

Climate change and raptor species current and future trends in distribution patterns and habitat suitability

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Abstract

Rapid changes in climate patterns may lead to the risk of extinction of many faunal species in Pakistan. These effects of climate change would lead to a shift and contraction in species distribution ranges and a shift in appropriate habitats, which could impact resource availability and biological conditions. According to Birdlife status, four avian raptor species *Haliaeetus leucoryphus*, *Neophron percnopterus*, are endangered, while *Falco chicquera*, and *Aegypius monachus*, are near threatened but are resident species of Pakistan. In the present work, we used species occurrence records from GBIF, while present and future climate variables from worldclim. Using two future peak scenarios of carbon emissions rcp 4.5 and 8.5, as well as two circulation models for 2050 and 2070, we used the MaxEnt model to simulate the current (normal range for 1980-2019) and future (up to 2050 and 2070) species distribution. The results depicted a prominent impact of bio17 (precipitation of driest month) on *H. leucoryphus*, for *N. percnopterus*, the impact of bio15 (precipitation seasonality) was prominent. In contrast, the impact of bio8 (wettest quarter mean temperature) was recorded on *F. chicquera* and *A. monachus*. Overall, the findings demonstrated that under two climate scenarios, the distribution of species was projected towards the latitudes of the north and the altitudes of the east, resulting in habitat destruction and a shift towards higher altitudes. Our study provides useful information to policymakers and conservationists to justify the effect of change in climate on four raptor species in Pakistan.

Keywords: Climate effect, RCPs, Climate models, Predicted variables, Avian raptors of Pakistan

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Introduction

Atmospheric gases such as carbon dioxide emissions cause variations in environmental factors such as temperature and precipitation, resulting in global climate change. The projected increase in temperature affects other events related to climate (IPCC, 2021), which directly impacts bird species (Jaffre et al., 2013) and indirectly disturbs the water cycle, which leads to heavy events of precipitation and severe drought (Smith, 2020). A further shift of tropical cyclones as well as hurricanes towards the poles and change the precipitation trends (Studholme et al., 2022). At the global level, an increase in temperature (Briga and Verhulst et al., 2015). is one of the main constraints for species distribution (Freeman et al., 2019). As the current estimate indicates, the temperature will increase up to 4°C at the turn of the twenty-first century (Zahoor et al., 2022).

In Pakistan, the emission of carbon dioxide is one of the main causes of temperature increase due to anthropogenic activities, which lead to heat waves, melting of glaciers, a rise in sea level (10 to 20cm), and changes in the pattern of precipitation, ultimately leading to events of floods due to heavy rainfall (Qureshi and Ali, 2011). According to the Birdlife report, changes in climate status of bird species in danger throughout the world. Climate variables are important for species with limited distribution (Hargreaves et al., 2014). Due to climate change, bird species are currently contracting and shifting their ranges toward the poles, which is an alarming situation for bird species in Pakistan (Yasin et al., 2021).

Raptors adopt diverse lifestyles, such as living in low-density areas, preferring colonization and migration over long ranges as compared to other groups of birds (Donazar et al., 2016). It is expected that migratory species are adversely affected by different climatic factors (Umar et al., 2018). After hunting, the second most crucial factor is the loss of habitat, causing the extinction of migratory species; all these events are stochastic for raptors. The vertebrate taxa of avian raptors have declined throughout the world (Cruz et al., 2021).

Overall, 50% of raptors have declined worldwide due to this reason; avian raptor species have gained more attention. In Pakistan, a total of 47 avian raptor species have been found, 7 endangered and 20 near-threatened raptor species recorded in the province of Sindh (Iqbal et al., 2023). Therefore, the present research deals with the distribution of avian raptors in Pakistan (Ghalib et

al., 2019). Ecologically, raptors are one of the most important scavengers as recyclers of dead matter and control pest species, as well as control the spread of disease within ecosystem services. Therefore, suitable protection of habitat is one of the most significant tasks in the first century in conservation biology (Khattak et al., 2022).

By influencing physiological tolerance, prey availability, nesting possibilities, and foraging conditions, environmental factors have a significant impact on raptor species' distribution and habitat preference. In addition to having an indirect impact on prey resources through their impacts on vegetation and ecosystem production, climate variables, especially temperature and precipitation, can have a direct impact on raptor physiology and behavior. By offering appropriate locations for breeding, roosting, and hunting, topographic elements like elevation and slope also have a significant impact on habitat appropriateness (William et al., 2025)

In the search for suitable habitats for endangered and rare species, data were accessed from websites such as GBIF (Sarda-Palomera et al., 2012) for conservation and management. Species distribution can give an important understanding (Guisan et al., 2013). For current and future species distribution projections, species distribution models are commonly used as a valuable insight into the geographical distribution and environmental requirements of species. Based on maximum entropy modeling (MaxEnt) response curves and binary distribution maps generated on the basis of ecological requirements, this approach is helpful for the evaluation of the habitat suitability of bird species for the present and future (Guisan et al., 2013).

The total number of species all over the world is 9042; in Asia, 2700 have been reported. (Zaman et al., 2022). While 750 bird species belong to 29 orders found in Pakistan. According to IUCN (2001), many bird species are at risk of extinction (Jadoon et al., 2019). These four avian raptor species are distributed in Pakistan; among these, three species belong to the order Accipitriformes (*Haliaeetus leucorphyus*, *Neophron percnopterus*, *Aegypius monachus*), and one species belongs to the order Falconiformes (*Falco chicquera*). The IUCN (2011) Red List categorizes them as endangered species (*Haliaeetus leucorphyus*, *Neophron percnopterus*) and near-threatened (*Aegypius monachus*, *Falco chicquera*). These raptor bird species maintained the balance in the ecosystem by keeping the prey species within limits. Based on

climate effects, there is a lack of studies on these four avian raptor species *Haliaeetus leucorphyus*, *Neophron percnopterus*, *Aegypius monachus*, *Falco chicquera*, in Pakistan. In this study, climatic suitability is projected on the basis of occurrence records and environmental variables of these four raptor species of Pakistan.

Our study's primary goal is to comprehend how climatic predictors affect avian raptor species, which could be helpful for management and conservation actions. (i) To update information about the present and future distribution of four avian raptors (ii) Prediction of suitable habitat for the present time as well as future time under climate scenarios (iii) To find the climatic bioclimatic variable which affects these distributions (iv) Projection of species extinction in the future under various climatic situations.

Material and Methods

Species occurrence records

The occurrence records of four avian raptor species in Pakistan were collected from 1980-2019. A total of 17597 records with details: *Haliaeetus leucorphyus* (2346), *Neophron percnopterus* (10048), *Falco chicquera* (3418), and *Aegypius monachus* (1785) were obtained from GBIF (Global Biodiversity Information Facility) based on human observation (Table 1). The SpThin Package was used in R to limit the impact of biased species occurrences by picking a 1km minimum distance between occurrence locations to avoid autocorrelation, with the help of the ArcGIS tool 10.2.2 (Zahoor et al., 2022).

Table-1. Record of the occurrence of four avian raptor species of Pakistan.

Avian raptor species	Presence records	Source of occurrence records
<i>Haliaeetus monachus</i>	2346	Observations of Human (Pallas, 1771)
<i>Neophron percnopterus</i>	10048	Observations of Human (Linnaeus, 1758)
<i>Falco chicquera</i>	3418	Observations of Human (Daudin, 1800)
<i>Aegypius monachus</i>	1785	Observations of Human (Linnaeus, 1766)

Data of climatic predictors

The worldclim 1.4 database provided information on 19 bioclimatic variables at a resolution of 0.5 arc per minute with grid cell area up to 1km before the period 1980-2019, whereas for future projections up to 2050 and up to 2070 (Fick and Hijmans., 2017; Merow et al., 2013) Temperature variables were selected from the bio1 annual range of mean temperature to bio11 coldest quarter mean temperature because temperature has a serious impact on species. According to the climate conditions of Pakistan, available data on precipitation variables were selected from bio12 per year precipitation to bio19 coldest quarter precipitation because of their extreme impact on species (Cavalcanti et al., 2016). Models used for species distribution prediction from the project CMIP5 generalized circulation models (GCMs) and the Hadley Center global environment model (HadGEM), including models that we used: HadGEM2-ES, CCSM4, MIROC5, GFDL-CM3, and IPSL-CM5A-LR. The two carbon emission scenarios (RCPs 4.5 and 8.5) were used for future predictions for 2050 and

2070, respectively for predictions of carbon emissions (Zahoor et al., 2022).

Model performance

An output of the model was used for modeling species distribution on the basis of occurrence records for the present and future of four avian raptor species (Dai et al., 2021). MaxEnt default settings were used (Auto features, regularization multiplier 0.5- 3, background points 10,000, replication subsampling and bootstrapping, evaluation by AUC and TSS, Occurrence preprocessing by spatial thinning). Model performance was evaluated using 70% data for training and 30% data for testing, while 24 replications were performed for confirmation of valid results (Zahoor et al., 2021; Dai et al., 2021). The jackknife test was used to determine the percentage contribution of climatic factors. As well as marginal response curves, binary distribution maps of avian raptor species of Pakistan were generated (Elith et al., 2011). Maps of habitat suitability were generated on the basis of threshold values as sensitivity values under the area of the curve by subsampling and bootstrapping

methods, while MTPS (Maximum Training Sensitivity plus specificity) values were used to differentiate between unsuitability and habitat suitability (Liu et al., 2013; Zahoor et al., 2021). The model's performance (Norberg et al., 2019) was evaluated using threshold values and area below the curve, following criteria used to assess the SDMs' performance with a range of values between 0 and 1. If AUC < 0.6, then not good; 0.6 to 0.7 is equal to bad, 0.7 to 0.8 is good, considered; 0.8 to 0.9 is better, while > 0.9 or equal represents outstanding model performance (Singh et al., 2020; Phillips et al., 2006; Kamyo and Asanok, 2020). The statistics ArcGIS 10.2.2, as well as $|r| > 0.8$, were used to eliminate multicollinearity between variables (Zahoor et al., 2021; Brown, 2014; Zahoor et al., 2021).

Results

The Species Distribution Model was applied to available data to evaluate the present-time and future-time habitat suitability for selected species of raptors based on the total number of species presence records, along with climatic variables that significantly affect them. Four species, along with a number of significant

environmental variables, were *Haliaeetus leucoryphus* (2346/8), *Neophron percnopterus* (10048/9), *Falco chicquera* (3418/10), and *Aegypius manachus* (1785/8).

Percentage contribution of environmental variables

The percentage contribution of climatic predictors was obtained from a jackknife test used to plot the habitat suitability of a species. Results showed the contribution of the percentage of environmental climatic variables' mean value for current and future scenarios and were obtained after 24 model replications. Climatic variables have maximum percentage contribution for Raptors species based on RCPs (4.5 and 8.5) for 2050 and 2070 revealed as *Haliaeetus leucoryphus* (bio17) 52.5% and 33.3%, *Neophron percnopterus* (bio15) 44.5% and 48%, *Falco chicquera* (bio8) 9.4% and 15% while *Aegypius monachus* (bio8) 23.7% and 17.1% respectively on the base of model predictions (Table 2 and 3). MaxEnt model performance for each species is indicated as values of area under the curve by training and testing of data between (0.7-0.9), as shown in (Table 4, Figure 3).

Table-2. Values of the percentage contribution of climatic predictors for four Raptor species under RCP 4.5 for 2050 'variable of temperature ($^{\circ}\text{C}$) and for precipitation (mm)'.

Code	Variables	Unit	<i>Haliaeetus leucoryphus</i>	<i>Neophron percnopterus</i>	<i>Falco chicquera</i>	<i>Aegypius monachus</i>
Bio1	Annual mean temperature	$^{\circ}\text{C}$	0%	0%	6%	0%
Bio2	Mean diurnal range	$^{\circ}\text{C}$	0.7%	11.7%	0.5%	6.7%
Bio3	Temperature consistency	$^{\circ}\text{C}$	0.6%	4.7%	3.6%	0%
Bio4	Temperature seasonality	$^{\circ}\text{C}$	0%	0%	0%	4.8%
Bio5	Maximum Temperature of warmest month	$^{\circ}\text{C}$	0%	0%	0%	0%
Bio6	Minimum temperature of coldest month	$^{\circ}\text{C}$	0%	0%	0%	0%
Bio7	Annual temperature range	$^{\circ}\text{C}$	0%	0%	0%	0%
Bio8	Mean temperature of wettest quarter	$^{\circ}\text{C}$	10.5%	2.6%	9.4%	23.7%
Bio9	Mean temperature of driest quarter	$^{\circ}\text{C}$	5.1%	5.6%	0.6%	0.7%
Bio10	Mean temperature of warmest quarter	$^{\circ}\text{C}$	0%	0%	0%	0%

Bio11	Mean temperature of coldest quarter	$^{\circ}\text{C}$	0%	0%	0%	0%
Bio12	Annual precipitation	mm	0%	0%	0%	0%
Bio13	Precipitation of wettest month	mm	21.7%	0.7%	1.7%	0.4%
Bio14	Precipitation of driest month	mm	11.2%	2.6%	4.8%	0.9%
Bio15	Precipitation seasonality	mm	0.5%	44.5%	3.4%	0%
Bio16	Precipitation of wettest month	mm	0%	0%	0%	0%
Bio17	Precipitation driest month	mm	52.5%	0%	0%	0%
Bio18	Precipitation of warmest quarter	mm	0%	0.2%	0.2%	18%
Bio19	Precipitation of coldest quarter	mm	0%	0.1 %	2.8%	0.9%

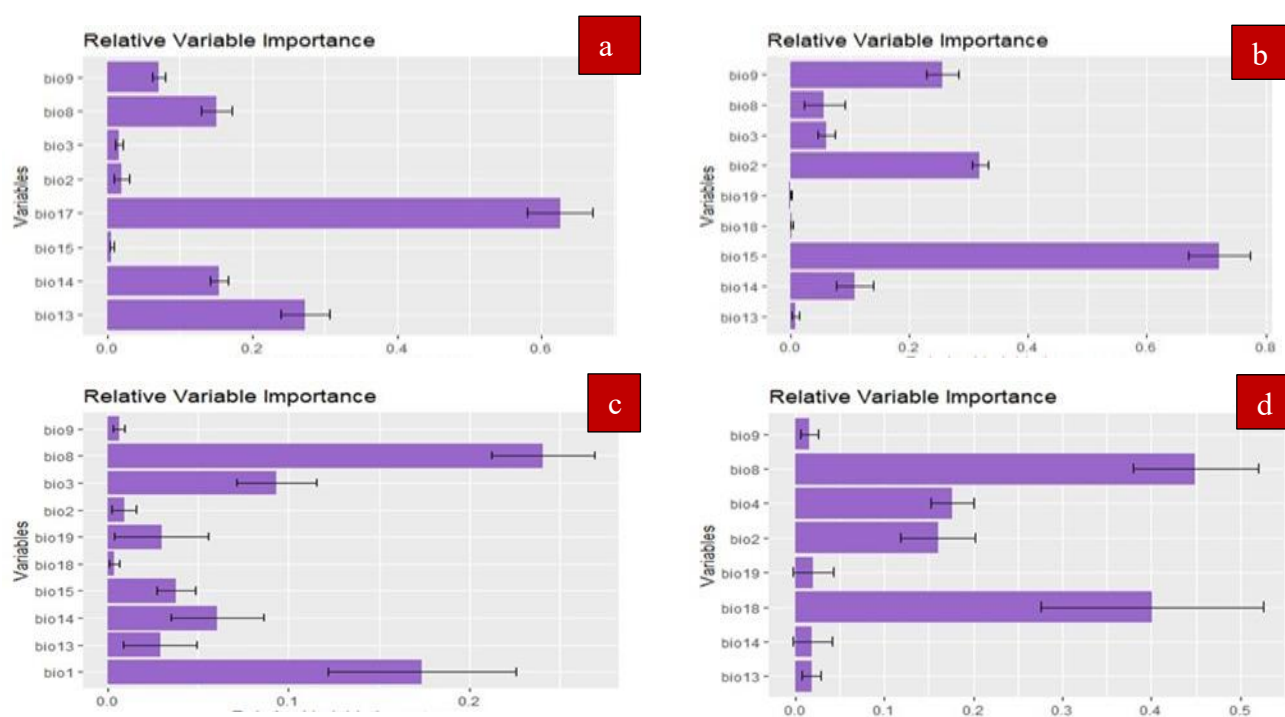


Figure-1. Plots indicate variables percentage importance of temperature and precipitation for (a) *Haliaeetus leucorphyus*, (b) *Neophron percnopterus*, (c) *Falco chiquera*, and (d) *Aegypius monachus*. The length of the purple bars indicates all variable effects, while the back bars show a gain of maximum variable contributors under RCP 4.5 for 2050.

Table-3. Values of the percentage contribution of climatic predictors for four raptor bird species of Pakistan under RCP 8.5 for 2070 variables of temperature ($^{\circ}\text{C}$) and precipitation variable (mm).

Code	Variables	Unit	<i>Haliaeetus leucorphyus</i>	<i>Neophron percnopterus</i>	<i>Falco chicquera</i>	<i>Aegyptius Monachus</i>
Bio1	Annual mean temperature	$^{\circ}\text{C}$	0%	0%	2.9%	0%
Bio2	Mean diurnal range	$^{\circ}\text{C}$	0.5%	14.8%	2.4%	3.3%
Bio3	Temperature consistency	$^{\circ}\text{C}$	0.1%	6.5%	3.9%	0%
Bio4	Temperature seasonality	$^{\circ}\text{C}$	0%	0%	0%	3.3%
Bio5	Minimum temperature of warmest month	$^{\circ}\text{C}$	0%	0%	0%	0%
Bio6	Minimum temperature of coldest month	$^{\circ}\text{C}$	0%	0%	0%	0%
Bio7	Annual temperature range	$^{\circ}\text{C}$	0%	0%	0%	0%
Bio8	Mean temperature of wettest quarter	$^{\circ}\text{C}$	7.2%	4.2%	15%	17.1%
Bio9	Mean temperature of driest quarter	$^{\circ}\text{C}$	6%	5.7%	0.3%	0.8%
Bio10	Mean temperature of warmest quarter	$^{\circ}\text{C}$	0%	0%	0%	0%
Bio11	Mean temperature of coldest quarter	$^{\circ}\text{C}$	0%	0%	0%	0%
Bio12	Annual precipitation	mm	0%	0%	0%	0%
Bio13	Precipitation of wettest month	mm	31.3%	0.9%	0.4%	6.5%
Bio14	Precipitation of driest month	mm	8.1%	1.2%	1.9%	7.4%
Bio15	Precipitation seasonality	mm	0.7%	48%	3.6%	0%
Bio16	Precipitation of wettest quarter	mm	0%	0%	0%	0%
Bio17	Precipitation driest quarter	mm	33.3%	0%	0%	0%
Bio18	Precipitation of warmest quarter	mm	0%	0.4%	0.2%	5.8%
Bio19	Precipitation of coldest quarter	mm	0%	0.2%	0.1%	0.5%

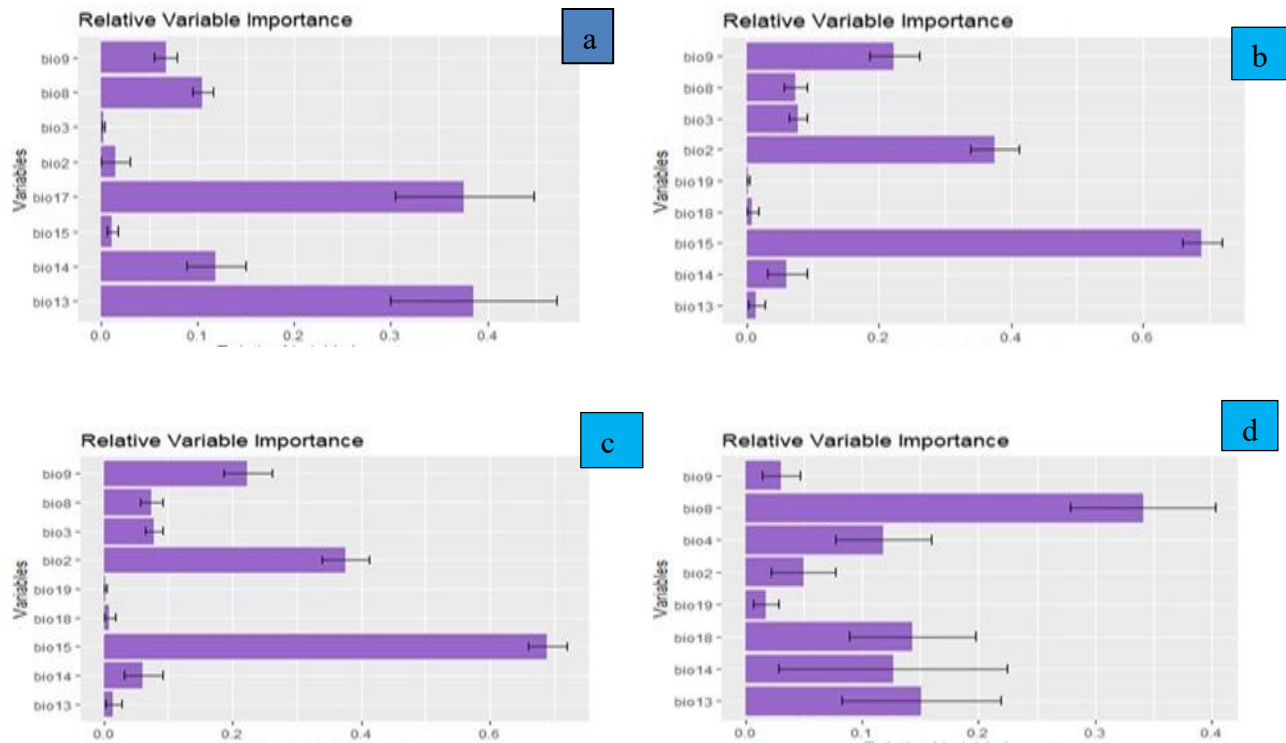


Figure-2. Plots indicate variables percentage importance of temperature and precipitation for (a) *Haliaeetus leucorphyus*, (b) *Neophron percnopterus*, (c) *Falco chiquera*, and (d) *Aegypius monachus*. “The length of purple bars indicates all variable effects while back bars showed a gain of maximum variable contributors under RCP 8.5 for 2070.

Table-4. Values of the area under the curve maxEnt output obtained by data splitting 30% as training and 70% testing of four avian raptor species with standard deviation (SD).

Raptors species	Training AUC	Test AUC
<i>Haliaeetus leucorphyus</i>	0.929 0.923	0.923 0.92
<i>Neophron percnopterus</i>	0.838 0.843	0.845 0.844
<i>Falco chicquera</i>	0.894 0.891	0.897 0.888
<i>Aegypius monachus</i>	0.723 0.715	0.72 0.723

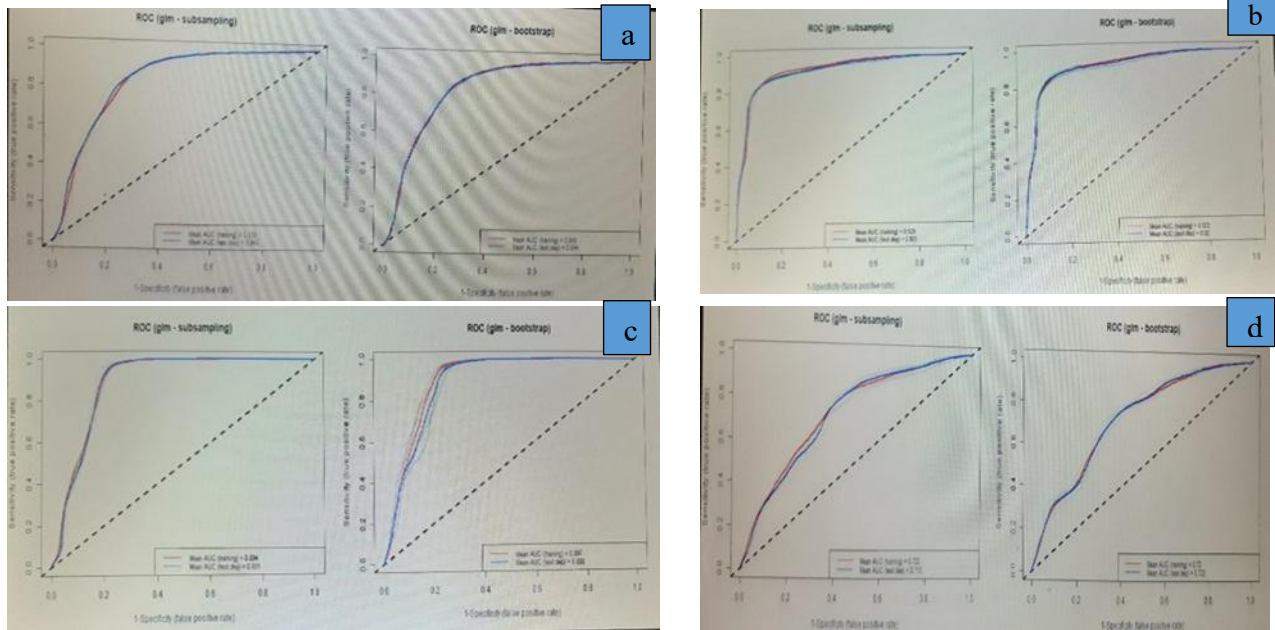


Figure-3. Roc curves of species distributions model for prediction of suitable habitat for Raptors species (a) *Haliaeetus leucorhynchus*, (b) *Neophron percnopterus*, (c) *Falco chichquera*, and (d) *Aegypius monachus* respectively. Samples are classified as sensitivity and specificity by two methods bootstrapping and sub-sampling replications while blue and red lines indicate the values of AUC.

Habitat suitability for raptor species during the current time

In the current scenario, the habitat suitability of *H. leucorhynchus* was more towards the center of the east (Figure 4a); *N. percnopterus* towards the center of the

east, northern latitudes to northern altitudes (Figure 4b); *F. chichquera* in the center of the east and western latitudes (Figure 4c); and *A. monachus* towards the center of the east and altitudes of east and north (Figure 4d).

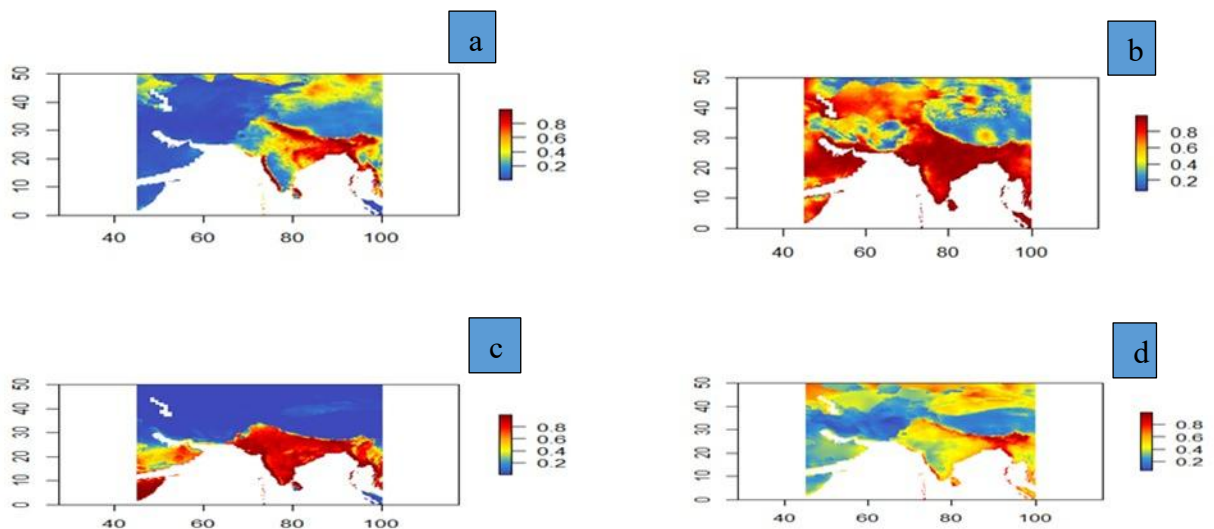


Figure-4. Habitat suitability maps of raptor bird species during the current time (a) *Haliaeetus leucorhynchus*, (b) *Neophron percnopterus*, (c) *Falco chichquera*, and (d) *Aegypius monachus* obtained by GCM models. Values close to 1 indicate more habitat suitability while close to zero indicate less suitability for the raptor's species.

Habitat suitability in response to projected impact of bioclimatic variables on raptor species

Habitat suitability for *H. leucorphyus* in the future scenario up to 2050 and 2070 is expected towards the center of the east (Figure 5a, 6a). For *N. percnopterus*, habitat suitability in the future scenario of 2050 is expected to be in the east, also towards northern latitudes and altitudes (Figure 5b) while up to 2070 more towards east and towards northern latitudes and altitudes (Figure 6b). Habitat is suitability for *F. chicquera* in the future scenario up to 2050 is expected towards latitudes of north and center of east (Figure 5c) and similar trend was observed up to 2070 (Figure 6c). For *A. monachus*, habitat suitability in the form of small pocket is expected in the future scenario of 2050 and 2070 towards center of the east (Figure 5d, 6d). These four avian raptor species of Pakistan are predicted to shift their ranges towards latitudes of the

north and the center of the east regions, and this contraction seems to be in response to climatic variables (Tables 2 and 3), which affected raptor distribution in Pakistan under RCPs 4.5 (2050) and 8.5 (2070) (Figures 2 and 3). For *H. leucorphyus*, climate variables (bio17) driest month precipitation and (bio15) seasonal precipitation were quite effective among the predicted variables (Figures 2a and 3a), while *N. percnopterus* was affected by (bio15) 'seasonal precipitation' as well as (bio19) coldest quarter precipitation among projected bioclimatic variables (Figures 2b and 3b). For *F. chicquera*, the climate variables (bio8) wettest quarter mean temperature and (bio18) warmest quarter precipitation were significant in the impact (Figures 2c and 3c), while *A. monachus* was significantly affected by climatic variables (bio8) wettest quarter mean temperature and (bio8) wettest quarter precipitation (Figures 2d and 3d).

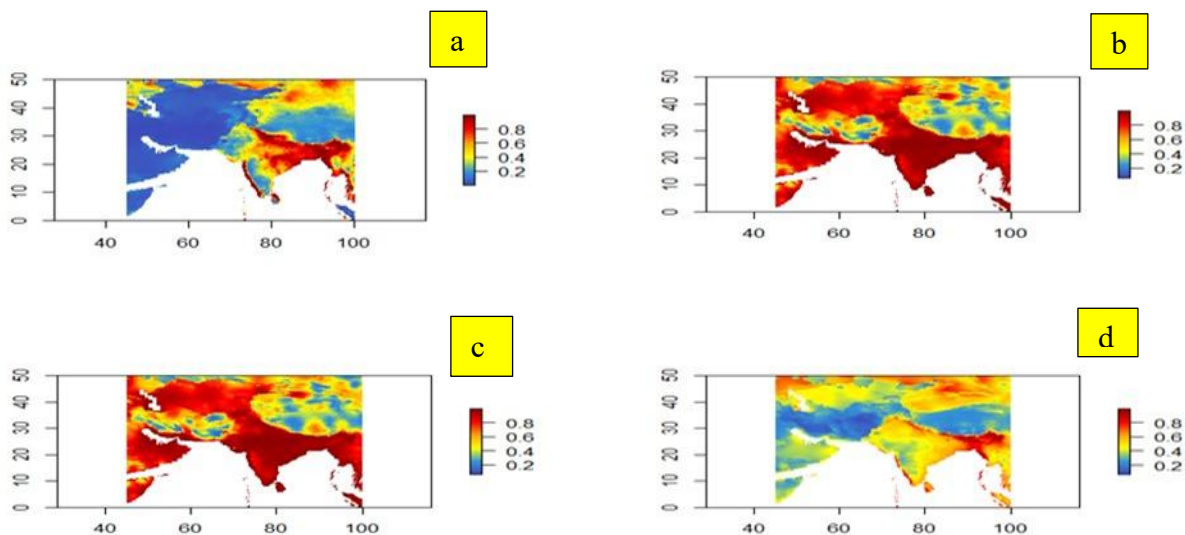


Figure-5. Projected species distribution maps for future scenario up to 2050 under RCP 4.5, maps generated on the basis of logistic threshold values by GCM models for (a) *Haliaeetus leucorphyus*, (b) *Neophron percnopterus*, (c) *Falco chicquera*, and (d) *Aegypius monachus*. Values close to 1 indicate more habitat suitability, and close to zero indicate less suitability for Raptor's species.

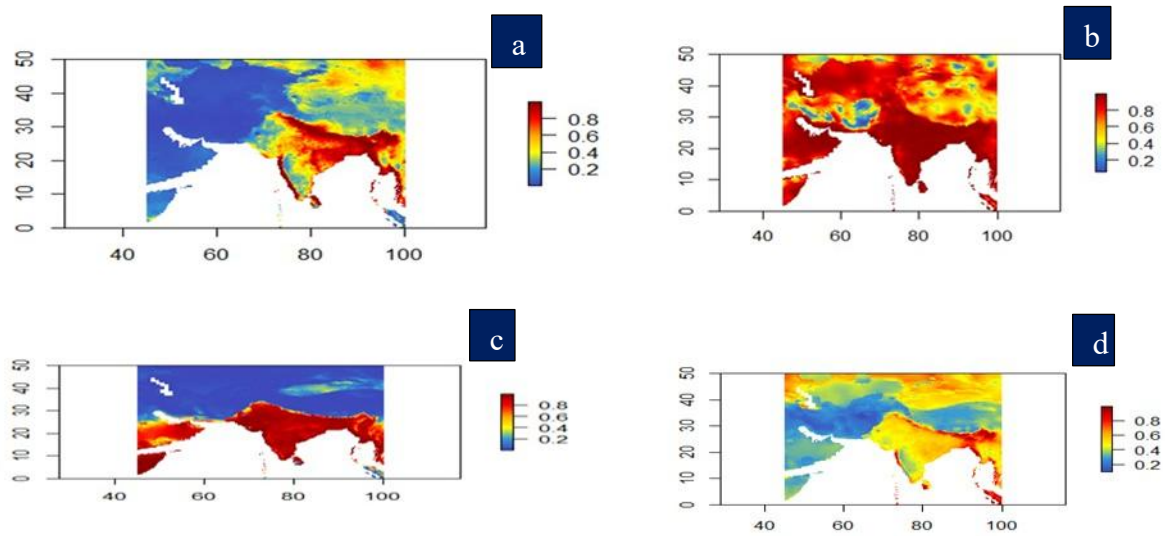


Figure-6. Projected species distribution maps for future scenarios up to 2070 under RCP 8.5, maps generated on the basis of logistic threshold values by GCM models for (a) *Haliaeetus leucorphyus*, (b) *Neophron percnopterus*, (c) *Falco chicquera*, and (d) *Aegyptius monachus*. Values close to 1 indicate more habitat suitability, and close to zero indicate less suitability for Raptor's species.

Current distribution of raptor bird species

Species distribution maps were generated on the basis of logistic threshold values that were obtained after training and testing of data for avian raptor species,

viz. *Haliaeetus leucorphyus* (0.929), *Neophron percnopterus* (0.845), *Falco chicquera* (0.894), and *Aegyptius monachus* (0.723) (Table 4). The current distribution study maps of the above-mentioned raptor species are shown in (Figure 7).

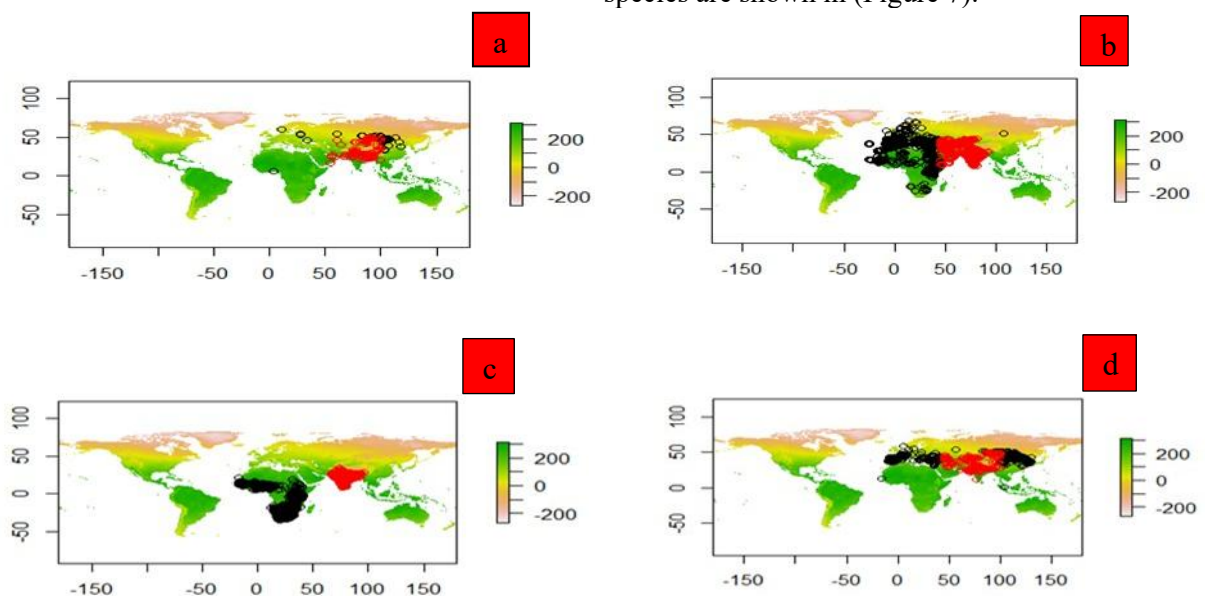


Figure-7. Maps of the current distribution of (a) *Haliaeetus leucorphyus*, (b) *Neophron percnopterus*, (c) *Falco chicquera*, and (d) *Aegyptius manachus*. The location maps contained red-filled circles, which indicate the current occurrence of these four species.

Future probability of distribution colonization/extinction of raptor species

The probability of occurrence in the future was obtained based on presence records under RCP 4.5 and 8.5 for 2050 and 2070, respectively, as shown in (Figures 8 and 9). For *H. leucorpyus*, the probability of colonization of 0.5-1% was observed towards east and eastern altitudes as well as 0.5% towards the altitudes of north up to 2050 (Figure 8a), whereas, colonization was more towards the center of east and in few pockets of eastern altitude up to 2070 (Figure 9a). The probability of extinction -1% for *H. leucorpyus* was observed towards the center of east till 2050 (Figure 8a) while in few pockets in the center of east till 2070 (Figure 9a). For *N. percunopteris*, the rate of colonization 0.5 to 1% was observed towards higher altitudes of north up to 2050 (Figure 8b) whereas, colonization was more towards northern altitudes on a broader scale up to 2070 (Figure 9b).

The probability of extinction -0.5 to -1% for *N. percunopteris* was observed towards latitudes of north till 2050 (Figure 8b) and on a minute spot at latitudes of north till 2070 (Figure 9b).

The possibility of colonization for *F. chicquera*, 0.5-1% was prominent in the central region of the east and lower latitudes of the north up to 2050 (Figure 8c), whereas, this colonization pattern was more towards latitudes of north regions up to 2070 (Figure 9c). A prediction about extinction -0.5 to -1% for *F. chicquera* was seen at a minute spots in the lower northern latitude till 2050 (Figure 8c) while no such specific areas were observed in maps generated till 2070 (Figure 9c). The possibility of colonization for *A. monachus* 0.5 to 1% was prominent towards altitudes of north up to 2050 and 2070 (Figures 8d and 9d). A prediction about extinction: -1% for *A. monachus* toward altitudes of the east in the center till 2050 (Figure 8d), and a minute spot was seen at altitudes of the east till 2070 (Figure 9d).

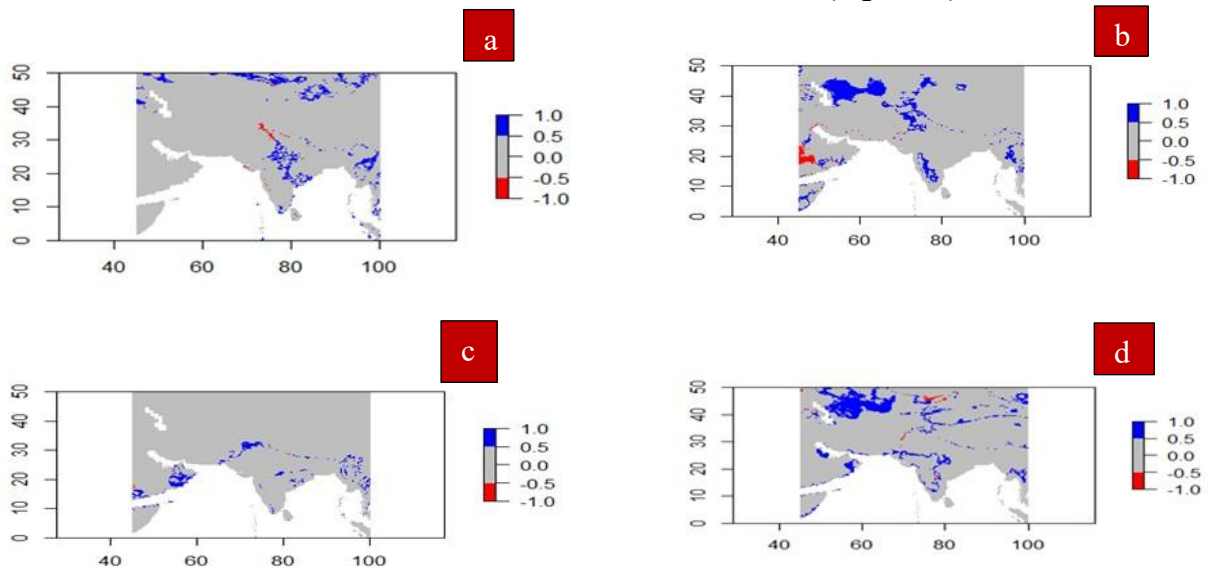


Figure-8. Future distribution maps of (a) *Haliaeetus leucorpyus*, (b) *Neophron percunopteris*, (c) *Falco chicquera*, and (d) *Aegypius monachus* for 2050 under the RCP 4.5 emission scenario of carbon by GCMs models. Model prediction maps show a value closer to 1 gain and -1 loss of species in the future.

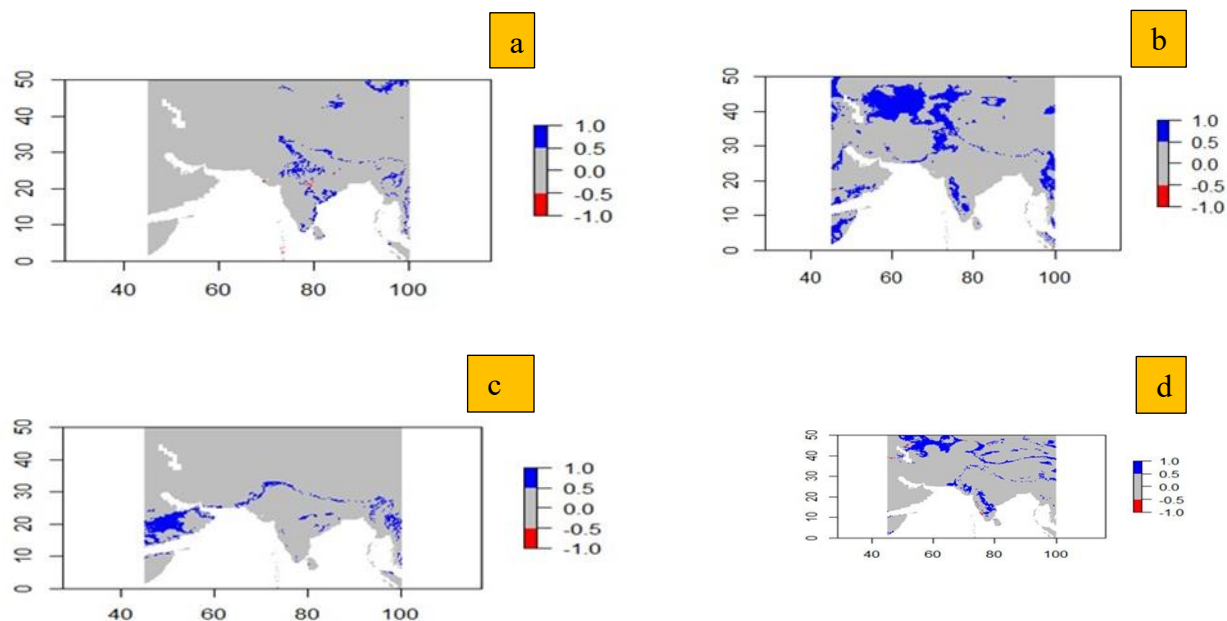


Figure-9. Future distribution maps of (a) *Haliaeetus leucoryphus*, (b) *Neophron percnopterus*, (c) *Falco chicquera*, and (d) *Aegypius monachus* for 2070 under the RCP 8.5 peak carbon emission scenario by the GCMs model. Model prediction maps show a value closer to 1 gain and -1 loss of species in the future.

Discussion

In the present research, the impact of environmental variables, temperature, and precipitation on four avian raptor species *Haliaeetus leucorhynchus*, *Neophron percnopterus*, *Falco chicquera*, *Aegypius monachus*, resident Raptor species of Pakistan, was assessed using bioclimatic variables and bird distribution data from model output, following the method as explained by (Elith et al., 2011) for a similar purpose. The primary objective was to find out the targeted raptor species' current habitat, future habitat suitability in the upcoming high carbon emission scenario, and ultimately a prediction about their colonization and extinction. An understanding of biogeography is crucial to understanding the geographical ranges of species and habitat preferences while working on endangered Raptor species in Kenya (Ngila et al., 2023). For future prediction of habitat suitability, geographical range, and future conservation studies, the species distribution model (SDM) used in the current study proved as a decisive tool as reported by many of the researchers while working on species' current and future distribution based on the impact of climatic factors (Lawler et al., 2010; Guisan et al., 2013; Zahoor et al., 2022).

The expected habitat suitability for three out of four species studied was seen towards latitudes of the north and east, and in the center of the east. The higher altitudes of the north and east experience winter temperature changes as well as seasonal rainfall from the past three decades, as depicted in studies conducted by (Hussain et al., 2005) on climate in mountain regions of Pakistan. According to them, the weather is continuously changing due to an increase in the temperature of the winter season. These results support the expected habitat suitability of *H. leucorhynchus*, *F. chicquera*, and *A. monachus* shown in the map generated regarding habitat suitability in the future scenario of 2050 and 2070. The climate has a definite impact on species distribution as depicted in the present work and is in accordance with the findings given by (Khaliq et al., 2023) that climate has a fixed impact on the richness of avian biodiversity in Pakistan. The current and future habitat suitability, along with colonization patterns in the future based on greenhouse gas emissions using species distribution model mapping (Chhetri et al., 2021), can be helpful for biologists working on avian species conservation. (Ngila et al., 2023) obtained similar results by working on raptor species of Kenya to assess the appropriate habitat map of the future in terms of conservation strategies (Mahananda et al., 2025) to fill the

information gap. (Wilson et al., 2016) explained in his research to focus on important regions of the world for conservation by analyzing species status. A similar approach was followed in the current study at visible regions of the Oriental region with a specific focus on the Indian sub-continent, especially Pakistan.

The climatic variables, viz. temperature and seasonal precipitation in particular, dominated in the predicted models. The prediction is in line with the results where the ecological niche of raptors was modeled using GPS tracking data (Liminana et al., 2012). The graphical representation of relative variable importance and response curves clearly indicates the significance of bioclimatic variables on species' geographical distribution, as explained in this study (Zhang et al., 2023). In the current research, *A. monachus* and *F. chicquera* were affected by mean temperature during the wet quarter in the Northern altitudes and would shift towards the center of eastern regions. Additionally, the precipitation during the driest month affects *H. leucorphyus* towards the center of the east and latitudes of the north, whereas seasonal precipitation was effective for *N. percnopterus*, shifting the distribution range from altitudes of North towards latitudes. The predicted findings are similar to (Virkkala and Rajasarkka, 2011), wherein they explained the range shift of birds from northern areas because of the effect of climate change. An increase in precipitation is related to an increase in the rate of temperature, which ultimately declines the chances of habitat suitability for many raptor species at the poles. This is consistent with the results concluded by (Phipps et al., 2017) on the impact of precipitation on raptors, where an ultimate shift in ranges was seen towards central regions. An understanding of current and future climatic variables showed a deterministic role in habitat suitability/geographic distribution of threatened species for future management plans.

At a global level, the variation in climate is projected to change the distribution of different species of birds (Sutton et al., 2020), and every species responds according to their own environmental requirements and ecological status. In the current research, the model predicted that habitat suitability was less contracted in 2070 when compared to 2050. (Sutton et al., 2020) worked on *Falco juggar* and observed the effect of temperature and precipitation on species distribution. The present findings of habitat contraction up to 2050 as a result of high carbon emissions and shifts in their ranges due to climate change, according to the conclusion given by (Sutton

et al., 2020) for raptors. A considerable variation was observed in the present and future suitability of the habitat of four raptor species studied in the present study, which worked on four approaches for the prediction of habitat suitability. Finally, he concluded that individual models show better performance, such as MaxEnt, as used in our research work. Moreover, a change in range shifts of raptors in a result of climate factors in Pakistan is in line with the hypothesis generated by (Zahoor et al., 2022) while working on three species of Galliformes under RCPs 4.5 and 8.5.

Conclusion

Four resident species of raptors, viz *H. leucoryphus*, *N. percnopterus*, *F. chicquera*, and *A. monachus*, were projected by a species distribution model for current and future up to 2050-2070. Due to changes in temperature patterns, the SDM models predicted future differences in the suitability of habitat for these resident raptor species. The current study demonstrated habitat growth, colonization, and contraction toward higher elevations in the northeast and lower altitudes in the north. Until 2050–2070, there was a noticeable decrease in habitat appropriateness under 4.5 RCP and 8.5 RCP. For the protection of these four resident raptor species *H. leucoryphus*, *N. percnopterus*, *F. chicquera*, and *A. monachus*, proper management is required for the protection of these areas in Pakistan to decrease the effect of climate change.

Suggestions for raptor's conservation

The necessity for climate-adaptive conservation planning is highlighted by anticipated changes in raptor range and habitat suitability. Future appropriate habitats and climate refugia that stay stable under various climate scenarios should be prioritized. Raptor range shifts and dispersal can be facilitated by maintaining connectivity between present and future appropriate habitats. Raptor populations, nesting grounds, migration paths, and habitat conditions should all be better monitored over an extended period of time. Planning for protected areas, habitat restoration, and adaptive management can be guided by the anticipated habitat-loss and gain regions found in this study. In the event of future climate change, these actions may contribute to better long-term raptor conservation in Pakistan.

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Contribution of Authors

Ruby T: Supervised the research, analyzed and interpreted the data and edited the manuscript.

Naqvi S: Conceived the idea, designed research methodology, collected the data, wrote and revised the manuscript.

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