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Impact of Climate Change on Reptiles (Order Testudinea) in Pakistan: current and future trends

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Abstract
Pakistan, located in South Asia between the Palearctic, Ethiopian, and Oriental biogeographic realms, possesses diverse landscapes including mountains, plains, deserts, arid regions, and the Arabian Sea coast, with climatic extremes such as floods, droughts, and monsoon variability shaping its biodiversity. Reptiles, constitute nearly one-fourth of known vertebrate fauna, and are highly influenced by climatic and geographic factors, thus making distribution and population densities dependent on temperature and other environmental gradients. Pakistan hosts around 170 living Reptilian species where Testudines (turtles and tortoises) consisted of fifteen spp. inhabiting freshwater, marine, and terrestrial ecosystems across tropical and subtropical regions and considered world's most threatened group because of habitat loss, illegal trade, diseases and climate change. The present analysis evaluated the impact of temperatures, moisture and changing weather (global warming) on three vulnerable species of Pakistan: Caretta caretta, Geochelone elegans, and Lepidochelys olivacea (IUCN, 2019). A total of 136,888 occurrence records of last 40 years from 1980–2019 were obtained from global biodiversity information facility (GBIF) and 19 climatic predictors taken from WorldClim 1.4 database using carbon emission level (RCP 4.5) for future projections of 2050 through generalized linear model (GLM) and maximum entropy (MaxEnt) models in R program. Results indicated a distribution range shifts for all three species: Caretta caretta was mainly affected by climatic variable (BIO-09) mean temperature of driest quarter and (BIO-08) mean temperature of wettest quarter, Geochelone elegans with a slight extinction risk of (-0.5%) was affected with BIO-I mean annual temperature and BIO-02 mean diurnal range while Lepidochelys olivacea was affected by BIO-19 precipitation of coldest quarter, BIO-02 mean diurnal range and BIO-08 mean temperature of wettest quarter. Overall, the study projected that future climate change under RCP 4.5 would significantly modify the geographic distribution and habitat suitability of vulnerable species of Reptiles in Pakistan by 2050.

Keywords: Species distribution modeling, Temperature, Vulnerable reptiles, RCP4.5, Pakistan.

INTRODUCTION

Pakistan, the fifth populated country in the world, is positioned in South-Asia amongst 24° and 37° N latitude & 61° and 78° E longitude, area of 796,096 km, physically residing predominantly within the Palearctic and Oriental zoogeographical realms, the nation is located at the junction of three major biogeographic monarchies, the Palearctic, Ethiopian, and Oriental (Boulenger,1890; Darlington,1957; Smith,1931; Safi et al., 2021). The Indus Valley, plains of northern Punjab and southern Sindh, vast mountain ranges, deserts, arid zones and a coastal belt along the Arabian Sea are parts of this diverse terrain (Khan,1980; Khan, 1996). According to Khan (1999), Pakistan has a continental climate with notable seasonal extremes, such as scorching summers, cold winters, and a monsoon season that lasts from July to September/October. The country also sees frequent floods and droughts, as well as spatial and temporal variations in rainfall. Waterlogging, aridity, desertification, and deforestation are affecting the forest cover, which makes up around 3.8% of the land surface to decrease (Khan, 2006). The country's biological patterns and biodiversity distribution are influenced by its distinct geographic location, unusual climate, and diverse topography (Karl,1997; Karl et al., 2024).

Comprising around one-fourth of all known vertebrate species, Reptiles are a varied family of ectothermic vertebrates that are found all over the world with the exception of Antarctica and the polar regions (Zug et al., 2001). The temperature, height/depth and environmental gradients have a significant impact on their activity patterns, population densities and spatial occurrence. The animal distribution and habitat preference are strongly correlated with climatic conditions and geographical parameters (Karl.,1997; Karl et al., 2024). Pakistan's geographic location and topographical diversity contribute to its extensive Reptilian fauna (Safi et al., 2021). The distribution, activity, and population densities of reptiles are significantly influenced by climatic gradients and environmental variability; warmer regions often sustain higher densities, while colder extreme conditions limit their occurrence (Karl., 1997; Karl et al., 2024). Order Testudinea inhibit temperate, subtropical, and tropical temperatures in freshwater, marine, and terrestrial habitats, inhale and exhale through their lungs and deposit eggs on land (Hutchinson, 1996).

It is assumed that half of turtle groups are in likelihood of going to be wiped out as a consequence of loss and degradation of their territory, harvesting for food, use in traditional medicine, emerging infectious diseases and above all the climate change directly involved in animal thermoregulation. The turtles and tortoises are among the endangered reptilian groups in the world (Stanford et al., 2020). In this current study, we discussed the influence of increasing temperature and changing climate on the future distribution pattern and habitat preference of three members belonged to order Testudinea in Pakistan. The representative species include Geochelone elegans, the Indian Star Tortoise or Sindh Star Tortoise native to southeastern Pakistan (Safi et al., 2021); Lepidochelys olivacea, inhabiting warm tropical waters (Spotila and James, 2004); and Caretta caretta, distributed across the Mediterranean Sea plus Atlantic, Indian, and Pacific Oceans (Spotila and James, 2004). The impact of increased temperature and allied environmental factors in the context of future carbon emission and subsequently changes in their habitat shift along with changes in distribution pattern in coming future was the aim of study.

MATERIAL AND METHOD

Species Occurrence Records

In total 136,888 occurrence records were found for 3 vulnerable species of Reptiles studied. Records gathered over-the previous forty-years ranging (1980-2019) from G.B.I.F (https:// www. gbif. org), incorporating human annotations and eliminated the points having no geographical coordinates (Table 1). The Spin-thin 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. A minimum of 10,000 random background points within a bias-corrected extent were included in spatial filtering method to reduce sampling data biasness (Zahoor et al., 2022).

Table 1 : Occurrence records and I.U.C.N status of reptilian species of Order Testudinea in Pakistan

Species Name	No of observations	Order	Status in IUCN
Caretta caretta	99999	Testudinea	Vulnerable
Geochelone elegans	153	Testudinea	Vulnerable
Lepidochelys olivacea	16646	Testudinea	Vulnerable

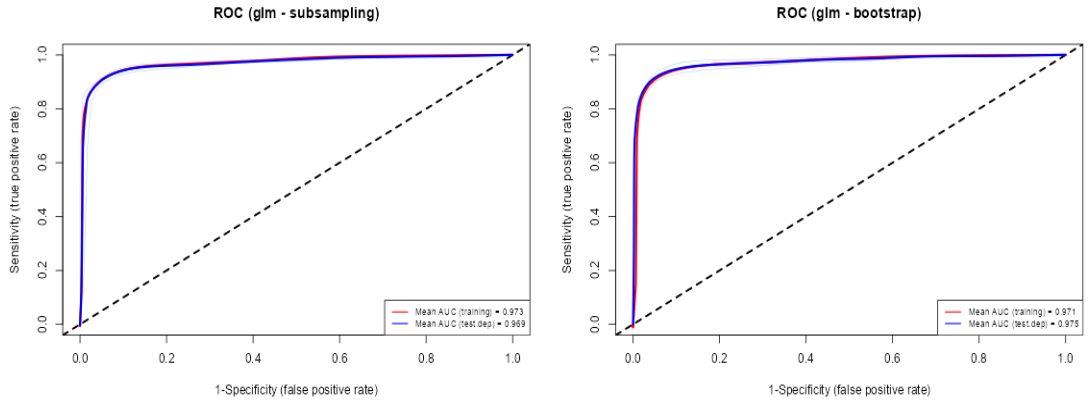
Climate Predictors Data

The Worldclim 1.4 database was used to download data of 19 climate predictors at a resolution of 0.5 arc per minute with grid cell area up to 1km for the period 1980-2019, whereas for future projections up to 2050 (Hijmans et al., 2005). Since climate is considered to play a significant role in species distribution, thus bioclimatic factors were crucial in this analysis (Chhetri et al., 2021). On the basis of existing information, temperature and precipitation variables depict monthly and seasonal extremes at the equator with a 10-minute resolution. Two models, such as the Hadley Centre Global Environment model version 2 (HadGEM2-ES version 2) and General Circulation Models (GCMs) from Coupled Model Intercomparison Project Phase 5 (CMIP5 project phase five), were used to estimate the distribution of species in the future (Ali et al., 2021). To ascertain the minimum and maximum peak concentrations of greenhouse gases, one carbon emission scenario, RCPs (4.5) (Zahoor et al., 2022), a main factor responsible for climate change, was employed for each model (Weyant, 2009).

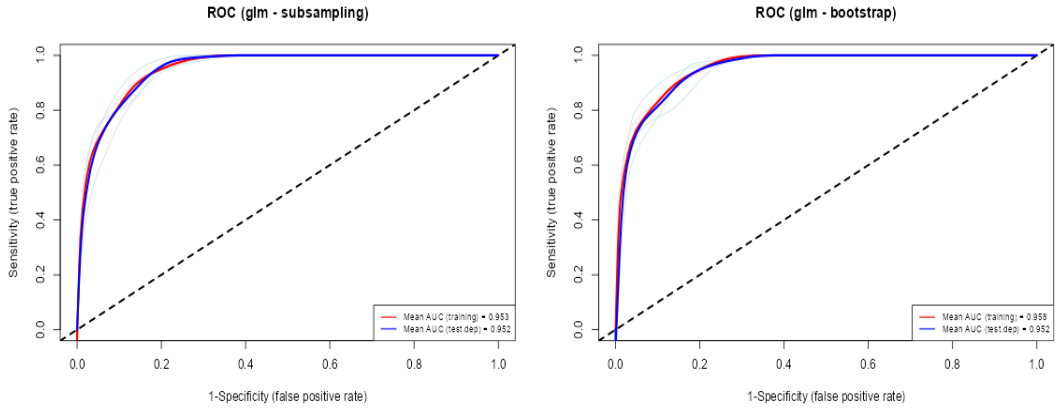
Model Performance and Species Distribution Model

Utilizing presence-only data, we employed the generalized linear model (GLM) and maximum entropy (MaxEnt) to estimate the distribution of three subcontinental (primarily Pakistani) vulnerable Reptile species. The models were validated using two duplicate techniques: bootstrapping and subsampling. MaxEnt default settings were used (Auto features, regularization multiplier 0.5- 3, background points 10,0000, replication subsampling and bootstrapping, evaluation by AUC and TSS, (occurrence preprocessing by spatial thinning). 30% of the presence data was used for testing while 70% was used for training, while 24 replications were performed for confirmation of valid results as suggested by (Zahoor et al., 2022; Dayananda et al., 2021).

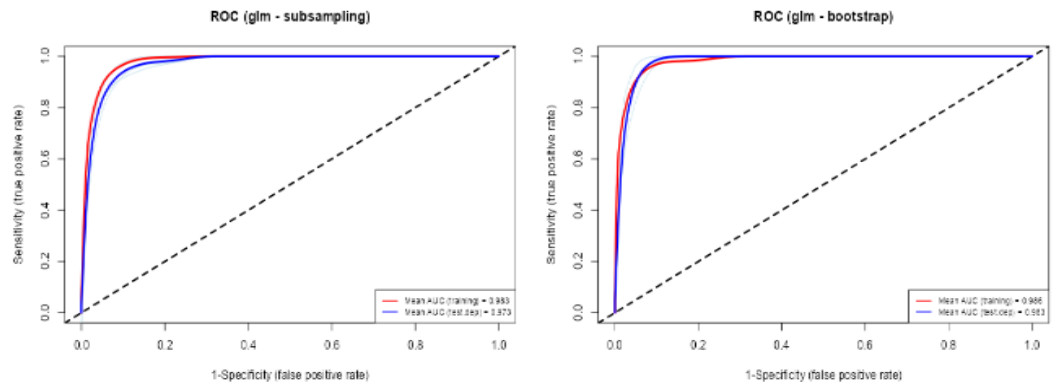
The jackknife test was used to determine the percentage contribution of climatic factors as well as marginal response curves and binary distribution maps of targeted species of Reptiles were generated (Elith et al., 2011). Maps of habitat suitability were generated on the basis of threshold values as 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 (Brown, 2014; Zahoor et al., 2022). 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 value <0.6, then not good; 0.6 to 0.7 is equal to weak/bad, 0.7 to 0.8 is considered good; 0.8 to 0.9 is better, while > 0.9 or equal represents outstanding model performance (Phipps et al., 2017; 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., 2022). Further, an independent threshold value i-e AUC (area under curve), was used to validate the accuracy of the model's output (Figure 1).



A: Mean ROC-AUC values for Caretta caretta (0.97 ± 0.0034 S.D) predicting higher climatic suitability



B: Mean ROC-AUC values for Geochelone elegans (0.95 ±0.0051 S.D) predicting higher climatic suitability



C: Mean ROC-AUC values for Lepidochelys olivacea (0.98 ± 0.0058 S.D) predicting higher climatic suitability

Figure 1 (a, b, c,): Model Performance, ROC curves evaluate habitat suitability using subsampling, bootstrapping, and mean AUC values showing higher suitability, with blue/red curves representing mean test/training AUC.

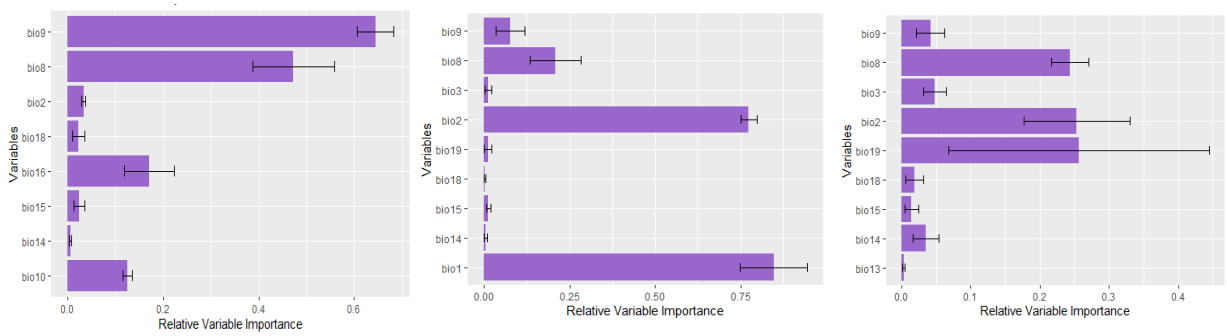
RESULTS

The present study evaluated the impacts of temperature, moisture and changing weather (global warming) on three vulnerable species of Pakistan: Caretta caretta, Geochelone elegans and Lepidochelys olivacea while taking into account approx. 19 climatic predictors from WorldClim 1.4 database using carbon emission level (RCP 4.5) for future projections of 2050 through GLM and MaxEnt models in R program.

Impact of Climatic Variables

Among 19 climatic variables, 11 were related to temperature include mean annual temperature, mean diurnal range, isothermality, mean annual temperature in a specific season, maximum temperature of warmest month, minimum temperature of coldest month, temperature annual range, mean temperature of wettest quarter, mean temperature of driest quarter, mean temperature of the warmest quarter and mean temperature of the coldest quarter. Remaining 8 variables were related to moisture pattern or precipitation include annual precipitation, precipitation of wettest month, precipitation of driest month,

precipitation seasonality, precipitation of wettest quarter, precipitation of driest quarter, precipitation of warmest quarter and precipitation of coldest quarter. For three species studied, the distribution of C. caretta was affected by BIO-09 mean temperature of driest quarter, BIO-08 mean temperature of wettest quarter, BIO-16 precipitation of wettest quarter and BIO-10 mean temperature of warmest quarter as shown in (Figure 2a). The distribution of G. elegans was pretentious to BIO-I mean annual temperature, BIO-02 mean diurnal range and BIO-08 mean temperature of wettest quarter as shown in (Figure 2b). The distribution of L. olivacea was affected by BIO-19 precipitation of coldest quarter, BIO-02 mean diurnal range and BIO-08 mean temperature of wettest quarter (Figure 2c).

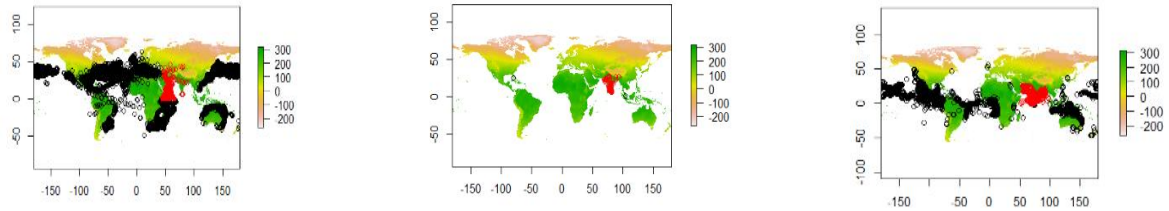


a. C. caretta **b. G.elegans** **c. L.olivacea**

Figure 2 (a, b, c): The bar graph illustrating relative significance of several bioclimatic variables on the distribution model of three vulnerable Reptile species under RCP 4.5 in 2050.

Current and Future Distribution

Following is the current distribution of Reptilian species on global map, red filled circles are representing three vulnerable species C. caretta, G.elegans and L.olivacea in Indian sub-continent specifically with reference to Pakistan.

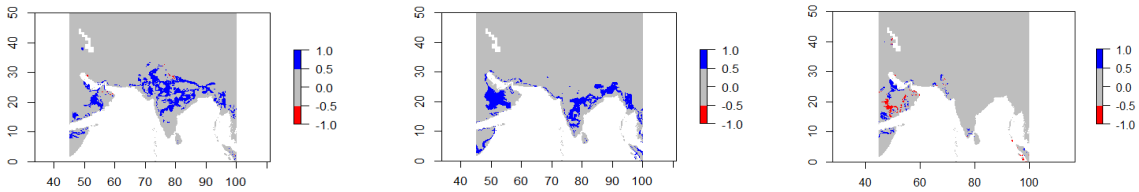


a. C. caretta **b. G.elegans** **c. L.olivacea**

Figure 3 (a, b, c): Current distribution for C. caretta, G. elegans, and L. olivacea is displayed on a world map. Known occurrences of species are shown by red marked areas.

The following figures (4a-c) showed spatial grid map involving spatial geography in the form of map grid and statistical outcome as binomial distribution. Such maps visualize binary data e.g. presence/absence or success/failure of species used in analysis. The spatial grid map displayed Indian subcontinent and surrounding south/southwest Asian regions. Coordinates representing Longitude (East) in the right corner along x-axis and Latitude (North) along y-axis. In the center of the grid India pointing down into the Indian Ocean, to the west is Arabian Sea and Arabian Peninsula and to its right (east) is the Bay of Bengal and parts of Southeast Asia.

In the first map (a), predicted presence or absence of C. caretta in 2050 under RCP 4.5 was shown. Areas with blue color reflects positive values depicting species increase or presence and is found across the Indo-Gangetic Plains, Central Indo-Pak, parts of Pakistan's Indus Basin, and coastal margins. Areas with red color reflects negative values depicting species decrease or absence. There are tiny sparse pockets appearing along the northern Himalayan borders and the western coastlines of Pakistan (Figure 4a). The light grey area represents land zones where the data is either neutral, zero, or does not meet the threshold for statistical significance. In second map (b), predicted presence or absence of G. elegans in 2050 under RCP 4.5 was shown. Areas with blur color shifted far towards west, there were only tiny fragments of blue remaining near the southern tip of Indo-Pak and along the coastlines of Pakistan. The blue band tightly wraps around the red cluster. Areas with red color describing species decrease or absence and lies toward southern portion (Figure 4b). In third map (c) predicted presence or absence for L.olivacea in 2050 under RCP 4.5 was shown. Area with blue significance is localized entirely to East and Northeast part with a distinct patch of blue right over Southeast. This colonization phenomenon is highly active in coastal, deltaic, or highly humid geographic zones. Area with red color is almost negligible except a tiny pixel or two in Southern Indo-Pak region (Figure 4c). It is suspected that temperature and moisture anomalies are heavily regulated by marine air masses—strongly impacting coastal zones and massive river basins while bypassing the dry continental interiors.

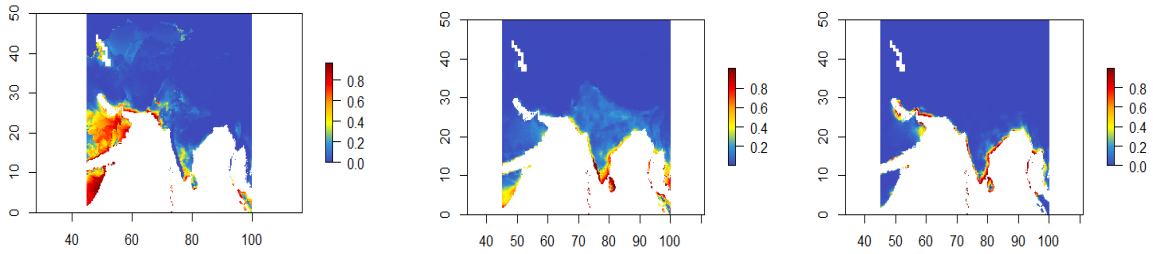


a. C.caretta **b. G.elegans** **c. L.olivacea.**

Figure 4 (a, b, c): Future distribution of three species' expected in 2050 under low carbon emissions scenario (RCP 4.5). Predicted distribution with blue areas (0.5 to 1) showing the expansion range of species while red color (-0.5 to -1) showing decline range of species in 2050.

Current habitat suitability

The SDM maps were read with a standard spatial orientation, with the horizontal X-axis representing longitude from 40° E to 100° E (west to east) and the vertical Y-axis representing latitude from 0° N to 50° N (south to north). Pakistan lies approximately between 24°N–37°N and 61°E–78°E in the center of the mapped region. Under the current habitat suitability, C. caretta distribution was revealed within the southern domain of Pakistan along Arabian Sea with moderate-to-high climatic suitability (~0.4–0.6) across the coastal and offshore waters of Sindh (including the Indus River Delta) and Balochistan along the Makran Coast. Core high-suitability hotspots (>0.7–0.8) extended westward and southwestward from the coastal waters of Pakistan to the marine areas of Oman, Yemen, and Iran (Figure 5a). G. elegans aggregated in the southern coastal habitat of Pakistan. High climatic suitability stretched around areas of northern Arabian Sea, the Indus River Delta and the adjacent coastlines of India and Iran (Figure 5b). L. olivacea showed high climatic adaptation centered in the coastal and marine regions of the northern Arabian Sea and the Indus Delta (Figure 5c).



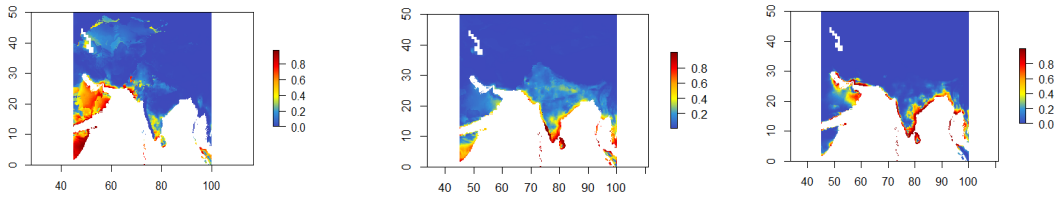
a. C.caretta **b. G.elegans** **c. L.olivacea.**

Figure 5 (a, b, c): Current suitable habitat; Using General Circulation Models (GCMs) to determine the current habitat appropriateness for three vulnerable species, values around 0.6-0.8 indicate good suitability.

Projected Future distribution and range shift

The SDM maps showed that climatic adaptability of three species would vary in different ways predicted for 2050 under RCP 4.5. The C. caretta would be available in secondary marine habitat on the offshore of coastlines of Sindh (Indus Delta) and Balochistan (Makran Coast). Moderate suitability (0.4–0.6) extended toward eastern marine waters whereas, core optimal habitats (0.6–0.8) moved primarily westward and southwestward toward the marine domains and few terrestrial regions of Pakistan (Figure 6a). G. elegans showed low-to-moderate suitability (~0.2–0.4) in southern and eastern Pakistan, especially in Sindh and Punjab, while ideal habitats (0.5–>0.8) would be expected in the eastward and southeastward into India (Figure 6b). L. olivacea, on the other hand, exhibited high climatic suitability (~0.5 to >0.8) along Pakistan's marine waters in southeast and southwest coastlines of Sindh and Balochistan (Figure 6c).

Future Habitat suitability



a. C.caretta **b. G.elegans** **c. L.olivacea**

Figure 6 (a, b, c). Using General Circulation Models (GCMs) to determine the Predicted distribution of three species in 2050 under RCP 4.5, values around 0.6-0.8 indicate good suitability.

DISCUSSION

The last 100 years have seen an intensification in the apparent global temperature of about 1.1°C due to carbon emissions. As a result, weather patterns have already changed and temperature extremes have observed in every part of the world (IPCC, 2021). Biodiversity and ecosystem functioning have already been negatively impacted by temperature change, and their consequences are going to worsen as warming continues (IPBES, 2019). Temperature changes may have a variety of impacts on animals as noted in the present study for three vulnerable species of Reptiles. This is in accordance with the work conducted by (Bowler et al., 2017), that climate change is affecting species distribution and abundance with numerous species moving theirs' span to upper latitudes and altitudes. However, idiosyncratic range adjustments are another way that some species react to temperature changes.

Few previous analyses showed, how temperature change affects vertebrate biodiversity especially the endotherms (birds and mammals). Despite making up one-third diversity of terrestrial vertebrates worldwide, Reptiles have received little attention (Pacifici et al., 2015). They are highly diversified in dry and semi-arid areas in Pakistan, indicating the fact that their distribution is influenced by environmental and evolutionary progressions, a bit different from other vertebrate taxonomic groups. The present study aligns future projections about their distribution pattern and habitat appropriateness for Testudines under carbon emission scenarios RCP 4.5 for year 2050 along with existing suitable habitats based on animal occurrence data.

For future projected distribution under RCP 4.5 climate scenario, probability of occurrence of C. caretta and L. olivacea was high towards eastern latitudes as compared to western side (Fig. 4a and 4c). In case of G. elegans only few pockets were depicting the species distribution range in the western latitude alongside of extinction patches in and around areas in western side (Fig. 4b). All species were expected to be affected by temperature changes in 2050 under RCP 4.5. A number of studies have shown that anthropogenic temperature change affects biological communities in a variety of ways, including phenology, distribution, and community interactions (Butler, 2003). According to Sekercioglu et al., (2008), anthropogenic temperature change may also increase the risk of extinction by affecting the space of suitable habitat range for a species. One of the biggest risks to reptile populations has been recognized as temperature change; species survival may depend not only on the climate's eventual persistence but also on their capacity to adapt to changing temperatures (Loarie et al., 2009). Additionally, invasive species, illnesses, overexploitation, habitat loss, predation, and climate change are some serious dangers that reptiles and especially the marine forms e.g. turtles face (Browne and Hecnar, 2007).

Being restricted range species and ectotherm, turtles and tortoises might not be able to adapt to anticipated temperature fluctuations (Gibbon et al., 2000) and face prominent physiological and behavioral changes as well as survival and reproductive success. Furthermore, in species with temperature-dependent sex determination (TSD), high temperatures might affect sex determination, resulting in distorted sex ratios and possible population reductions (Biber et al., 2023).

Research on the rainforest sunskink (Lampropholis coggeri) demonstrates a high degree of trait lability caused by local adaptation and acclimatization. This implies that in order to adapt to rising temperatures, certain tropical ectotherms may quickly change climate-relevant features (Llewelyn et al., 2018). In reaction to temperature fluctuations, sea turtles modify the time and location of their nests. Such behavioral adaptations aid in mitigating the impacts of temperature on embryo development and hatchling survival (Du et al., 2023) although it affects species on long term basis.

Reptile's habitat suitability may shift as a result of altered precipitation patterns brought on by temperature changes. An extended drought season may decrease water availability and affect animals that depend on wet settings of ambient environment. Resultantly, Reptiles' breeding and feeding habitats may change in result of changes in wetland water levels (Dayananda et al.,2021). Reptilian abundance and distribution are seriously obstructed by variations in rainfall patterns as observed in crocodile lizard (Shinisaurus crocodilurus), it might have their breeding grounds changed by variations in water levels, which leads to change in their population dynamics and reproductive success (Zhang et al., 2022).

In the present study, under the future climate scenarios, suitable habitat for C. caretta were predicted to be shifted to lower north latitude in 2050 due to climate variable Bio-09 i.e. average temperature of driest quarter. The suitable habitat of G. elegans was predicted to shift towards lower latitude of east in 2050 due to bioclimatic variable Bio-19 i-e precipitation of coldest quarter. Similarly suitable habitat for L. olivacea predicted to shift to lower latitude of east in 2050 due to bioclimatic variable Bio-01 i-e annual mean temperature. Moreover, the species dissemination, habitat liking and richness, all predicted

high in warm and moist regions, with these zone's being likely to swing more towards temperature extremes in future (Moore et al., 2018). The extent of occurrence (range size) was possibly to condense prominently in the forthcoming times, with a lesser degree of overlap between their current and future trends.

CONCLUSION

In future projected scenarios of high temperatures and reduced moisture (drought stress), the distribution of turtles and tortoises in Pakistan will experience habitat contraction which may result in forceful species away from arid lowlands toward fragmented refugia and marine costal lines for turtles and tortoises.

Conflict of Interests

The authors have no conflict of interests in the above manuscript.

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