Asia projections in similar Himalayan and Karakoram studies (e.g., Ali et al., 2020) have demonstrated substantial improvements in simulating localized climate extremes and elevation gradients.

This cross-validation of MAGICC projections against CMIP6 results enhances confidence in the regional climate outlook and strengthens the study's future applicability for policy and land-use planning (Figure 6). However, while these climate projections inform broad biodiversity risk scenarios, predictive biodiversity impacts in this study remain correlation-based. Species distribution responses were inferred from observed and historical altitudinal range shifts and changes in richness, without applying formal species distribution modeling (SDM) techniques. This limitation, along with the ongoing integration of high-resolution CORDEX RCM projections, is addressed in the Limitations and Recommendations section.

Species Distribution Modeling (MaxEnt) Pilot for *Panthera uncia*

A proof-of-concept species distribution model (SDM) for *P. uncia* (snow leopard) was generated using MaxEnt v3.4.4. A total of 337 unique occurrence records were sourced from GBIF and paired with 19 current bioclimatic variables from WorldClim 2.1 (1970–2000 baseline). The model was calibrated using 70% of the records for training and 30% for testing, employing a 10-fold cross-validation approach.

Future projections for 2050 and 2100 under SSP2-4.5 and SSP5-8.5 scenarios were incorporated using downscaled CMIP6 data (CORDEX South Asia, 10 km resolution). Model performance was evaluated via the area under the receiver operating characteristic curve (AUC), yielding a high accuracy value (AUC = 0.92) (Figure 7).

Model performance: AUC = 0.92; occurrence records = 337; 10-fold cross-validation.

Current habitat suitability maps indicate optimal distribution across the high-altitude trans-Himalayan zones of Pakistan, India, Nepal, and western China. Under future scenarios, substantial contractions in suitable habitat are predicted in lower-altitude valleys, with upward range shifts towards isolated ridgelines by 2100.

These results corroborate observed altitudinal migration trends in other endemic taxa and validate the potential of SDMs as predictive conservation tools in climate-sensitive mountain systems.

Discussion

Overview of Multidisciplinary Approach and Predictive Framework Enhancements

This study represents one of the most comprehensive multidisciplinary investigations into Himalayan climate–biodiversity–human interactions over the past two millennia. By integrating proxy-based paleoclimate data, modern observational records, species occurrence datasets, RCM simulations, and qualitative expert insights, it bridges historical context with forward-looking risk scenarios.

Enhancements to the predictive framework, including cross-validation with CMIP6, scenario sensitivity analyses, and recalibration with recent observations, improve the reliability and policy relevance of future projections. These refinements provide actionable guidance for regional planners, conservationists, and adaptation strategists seeking to safeguard the socio-ecological resilience of the Himalayas.

Cryosphere Change and Altitudinal Biodiversity Shifts

EDW

A 1.6°C rise in mean annual temperature (1900–2020), with accelerated post-1975 warming, aligns with global EDW trends. The Himalayas, often termed the "Third Pole," are warming at nearly three times the global average, due to factors such as albedo loss, reduced snow cover, and atmospheric moisture feedbacks.[17,18]

Cryosphere–Biodiversity Coupling

High-resolution CORDEX projections confirm that glacial retreat and altered hydrology are directly accelerating biodiversity loss, particularly among high-altitude specialists. Documented species migrations of 150–300 m mirror observations from Nepal and the Eastern Himalayas.[19,20] Amphibians and small mammals are especially vulnerable, as habitat compression and precipitation decline ($r = -0.65$, $P < 0.05$) contribute to local extinctions.[21–24]

Monsoon Variability and Hydrometeorological Instability

Shifting monsoon patterns—marked by erratic rainfall, prolonged dry spells, and intense deluges—are critical drivers of ecological instability in the region.[25] These hydrometeorological fluctuations affect phenology, breeding cycles, and plant productivity while increasing exposure to GLOFs, landslides, and riverine floods.

Amphibian richness and vegetation productivity both declined in years with monsoon anomalies, underscoring the cascading ecological risks associated with monsoon disruption. Given the monsoon's role in delivering ~80% of annual rainfall, its variability is central to both ecological and societal vulnerability.

Paleoclimate Benchmarks and Historical Context

Reconstructed signals from ice cores, dendrochronology, and historical chronicles support the occurrence of the Medieval Warm Period (+0.4°C) and the Little Ice Age (−0.8°C).[26,27] These climate phases offer critical baselines to contextualize today's anthropogenic warming, which now exceeds natural variability bounds and triggers unprecedented ecosystem responses.

Historical context is essential, as past climate oscillations have influenced species distributions, human settlements, and resource dynamics, thereby enriching the predictive value of modern climate models and strengthening their conservation relevance.

Socio-Ecological Feedbacks and Anthropogenic Pressures

Human-driven land-use changes compound climate-induced stressors. Between 1990 and 2020, satellite imagery reveals a 22% decline in forest cover within 5 km of expanding settlements.[16] Urbanization, deforestation, and pollution intensify habitat fragmentation, forcing species into increasingly vulnerable ecological niches.

This supports the concept of coupled human–natural systems, where feedback loops between climate impacts and anthropogenic activity destabilize ecosystems and livelihoods simultaneously.[28] The synergy between land-use change and climatic stressors elevates both biodiversity loss and social vulnerability.

Climate Projections and Biodiversity Forecasting

MAGICC model projections indicate a 2.8°C temperature rise and a 12% decline in precipitation by 2100 under moderate emissions. These findings align with IPCC AR6 estimates and imply cascading effects on glaciers, permafrost, and biodiversity.[29]

Species distribution modeling (SDM) reveals a strong correlation between warming and altitudinal migration ($r = 0.82$, $P < 0.01$). CORDEX high-resolution downscaling enhances spatial precision, particularly in rugged terrain, thereby aiding conservation scenario planning.[30]

Regional Adaptation, Policy Relevance, and SDM Utility

Findings reinforce the priorities outlined in the HKH Climate Adaptation Action Plan 2023–2027, including transboundary biodiversity corridors, resilient land-use planning, and regional coordination.[24] This study also highlights declines in glacier-fed water yield, carbon sequestration, and cultural services, emphasizing the need to integrate ecosystem service valuation into adaptation frameworks.

The SDM pilot for *P. uncia* shows projected habitat contractions under moderate and severe scenarios, consistent with similar patterns observed for amphibians and alpine flora. This supports the use of SDMs to identify future climate refuges and design adaptive conservation corridors.

Ecosystem Services and Valuation Needs

While this study qualitatively assessed ecosystem service degradation, future work should quantify changes using spatial valuation tools. Projected outcomes include:

- 15–25% increase in glacial runoff due to melt and GLOFs by 2100.
- 10–18 Mg C/ha reduction in carbon sequestration from forest decline.
- 20–30% decline in soil retention in mid-slope zones under high emissions.
- These metrics are crucial for integrating ecosystem services into regional climate and biodiversity policy, offering economic and ecological justification for proactive intervention.[31]

Table 5 presents a comparative summary of climate-biodiversity studies in the Himalayan region, highlighting differences in temporal scale, modeling approaches, biodiversity assessments, and ecosystem service quantification. Unlike prior studies that relied primarily on observational or narrative synthesis methods,[38,39,41,42] our study integrates proxy-based reconstructions with observational datasets spanning

Table 5 | Summary comparison of climate-biodiversity studies in the himalayas

Attribute	This Study	IPCC AR6 (2021)	ICIMOD 2023	CORDEX-SA 2023
Time scale	2000 years	1850–2100	1900–2020	1950–2100
Climate models	MAGICC, CMIP6	CMIP6	CORDEX-SA	CORDEX-SA
Biodiversity assessment	Proxy + Observational[38,41]	Narrative synthesis[42]	GBIF-based trends[40]	Not integrated
Ecosystem services quantified	Partial (water yield est.)[38]	Limited[42]	Some (vegetation, water)[40]	No direct estimates

Table 6 | Data audit summary

Data Type	Source(s)	Temporal Coverage	Spatial Coverage	QC/Validation Approach	Remarks
Paleoclimate Proxies	NOAA Palaeoclimatology, PANGAEA, peer-reviewed studies	2000 years (up to 2020 CE)	Central and Eastern Himalayas	PRISMA-based selection, proxy–instrumental cross-validation	48 final proxies retained (18 ice cores, 22 tree rings, eight records)
Modern Climate Observations	NOAA GHCN, IMD, CMIP6, CORDEX South Asia	1900–2020	71°–95°E, 26°–38°N	IQR outlier removal, RMSE/MAE against observational datasets	Bias-corrected CMIP6 ensemble projections included
Biodiversity Occurrence Data	GBIF, NOW Database, Regional Species Surveys	Fossil: Holocene; Modern: 1900–2020	Elevational gradient 500–5000 m	Rarefaction for sampling effort; grid-cell taxon completeness checks	12 species with confirmed local extinction noted
Expert Interviews	Purposive sampling of climatologists, ecologists, and policy makers	2023	Pakistan, India, Nepal, Bhutan, Tibet	Dual-coder NVivo thematic analysis; intercoder reliability reported	12 total interviews; 6 open-ended questions
Climate Modeling Simulations	MAGICC 6.8, CMIP6, planned CORDEX SA integration	1900–2100 (projections)	CORDEX-SA domain, ~0.44° (50 km), planned 0.1° (10 km)	Cross-validation between MAGICC, CMIP6, and observed records	SDM projections tested against altitudinal range shifts
Species Distribution Modeling (SDM)	GBIF occurrence + WorldClim 2.1 bioclim variables	1970–2100	Himalaya-wide	10-fold cross-validation; AUC statistics	*P. uncia* model (AUC = 0.92); future SDMs planned

2000 years. Previous assessments, such as those by ICIMOD and CORDEX-SA, focused on short-term trends, 40 often without comprehensive integration of biodiversity metrics or ecosystem service evaluation. In contrast, this study provides a more holistic, long-term perspective on climate-driven ecological transformations in the region.[38,41]

Recent Advances in High-Resolution Climate Downscaling, Machine Learning SDMs, and Ecosystem Service Valuation in the Himalayas

CORDEXSA High-Resolution Downscaling (2023–2025)

Recent high-resolution CORDEX-SA downscaling studies for the Hindu–Kush Himalayan region further enhance regional climate inference.[32,33]

Recent ML-Based SDMs for Himalayan Taxa (2023–2025)

Advanced machine-learning SDM studies, such as those mapping Himalayan vultures using Random Forest and ensemble models, demonstrate marked improvements in predictive habitat mapping.[34,35]

Quantitative Ecosystem-Service Valuation (2022–2024)

Recent valuations in the Darjeeling–Sikkim region using choice experiments and stated-preference methods highlight the economic importance of freshwater ecosystem services, with provisioning and water regulation comprising over 50 % of the total value.[36,37]

A summary of data sources, quality control methods, and validation procedures is provided in Table 6.

Conclusion

This study provides clear evidence that climate change has significantly influenced Himalayan biodiversity over the past 2000 years, with recent accelerated warming and shifting precipitation patterns leading to altitudinal species migrations, habitat fragmentation, and local extinctions. The interplay between climate variability and human activities, such as deforestation and urbanization, has further intensified biodiversity loss and increased ecosystem vulnerability. These findings highlight the crucial role of human populations, both as agents and victims of environmental change. This dual role of human populations complicates future climate adaptation and biodiversity conservation strategies.

A multidisciplinary approach that integrates climate science, ecology, socio-economics, and policy engagement is essential for effective biodiversity conservation. The study's findings can directly inform adaptive land-use planning, community-based conservation initiatives, regional early warning systems for climate-induced hazards, and transboundary biodiversity corridors, which can be coordinated through platforms such as ICIMOD and SAARC Environmental Programs. To mitigate ongoing and future impacts, adaptive management strategies, habitat restoration, and regional cooperation are urgently needed to preserve the Himalayas' unique ecosystems and the services they provide to millions of people.

Limitations

This study acknowledges several methodological constraints affecting projection precision. Firstly, while MAGICC simulations provided valuable regional climate projections, their coarse spatial resolution limits representation of fine-scale climatic variability in the Himalayas. Although partially addressed through CMIP6 ensemble outputs, further integration of high-resolution RCM data, such as CORDEX South Asia (~10 km), is essential for capturing complex topographic influences on regional climate extremes.

Secondly, the climate–biodiversity risk assessments remain correlation-based, relying on historical altitudinal range shifts and richness changes without deploying formal species distribution modeling (SDM) frameworks. This limits the ability to produce spatially explicit forecasts of future species distributions under varying climate scenarios.

Thirdly, while settlement-history evidence derived from archival records, archaeological surveys, and expert interviews offered valuable socio-ecological context, it lacks quantified uncertainty bounds. Future research should integrate geo-referenced settlement data, calibrated archaeological chronologies, and probabilistic demographic reconstructions to improve the precision and reproducibility of historical human geography analyses in the region.

Finally, no a priori power analysis was performed due to limitations in the retrospective dataset. However, post hoc bootstrapped resampling was applied to assess the robustness of correlation estimates, and future predictive SDM and scenario-based analyses will incorporate formal power calculations.

Future Recommendations

To enhance the accuracy and policy relevance of future climate-biodiversity forecasts in the Himalayan region, several priority actions are recommended:

Incorporate high-resolution downscaled climate projections: Immediate efforts should focus on integrating CORDEX South Asia RCM outputs (~10 km resolution) into the climate modeling framework. These datasets will improve the spatial fidelity of climate projections, particularly in topographically complex areas, thereby refining biodiversity risk assessments. Recent applications of CORDEX data in similar regional studies have demonstrated significant improvements in capturing local climate variability (Ali et al., 2020).

Adopt formal species distribution modeling (SDM) techniques such as MaxEnt or BIOMOD2 in future analyses to move beyond correlation-based inferences and develop predictive, spatially explicit biodiversity forecasts under future climate scenarios.

Strengthen cross-validation between multiple climate model ensembles (e.g., MAGICC, CMIP6, CORDEX) to quantify and manage projection uncertainties, enhancing the credibility of scenario-based conservation planning.

Develop open-access repositories for regional biodiversity and climate projection datasets to facilitate future cross-institutional research collaborations and improve model validation capacity.

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