Conserving the critically endangered Hangul (Cervus hanglu hanglu) - Future distribution and efficiency of protected areas under climate change: Implications for the conservation of Dachigam landscape

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Abstract

Climate change is impacting species distribution, posing a significant threat to biodiversity. Special attention is needed for vulnerable species like the Kashmir Red Deer (*Cervus hanglu hanglu*). Despite being a global conservation symbol, holistic management is hindered by limited research. A comprehensive study mapping the potential habitat changes for the Hangul in the Dachigam landscape is crucial to enhance conservation efforts. We examined the prospective effects of expected global warming on the distribution of Hangul by assessing species range shifts and employing a maximum entropy approach. The Hangul was anticipated to be sensitive to upcoming global warming and would raise its risk of local extinction. The severity of repercussions from climate change grew as the time horizon increased and decreased the species' suitable habitat. By 2080, predictions indicated a gradual reduction in range or, in some scenarios, the complete loss of habitat, regardless of the potential for Hangul to disperse indefinitely. We estimated that the overall very highly suitable habitat in the protected region is currently 2220 ha, while its huge distribution area in the unprotected zone is 30,445 ha, emphasizing the necessity of establishing corridor connectivity between fragment populations and promoting conservation efforts. Among various climate conditions, the core-to-edge ratio is at its highest level in the current conditions. Our study reveals two critical findings: Firstly, endangered species unique to a particular region are highly susceptible to the ramifications of global warming. Secondly, when evaluating the outcomes of global warming, the highly suitable habitat is expected to shift under predicted climatic changes, with an average altitudinal migration of 700m. Consequently, conservation strategies must consider the expected regional shifts and are designed with a clear understanding of the accuracy in projecting climate change effects.

1. Introduction

Global warming is an additional threat to high-altitude ecosystems, and as a result, their entire faunal assemblages, particularly critically endangered species, may become extinct (Schneiderbauer et al. 2021; Albrich et al. 2020; Weiskopf et al. 2020; Hoffmann et al. 2019). The survival and geographic ranges of the species may be impacted by global warming, and this influence may be severe especially for endemic species (Manes et al. 2021; Leclerc et al. 2020; Silva et al. 2019). For conservation, it is vital to forecast how the distribution of these animals differs under various future scenarios of global warming (De Frenne et al. 2021). Global warming can prompt species to migrate from their original distribution areas to new habitats, highlighting their potential to consistently track their preferred climate niche, even in the face of evolving geographic conditions over time (Antao et al, 2022; Littlefield et al. 2019). Local extinctions may also be a result of this dynamic process, particularly for species with little capacity for dispersal and adaptation (Román-Palacios and Wiens, 2020). Phenotypic plasticity, genetic changes, and climate equilibrium all affect a species' capacity to adapt to climatic change; without these factors, the species may go extinct (Buchholz et al. 2019). Additionally, variables including a species' reproductive rates, spatial extent, migration capability, and niche specificity will affect how that species reacts to global warming (Viana et al. 2022; Ghisbain et al. 2021). It seems unlikely that individual species would react to climate change in a predictable manner. Therefore, in order to forecast how specific species' distributions may vary in response to climate change, we must concentrate on them individually.

Temperature and precipitation are just two climate variables that affect how species distributions evolve (Brun et al. 2020; Waheed et al. 2023; DeMarche et al. 2019), but the main difficulty faced by ecologists and conservation biologists is predicting which components of climate will have the biggest impacts on species distributions. We have recently been helped to grasp possible species distribution shifts more thoroughly by better methods of simulating species distributions and climate change. It has been shown that the Maxent Model works very adept at forecasting the geographic ranges of species because of climate change (Ab Lah et al. 2021; Gilani et al. 2020; Haq et al. 2023). While acknowledging the temporal variability, mapping species distributions under climate change offers valuable insights into understanding its comprehensive impact. Utilizing geospatial analysis enables the anticipation of habitat shifts, both in terms of their direction and extent, offering insights into the future distribution of biodiversity (Yang et al. 2023; Li et al. 2022). Conservation biologists and pertinent authorities can leverage these projections as a foundation for developing proactive solutions aimed at addressing and mitigating the potential impacts of environmental changes.

Hangul, classified as the world's most endangered red deer, faces uncertain impacts from climate change on its future ranges and current precarious status (Mukesh et al. 2015). Many studies have assumed that the Dachigam landscape is critical for Hangul foraging habitats and provides key habitats (Ahmad 2004; Sharma et al. 2010; Mukherjee et al. 2021). The population of Hangul has drastically dropped due to habitat loss, overgrazing, poaching, and disturbances caused by human activities (Shah et al. 2011; Hassan et al. 2013; Ahmad 2022). Furthermore, Hangul migrates to alpine pastures in summer, which have been disturbed due to heavy livestock grazing and turmoil for the last few decades, resulting in a negative impact on the Hangul's population and distribution (Kaul et al. 2020; Bhat et al. 2020). The species primarily inhabits the temperate grasslands, dense riverine forests, and high-altitude meadows of the Dachigam landscape (Ahmad et al. 2016), and is typically found in small family groups (outside mating period) or herds consisting of females and their offspring. Males are usually solitary and only join the groups during the mating season. The Hangul mating season starts in early autumn (September) and continues till mid to late autumn (October-November) (Bhat et al. 2009; Ahmad et al. 2009), and the calves are produced in Spring (March-April) with the snowmelt and new plant growth. We employed ensemble species distribution models to assess the influence of climate change on the future abundance and spatial distribution of over 250 + individuals. This analysis aimed to investigate potential shifts in distribution patterns attributed to forthcoming climate changes (Jain 2022). The predictive ability of these studies is increased by novel approaches developed here for using biological information to enhance the selection of pseudo-absence points. The findings suggest a complicated combination of future habitat persistence and reduction. We identified locations in desperate need of conservation, each exhibiting diverse levels of current forest cover and protection, and each characterized by distinct climatic and ecological conditions. We employed Species Distribution Models (SDMs) to forecast suitable habitats under multiple climate change scenarios for the years 2020, 2050, and 2080. This analysis aimed to assess the potential impact of anticipated climate changes on Hangul. We specifically asked (1) Whether the existing Hangul suitable habitat would be altered by expected global warming. (2) If there would be more or less suitable habitat? (3) How much of a threat global warming might be to Hangul in the future?

The findings of this research will provide valuable perspectives for the preservation of landscape connectivity, considering the existing distribution of suitable habitats. This information can facilitate and guide future species movements counter to the challenges confronted by climate change. Our study will provide pertinent decision-makers and conservation authorities with information on the possible climate change vulnerabilities and can direct future conservation planning for both the Hangul and other threatened ungulate species. Most importantly, the outcomes of this study suggest that the distributions for the Hangul will change and in the future be located in some cases outside of the protected zones. To ensure the prolonged viability of Hangul, it is imperative to initiate and sustain conservation efforts aimed at establishing and safeguarding ecological connectivity. Such connectivity will enable Hangul and other species to migrate to suitable habitats in response to the shifting patterns of global climate.

2. Materials and Methods

2.1 Study area

The central element of the study area is Dachigam National Park (DNP), as it holds the only viable population of Kashmir stag (Hangul) on earth. The 141 km^2 DNP, with an altitudinal range of 1700 to 4250 m is located in the Zanskar Mountain Range of the northwestern Himalayas (Fig. 1). Zanskar range runs from Gurez to Kishtwar bordering the region from northwest to southeast and covers the historical distribution range of Hangul almost fully. Other important mammals that habitat the DNP include large mammals in the area include musk deer (*Moschus chrysogaster*), serow (*Capricornis sumatraensis*), Asiatic black bear (*Ursus thibetanus*), brown bear (*Ursus arctos*), and common leopard (*Panthera pardus*), Himalayan grey langur (*Semnopithecus ajax*), red fox (*Vulpes vulpes*), golden jackal (*Canis aureus*), small Indian civet (*Viverricula indica*) and yellow-throated marten (*Martes flavigula*) (Ahmad et al. 2016).

The area exhibits five primary forest categories: *Pinus wallichiana*, Oak, *Acacia*, Broad-leaved, and Scrub forests. Within the Dachigam National Park (DNP), deciduous trees and shrubs, such as *Populus alba*, *Prunus armeniaca*, and *Pinus wallichiana*, predominate, while species like Salix alba and Juglans regia characterize riparian areas. The northern aspects host extensive forests of *Pinus wallichiana* and *Prunus armeniaca*, with cultivated intentionally invasive tree species, *Quercus robur*, and *Robinia pseudoacacia*, serving as a food and habitat source for wildlife in the park. For comprehensive details about the research area, further information is available (Haq et al. 2022).

The climate of the region is classified as sub-Mediterranean, marked by four distinct distant seasons viz. spring, summer, autumn, and winter. The dry periods spanning from April to June and September to November. Autumn in Kashmir is known for its vibrant colors as the foliage turns into hues of gold and red. Winter in Kashmir is cold and often snowy, especially in higher elevations and the temperatures can drop below freezing, fluctuating between − 2°C to 10°C in the plains with even low temperatures at higher elevations. Temperature variations in the Zanskar region typically range from approximately range between − 2°C and 30°C. Snow serves as the primary source of precipitation in the Zanskar range, and its melting continues until June in higher altitudes and has a significant impact on the annual precipitation levels. The Zanskar Range experiences a considerable range in minimum and maximum rainfall, varying from 32 mm to 546 mm annually. This fluctuation in precipitation is vital for the ecological dynamics and sustenance of the Hangul population (Haq et al., 2023).

2.2 Data regarding the presence of species

In this investigation, information related to the existence of Hangul in the research area was gathered through a combination of methods. To acquire information about the locations where the species was found (presence points), a two-year-long field survey was conducted, and existing data from information from existing literature and the GBIF (Global Biodiversity Information Facility) database, covering the period from 1864 to 2019, was gathered. To prevent any concentration in specific regions, duplicate records were carefully removed. Choosing these occurrence points was a meticulous process aimed at avoiding spatial pseudo-replication. It was based on the resolution of raster data (specifically, 2.5 arc-minutes). We selected and filtered GPS locations, retaining only those with a 15-meter accuracy, and ensured that each 5 km^2 pixel contained just one presence point. This was done to prevent the potential bias that multiple presence points within a small area could introduce to the results.

We conducted field surveys between 2019 and 2022 to record the occurrence of Hangul in the Greater Dachigam landscape. We gathered data on species presence through interviews with local wildlife scholars, trackers, livestock herders, and wildlife field staff operating in the landscape. In our study, we employed binoculars and perceiving scopes to observe the Hangul species from various vantage points in its potential habitat. During these observations, we meticulously documented habitat characteristics, including vegetation cover, type, physical attributes, and ruggedness. Additionally, we recorded precise location and elevation using GPS devices while also noting any illicit activities such as habitat destruction, illegal poaching, and natural disturbances (Photo plate 1). To further enhance our understanding of Hangul's presence and assess illegal activities within its habitat, we conducted a questionnaire survey, engaging with local individuals and departmental staff. These efforts resulted in the collection of 47 unique Hangul presence points, which served as the foundation for developing the Distribution Prediction Model.

2.3 The compilation of environmental data and the procedure for variable selection

Our study involved the gathering of a comprehensive set of environmental and topographic data to enhance the analytical framework. Nineteen bioclimatic variables, with a resolution of 2.5 arc-minutes, and elevation data, at a resolution of 30 arc-seconds, were sourced from the WorldClim website (ver. 2.1) (www.worldclim.org, accessed on 15 March 2023) (Supplementary Table 1). To supplement the dataset, topographic information, including altitude, slope gradient, and aspect, was acquired through ArcGIS 10.5 software, enabling the creation of a Digital Elevation Model (DEM) via spatial analysis tools. In addition to natural variables, four anthropogenic factors were included as indicators of human influence. These factors encompassed land cover, road proximity, population density, and the Human Footprint (HFP), measuring human perturbation. The HFP map, obtained from the Socio-Economic Data and Applications Centre (http://sedac.ciesin.columbia.edu), amalgamates global data layers associated with various factors affecting ecosystems, including human population distribution, urbanization, navigable rivers, roads, and diverse agricultural land uses. The HFP layer spans a range from 0, signifying areas in proximity to natural or pristine conditions, to 50, indicating regions that have experienced significant degradation.

The study incorporated comprehensive data sources and variables for a thorough analysis. The Global Land Cover data, outlining nine categories (including grassland, forest, savannah, shrubland, cropland/natural vegetation, snow/ice, wetland, urban, and barren/sparsely vegetated areas), was sourced from the International Geosphere-Biosphere Program (MODIS Global Land Cover Classification v2). To consider the influence of human population density on species distribution, a separate layer of population density data was extracted from Oak Ridge National Laboratory. For vegetation analysis, the Enhanced Vegetation Index (EVI) derived from MODIS products (MOD13A3) was used, covering both mean annual EVI and EVI seasonality. The choice of EVI over NDVI was based on its ability to minimize background interference and handle issues like smoke and sub-pixel cloud contamination. The EVI data was obtained from Terra MODIS ready-to-use files (MOD11 and MOD13). Future simulations included two distinct sets of Shared Socioeconomic Pathways (SSPs), specifically SSPs 245 and SSPs 585, obtained from the Coupled Model Intercomparing Project, Phase 6 (CMIP6). These simulations were carried out using the Global Climate Model BCC-CSM2-MR, operating at a resolution of 2.5 arc-minutes. This comprehensive approach facilitated a thorough analysis of the potential impact of environmental and climatic variables on species distribution under different scenarios.

The distribution of the Hangul is influenced by a multitude of features, including precipitation, temperature, natural impediments, physical land structures, and various biological variables, as previously evidenced in research by Gao et al. (2022) and Zhang et al. (2015). In our model, we sought to evaluate the specific ecological aspects that impact the species' dispersion. To achieve this, we incorporated a comprehensive set of variables, encompassing 19 bioclimatic factors, four anthropogenic indicators (land cover, human footprint, human population density, and road proximity), and three ecological parameters (slope, aspect, and elevation). These factors, in conjunction with vegetation data, enabled a comprehensive evaluation of the factors influencing the western Hangul's distribution.

To ensure data independence and eliminate potential correlations among variables, we employed a two-step approach in this study. First, we utilized the initial model with default configurations to evaluate the influence of each variable, establishing a threshold of > 1% to exclude variables that didn't meet this requirement. Subsequently, to further remove possible spatial associations, we subjected the remaining variables (those surpassing the contribution threshold) to pairwise Pearson's correlation (r) analysis. To streamline the variable count, a threshold value of $r \geq \pm 0.8$ was implemented. In cases where two variables displayed an r value surpassing this threshold, the one with the lower contribution was excluded (Arshad et al., 2022; Bosso et al., 2016; Gao et al., 2022; Hassan et al., 2021; Hijmans et al., 2005; Khattak et al., 2022). Following this procedure, eight significant bioclimatic and topographic variables were identified: mean diurnal range (Bio02), mean temperature of the wettest quarter (Bio08), mean temperature of the coldest quarter (Bio11), annual precipitation (Bio12), precipitation of the driest month (Bio14), precipitation of the warmest quarter (Bio18), precipitation of the coldest month (Bio19), and elevation (elev) (Graham, 2003).

2.4. Modeling procedures

In the realm of habitat modeling, the calibration and optimization of MaxEnt species distribution models stand as pivotal steps in achieving accurate and reliable results. This involves a systematic exploration of various combinations of regularization multiplier (RM) values and feature classes (FC) to strike a balance between predictive power and overfitting prevention. Threshold-dependent evaluation metrics, such as the omission rate, are harnessed to identify the optimal MaxEnt model settings, ensuring that the model can be effectively applied to different contexts. To illustrate, researchers in this study investigated multiple permutations of eight Regularization Multiplier values (ranging from 1 to 4 with a 0.5 interval) and six Feature Classes, including Linear, Quadratic, Hinge, and more (Eyring et al., 2019; Khattak et al., 2022).

Once the optimal MaxEnt model configuration was established, the study proceeded to construct a bias file by leveraging occurrence and environmental data with the ENMEval package in R. Subsequently, utilized MaxEnt version 3.4.4 to evaluate the data and predict the most suitable habitats for Hangul in the research area, following established methodologies (Awan et al., 2021; Hijmans et al., 2005; Phillips et al., 2006; Singh et al., 2020). MaxEnt, grounded in ecological niche theory and informed by presence data, has emerged as a preeminent tool for predicting the potential distribution of species within defined geographic regions (Graham, 2003; Bai et al., 2018). Its exceptional predictive accuracy has led to its widespread adoption as the preferred species distribution modeling method over competing alternatives (Bai et al., 2018; Fourcade et al., 2014; Elith et al., 2006; Summers et al., 2012).

The study employed MaxEnt, a robust machine-learning method, to explore the intricate connection between ecological conditions and the spatial arrangement of wildlife (Díaz et al., 2022; Haq et al., 2021). To enhance model accuracy and performance, a range of MaxEnt configurations, including cross-validation, output format selection, and response curve generation, were meticulously employed. Model evaluation was conducted using receiver-operator characteristic (ROC) curves and the calculation of area under the curve (AUC) values, with AUC scores above 0.9 indicative of well-performing models (Fourcade et al., 2014; Hijmans et al., 2005; Merow et al., 2013; Phillips et al., 2006; Phillips et al., 2009; Summers et al., 2012). This comprehensive approach not only aids in optimizing SDMs but also contributes to advancing our knowledge of the intricate interplay between environmental factors and species distribution. The results generated by MaxEnt prediction for the suitability of Hangul habitat varied from 0 to 1, categorized into four levels: low (0.21–0.4), moderate (0.41–0.6), high (0.61–0.80), and very high (0.81-1) (Elith et al., 2006; Phillips et al., 2006; Waheed et al., 2023).

2.5. Range and corridor estimation

Guidos Toolbox (Vogt and Riitters 2017) software was used to estimate the division of potential range into the core and edge using the “Entropy Map” method. The same software was used to prepare the morphological-spatial analysis (MSPA), which allows to categorization of the potential distribution of the species into functional classes (Soille and Vogt 2009). For Guidos Toolbox analyses, the MaxEnt output with suitability above 0.2 was used as an input raster. The area of each MSPA class and Edge/Core/Remote Core class in Entropy Map was calculated in QGIS 3.32.1 “Lima” (QGIS Development Team 2023).

CIRCUITSCAPE was employed to estimate the location of potential corridors for species migration between the existing core of the range and several potential cores. As potential future cores, six locations were chosen: four of them are current protected areas and two, in the southern part of the analyzed area, were estimated by MaxEnt as regions with high suitability. The final connectivity raster was calculated using the output of three CIRCUITSCAPE analyses: one with suitability as a conductance, second with altitude as a resistance (Danielson and Gesch 2011), and third with a land cover (Zanaga et al. 2021), where built-up areas had high resistance, crop fields medium resistance and natural vegetation low resistance. As a potential corridor, we have chosen an area that connects the current range core to the potential range core via a continuous path with high conductance.

Zonation 5.0 (Moilanen et al. 2022) was used to identify areas that should be prioritized for protection to save the species. Analysis was performed with the following raters: potential current range as input with weight 1.0, future models as inputs with weight 0.5 each, land cover (Zanaga et al. 2021) as a condition raster, population density as a cost raster. The protected areas were used as a retention raster to exclude them from analysis. Results were visualized using QGIS 3.32.1 “Lima” (QGIS Development Team 2023).

3. Results

3.1. Model evaluation

MaxEnt was utilized to compute a forecasted ecological suitability score for the Hangul species within the Jammu and Kashmir region. The suitability score exhibited a range from 0 to 0.96, representing the anticipated appropriate conditions of various habitats for the species. In this investigation, the top-performing model attained an AUC score of 0.963, signifying a high level of accuracy and a close alignment between the model's predictions and the actual distribution of the Hangul species (Supplementary data: Figure S1).

Among the climatic variables considered, the precipitation of the driest month (Bio14) and precipitation of the coldest month (Bio19), elevation (elev), and the mean temperature of the wettest quarter (Bio08) contributed 85% in the distribution Hangul. Bio14 and 19 had the highest contribution, accounting for 41.4% and 15.3%, respectively. So, the Jackknife test revealed that those variables were influential in shaping the species' distribution (Supplementary data: Figure S2, S3). Subsequently, both elevation (elev) and the mean temperature of the wettest quarter (Bio08) made contributions of 15.1% each. The least contributed variable, the mean temperature of the coldest quarter (Bio11) accounted for 13.1% of the variance, while the mean diurnal range (Bio02) contributed 4.5%. Additionally, both the precipitation of the warmest quarter (Bio18) and the annual precipitation (Bio12) demonstrated equal contributions of 0.7% each to the model's overall accuracy (Supplementary data: Figure S2).

As depicted in Figure S4, when precipitation levels exceeded 40 mm, the probability of encountering Hangul was notably higher than 0.6, signifying a region of high suitability. The highest probability of occurrence was observed around 500 mm of precipitation, where the likelihood reached approximately 0.7. The elevation range that proved most conducive to Hangul habitats spanned from 1600 to 2200 meters. Notably, habitats considered suitable with a high likelihood exhibited a bio19 range falling between 400 and 600 mm. The optimal range of bio11 for Hangul is -5°C to 5°C. Likewise, the mean diurnal range is considered most suitable when it falls within 5°C to 12°C, as illustrated in Figure S4. Furthermore, the ideal range for annual precipitation lies between 800 mm and 1000 mm, while the bio18 variable is found to be most conducive within the range of 100 mm to 300 mm.

3.2. Current distribution

Employing a species distribution model, we successfully identified the current potential locations for finding the Hangul, as depicted in Fig. 2. Traditionally, Hangul is known to inhabit the coniferous, oak, broadleaved, and grassland areas within Dachigam National Park, the adjacent Zabarwan mountains, Lidder, and Sindh valleys. However, the allocation of favorable habitats across the upper Himalayan region exhibits significant variation. The results of our study indicate that regions with very high and high suitability for the species are dispersed in a patchwork pattern throughout central Kashmir, spanning from Kulgam, Anantnag, and Pulwama, and extending to Ganderbal. Furthermore, there are constant strips of moderately suitable habitats along the elevated areas of Bandipura and Budgam districts under the prevailing climatic conditions (from the 1970s to the 2000s).

3.3. The assessment of habitat suitability under prospective scenarios of climate change

Subsequently, a thorough investigation of the potential consequences of climate change on Hangul spreading, our findings suggest the present habitat that is currently the most suitable for the species is possible to contract and shift northward across varying elevation gradients. In the context of the 2050s and 2070s, encompassing all four Shared Socioeconomic Pathways (SSPs) scenarios, the migratory trajectory of Hangul's suitable habitat is poised to shift northward, encompassing regions like Kishtwar, Ganderbal, and Bandipora. This anticipates the emergence of an extended expanse of highly suitable habitats in the northern sector of Jammu and Kashmir and its neighboring areas, as visually depicted in Fig. 3. As we approach 2050, the availability of suitable habitats for Hangul is expected to dwindle, particularly under the SSPs 245 and SSPs 585 scenarios, where the predominant suitable areas will be primarily concentrated in the northern domains of Kashmir. Under the SSPs 346 scenario, there is an envisaged reduction in habitat availability between Pulwama and Haramukh by 2050, leaving only slender segments of viable habitat in locales such as Bandi Bagh and Takya Sangi Reshi. Consequently, Hangul might confront a scarcity of suitable habitats in the Kulgam, Ramban, Budgam, and Shopian regions by 2050, particularly within the ambit of the SSPs 245 and SSPs 585 scenarios (Fig. 3).

Across all four of the climate change scenarios under investigation, it is anticipated that the once highly suitable habitats near Anantnag, Mattan, and Kishtwar will no longer be viable by the 2070s. Furthermore, regions like Budgam and Shopian face a critical risk of losing all of their present suitable and highly suitable habitats as early as the 2050s and continuing into the 2070s, particularly under the influence of the SSPs 245 and SSPs 585 scenarios. Additionally, during the transitional period between 2050 and 2070, there may only be limited availability of marginally suitable locations in areas like Kargil, Bandipora, and Ganderbal, predominantly at higher altitudes (Fig. 3).

In our analysis, we have estimated the likelihood of Hangul occurrence within different habitat suitability categories. Our findings suggest that the overall potential habitat suitability for Hangul, with a probability greater than 0.2 ($p > 0.2$), is expected to decline in the future. In a more concise and comparative format, the projected reduction in potential habitat suitability is expected to be -5.06% in comparison to the current distribution range. This translates to 11,851 km^2 potential habitat suitability under SSPs 245 for the 2050s, and a more significant decline of -10.31%, resulting in 9,687 km^2 potential habitat suitability under SSPs 585 for the 2050s. Similarly, for the 2070s, under SSPs 245, potential habitat suitability is forecasted to decrease to 10,163 km^2, representing a -9.15% change, and to 10,310 km^2 (-9.33% change) under SSPs 585 for the 2070s.

Taking a closer look, considering SSPs 245 in the 2050s, there is a forecasted slight reduction in very high suitability habitat (VHSR) compared to its current climatic conditions, specifically decreasing from 2,147 km^2 to 7,838 km^2 at a rate of -1.54%. Likewise, in the highly suitable habitat (VHSR), the potentially suitable land area is expected to diminish as follows: a decrease to 1,837 km^2 (-2.29%) under SSPs 585 for the 2050s, a reduction to 2,095 km^2 (-1.66%) under SSPs 245 for the 2070s, and a decline to 2,232 km^2 (-1.45%) under SSPs 585 for the 2070s (Table 1).

Table 1
The expected likelihood of Hangul's habitat suitability under different climate change scenarios offers valuable perspectives on the potential consequences of evolving environmental conditions for this particular species.

Climate change scenario	**The projected probability of Hangul occurrence within the assessed habitat suitability categories**					
NSR	LSR	MSR	HSR	VHSR	Total suitable land area (km^2)	
(≤ 0.2)	(0.21–0.4)	(0.41–0.6)	(0.61–0.8)	(≥ 0.81)		
Current climate	27267	5345	3421	2387	2783	13936
SSPs_245_2050	29352	4303	3245	2156	2147	11851
Rate of change (%)	5.06	-2.52	-0.42	-0.56	-1.54	-5.06
SSPs_585_2050	31516	3423	2512	1915	1837	9687
Rate of change (%)	10.31	-4.66	-2.20	-1.14	-2.29	-10.31
SSPs_245_2070	31040	3795	1582	2691	2095	10163
Rate of change (%)	9.15	-3.76	-4.46	0.73	-1.66	-9.15
SSPs_585_2070	31793	3513	1834	2731	2232	10310
Rate of change (%)	9.33	-4.62	-3.94	0.69	-1.45	-9.33

3.4. The Altitudinal shift of habitat

The projected areas suitable for Hangul fluctuated across various periods and were determined using different climate scenarios. However, the overarching pattern remained consistent, indicating a shrink of very highly and highly suitable regions, a rise in areas moderately suitable and less suitable, and a notable enhancement in habitat fragmentation. Considering future climate conditions, the centroids of the highly suitable and moderate regions gradually shifted northwestward over time, whereas the centroids of the least suitable areas moved northeastward. In general, the centroids migrated toward higher altitudes under future climate change. In 2050 under SSP245 and SSP585 the highly suitable habitat will shift from 3000m to 4000m elevation with an average 700m altitudinal migration habitats. Similarly, in 2070 the habitat shifts from 3000 to 5000m with an average 1300m altitudinal shift (Supplementary data: Figure S5).

3.5. Potential corridors for Hangul movement

The corridors associated with Hangul's potential movements are illustrated in Fig. 4, while the values denote potential dispersal distances from the core to new habitats. The total very highly suitable area in the protected region was (7%) 2220 ha and in the unprotected region (93%) 30445 ha. These corridors can bridge isolated remnant habitat patches, thereby enhancing connectivity and offering opportunities for the establishment of new habitats. A comprehensive ecological network spanning 1200 km² (depicted in violet) has been delineated. Among this, approximately 200 km² is designated as continuous corridors. The shortest corridor, spanning approximately 30 km, traverses the Haramukh mountain region adjacent to Wular Lake, which holds protected status. On the other hand, the most extensive corridor, with a length of around 70 km, extends along the PirPanjal Range in proximity to the Dachigam protected area. A point of significance is that the corridors denoted as C2, C3, and C4 prominently exhibit a persistent linkage between the core hotspot of Hangul distribution (depicted in red) and the designated protected area (highlighted in yellow). Notably, the corridor labeled as C1 terminates at potential new habitats (as shown in Fig. 4). It's worth noting that while additional potential corridors exist, they lack the feasibility of maintaining a continuous connection to the central core.

3.6. Functional landscape changes

The prevalent morphological type within the species' current distribution and projected future distribution (under SSP585-2070) is the "core" type, which collectively constitutes 54.17% of the total study area. The percentage varies across scenarios, with proportions of 49.90% under the SSPs245-2050 scenario, 37.24% under the SSPs245-2070 scenario, and 35.59% under the SSPs585-2050 scenario (Table S1). The findings indicate that the suitable habitat for the Hangul might undergo a northward shift, reaching the Zanskar range of the Himalayas. Anticipated changes include the expansion of core areas to this new location in future scenarios, signifying a potential change in the species distribution (Fig. 5). Despite the alterations observed in Loop and Islet configurations, both classes exhibit similarities between their patterns under present and future conditions (Table S1; Fig. 5). Although the percentage of changes in perforation is relatively small, there is a noticeable internal fragmentation process within the Core habitat, particularly under the SSPs245-2050 scenario. These alterations are primarily concentrated in the Kashmir region, encompassing districts like Kulgam, Anantnag, Pulwama, and Ganderbal. Importantly, these changes result in a loss due to perforation, constituting 1.39% of the total range (Table S1; Fig. 5B). Under the SSPs585-2050 and SSPs245-2070 scenarios, there was a notable reduction in the intensity of Core habitat loss, marked by contraction. Moreover, there were hardly any significant large-area cores observed in the PirPanjal Range when moving towards the northern direction. This observation was accompanied by an increasing percentage of bridges and branches within the habitat (Table S1; Fig. 5C and D). Interestingly, the pessimistic scenario for 2070 predicts an expansion of the core area to higher altitudes (Fig. 5E).

In Fig. 6A, among various climate conditions, the core-to-edge ratio is at its highest level in the current conditions. The spatial patterns of habitat edges in both optimistic and pessimistic scenarios for 2050, when compared to the present condition, exhibit a clear rise in the percentage of edges and remote edges (including perforation, loop and bridge connectors, and branches). Notably, the results indicate an increase in edge length due to habitat gain in the SSPs585-2070 scenario, while the processes of fragmentation become more pronounced under the SSPs245-585-2050 and SSPs245-2070 scenarios (Fig. 6B, C, D, and E). Consequently, there is an observed disparity in the abundance of edge habitat versus core habitat in the southern and northern regions within the study area. This discrepancy suggests greater habitat fragmentation in these areas. Conversely, the central region generally displays a higher ratio of core-to-edge habitat, which suggests a less fragmented habitat configuration (Fig. 6).

Table S1
Area of each class of species potential range according to the MSPA analysis.

Climate condition	Core	Loop	Bridge	Islet	Edge	Branch	Perforation	Total
				Area (km^2)				
Current	7549.45	1114.85	1064.55	663.65	1970.69	1498.48	74.32	13936
SSPs_245_2050	5913.99	781.56	1322.47	400.72	1871.24	1395.71	165.31	11851
SSPs_585_2050	3447.95	577.24	1973.52	562.49	1377.12	1748.67	0	9687
SSPs_245_2070	3784.29	765.21	2308.57	229.97	1690.4	1341.03	43.52	10163
SSPs_585_2070	5585.16	824.78	787.57	490.98	1457.94	1108.59	54.99	10310
				Percentage				
Current	0.5417	0.08	0.0764	0.0476	0.1414	0.1075	0.0053	1
SSPs_245_2050	0.499	0.0659	0.1116	0.0338	0.1579	0.1178	0.0139	1
SSPs_585_2050	0.3559	0.0596	0.2037	0.0581	0.1422	0.1805	0	1
SSPs_245_2070	0.3724	0.0753	0.2272	0.0226	0.1663	0.132	0.0043	1
SSPs_585_2070	0.5417	0.08	0.0764	0.0476	0.1414	0.1075	0.0053	1

3.7. Priority area for conservation

We developed a prioritization framework utilizing our methodology to select priority areas. This strategy identified core regions that hold significant conservation promise due to their available space with suitable conditions, their capacity to enhance connectivity, and a preference for locations with minimal human impact (Fig. 7). The core areas that are currently most conducive to the species' well-being and have been classified as priority areas fall into two categories: "very high priority," covering an area of 456.87 km², and "high priority," encompassing 930.51 km². These areas include a narrow strip along the Himalayan range and northwest broadleaf forests, concentrated in both higher and lower elevations of the range. Based on the results, it's evident that an opportunity exists to extend certain existing protected areas, such as the Overa-Aru Wildlife Sanctuary, towards the direction of the Dachigam National Park (Fig. 7).

4. Discussion

Forecasting the outcomes of anthropogenic climate change on the geographical distribution of species is crucial, given that these shifts may result in mass extinctions (Wallingford et al., 2020). The vast majority of existing data points to climate change as the primary driver of widespread species extinctions, and its effects on species distributions or hastening the rate of extinction should be anticipated (Román-Palacios and Wiens, 2020; Kemp et al., 2022). Predicting how a species like Hangul, with only 250 + individuals left, will react to climate change is difficult because unsuccessful reproduction and colonization are dependent on diverse factors, including geographic range, ecologically isolated populations, low reproductive rates, and a high degree of specific habitat requirements (Maviya Majid et al., 2019; Mukherjee et al., 2019; Malhi et al., 2020; Inouye, 2022). Hangul is already facing the risk of low reproductive rates and isolated populations (Ahmad et al., 2023) and thus climate change may aggravate it further. However, SDMs offer a valuable method for integrating future conditions into approaches and choices in conservation and management, when the consequences of incorrect conservation strategies or inaction are balanced against the uncertainties of model forecasts (Hu and Jiang, 2011). In light of this, we investigated any potential changes in the Greater Dachigam landscape's distribution of endangered species caused by climate change. Based on the current suitable habitat in the Greater Dachigam landscape, our findings highlight the complexity of changes in species distributions under climate change (Table 1). Hangul's distribution is therefore anticipated to decrease in the Dachigam landscape (Table 1). According to earlier findings, individual species' distributions are uniformly influenced by climate change because they react to it in the same patterns (Semenzato et al., 2021; Haq et al., 2023). The ability of individuals from the same species to adapt to local climate change is probably similar (Thurman et al., 2020), the likelihood of those individuals surviving in their current habitats in the face of large climate change decreased as the time horizon grew longer and the severity of the consequences from climate change increased (Pearce-Higgins et al., 2022). Similar findings were also reported by Hu and Jiang (2011) and Mason et al. (2014) when predicting the likely responses of endangered ungulates to future climatic conditions. When Thorstad et al. (2021) studied the effect of climate change on the survival of Atlantic salmon, they came to similar findings. Our conclusions are supported by Scapini et al. (2019).

Our model's goal was to elucidate if environmental factors may independently predict the habitat that is suitable for Hangul within the Himalayas surrounding the Dachigam landscape. Bio14 was the most important variable, showing that the precipitation in the driest month may have a greater impact on species distributions. According to Bradie and Leung (2017), precipitation and temperature had the greatest overall contributions to species distribution for terrestrial species. Similarly, Jiang (2018), and Chen et al. (2023) observed that the driest months' precipitation exerted a notable influence on the distribution of endemic, rare, and threatened species, similar to our findings. This is corroborated by numerous other investigations, e.g., for *Pygathrix cinerea* (Tran et al., 2018); Himalayan Goral (Haq et al., 2023), Red panda (Thapa et al., 2018) and *Tragopan melanocephalus* (Jameel et al., 2023). The second most important variable was bio19 (coldest month precipitation), the third elevation, and the fourth was bio08 (wettest quarter mean temperature). Previous studies revealed that average precipitation alone may not accurately predict bioclimatic variance and that the mean temperature of the bio19 (coldest month precipitation), (Jiang et al., 2019); wettest quarter (bio08) (Zhong et al., 2022) and elevation (Campos et al., 2020; Jameel et al., 2023) may also play a key role in species distributions potentially causing species to extend or decrease their ranges. Our findings underline that rather than focusing solely on rising global temperatures, it is necessary to incorporate precipitation and other climate variables (including extreme circumstances) into future expected species distributions.

When assessing important environmental variables, our model of the appropriateness of the current Hangul habitat functioned well (Table 1). Our best model suggested that the overall suitable Hangul habitat spanned 13936 km^2 based on a 10-percentile criterion, accounting for 8% of moderately suitable habitat and 7% of high-suitability habitat. Ali et al. (2021) compare well to our findings, indicating that under current climatic conditions, 9% of the overall study region was suitable for blue sheep from the Hindu Kush ranges. When the repercussions of global warming are considered, the highly suitable habitats for Hangul distributions in the Dachigam Landscape will decrease in the future (from 5.06 to 9.33 km^2). Numerous other studies also emphasized how threatened species will face a considerable loss of their habitats due to the altering climate, particularly in the Himalayan regions (Ali et al., 2021; Liang et al., 2021; Jameel et al., 2023; Haq et al., 2023). Examples include

Himalayan musk deer (Khadka and James 2017) blue sheep (Islam et al., 2023), and NilgiriTahr (Sony et al. 2018).

The current distribution of the Hangul is anticipated to shift along both elevational and latitudinal gradients because of climate change. Instead of an expansion of their range to higher altitudes, the projected changes along the elevational gradient were mostly attributable to a significant reduction in their geographic distribution. This result was consistent with the idea put forth by Luo et al. (2015), and it is possible that the geography of the Dachigam terrain, covering a relatively narrow range, may have had a major role in these results. Our data indicate that Hangul is mostly found at the elevation of 2000 to 4000m, which highlights the species' preference for high-elevation habitats with colder climates and less anthropogenic disturbance. It aligns with the findings of Ahmad et al. (2016) in Dachigam National Park, reporting Hangul occurrence at elevations ranging from 1700–2300 m and an altitudinal range of 1700–3500 m (Qureshi et al. 2009). Our findings confirmed what was previously known about the altitudinal habitat range of Hangul and this helps to understand the ecological needs and niche of Hangul for formulating an effective conservation strategy. This altitudinal preference can be seen as a result of different bioclimatic and anthropogenic factors, including vegetation types occurring at that elevation and less snow cover. Similar preferences for vegetation types were determined by Sharma et al. (2010) and Qureshi et al. (2016). However, our results indicate that climate change is likely to cause the Hangul population to move upwards to northern regions as its habitat range shifts to higher elevations. Similarly, Chen et al. (2011) noted that species were rapidly moving towards higher elevations to combat heat due to climate change. This is further corroborated by the study results of Lenoir et al. (2008) who determined an upward shift of plant species especially in mountainous regions due to climate change. Agnihotri et al. (2017), He et al. (2019), and Yadav et al. (2021) also documented the climate change-driven altitudinal shift of Himalayan vegetation. As a result, animal species will follow, e.g. Himalayan Goral (Haq et al. 2023). We suggest that climate change is causing altitudinal shift in Hangul and there is a need to conserve the present and future habitat range for Hangul so that climate change and elevation shifts could not pose a threat to the survival of this species.

Currently, Hangul populations are also found outside the protected areas, particularly during summer. Of the 34975 km^2 of predicted habitat, 30445 km^2 (93%) lie outside the protected areas, which is a serious concern for this highly threatened species. The effectiveness of this unprotected network and potential changes in protected habitat suitability for the Hangul have not yet been assessed under climate change. Different parts of the unprotected habitat are under varying levels of restrictions on human activity. As a result, the effectiveness of some of these sites under climate change may be significantly influenced by the management techniques used in the future. This holds particularly true for unprotected regions but has the potential to have high conservation value in the future. Considering the crucial role that unprotected regions play in the survival of the Hangul, projecting the species' future distribution to guide the selection of new sites or expanding the current array of protected zones could be an efficient conservation approach to confronting the challenges posed by climate change. More crucially, in response to climate change, the effectiveness of the network of protected zones might be significantly increased by sustaining crucial corridors that permit Hangul mobility. Given the expansion of anthropogenic activities, several protected sites already become unsuitable for Hangul. The Zonation analysis (Fig. 7) has given a very good and practical result for Hangul conservation. The securement and protection of very high and high-priority zones occurring between the existing protected areas can boost the conservation of hangul for the long term. For example, the areas between Tral and Achabal PAs, between Dachigam and

Wanghat, Wanghat and Ajas, and Ajas and Kishan Ganga (Fig. 7). Securing such an area will provide a contiguous landscape for long-term conservation for a mobile species like Hangul.

We identified critical sites with the potential for future Hangul conservation. We also identified corridors for Hangul that would last well into the future, enabling affected populations to relocate in response to climate change. Enhancing habitat availability and accessibility is crucial for species adjusting to the challenges of climate change. Improving landscape connectivity, and the facilitation of species movement emerge as a key conservation strategy. Identifying and maintaining well-suited corridors through methods like Species Distribution Models (SDMs) enhances animal resilience by providing avenues to escape unsuitable conditions. Our forecast identified south Kashmir, notably the high-altitude conifer forest areas of Anantnag, Kulgam, and Pulwama districts, as highly suitable habitats for Hangul conservation in the Kashmir Himalayas. Kaul et al. (2018) also found *Cervus hangul hanglu* in Central/north Kashmir conifer woodlands such as Wanghat-Naranag, Rajparian-Daksum, Overa-Aru, and Thajwas-Baltal, confirming our predictions with field-based survey data.

4.1. Implications for conservation of Dachigam landscape

Habitat conservation through protected areas has been a primary issue in maintaining the survival and sustainability of the critically endangered Hangul population. However, isolated protected areas cannot help to conserve the hangul population for the long term due to the issues of inbreeding, and thus connectivity among these isolated protected areas becomes crucial. Existing PAs cover only 7.7% (2220 km^2) of the expected future Hangul habitat. This indicates that most of the Hangul habitat (93%) is currently unprotected, highlighting a huge risk of extinction as anthropogenic disturbance and climate change increase. As a result, we propose that nearby core habitat regions must be protected to connect the Hangul subpopulations. Our results revealed that 9.33% of high-suitability areas for the Hangul movement might become unsuitable by 2070 (Fig. 9), adding to the issues of Hangul conservation. On the other hand, overexploitation in the form of illicit wildlife poaching, habitat degradation, and fragmentation pose serious threats to its main abode, the Greater Dachigam landscape. These issues have led to ecological isolation, population decline, and inbreeding and brought the species to the brink (Ahmad, 2022; Ahmad et al., 2023). Although the establishment of protected areas is a helpful conservation strategy, it has been found that poor management and smaller size may negate the advantages of all conservation initiatives aimed at enhancing biodiversity. There restricted distribution of Hangul and its core areas in the context of existing and prospective climate change scenarios implies that the Dachigam Landscape is seriously lacking in space. As a result, Dachigam Landscape urgently needs to be expanded or connected to the potential hangul sites including the neighboring reserves and the hotspots/core areas. Ecological corridors around greater Dachigam landscape should be prioritized for conservation and management to secure it and the Hangul. According to our findings, hotspots may mostly move outside of the Dachigam landscape due to climate change. Therefore, our suggestions can assist in developing dynamic protected areas within the Dachigam landscape over an extended period.

5. Conclusions

It is crucial to foresee how anthropogenic global warming could have an impact on species distributions because these changes are expected to result in widespread extinctions of species. According to the projected distribution of Hangul under various climate change scenarios, the available habitat for this species would become significantly scarcer. In the future, it is anticipated that a sizable section of the current habitat with a high likelihood of occurrence will become unsuitable due to climate change. Our model detected a robust Hangul response to bioclimatic factors associated with precipitation in the Himalayas, with a notable emphasis on rainfall during the driest month and precipitation during the coldest quarter. Despite these factors, Dachigam Landscape's some of the current meta-populations and potential future sites of Hangul are connected through a contiguous forest landscape which can act as corridors and can play a crucial role for the long-term conservation of Hangul. We recommend that such corridors and sites be surveyed and secured on priority to improve habitat connectivity and ensure Hangul conservation in the realm of global warming and the critical status of Hangul.

Declarations

Author Contribution

Conceptualization S.M.H; Study Design S.M.H; Data collection- R.A., S.M.H; Data analysis- L.W; S.A; M.W; S.M.H; Original draft writing S.M.H; Review and editing-R. A; R.W.B; L.W; S.A; M.W; S.M.H. All authors read and approved the final manuscript.We have no conflict of interest to disclose. Moreover, the sequence of authorships mentioned in the article is based upon the contribution of the work by all authors.

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Photo plate 1

Photo plate 1 is available in the Supplementary Files section.

Figures

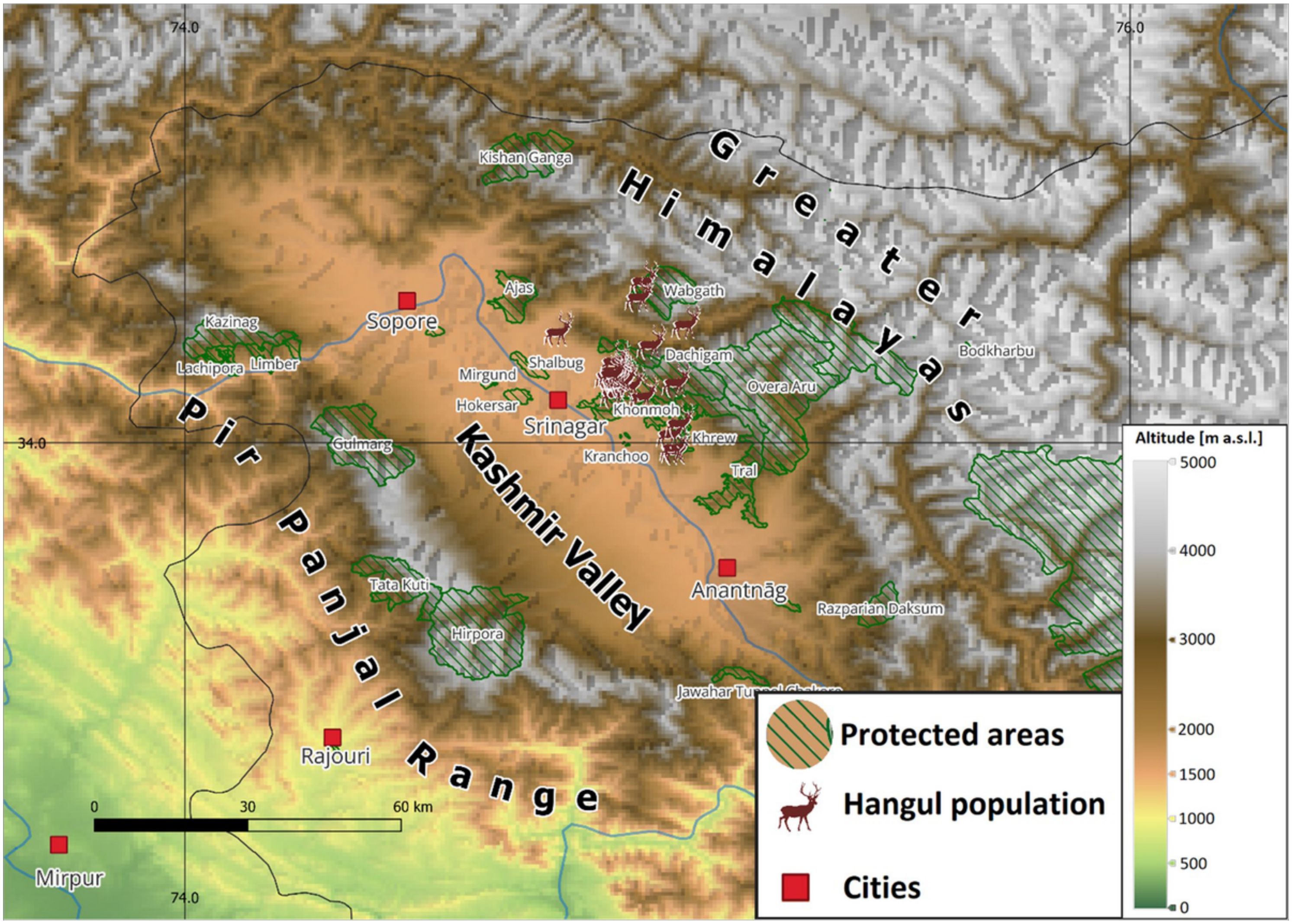

Figure 1

Map of the research region and points showing the presence records of Hangul in the Kashmir Valley.

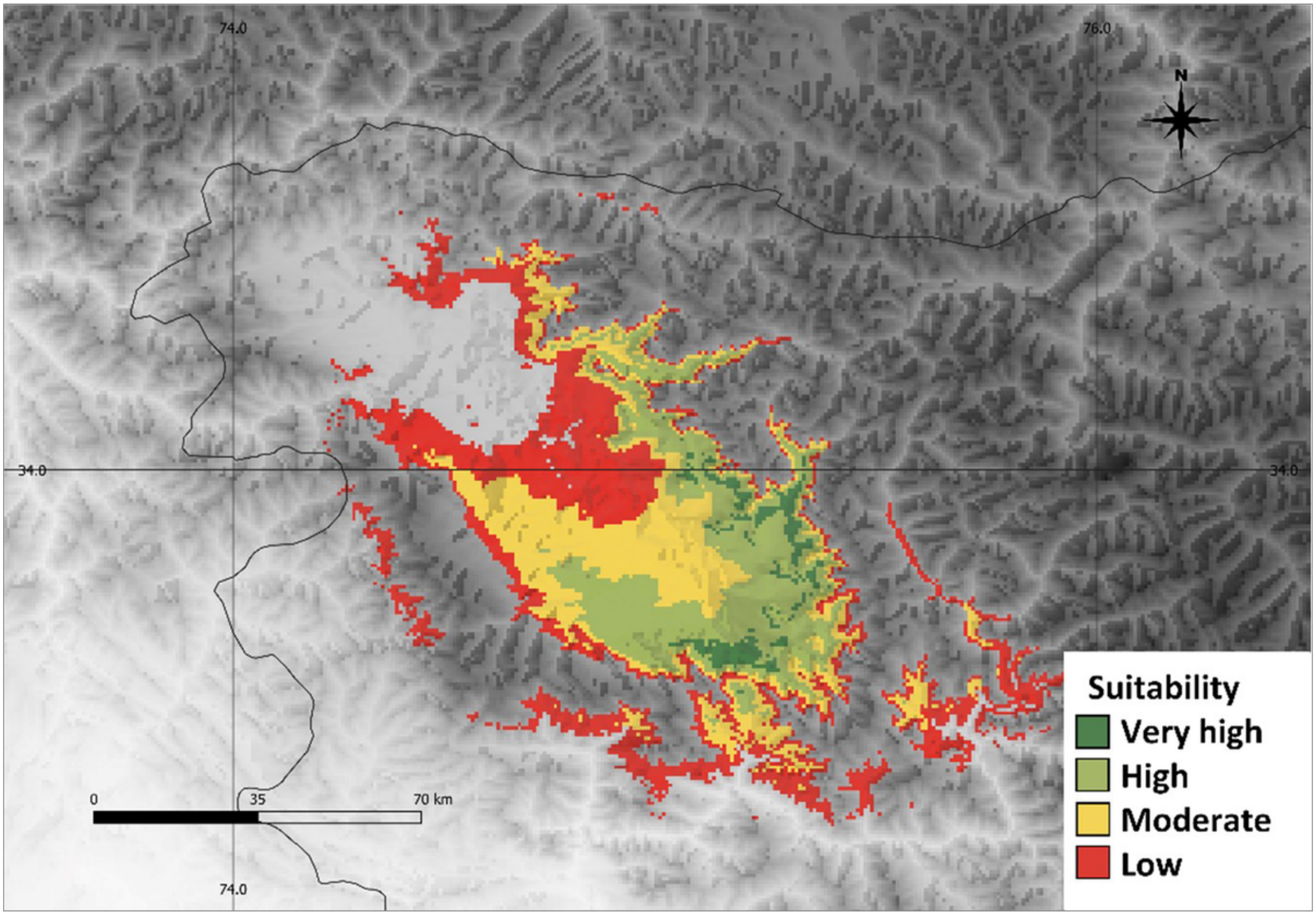

Figure 2

The MaxEnt prediction map presents a comprehensive classification of the potential habitat suitability for Hangul, which is the focus of this study. It provides a detailed visualization of the anticipated suitability of habitats for the Hangul species within the research area.

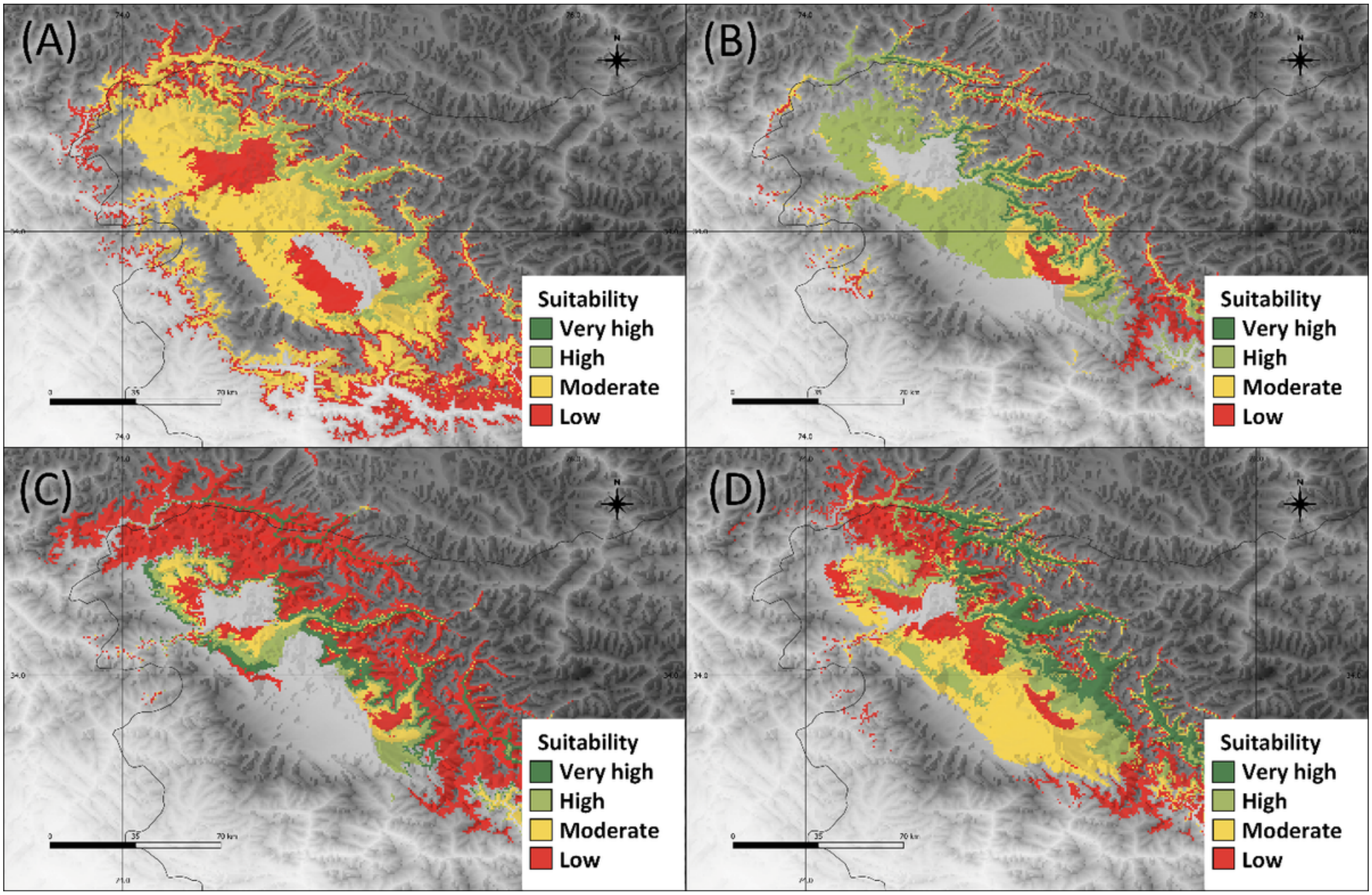

Figure 3

The MaxEnt-generated maps provide a visual representation of forecasted habitat suitability classifications across a range of future climate change scenarios. As illustrated in the figures, we observe: Figure A presents the habitat suitability under the SSPs-245 scenario in the 2050s, while Figure B displays the habitat suitability under the SSPs-585 scenario in the 2070s. Furthermore, Figure C showcases the habitat suitability under the SSPs-245 scenario in the 2070s, and Figure D represents the habitat suitability under the SSPs-585 scenario in the 2070s.

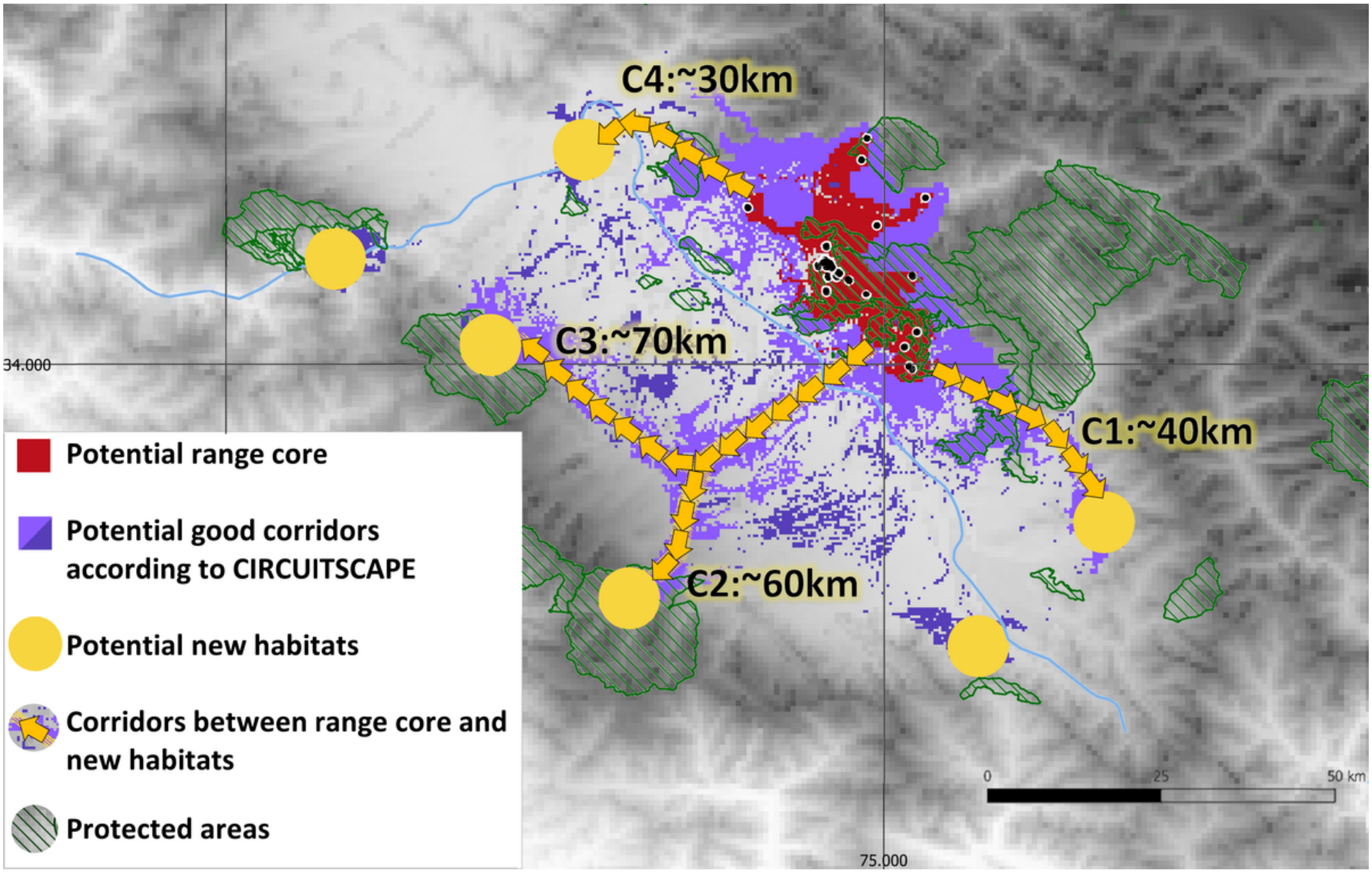

Figure 4

The potential identified connecting very highly suitable habitat that provides potential movement corridors for Hangul in the Dachigam landscape.

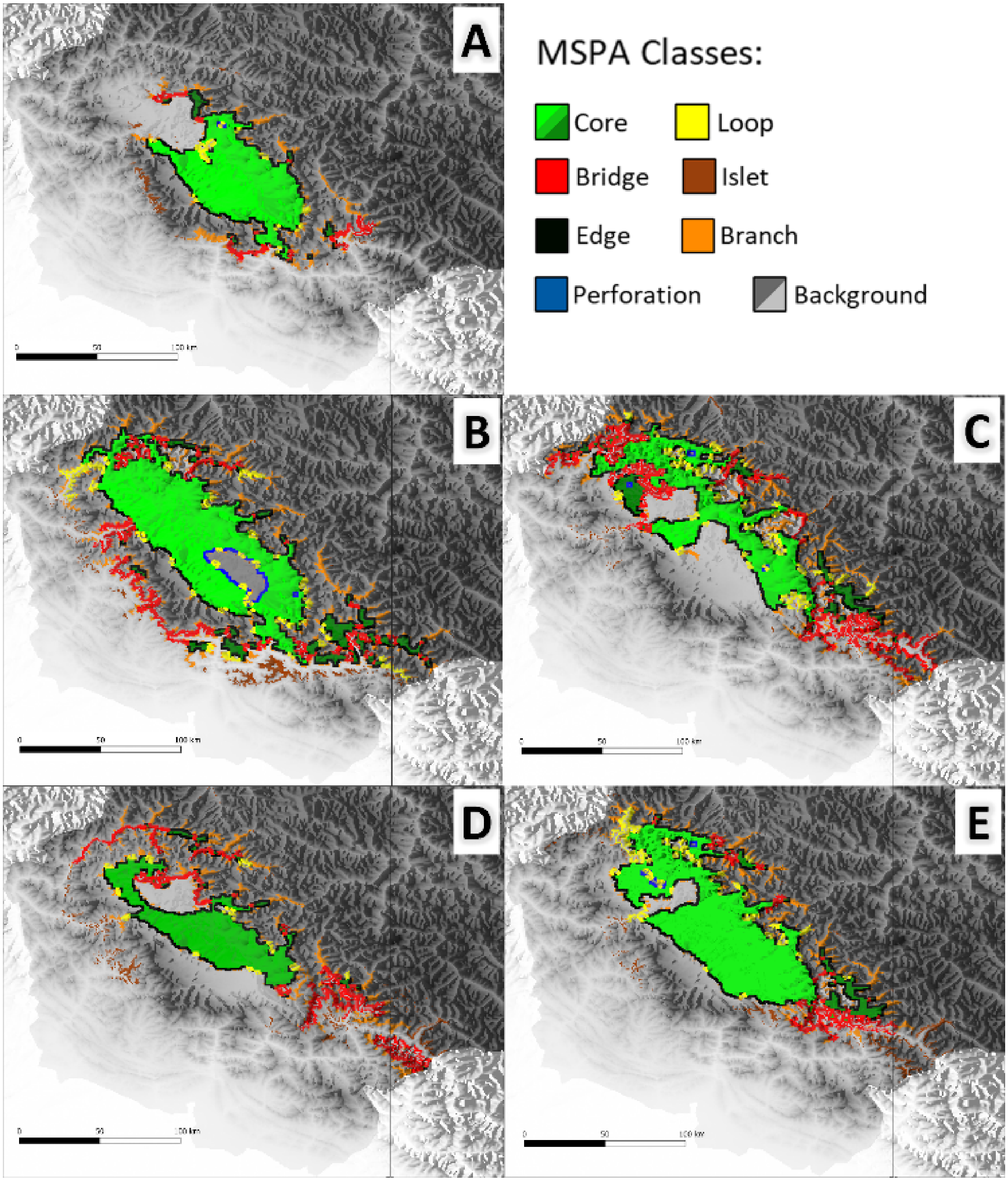

Figure 5

Changes in structural elements based on MSPA under (A) current and future scenarios (B) SSPs_245_2050, (C) SSPs_585_2050, (D) SSPs_245_2070, and (E) SSPs_585_2070

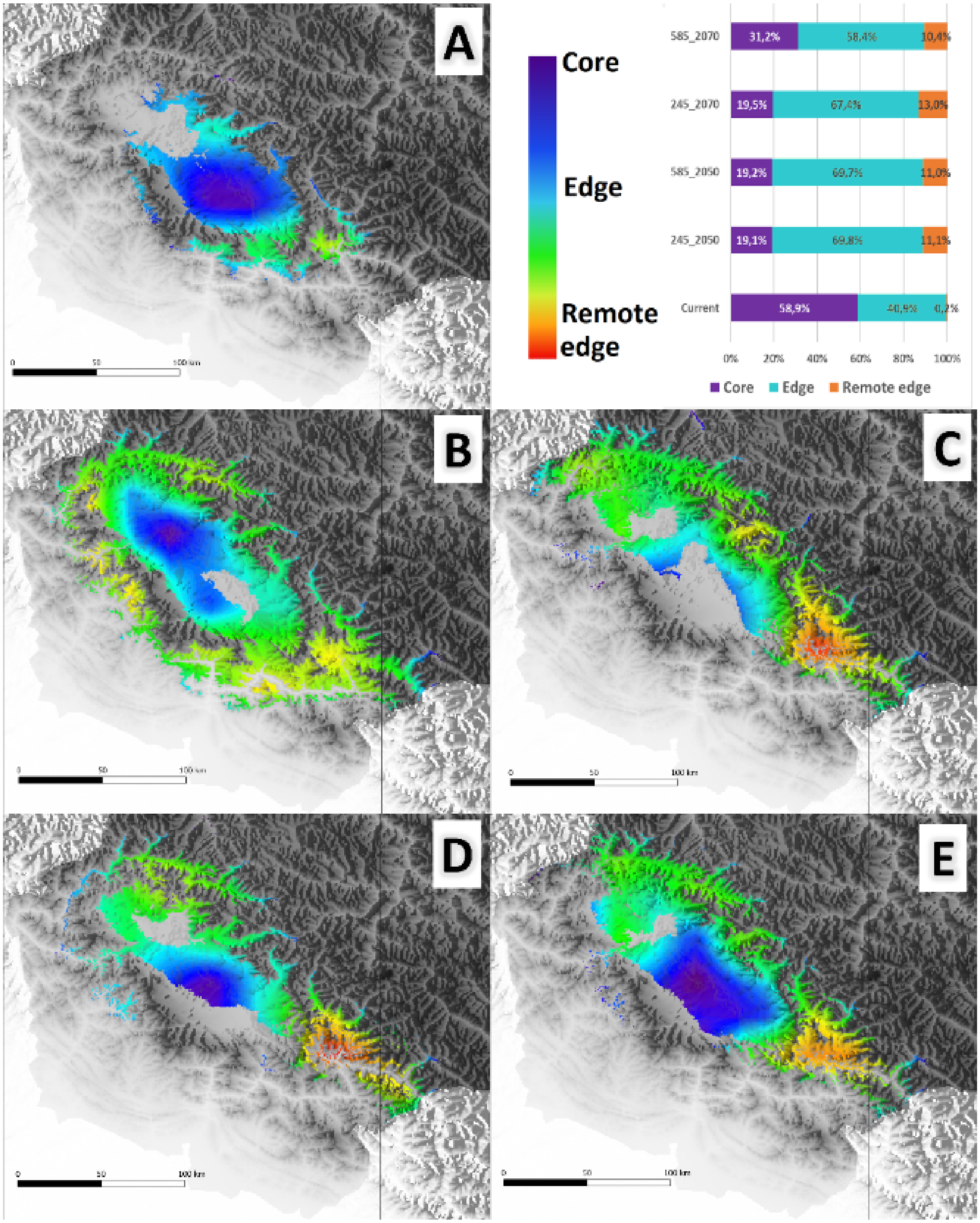

Figure 6

Hangul habitat fragmentation process and Core/Edge ratio under (A) current and future scenarios (B) SSPs_245_2050, (C) SSPs_585_2050, (D) SSPs_245_2070, and (E) SSPs_585_2070

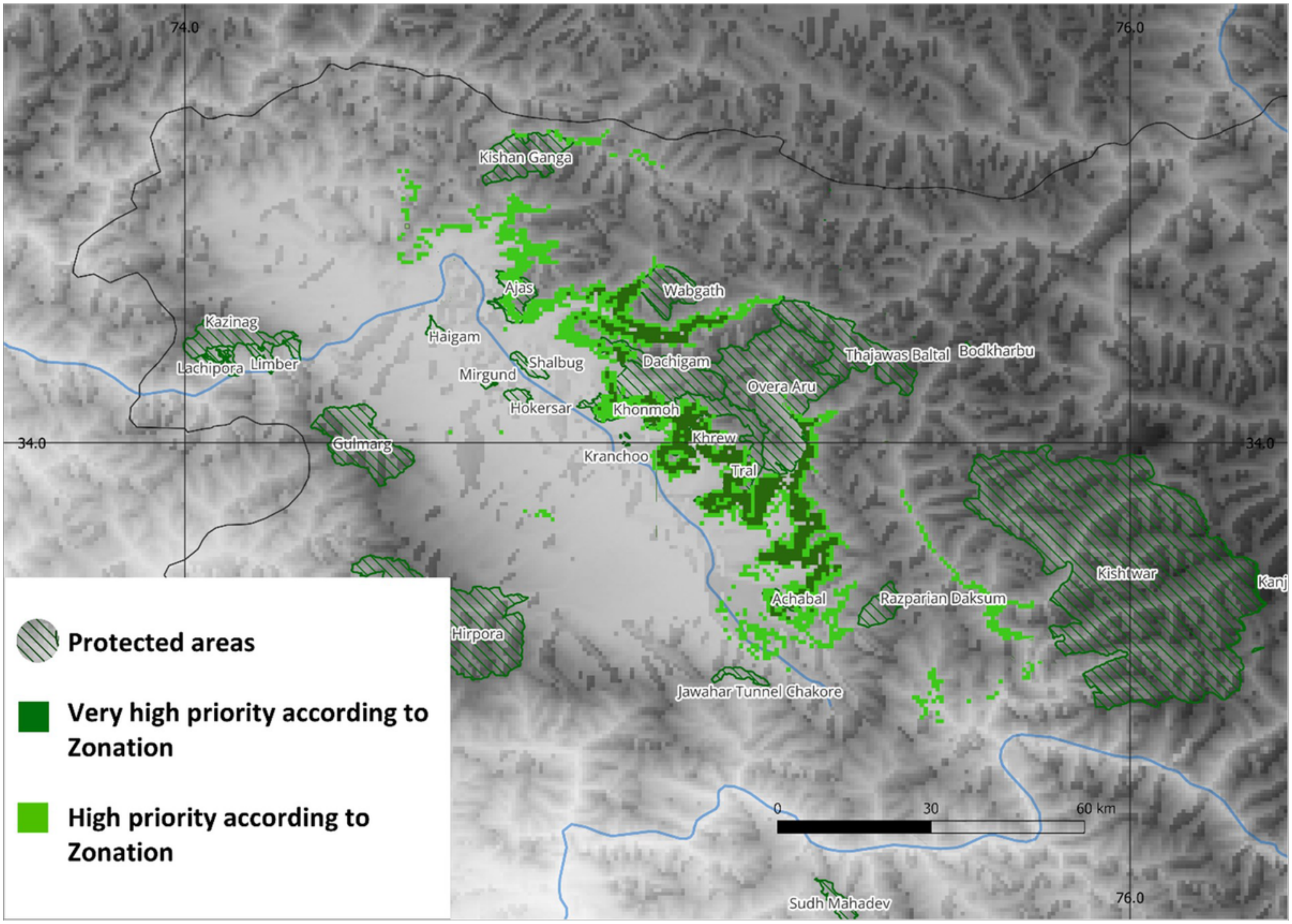

Figure 7

Result of Zonation analyses, showing the areas with the highest priority for conservation.

Supplementary Files

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- Photoplate1.png
- Supplementarydata.docx