Predicting habitat distributions for the endemic fish *Garra shamal* (Teleostei: Cyprinidae) in the Omani Hajar Mountain under present and future climate change scenarios using MaxEnt

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Abstract:
Climate change significantly influences ecological habitat and species distribution, which could accelerate the rate of species extinction or increase their vulnerability. The current study aimed to investigate the implications of climate change on *Garra shamal* (Teleostei: Cyprinidae), a vulnerable and endemic species found in Oman. The maximum entropy model (MaxEnt) in association with ArcGIS (10.8.2) was used to model climate change impacts under current and future projections on two representative concentration pathways (RCPs) (RCP2.6 and RCP8.5) for 1981-2010, 2011-2040, 2041-2070, and 2071-2100. The results revealed that the area under the curve (AUC) value of the training set is 0.991, indicating that the model's prediction was excellent. The contribution rates of Freshwater Ecoregions of the World, mean diurnal air temperature range (Bio2), terrain ruggedness index, sediment transport index, and precipitation seasonality (Bio15) of *Garra shamal* were 39.1%, 26%, 13.3%, 9.6%, and 8.2%, respectively. Compared to the current distribution, the total area of the medium-suitable habitat and the least-suitable habitat for *Garra shamal* under the two RCPs (RCP2.6 and RCP8.5) would increase by 1% in the 2011-2040 and 2041-2070. However, the total area of the high-suitable habitat under RCP2.6 in the 2071-2100 would decrease by 0.2% and increase by 0.3% under RCP8.5. Overall, the findings of this study provide insight for decision-makers to develop proactive strategies that could help reduce the consequences of climate change on *Garra shamal* and their habitats. This study recommends further exploration of the benefits of integrating scientific information for sustainable management, protection, and restoration of *Garra Shamal's* suitable habitat and other endangered species in Oman.

Key words: *Garra shamal*, MaxEnt, Habitat suitability, Climate change projection, Hajar Mountain, Oman

1. Introduction:

Freshwater species worldwide are facing significant declines, primarily due to habitat degradation brought on by human activities and partially attributed to accelerating climate change (Filipe et al., 2013; Tsang et al., 2021). Freshwater species and ecosystems are particularly vulnerable to the impacts of climate change, making them a serious concern (Harrod, 2015). Climate change, specifically alterations in temperature and precipitation, will impact the thermal and hydrological conditions of freshwater systems, leading to changes in fish composition within river systems (Tsang et al., 2021). As a result of climate change, species' geographic ranges are evidently shifting in longitude and latitude (Lenoir et al., 2010; Parmesan and Yohe, 2003; Yudaputra and Hutabarat, 2021).

Freshwater fish are considered both widely distributed and highly vulnerable, making them valuable indicators for assessing aquatic ecosystem changes. Monitoring their populations and behavior can provide insights into freshwater environments' health and quality (Yousefi et al., 2020). Climate change impacts fish directly through factors like metabolism and reproduction, as well as indirectly through changes in phenology, prey availability, predators, and competition (Harrod, 2015). To address the widespread degradation of freshwater ecosystems, efforts have been made to understand the complex relationships between human activities and these ecosystems, aiming to develop effective management and conservation strategies (Maloney et al., 2022). Species distribution models (SDMs) have become increasingly valuable tools in ecology and conservation biogeography for predicting and projecting species distributions over space and time, as well as managing potential spread (Jiménez-Valverde et al., 2011; Khajoei Nasab et al., 2020; Yudaputra and Hutabarat, 2021). SDMs utilize climate data as predictors to estimate the similarity between observed conditions and conditions at other locations, assisting in the prediction of species range (Hijmans and Elith, 2021). This modeling approach is effective in assessing the potential impact of future climate change on species (Beaumont et al., 2008; Garcia et al., 2012; Schwartz, 2012).

According to Albouy et al. (2013), climate change will result in diminished habitats for 54 species of fish in the Mediterranean Sea; they studied the implications on 288 fish species by using SDMs. Research by Yousefi et al. (2020) revealed that five species in Iran will lose some of their existing acceptable ranges due to climate change, while ten other species will acquire new suitable habitats.

Garra shamal, (Fig 1) a vulnerable species of cyprinid fish native to the Arabian Peninsula, is found exclusively in the northern region of Oman in wadis originating from the Hajar mountain range and extending to the Oman sea coast, both east and west of Muscat (Esmaeili et al., 2022; Freyhof et al., 2021; Kirchner et al., 2020). It stands apart from other Garra species in the Hajar Mountains due to the lack of prominent black middle caudal-fin rays with white membranes (Al Jufaili et al., 2022; Esmaeili et al., 2022). This fish thrives in various habitats such as mountain wadis, pools, streams, falaj systems, and springs, preferring stagnant or slow-flowing water with a gravel or bedrock bottom. Their diet primarily consists of periphyton and detritus. This species faces conservation challenges due to its limited range and the impact of human activities. It is particularly vulnerable to water overuse, pollution, and climate change, leading to the loss of multiple individual populations (Freyhof et al., 2021). Consequently, it is crucial to comprehend how climate change affects freshwater fish distribution in Oman, using innovative and efficient tools such as Species Distribution Models (SDMs), to ensure the successful conservation of native fish species in their natural habitats.

Freshwater fish hold significant ecological, economic, social, and aesthetic value in many countries. They play a crucial role in environmental policy as indicators of biological diversity and ecological quality. Fish have been successfully employed in various studies, including biogeographical and evolutionary research, assessments of ecoregions, conservation evaluations, and the development of water management plans that prioritize ecological well-being (Economou et al., 2007; Esmaeili et al., 2022). Thus, understanding the diversity, distribution, and conservation of freshwater fish species in different water bodies is necessary. Therefore, MaxEnt (Maximum entropy modeling) was used in this study to explore the environmental factors that influence the distribution of the endemic fish *Garra shamal* in the Hajar Mountain ecoregion using relevant environmental variables and species occurrence data. Furthermore, a predictive assessment has been made of the potential impact of climate change on habitat suitability under RCP 2.6 and RCP 8.5 climatic scenarios. Providing this information will aid in the conservation of *G. shamal* and their natural habitats.

Figure 1*: *Garra shamal

2. Materials & Methods

2.1 Study area

The study area is located in Hajar Mountain, which is a vast mountain chain that stretches along Oman's northern coast and a small portion of the UAE's. This chain is divided into three distinct blocks: Western Hajars, Jebel Akhdar, and Eastern Hajars (Burriel-Carranza et al., 2022; Carranza et al., 2021; Monks et al., 2019). The mountain range and its surrounding areas are covered with limestones, dolomites, and partially metamorphosed clastic deposits and cherts (Wheater and Bell, 1983). In spite of their arid climate, the Hajar Mountains are climatically atypical in southeastern Arabia (Burriel-Carranza et al., 2022; Carranza et al., 2021). A diversity of ecological niches, high elevations, deep canyons, and geography make Hajar Mountain an ideal location for locating endemic species of animals and plants (Burriel-Carranza et al., 2022; Carranza et al., 2021; Monks et al., 2019). The Oman Mountains are considered one of the freshwater ecoregions (ID 443) by the World Wildlife Fund for Nature (WWF) (Abell et al., 2008). Despite low and infrequent rainfall in the Hajar mountain range, there are numerous spring-fed streams called wadis (Burt, 2003). In these mountains, rainwater accumulates in underground aquifers and, in some places, runs over the ground surface as small lakes or small creeks (Al Barwani and Helmi, 2006). Fish species are found in this freshwater body, such as wadis, pools, streams, falaj systems, and springs (Freyhof et al., 2021).

2.2 Species occurrence data

In this study, a total of 21 localities for *Garra shamal* were gathered from databases originating from previous field sampling in the Hajar mountain ecoregion, the Global Biodiversity Information Facility (Lane and Edwards, 2007), and available published data (Esmaeili et al., 2022; Freyhof et al., 2021; Kirchner et al., 2020) (See Fig 2). The data were cleaned by removing duplications, removing spatial autocorrelation using ArcGIS's Species Distribution Model Toolbox 2.0 (Brown, 2020) between points, and removing outliers from the study area. To keep maximum records, occurrence data were kept 5 km apart (Elith et al., 2010; Mostafavi et al., 2014).

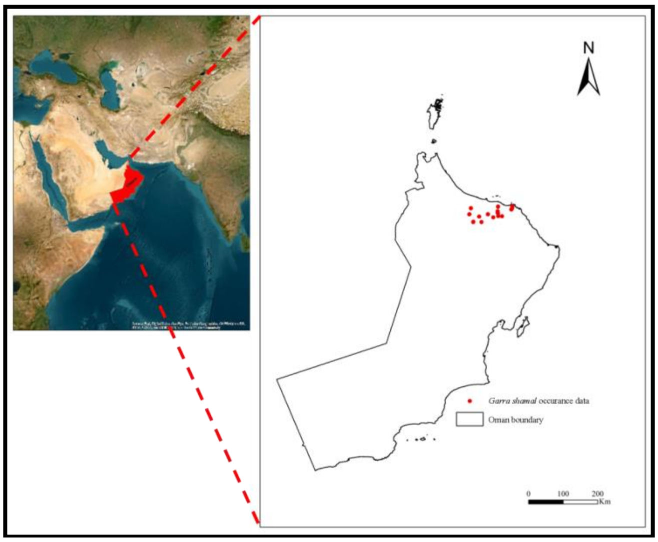

Figure 2. Occurrence data distribution for *Garra shamal*.

2.3 Environmental data

Several environmental factors that vary over different geographical scales have a significant impact on the distribution ranges of freshwater fish (Buisson et al., 2008; Panja et al., 2021). Based on ecological and life-history characteristics, environmental predictors were categorized by climate, topography, and hydrology classes with a desired spatial grain (30 arcsec~1 km) (Domisch et al., 2015). These variables were used to create a predictive model to identify areas of suitable habitat for *Garra shamal* (see Table 1).

2.3.1 Climatic Variables

The bioclimatic variables were derived from CHELSA V2.1 (Climatologies at high resolution for the earth's land surface areas), which is a global climate downscaled data set at very high resolution (30 arc sec, ~1 km). It was built to provide easy access to high resolution climate data for research, and it is constantly being updated and refined. CHELSA's climate data (time period: 1979–2013) is hosted by the Swiss Federal Institute for Forest, Snow, and Landscape Research WSL (Karger et al., 2017). To predict future *Garra shamal* suitable habitat distributions, climatic data from the following general circulation models (GCMs) were used. The selection is based on the models given by the Intersectoral Impact Model Intercomparion Project (ISIMIP) (Karger and Zimmermann, 2019). The optimistic and pessimistic scenarios (RCP 2.6 and RCP 8.5) were used to assess the potential effect of climate change on the geographic distribution of *Garra shamal* over the periods 1981-2010, 2011-2040, 2041-2070, and 2071-2100. Moreover, variables redundancy within the nineteen bioclimatic variables were tested by the Pearson Correlation Matrix (r). Using the threshold ($r>|0.7|$) the highly correlated variables were excluded to avoid co-linearity according to our expert judgment and available scientific literatures (Guisan et al., 2017; Yousefi et al., 2020). According to Gardner et al. (2019), temperature, precipitation, and seasonality are the most significant environmental predictors of species distributions. Therefore, three variables were derived from this procedure: mean diurnal air temperature range (Bio2), annual precipitation amount (Bio12), and precipitation seasonality (Bio15).

2.3.2 Geophysical Variables

Garra shamal's habitat features are described by nine variables describing topography, soil, and hydrology (see Table 1). That included the digital elevation model (DEM) which is an invaluable tool for comprehending the physical properties of a specific given area. Based on the obtained DEM, the slope (SL), topographical wetness index (TWI), flow accumulation (FA), sediment transport index (STI), stream power index (SPI), and terrain ruggedness index (TRI) (Panja et al., 2021) were calculated using ArcGIS (10.8.2) (Environmental Systems Research Institute, 2020). The ecoregion layer was obtained from the WWF-FEOW database. This data is particularly crucial for identifying and locating ecological hotspots, which are areas with a large concentration of species or habitats. It can also be used to forecast how changes in the climate would affect the distribution of species (Abell et al., 2008). The soil layer (Leanza et al., 2022) was downloaded from the HWSD, or Harmonized World Soil Database, developed by the Food and Agriculture Organization (FAO). The HWSD is the most comprehensive global dataset of soil properties, and it is updated regularly. It is widely used in environmental studies and land management (FAO and ISRIC, 2012; Fischer et al., 2008).

Table 1: List of predictor variables selected for the *Garra shamal* species distribution model

Categories	Sub-categories	Name of the variables	Unit	Source
Climatic variables	Bio-climatic variables	Mean diurnal range (Bio2)	°C	CHELSA-Climatologies at high resolution for the earth's land surface areas (Karger et al., 2017)
		Annual precipitation (Bio12)	mm	
		Precipitation seasonality (Bio15)	mm	
Geophysical variables	Topography	Elevation (DEM)	m	WorldClim 2.1 elevation data (Fick and Hijmans, 2017)
		Slope (SL)	m	User creation
	Soil	Soil layer	NA	Harmonized World Soil Database v 1.2 (FAO and ISRIC, 2012)
	Hydrology	Freshwater Ecoregions of the World (FEOW)	NA	WWF-FEOW database (Abell et al., 2008)
		Flow accumulation (FA)	m	User creation
		Topographical wetness index (TWI)	NA	User creation
		Sediment transport index (STI)	NA	User creation
		Stream power index (SPI)	NA	User creation
		Terrain ruggedness index (TRI)	NA	User creation

2.4 Distribution modeling

In this study, the possible habitat distribution of the *Garra shamal* in the Northern Hajar Mountain ecoregion was analyzed and mapped using MaxEnt (Maximum entropy modeling) version 3.4.4 (Philips et al., 2021), both in the present (1981-2010) and in the future (2011-2040, 2041-2070, and 2071-2100). The MaxEnt algorithm computes the probability of occurrence based on random background points and records of the species presence. Furthermore, based on climatic, geophysical, and species-specific factors, the model forecasts species' capacity to colonize new environments. The MaxEnt algorithm supports both continuous and categorical variables, and regularization parameters can be used to control overlaps (Phillips et al., 2006). Furthermore, one of MaxEnt advantage is, its capacity to produce a reliable model even with a small sample size (Al Ruheili et al., 2021; Panja et al., 2021; Pearson et al., 2007; Yousefi et al., 2020).

2.5 Model performance

The performance of the *Garra shamal* distribution model was evaluated using the area under the Receiving Operator Characteristic (ROC) curve (AUC) and Jackknife test. MaxEnt uses AUC to assess the model's performance, which is an excellent indicator of the model's effectiveness. In addition, AUC model performance is assessed using ROC thresholding, allowing users to assess the model's performance at different thresholds (Prabhulinga et al., 2017). This helps to identify the most effective threshold for their application (AUC suitability index ranges from 0 to 1) (Swets, 1988). Using the AUC model, performance is evaluated according to five categories: not suitable (0.5–0.6), low suitability (0.6–0.7), moderate suitability (0.7–0.8), suitable (0.8-0.9), highly suitable (0.9–1) (Al Ruheili et al., 2021; Prabhulinga et al., 2017). Models with AUC values closer to 1 perform well. Low AUC values close to 0.5 are therefore considered unreliable, and vice versa (Guisan and Thuiller, 2005; Phillips et al., 2006). Due to that, this study used Jackknife tests to assess model performance for the potential distributions of *Garra shamal* (Li et al., 2016).

3. Results:

3.1 Model performance

The average training AUC for the 20 replicate runs was 0.991, with a 0.003 standard deviation. The results indicate a high performance of the model for predicting the potential distribution of *Garra shamal* (Fig 3). The jackknife test was used to assess each variable's contribution to the overall model's performance. The test showed that the variables: Freshwater Ecoregions of the World (FEOW), mean diurnal range (Bio2), and terrain ruggedness index (TRI) were the most important variables. Whereas, sediment transport index (STI), annual precipitation (Bio12), and precipitation seasonality (Bio15) had moderate gains, remaining variables had less or no gains (Fig 4). In isolation, Freshwater Ecoregions of the World (FEOW) has the highest gain, indicating that it has the most useful information.

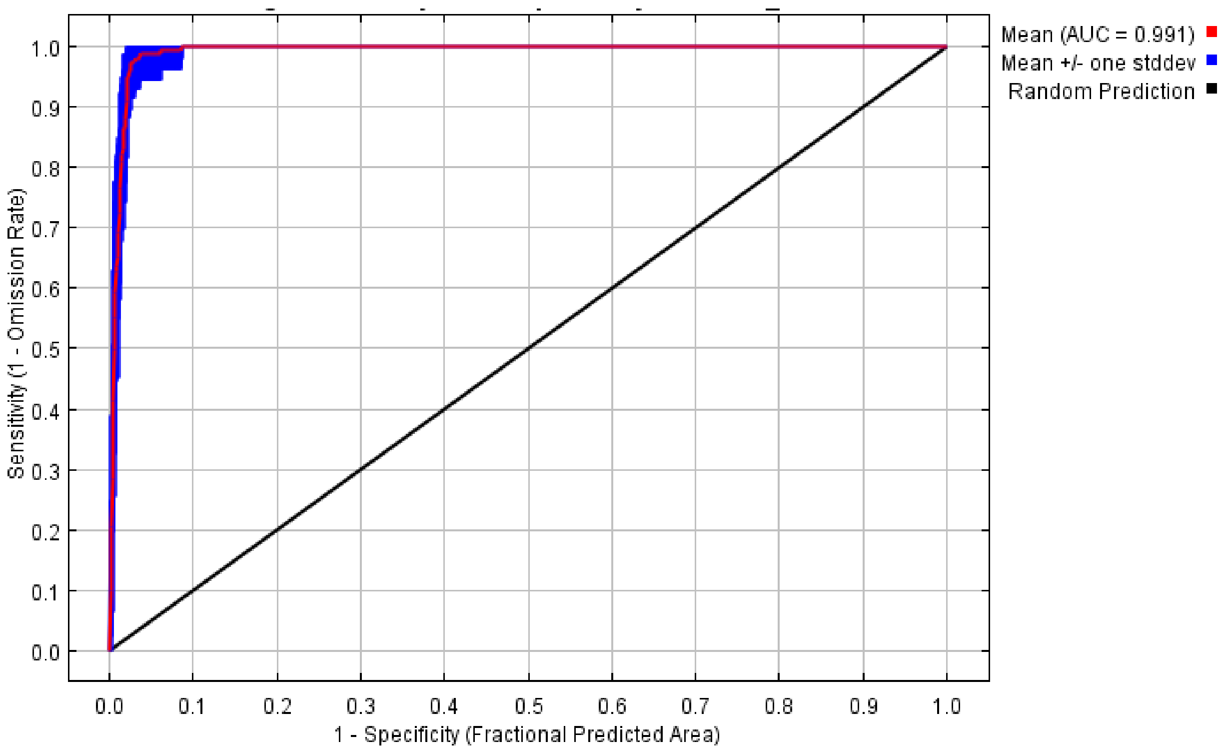

Figure 3: Receiver operating characteristic curve for *Garra shamal* model

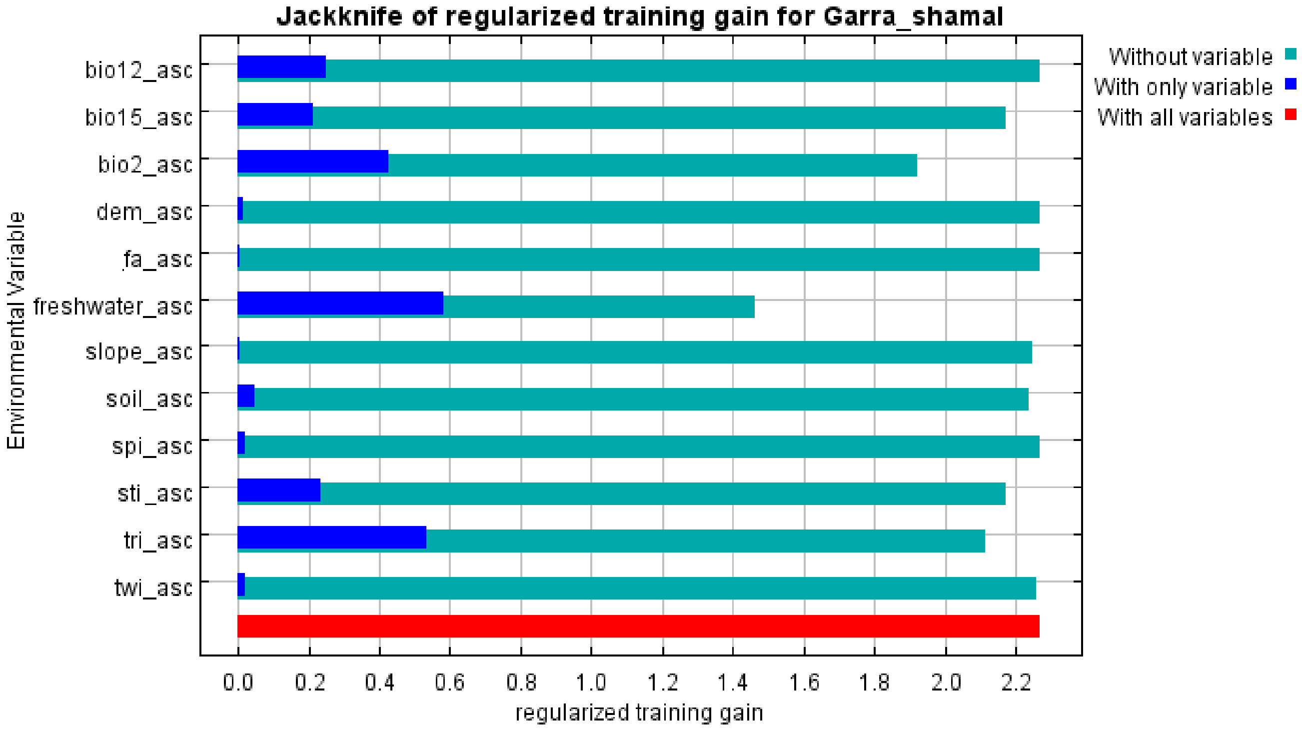

Figure 4: The relative importance of 12 predictive variables based on Jackknife tests in MaxEnt.

3.2 Variables contribution

The percentage contribution indicates how much each variable contributes to the MaxEnt model, while permutation importance is determined by observing how varying the predictors' values affects the AUC (Songer et al., 2012). Based on Table 2, the Freshwater Ecoregions of the World (FEOW) and mean diurnal range (Bio2) play the highest roles, contributing 39.1% and 26%, respectively. The terrain ruggedness index (TRI), sediment transport index (STI), and precipitation seasonality (Bio15) also have relatively high contributions at 13.3%, 9.6%, and 8.2%, respectively. In comparison, soil, slope (SL), topographical wetness index (TWI), stream power index (SPI), flow accumulation (FA), annual precipitation (Bio12), and elevation (DEM) contribute much less and have much lower permutation importance. According to these findings, the FEOW and Bio2 are critical variables in predicting the distributions of *Garra shamal*, while other variables play a lesser role.

Table 2: Percent contribution and permutation importance of the environmental variables used in the MaxEnt model.

Variables are listed in order of highest to lowest percentage contribution.

Variables	Percentage contribution	Permutation importance
Freshwater Ecoregions of the World (FEOW)	39.1	65.2
Mean diurnal range (Bio2)	26	16
Terrain ruggedness index (TRI)	13.3	5.8
Sediment transport index (STI)	9.6	2.4
Precipitation seasonality (Bio15)	8.2	6.6
Soil	1.5	1.4
Slope (SL)	1.2	0.3
Topographical wetness index (TWI)	0.6	0.2
Stream power index (SPI)	0.3	0.1
Flow accumulation (FA)	0.1	0
Annual precipitation (Bio12)	0.1	0.7
Elevation (DEM)	0	1.4

3.3 Response of variables to the suitability

Garra shamal's current and projected habitat suitability under RCP 2.6 and RCP 8.5 climate change scenarios are spatially shown in Figs 5 and 6. The amount of increase or decrease in each category is discussed in Tables 3 and 4.

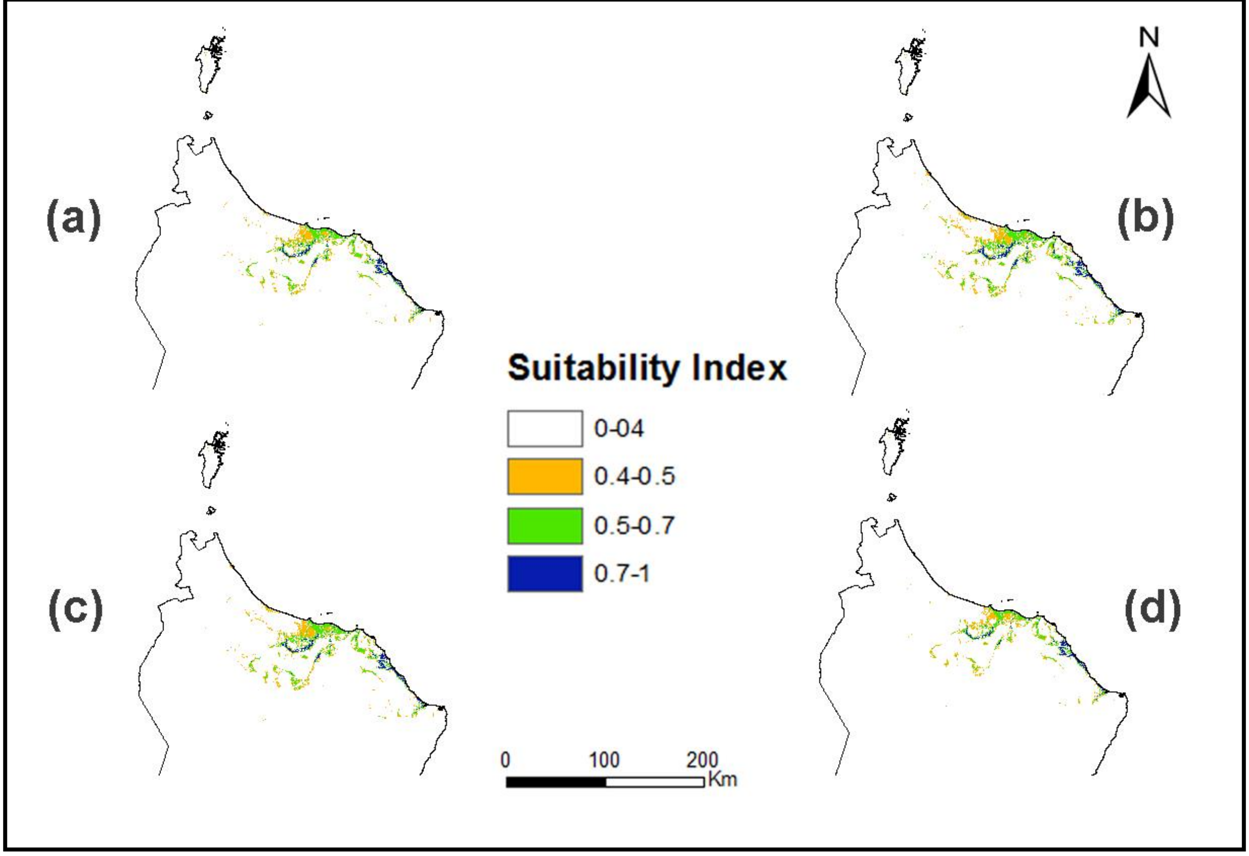

Figure 5: Predicted habitat suitability for *Garra shamal* under current and future climate change scenarios in RCP 2.6 for the Hajar Mountain ecoregion in Oman for the periods (a) 1981-2010, (b) 2011-2040, (c) 2041-2070, and (d) 2071-2100. The orange (0.4–0.5) and navy blue (0.7–1.0) indicates *G. shamal's* low and high suitability areas, respectively.

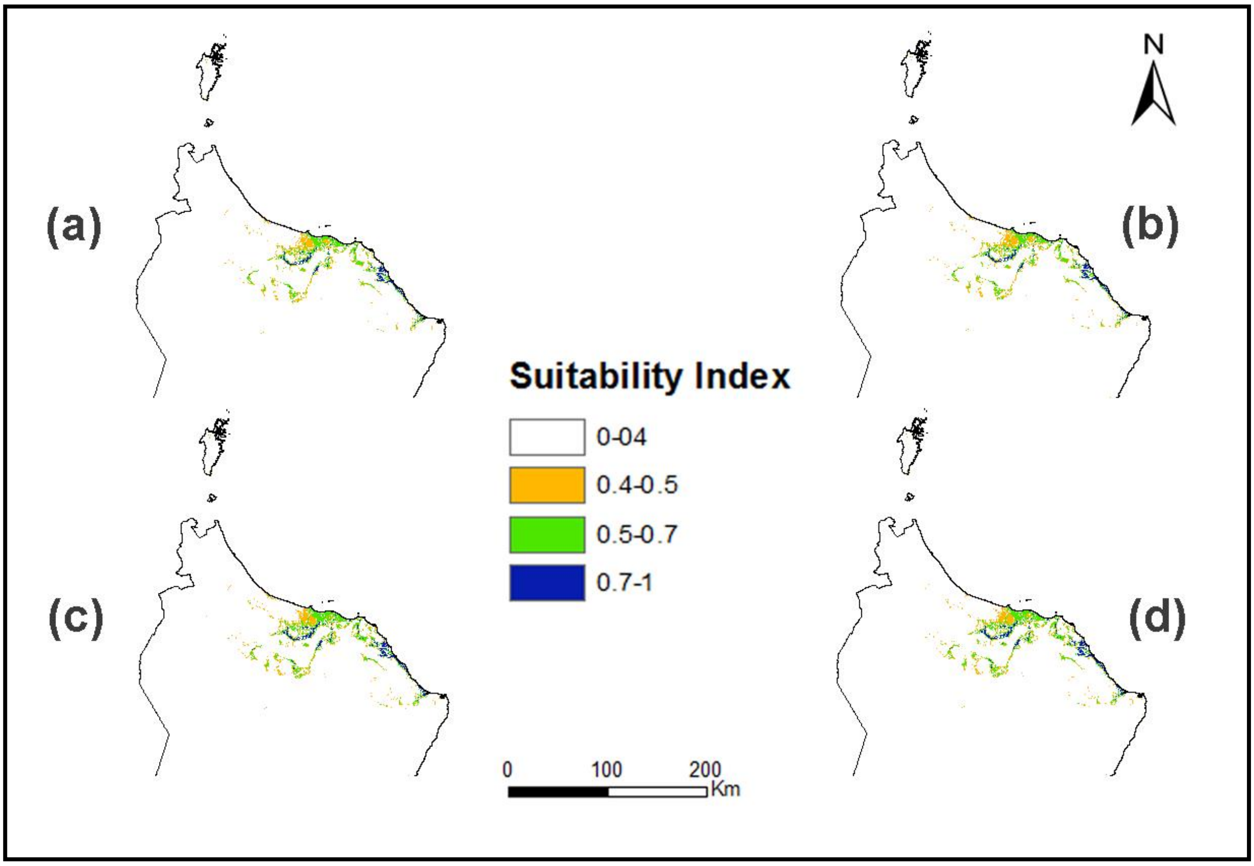

Figure 6: Predicted habitat suitability for *Garra shamal* under current and future climate change scenarios in RCP 8.5 for the Hajar Mountain ecoregion in Oman for the periods (a) 1981-2010, (b) 2011-2040, (c) 2041-2070, and (d) 2071-2100. The orange (0.4–0.5) and navy blue (0.7–1.0) indicates *G. shamal's* low and high suitability areas, respectively.

Tables 3 and 4 present the predicted suitable areas for *G. shamal* under two different climate scenarios, RCP 2.6 and RCP 8.5, across various time periods, 1981-2010 (baseline/ current), 2011-2040, 2041-2070, and 2071-2100. In both scenarios, the predicted areas are measured in square kilometers (km2) and classified into four suitability categories: Absent (AB), Low-suitability (LS), Medium-suitability (MS), and High-suitability (HS), based on a suitability score ranging from 0 to 1. Compared to the current distribution, the total area of the medium-suitable habitat (MS) and the least-suitable habitat (LS) for *Garra shamal* under the two RCPs (RCP2.6 and RCP8.5) would increase by 1% in the 2011-2040 and 2041-2070. However, the total area of the high-suitable habitat under RCP2.6 in the 2071-2100 would decrease by 0.2% and increase by 0.3% under RCP8.5.

Based on Table 3, we can see that the rate of increase/decrease (%) of the predicted area for *Garra shamal* is expected to increase slightly in the first two future periods (2011-2040 and 2041-2070) in comparison to the baseline period for the classifications LS and MS by 0.31%, 0.20%, 0.12%, and 0.08%, respectively. By contrast, in the last period (2071-2100), the predicted area is expected to decrease by -0.15% and -0.09%, respectively. On the other hand, the rate of increase/decrease (%) compared to 1981-2010 of the predicted area for *Garra shamal* under RCP 8.5 (Table 4) for the classification LS would decrease by -0.01%, -0.44%, -0.35% in 2011-2040, 2041- 2070, and 2071-2100, respectively. For MS, the rate is expected to rise by 0.23% and 0.16% in 2041-2070 and 2071-2100, respectively. HS classification would increase in 2041-2070 and 2071-2100 by 0.13%, 0.12%, respectively.

Table 3: Predicted suitable areas for *Garra shamal* in future Climatic Conditions (RCP 2.6)

Scenarios								
Period	**Predicted area (km^2)**				**Rate increase/decrease (%) compared to 1981-2010**			
	AB	**LS**	**MS**	**HS**	**AB**	**LS**	**MS**	**HS**
1981-2010	4200698	25110	20980.8	10788	NA	NA	NA	NA
2011-2040	4174435	38260.2	29667	15214.8	-0.62	0.31	0.20	0.10
2041-2070	4190989	30392.4	24198.6	11997	-0.23	0.12	0.08	0.03
2071-2100	4213030	18916.2	16981.8	8649	0.29	-0.15	-0.09	-0.05

Table 4: Predicted suitable areas for *Garra shamal* in future Climatic Conditions (RCP 8.5)

Scenarios								
Period	**Predicted area (km^2)**				**Rate increase/decrease (%) compared to 1981-2010**			
	AB	**LS**	**MS**	**HS**	**AB**	**LS**	**MS**	**HS**
1981-2010	1981-2010	4200698	25110	20980.8	10788	NA	NA	NA
2011-2040	2011-2040	4200122	24849.6	21743.4	10862.4	-0.01	-0.01	0.02
2041-2070	2041-2070	4182043	34726.2	26579.4	14229	-0.44	0.23	0.13
2071-2100	2071-2100	4185595	31973.4	25909.8	14098.8	-0.35	0.16	0.12

4 Discussions:

The present study is the first of its kind to use MaxEnt modeling to integrate spatial and temporal data on the range and habitat of the endemic freshwater fish *Garra shamal* in the Hajar mountain ecoregion of Oman. This data is used to assess the fish's status and predict the fish's needs for conservation under climate change. The MaxEnt model has gained popularity in the fields of ecology and conservation biogeography as an effective tool to forecast the distribution of species over time and space (Fourcade et al., 2014).

The model yielded an excellent AUC value of 0.991, indicating a high performance of the model for predicting the potential distribution of *G. shamal* which is of parallel output to other MaxEnt applications worldwide (Maloney et al., 2022; Panja et al., 2021; Yousefi et al., 2020; Zhang et al., 2021). Moreover, this model was most influenced by the geophysical variable Freshwater Ecoregions of the World (FEOW) by a 39.1% percentage contribution. Maloney et al. (2013) and Panja et al. (2021) suggest that freshwater fish in streams are often restricted to ecoregion boundaries due to broad biogeographical trends and the size of aquatic systems. Oman faces the potential threat of amplified average temperatures, reduced precipitation, desertification, and an elevation in sea level as a result of the adverse effects of climate change. These climatic changes are expected to increase temperatures and reduce rainfall, thus stressing limited freshwater resources, including their quantity and quality. Furthermore, it has been predicted by Ahmed and Choudri (2012) that the water resources in Oman, as an arid and semiarid region, will experience a decrease due to the effects of climate change. The results of this study are in line with this statement. The mean diurnal range (Bio2) came second after (FEOW) and critically contributed to the distribution of *G. shamal* followed by the terrain ruggedness index (TRI), sediment transport index (STI), and precipitation seasonality (Bio15) at rates of 26%, 13.3%, 9.6%, and 8.2%, respectively.

The results of the MaxEnt modeling in Tables 3 and 4 have provided a predictive assessment of the potential impact of climate change on habitat suitability of *G. shamal* under RCP 2.6 and RCP 8.5 climatic scenarios that revealed few similarities between the two RCPs at different predicted suitable areas. It is predicted that under the two RCPs, medium-suitable habitat and the least-suitable habitat for *Garra shamal* will experience a 1% expansion during the periods of 2011-2040 and 2041-2070 in comparison to the present distribution. During the time span of 2071-2100, it is projected that the overall area of high- suitable habitat will decrease by 0.2% and increase by 0.3% under RCP2.6 and RCP8.5, respectively. These observed trends might be due to the uncertainties associated with the spatial resolution of the input data for the environmental variables selected for this study. The bioclimatic variables attained from CHELSA were of coarse resolution-which-might result in overestimation of habitat suitability or omission of small scale features leading to underestimation. Nevertheless, this study, by analyzing the selected 12 environmental variables, highlights the current and future distributions. This will aid in the conservation of *G. shamal* and its natural habitats.

In conclusion, *Garra shamal*, like other freshwater fishes in Oman, has conservation challenges and concerns due to its limited range and the impact of human activity. It is particularly vulnerable and sensitive to water overuse, pollution, and climate change, leading to the loss of multiple individual populations (Freyhof et al., 2021). Consequently, it is crucial to comprehend how climate change impacts freshwater fish distribution in Oman, using innovative, cutting-edge, and efficient tools such as Species Distribution Models (SDMs), in order to successfully conserve native fish species in their natural habitats. This research proposes further investigation into the benefits associated with the integration of scientific knowledge for the sustainable management, protection, and restoration of *Garra Shamal's* appropriate habitat and other endangered species in Oman.

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Conflicts of interest:

The authors have declared that they have no potential conflicts of interest concerning the research, authorship, and/or publication of this article.

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