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MaxEnt-based Habitat Suitability Modeling of *Tor tor* (Hamilton 1822) under Climate Change Scenario in Arunachal Pradesh, India

RANJIT MAHATO[1], SANTOSHKUMAR ABUJAM[2], BIKASH JYOTI GAUTAM[3], OYI DAI NIMASOW[4], BIKUL BARMAN[5], GIBJI NIMASOW[1*] AND DEBANGSHU NARAYAN DAS[2]
[1]Department of Geography, [2]Department of Zoology, [4]Department of Botany, Rajiv Gandhi University, Arunachal Pradesh, India
[3]Department of Geography, Cotton University, Assam, India
[5]Department of Geography, Bhattadev University, Assam, India
E-mail: ranjit.mahato@rgu.ac.in, santoshabujam@gmail.com, bjgautam123@gmail.com, oyidai.nimasow@rgu.ac.in, bikulbarman@gmail.com, gibji.nimasow@rgu.ac.in, dndas2011@gmail.com
***Author for correspondence**

ABSTRACT

The Indian Himalayan Region is home to numerous freshwater fish species, while wild stock is declining at an alarming rate due to human interventions and the impact of climate change. Arunachal Pradesh has a variety of fish habitats with a high degree of endemism. Species distribution models predict the probable species distribution under current and future climatic conditions. Hence, an attempt has been made to predict the habitat suitability of *Tor tor* in the drainage systems of Arunachal Pradesh (current and future). The study used the Maximum Entropy technique with seven environmental variables and 40 species occurrence records. The model performance was consistent with an area under the ROC curve of 0.97 and true skill statistics of 0.889. The species distribution was highly influenced by flow accumulation, elevation, and minimum temperature of the coldest month. The model showed a total river length of 815.62 km as very high and 814.74 km as high suitable habitat of *T. tor* in the mid-altitude and lower reaches of the major rivers like Kameng, Subansiri, Siang, Lohit, and Tirap under the current climate. The results of future climate (SSP245 and SSP585) showed a significant gain in the high and very high suitable categories with a shift of suitable habitat towards the northern parts. The findings could help to formulate conservation strategies for *T. tor* under climate change scenarios.

Key words: Species distribution modeling; MaxEnt; Climate change; Conservation.

INTRODUCTION

Mountain ecosystems provide vital public goods and services, including freshwater, food, medicinal resources, energy, rich biodiversity, and traditional knowledge (Tewari et al. 2017). However, the rich biodiversity of the Himalayan region faces significant threats due to the impacts of climate change (Ahmad et al. 2023), and the human influence on biotic elements is also accelerating (Mooney et al. 2009). Any alteration of the natural ecosystem threatens biodiversity and influences global food production (Malhi et al. 2020). Aquatic ecosystems are sensitive to climate change, with projected extinction rates for aquatic biodiversity surpassing those of terrestrial species in the current and future scenarios (Huang et al. 2021). Climate change, rapid land use changes, habitat alteration, pollution, nutrient enrichment, hydrological modifications, invasive species introductions, and rising ultraviolet (UV) radiation levels present significant challenges to aquatic ecosystems (Prakash 2021). Climatic parameters fundamentally regulate ecosystem distribution, species ranges, and the rate of Earth's natural processes (Grimm et al. 2013). In addition to the alteration of species distribution, climate change also disturbs the web of interaction in communities, including phenological shifts (Mooney et al. 2009). The Eastern Himalayas of India are known to have a vast network of freshwater systems with exclusive species diversity (Panja et al. 2021a). However, species diversity in freshwater ecosystems is declining at an alarming rate due to various factors, including changes in land use patterns, water pollution, overexploitation of fish resources, anthropogenic pressures, and shifting climatic conditions (Panja et al. 2021b). Arunachal Pradesh falls under the Himalayan biodiversity hotspot and constitutes a variety of habitats with a high degree of endemism (Gurumayum et al. 2016). *Tor tor,* commonly known as the mahseer or *Tor* barb, is a species belonging to the genus *Tor* (Pinder et al. 2019). It was first described by Hamilton (1822) from the Mahananda River, a tributary of the Ganges that flows through Northeast Bengal, India. The species belongs to the Cyprinidae family and is often called the "King of Indian freshwater systems." It holds significant commercial and recreational value, with high potential as a game and food fish (Yadav et al. 2012). Hence, the exploitation rate of *T. tor* is very high, resulting in a decreasing trend in the average size of the fish (Dwivedi and Nautiyal 2012). It prefers torrential streams/rivers with oxygenated water, rocky deep pools, gravel, small cascades, fast-flowing riffles, and reservoirs, and avoid icy water (Rayamajhi et al. 2018, Nautiyal and Dwivedi 2020). Species distribution models (SDMs) are emerging as important ecology, biogeography, and conservation sciences techniques. These models predict the possible geographic distribution of target species and quantify the relationship between environmental factors and the species distribution (Miller 2010, Hao et al. 2019). SDMs are used to delineate the potential distribution of species, mainly when well-designed survey data and relevant predictors are used in an appropriate model (Elith and Leathwick, 2009). SDMs are often called correlative or statistical models, habitat models, or ecological niche models. They can be broadly classified into correlative and process-based (or mechanistic) models (Srivastava et al. 2019). Many SDM techniques have been used to simulate the geographic distribution of species, such as BIOCLIM, DOMAIN, GARP, GLMs, and GAMs. Maximum Entropy (MaxEnt) is a popular SDM technique introduced by Phillips et al. (2006). It generates the suitable geographic distribution of a species using presence-only data in conjunction with environmental variables (Yuan et al. 2015). Additionally, MaxEnt can be used to project future

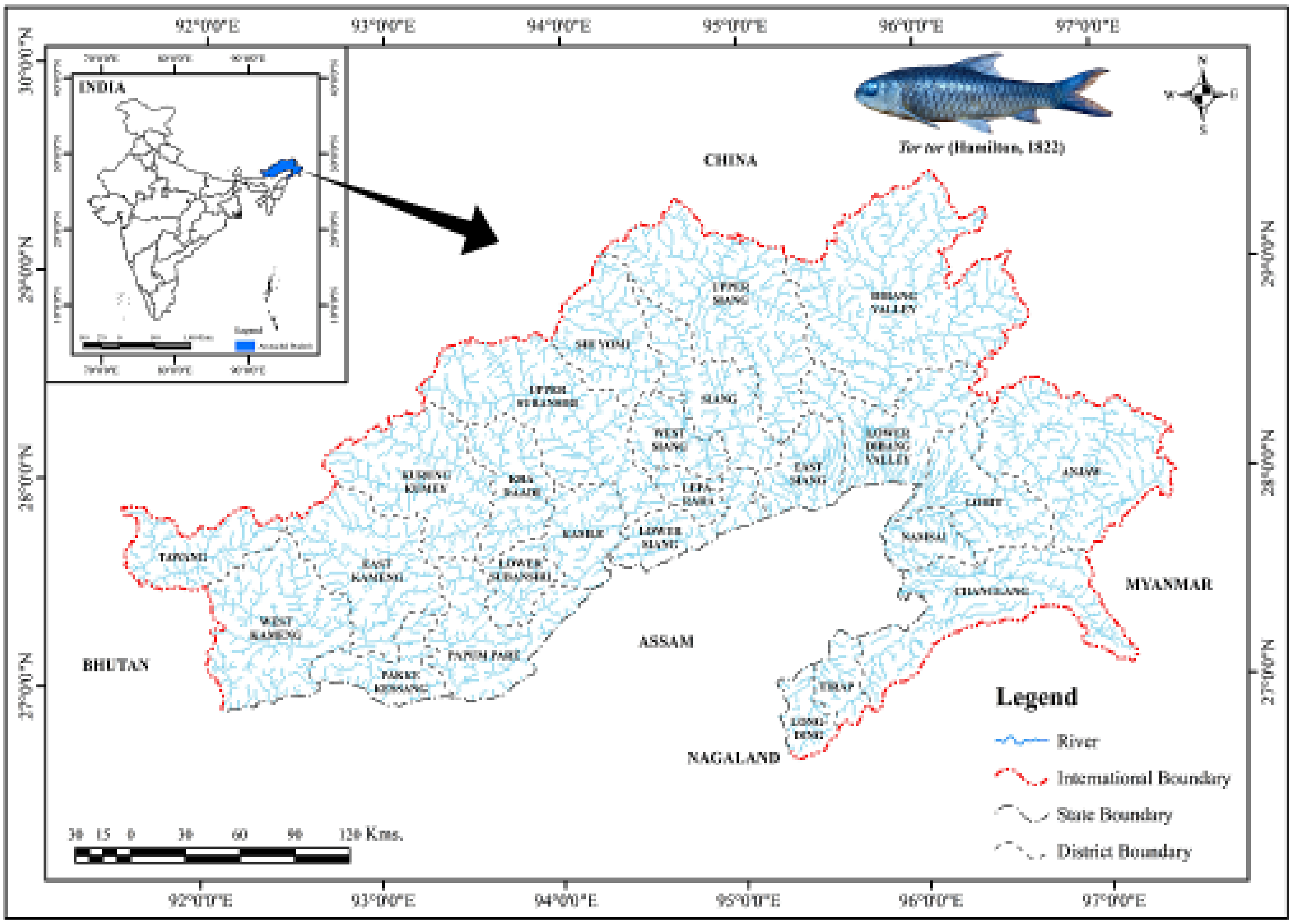


Figure 1. Location map of the study area

scenarios under climate change to predict habitat changes, which may be helpful in conservation measures (Abdelaal et al. 2019). Therefore, this study aims to predict the suitable habitat of *T. tor* under both current and future climate change scenarios.

MATERIALS AND METHODS

Study area

Arunachal Pradesh, the easternmost state of India, is home to a diverse range of ichthyofaunal species. *T. tor* is one of the native species of the state. Major rivers like Siang, Kameng, Dikrong, Subansiri, Lohit, Tirap, and various tributaries form the prime habitat of the target species. The state lies between 26°28' and 29°30' North latitudes and 91°30' and 97°30' East longitudes. Bhutan bounds it in the west, Tibet (China) in the north and northeast, Myanmar in the east and southeast, and Assam and Nagaland in the south (Fig. 1). It is the largest state of North East India, covering 83,743 km^2 of geographical area. The climate is hot and humid in the southern part and cold in the northern part, with heavy rainfall during the monsoon period. Various ethnic groups with diverse traditions and cultures inhabit the state.

Occurrence record of *T. tor*

The occurrence information of the species was gathered from both primary and secondary sources. The primary data were collected from various rivers in the state using a Global Positioning System (GPS) during field surveys conducted between 2021 and 2023. The fish was identified in the soil and limnological laboratory, Department of Geography and Ichthyologists of Rajiv Gandhi University. The secondary occurrence points were derived from the Global Biodiversity Information Facility (GBIF) using *the dismo* package in R (version 4.0.3) following Hijmans et al. (2011). Further, various published literature on the ichthyofauna of the state were consulted for additional occurrence records. Initially, 180 species location points were generated after removing the records with no coordinate information. We used a 1 km spatial distance as a snapping tolerance to snap occurrence records to the nearest drainage line, and the records that fell beyond this radius were removed. Further, the records with the same coordinate information and the information biases were removed using *the spThin* package in R with a spatial grid of 10 km, where the algorithm retained only a single record within the grid. Finally, 40 occurrence records were used to run the final model.

Selection of environmental variables

Environmental factors highly influence the distribution of fish species. Initially, we selected 23 environmental variables of ≈1km spatial resolution for the model. Among these, 19 bioclimatic and elevation layers were downloaded from https://www.worldclim.org. The flow accumulation, aspect, and slope were generated from the elevation layer to model the current distribution of *T. tor*. The Coupled Model Intercomparison Project Phase 6 (CMIP6) available in GeoTiff files for different global climate models (GCMs) and four Shared Socio-economic Pathways (SSPs) viz. 126, 245, 370 and 585 representing 2021-2040, 2041-2060, 2061-2080, and 2081-2100 were downloaded from https://worldclim.org/data/cmip6/cmip6_clim30s.html. We used the Max Planck Institute Earth System Model (MPI-ESM) 1-2-HR global climate model of SSP 245 and 585 for 2041-2060 to predict the future distribution of *T. tor* under climate change scenario.

Predictor data filtration, variable selection and model evaluation

Statistical models encounter multicollinearity issues due to high correlation among variables (Miller 2010). It negatively influences the model's performance and makes it challenging to interpret the relative importance of variables in the predictions (Dormann et al. 2012, Manzoor et al. 2018). Therefore, a correlation coefficient threshold of $|r| > 0.7$ between environmental variables is considered an appropriate indicator of multicollinearity (Dormann et al. 2012, Manzoor et al. 2018, Sony et al. 2018, Farrell et al. 2019, Feng et al. 2019). A variance inflation factor (VIF) is a tool that helps to identify the degree of multicollinearity, where a VIF value of >5 indicates that the selected independent variables have a multicollinearity problem (Saha et al. 2022, Arabameri et al. 2022). A multicollinearity test was performed using *the usdm* package in R (Naimi and Araújo 2016). The test returned eight variables with a correlation coefficient of $|r| < 0.7$

and VIF of less than 5 (Table 1). Further, a model test was performed, and six variables were retained based on the contribution percentage toward the model. The final model included the six variables and the elevation layer based on its importance towards the target species (Table 2). The performance of the final model was evaluated using the area under the curve (AUC) of the receiver operating characteristics (ROC) curve and true skill statistics (TSS). The values of AUC range from models with no predictive ability (AUC = ≤ 0.5) to models having perfect predictions (AUC = 1.0), where 0.9 – 1 = excellent; 0.8 - 0.9 = good; 0.7 - 0.8 = satisfactory; 0.6 - 0.7 = poor and <0.6 = very bad or model failed (Araujo et al. 2005, Lissovsky and Dudov 2021). The detailed workflow procedure is shown in Figure 2.

Table 1. Variance influence factor of remaining variables

Variables	**VIF**
Slope	1.41
Aspect	1.46
Flow accumulation	1.53
Bio_2: Mean Diurnal Range (Mean of monthly (max. temp – min. temp))	1.97
Bio_4: Temperature Seasonality (standard deviation ×100)	4.61
Bio_6: Min. Temperature of the Coldest Month	4.11
Bio_15: Precipitation Seasonality (Coefficient of Variation)	2.94
Bio_18: Precipitation of Warmest Quarter	2.05

Table 2. Variable contributions

Variables	**Contribution (%)**	**Permutation importance**
Slope	1.9	1
Aspect	1.2	0.5
Flow accumulation	70.4	28.1
Bio_4	0.7	0.9
Bio_6	11.1	67.6
Bio_18	0.8	0.2
Elevation	13.9	1.7

RESULTS

Model performance

MaxEnt (version 3.4.4) was used to model the current and future distribution of *T. tor* within the study area. The results reveal that the distribution of *T. tor* is mostly influenced by flow accumulation (70.4%), elevation (13.9%), and Bio_6 (11.1%). The rest of the variables, such as slope (1.9%), aspect (1.2%), Bio_18 (0.8%), and Bio_4 (0.7%), also exerted some influence on the distribution of *T. tor* in the study area. The model's performance was excellent, achieving a mean AUC of 0.970 (Fig. 3) and a TSS value of 0.889. The jackknife of regularized training gain and test also revealed that the model is highly influenced by flow accumulation followed by Bio_6 (Fig. 4a,b). Similarly, all the variables except the aspect were significant to the overall AUC of the model when using only the variables (Fig. 4c). Moreover, the AUC of the model showed slight fluctuation without the variables except flow accumulation.

Species distribution under the current climate

The suitability map of *T. tor* was classified into five classes, i.e., very high (>0.80), high (0.60 - 0.80), moderate (0.40 - 0.60), least (0.20 - 0.40), and not suitable (<0.20). Across the entire river network of 14,753.91 km, the model classified 815.62 km (5.53%) as highly suitable and 814.74 km (5.52%) as highly suitable. Further, it predicted 843.99 km (5.72%) as moderately suitable, 1,547.02 km (10.49%) as least suitable, and 10,732.54 km (72.74%) as unsuitable (Table 3). The model revealed that the majority of the streams/ rivers of the northern parts fall under the not suitable and least suitable. On the other hand, the mid-altitude and lower reaches of the major rivers like Kameng, Subansiri, Siang, Lohit, and Tirap showed very high and highly suitable habitats of *T. tor* (Fig. 5).

Distribution of species under climate change

A significant and consistent increase in the area under very high, high, and moderate suitable categories of *T. tor* was observed from current to SSP245 and SSP585. On the contrary, the area under the least and not suitable categories significantly declined in SSP245 and SSP585 compared to the current climate.

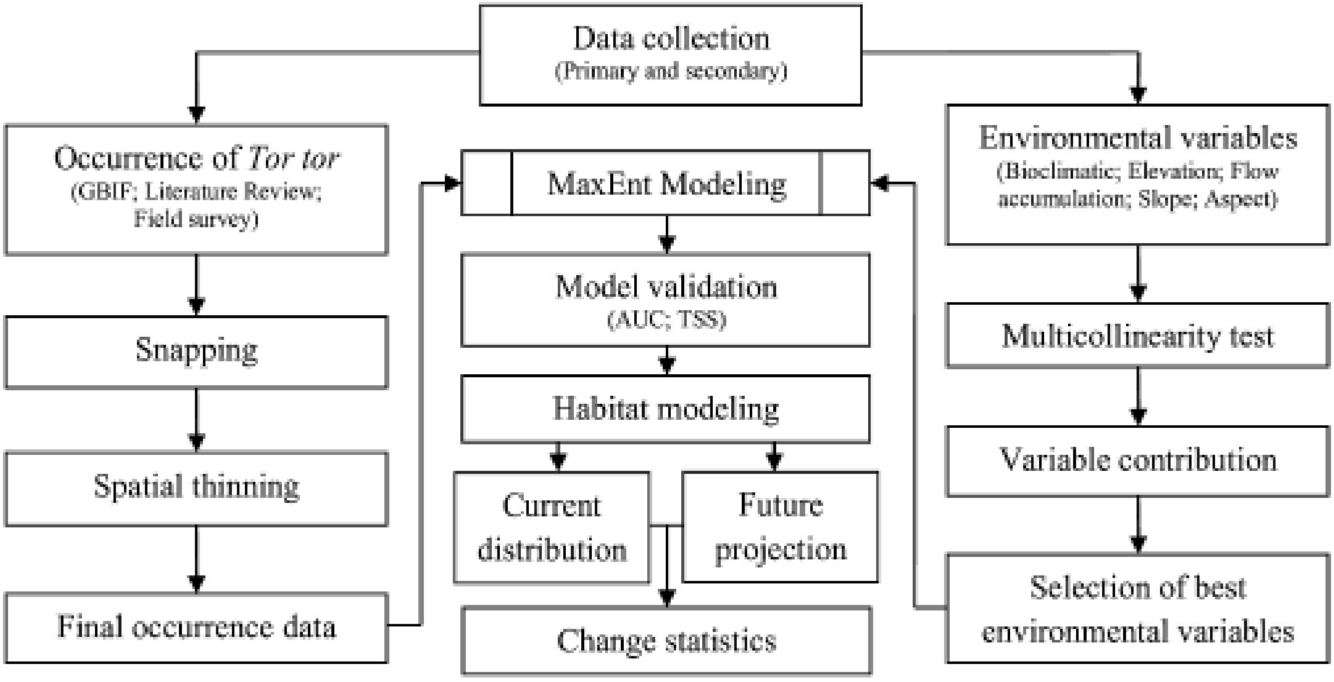


Figure 2. Flowchart of the methodology

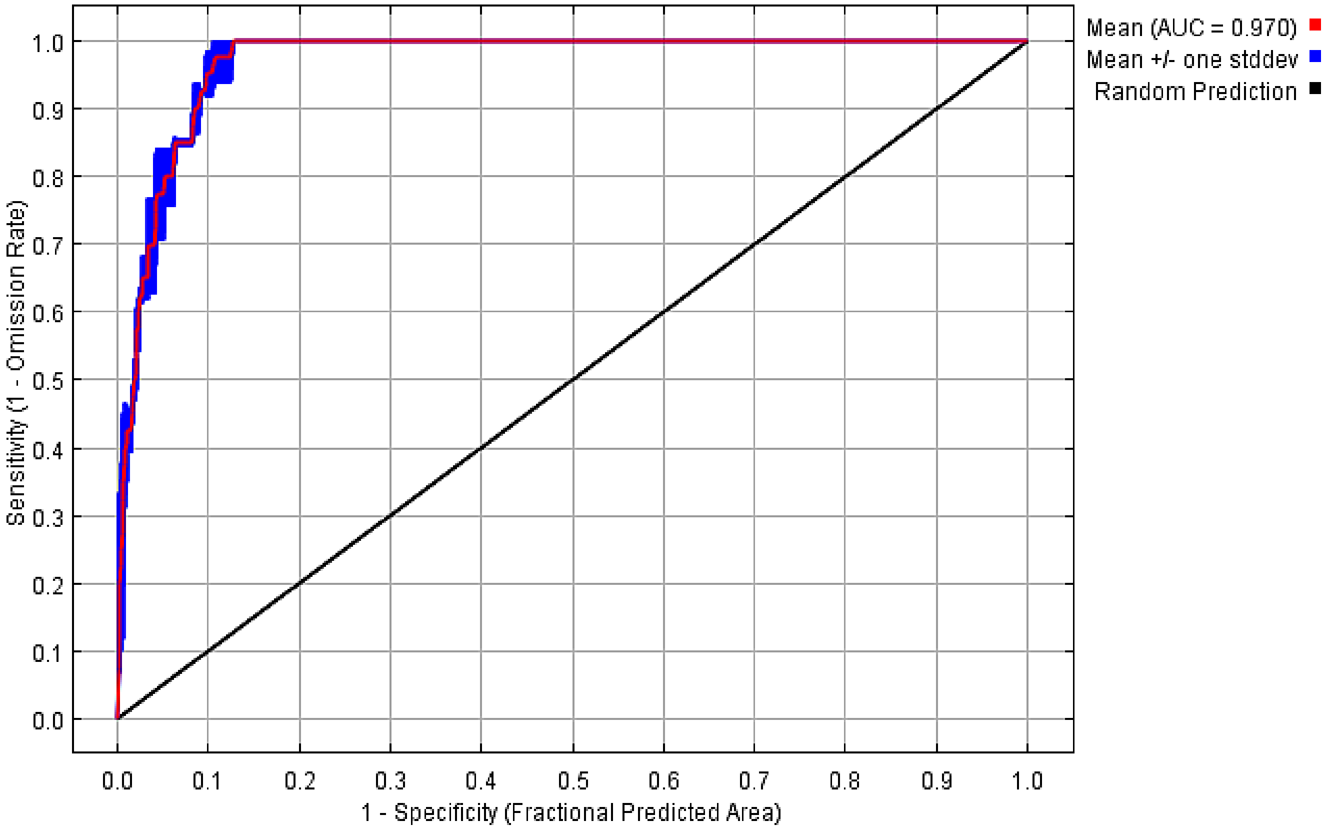


Figure 3. ROC curve of the model

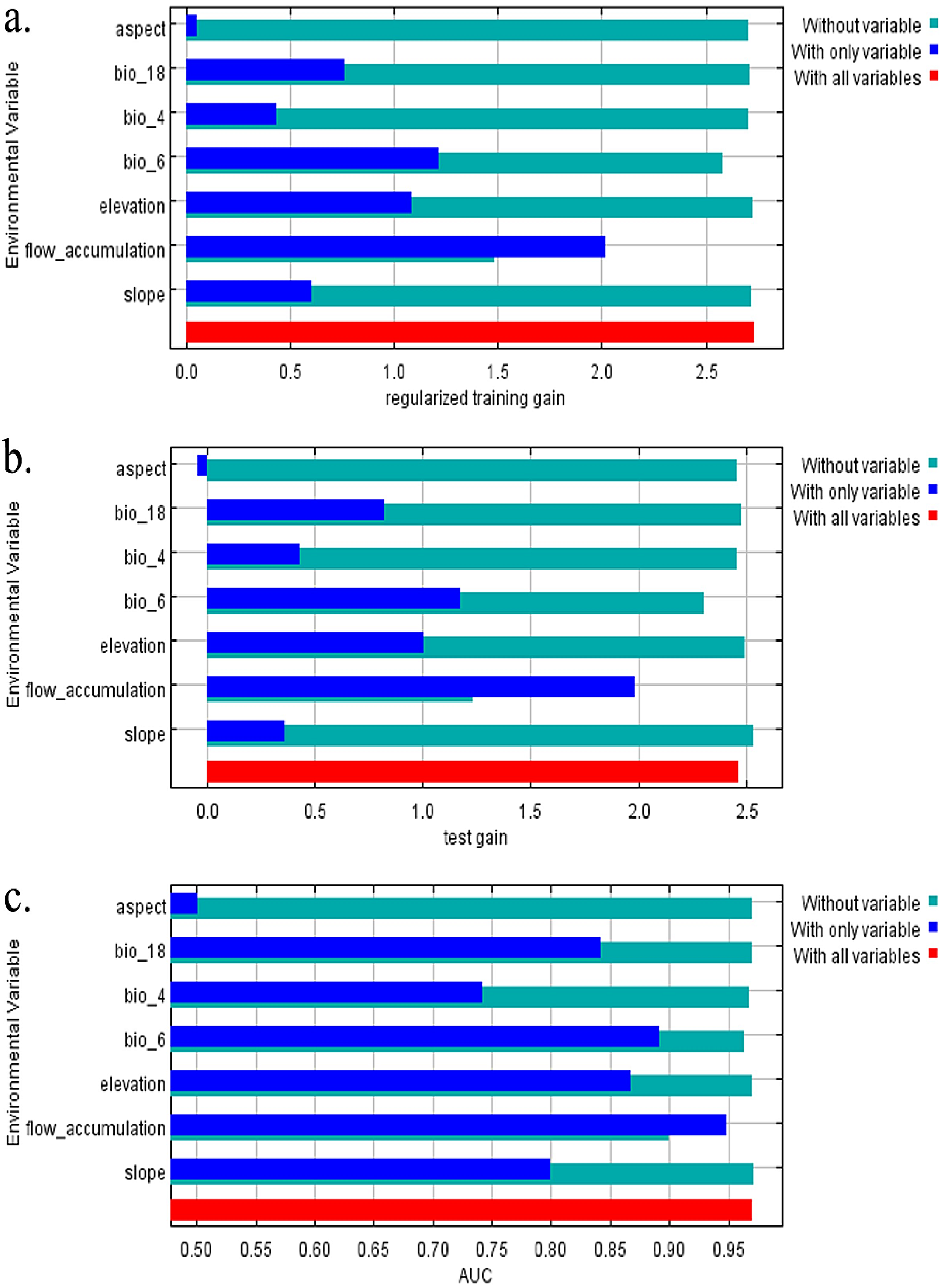


Figure 4. a. Jackknife of regularized training gain; b. Jackknife of test gain; c. Jackknife of AUC

Table 3. Habitat suitability of *T. tor* in Arunachal Pradesh under climate change

Class	Value	Current climate		SSP245		SSP585	
		Length (km)	%	Length (km)	%	Length (km)	%
Not suitable	0 - 0.2	10732.54	72.74	7954.10	53.91	7605.68	51.55
Least	0.2 - 0.4	1547.02	10.49	2091.36	14.18	2073.63	14.06
Moderate	0.4 - 0.6	843.99	5.72	1512.45	10.25	1600.22	10.85
High	0.6 - 0.8	814.74	5.52	933.53	6.33	1049.67	7.11
Very High	0.8 - 1.0	815.62	5.53	2262.47	15.33	2424.71	16.43
Total		**14753.91**	**100**	**14753.91**	**100.00**	**14753.91**	**100.00**

The model results of SSP245 showed a river length of 7954.10 km (53.91%) as not suitable, 2091.36 km (14.18%) as least suitable, 1512.45 km (10.25%) as moderately suitable, 933.53 km (6.33) as highly suitable, and 2262.47 km (15.33%) very high suitable (Table 3). Hence, a significant increase in the very high suitable area of *T. tor* is visible from the current to SSP245. Similarly, the results of SSP585 showed a river length of 7605.68 km (51.55%) as not suitable, 2073.63 km (14.06%) as least suitable, and 1600.22 km (10.85%) as moderately suitable. The total river length under high and very high suitable categories was 1049.67 km (7.11%) and 2424.71 km (16.43%), respectively (Table 3). The increase in high and very highly suitable areas was highest in SSP585 compared to the current climate and SSP245. In both the SSPs, the suitable habitat of *T. tor* appears to move towards the northern part of the state (Fig. 5). This increasing and shifting trend of suitable habitat of *T. tor* under climate change scenario could be attributed to the normalization of temperature in the high-altitude colder parts of the state.

Change detection

The change detection result between current and future climates (SSP245 and SSP585) reveals a linear pattern of change from unsuitable to other categories. Most of the river length remains unchanged for the SSPs (SSP245 = 59.48% and SSP585 = 57.10%) compared to the current climate (Table 4). In the case of SSP245, the largest change in river length was observed from not suitable to least (14.14%), followed by the least to moderate (5.58%), high to very high (5.52%), not suitable to moderate (4.67%), least to high (4.60%), moderate to very high (4.02%) and rest of the categories recorded less than 2%. Similarly, the largest change in river length for SSP585 was observed from not suitable to least (14.03%), followed by not suitable to moderate (7.06%), least to high (6.09%), high to very high (5.52%), moderate to very high (4.81%), least to moderate (3.79%) and rest of the categories showed less than 2% change in river length. The results indicate a notable increase in the high to very high suitability category, rising from the current scenario to 16.11% under SSP245 and 17.91% under SSP585. The suitable habitats appear to shift from lower elevation ranges to mid and high-altitudinal habitats in the future compared to the current distribution (Fig. 6).

DISCUSSION

T. tor is one of the most widely distributed mahseers ranging from Ganga, Brahmaputra, and Narmada drainage systems (Lal et al. 2012). The range extends from Pakistan in the west to Myanmar in the east, southward to the rivers of peninsular India (Pinder et al. 2019). *T. tor* is widely distributed in India, Myanmar, Bhutan, Bangladesh, Pakistan, and Nepal. In contrast, in India, it is distributed in the state of Assam, Arunachal Pradesh, Manipur, Meghalaya, Nagaland, Sikkim, Bihar, Uttar Pradesh, Uttaranchal, Punjab, and Haryana (Khajuria and Langer 2016). Arunachal Pradesh is one of the suitable habitats for the species, and many researchers have identified the presence of the species in different drainage systems of the state (Tamang et al. 2007, Bagra et al. 2009, Tripathi et al. 2016, Gurumayum et al. 2016, Loyi et al. 2018, Sinha 2022). Recently, a study on

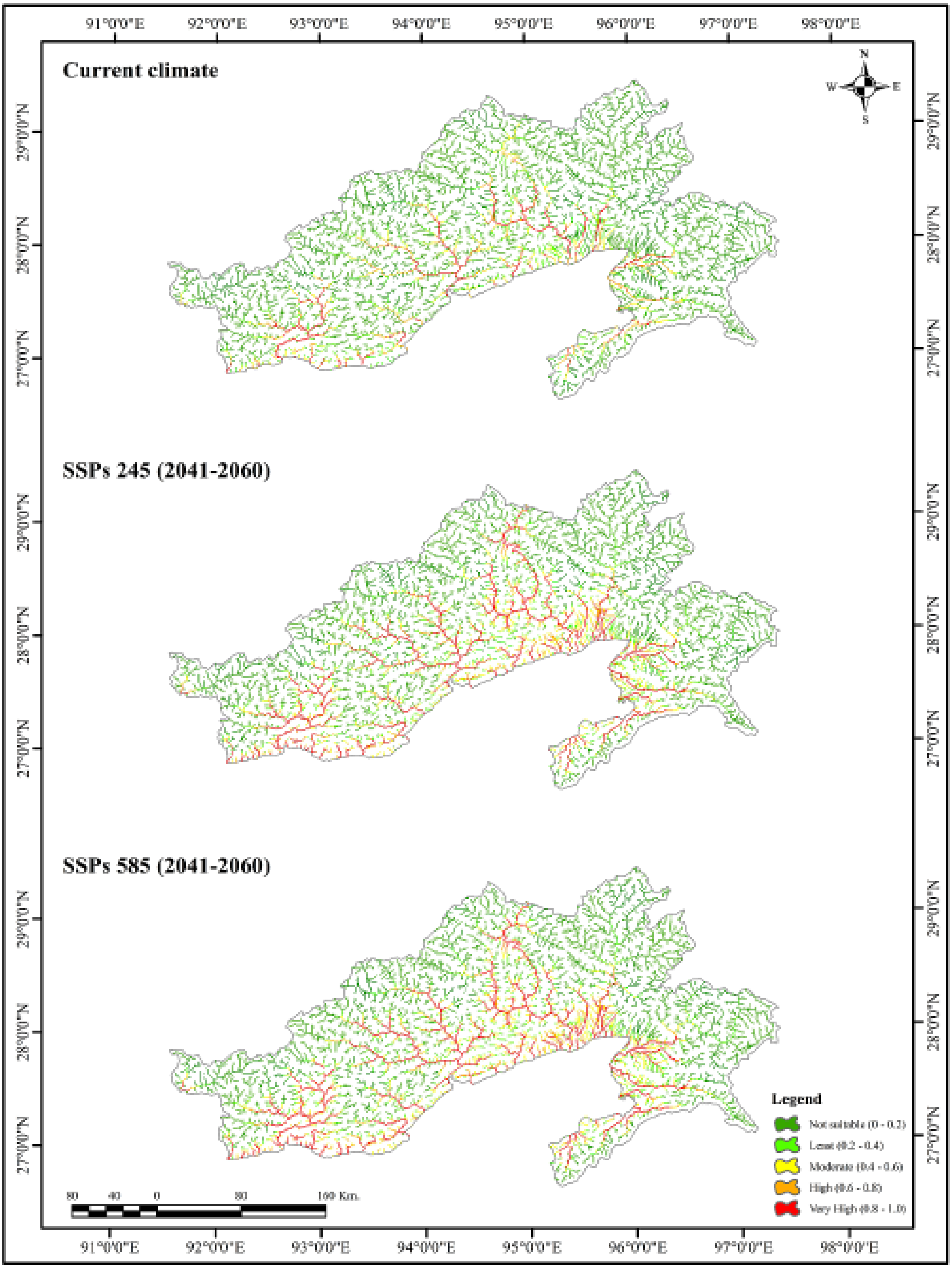
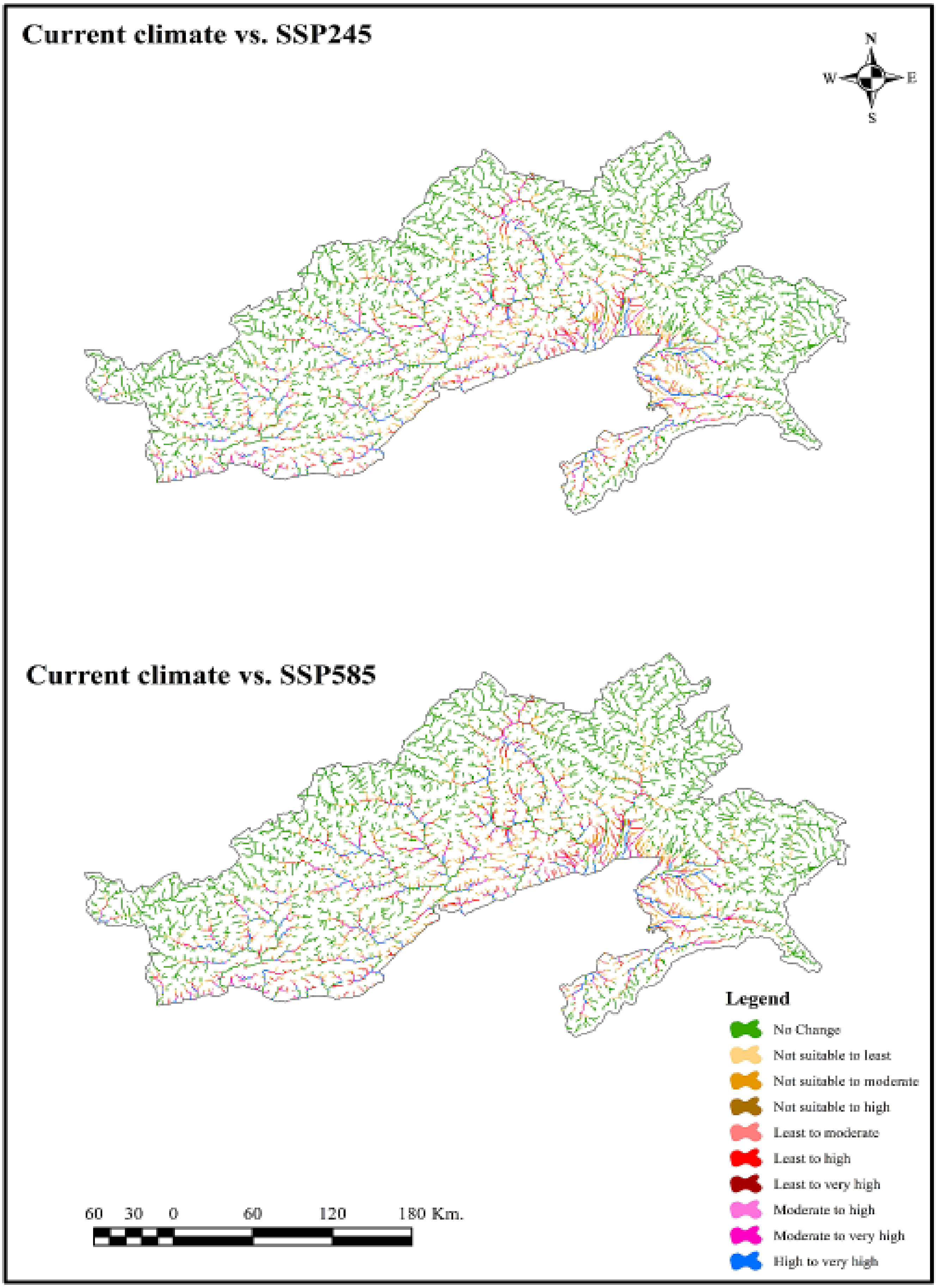


Figure 5. Habitat suitability of *T. tor* under current and climate change scenarios



Current climate vs. SSP245

Current climate vs. SSP585

Figure 6. Change detection of habitat suitability for *T. tor* in Arunachal Pradesh

Table 4. Change detection of habitat suitability of *Tor tor* in Arunachal Pradesh

Change detection	**Current vs. SSP245**		**Current vs. SSP585**	
	Area (km)	**%**	**Area (km)**	**%**
No Change	8775.93	59.48	8424.85	57.10
Not suitable to least	2086.04	14.14	2070.09	14.03
Not suitable to moderate	688.85	4.67	1040.80	7.06
Not suitable to high	3.55	0.02	15.96	0.11
Least to moderate	823.60	5.58	559.41	3.79
Least to high	678.21	4.60	898.96	6.09
Least to very high	39.89	0.27	85.11	0.58
Moderate to high	250.89	1.70	134.75	0.91
Moderate to very high	593.10	4.02	709.24	4.81
High to very high	813.85	5.52	814.74	5.52
Total	**14753.91**	**100.00**	**14753.91**	**100.00**

the habitat suitability of *T. tor* in the Indian drainage system by Mahato et al. (2023) also reported the species from Arunachal Pradesh.

The fish habitat is primarily shaped by factors such as the meandering of streams, the gradient of riverbanks, riparian vegetation, and stream flow dynamics (Gebrekiros 2016). The study found a significant influence of flow accumulation on the distribution of *T. tor*. Additionally, elevation and the minimum temperature of the coldest month also play crucial roles in shaping the species' distribution. Based on the results, a strong influence of hydrologic flow/ regime on the distribution of *T. tor* was observed, as flow regimes and hydrological variations are often associated with stream fish assemblages (Bruckerhoff et al. 2019). Flow accumulation plays a crucial role in habitat availability (Bovee 1982) and trophic interactions (Poole and Berman, 2001), directly and indirectly affecting fish growth and productivity. The distribution pattern of *T. tor* at various elevations along the major rivers in this study may be attributed to its highly adaptive, eurythermal, and wide apparent distribution at various altitudes (Rayamajhi et al. 2018). Further, the distribution is also influenced by the minimum temperature of the coldest month because, in Himalayan rivers, mahseer faces delayed maturity, low fecundity, long hatching period of 60–80 hrs at 24-28°C and slow growth rate (Nautiyal 1988). The model predicted suitable habitats over the major rivers of the state. This may be the species preferred rivers with rocky surfaces for better growth and distribution (Brraich and Saini 2019), clear and fast water velocity, and optimum temperature and pH range (Patil and Saxena 2021). The model results also showed a shift in the suitable habitat of *T. tor* in the future towards the northern parts of the state due to climate change. Similar findings of the northward shift of suitable habitat under climate change for *Neolissochilus hexagonolepis* (Chocolate mahseer or Copper mahseer) were predicted by Panja et al. (2021) in the Ganges-Brahmaputra basin.

Climate-induced changes in temperature and precipitation directly affect fish habitats through changes in the chemical properties of the water or indirect effects through changes in the terrestrial landscape (Whitney et al. 2016). Fish species are distinctively vulnerable to climate-induced changes in temperature and precipitation as they are confined to the waterbody, and their movement is mostly limited to the terrestrial system (Lynch et al. 2016). Although the state is very rich in fish diversity, Loyi et al. (2018) revealed a drastic decline in fish catch during the last decade. Recently, *T. tor* has been reported to be occasionally encountered with a declining population trend in Arunachal Pradesh (Gurumayum and Nath 2022, Taro et al. 2022). Riverine ecosystems suffer from intense human involvement, resulting in habitat loss and degradation and many fish diversity becoming endangered (Sarkar et al. 2012). Overexploitation along with destructive fishing methods, water pollution, flow modification due to construction of dams, destruction and degradation of riverine habitat, and invasion of exotic species are the major threats to fish biodiversity (Gurumayum et al. 2016, Dutta et al. 2018). Sinha (2019) revealed an explicit restriction in the natural fish movement by the dam, where a relatively higher diversity is present downstream than upstream. Thus, the study emphasizes the significant expansion of suitable habitats for *T. tor* in the future compared to the existing distribution pattern and stresses the need to understand the species' climate-related dispersal. Such an effort would be helpful in the conservation and sustainably utilize this economically important fish species in the study area.

CONCLUSIONS

The present study portrayed the suitable habitat of *T. tor* in the drainage of Arunachal Pradesh under a climate change scenario. The model was performed based on the 19 bioclimatic variables associated with elevation, slope, aspect, and flow accumulation. The future scenario of *T. tor* was projected for 2041-2060 using the GSM of MPI-ESM1-2HR with SSP245 and SSP585. The model performance was found to be consistent and excellent. Out of the total river length, the model predicts 72.74% as unsuitable, followed by 10.49% as least suitable, 5.72% as moderately suitable, 5.52% as highly suitable, and 5.53% as very highly suitable. The result of SSP245 revealed a length of 53.91% as unsuitable, 14.18% as least suitable, 10.25% as moderately suitable, 6.33% as highly suitable, and 15.33% as very highly suitable. Similarly, the results of SSP585 showed a river length of 51.55% as unsuitable, 14.06% as least suitable, 10.85% as moderately suitable, 7.11% as highly suitable, and 16.43% as very highly suitable. Hence, a significant increase in the very high suitable area of *T. tor* in the state is visible from the current to SSP245 and SSP585 with a northward shifting of suitable area. Unfortunately, many researchers have reported a declining trend in the state's population of *T. tor*. Therefore, there is an urgent need to take necessary action to conserve the species.

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Authors' contributions: RM and SA prepared the initial draft of the manuscript. RM and BJG prepared the thematic layers and collected the data. ODN, BB, and GN commented, edited, and revised the manuscript by consulting the relevant literature. DND further revised the manuscript after proofreading. Finally, the manuscript was read by all the authors and approved it to submit for possible publication.

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