Environmental drivers dependent habitat expansion of introduced alien trout (*Salmo trutta fario* and *Oncorhynchus mykiss*) in the Himalayan ecosystem and management concerns in the time of climate change

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Research Article

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Abstract

Introduced alien brown trout *Salmo trutta fario* and rainbow trout *Oncorhynchus mykiss* are although abundantly available in western Himalaya, its distribution is now expanding in different Himalayan states. We present the first assessment of environmental drivers' responsible for current distribution and potential expansion of *S. trutta fario* and *O. mykiss* in the Himalayan ecosystem. MaxEnt model was used in this study, which was overlaid with presence data into environmental layers with a total of 81 occurrence points to estimate contemporary suitable habitat. Results of this study indicated that the precipitation of driest quarter (Bio_17) contributed 71.4% for *S. trutta fario* and 61.1% for *O. mykiss* distribution respectively. The other environmental variables responsible were altitudinal variable (GMTED_DEM) 7.9% and precipitation seasonality (Bio_15) 10.9% for brown trout distribution. In case of *O. mykiss*, the contributed three layer of permutation importance were driest quarter (Bio_9) 10.8%; precipitation (Prec_03) 9.6% and length_slope 7%. Our findings facilitate understanding of bioclimatic factors responsible for expanding habitat distribution of trout and forecasting environmental variables and climate change trade-offs towards habitat regime shift in the Himalayan region of Asian continent suggesting need of their sustainable management.

Introduction

The introduction of alien brown trout *Salmo trutta fario* happened in 1860s and rainbow trout (*Oncorhynchus mykiss*) in 1909 by the Britishers in the streams and rivers of the Indian Himalaya (Sehgal, 1999; Singh and Lakra, 2011). Trout attracts anglers, particularly foreigners, to high-altitude lakes and numerous snow-fed freshwater streams in J&K and Himachal Pradesh, making it an important part of the tourism industry besides economical gains through farming (Singh, 2020). Trout farming has received a major thrust in 2020 with the launch of the Pradhan Mantri Matsya Sampada Yojana (PMSSY) in the country (nfdb.gov.in). In the year 2020 alone, 700,00 trout ova were airlifted to Arunachal Pradesh, Nagaland, Sikkim and Uttarakhand for rearing in the respective states. There is a growing apprehension that environmental variability can shape up trout population wherever it were introduced because its stocking was common in Himalayan lakes, streams and rivers. Given that temperature is often a master variable dictating the distribution and abundance of trout in Himalayan ecosystem, climate-change-induced stream warming or other environmental driver(s) might be expected to mobilize trout population.

Trout streams in Himalaya are typically fast-flowing, soft-water with rocky stony riverbeds and clear water within the temperature range of 10-18°C. Understanding the spatial behaviour of fish, and how they respond to environmental variation is critical to ensure their effective management, especially in the time of growing pressures such as climate change (Tewari et al., 2016), invasive species (Singh and Lakra, 2011; Singh, 2021) and altered habitat (e.g. river fragmentation) (Arlinghaus et al. 2016; Jones et al. 2019) all of such factors can influence native fish existence and consequently long term viability in their natural habitats. Himalayan ecosystems are usually sensitive even to small disturbances (Tewari et al., 2017) and consequently such disturbances may affect the distribution of introduced trout and also the local fishes. These changes might lead to an overall expansion or contraction of suitable habitats and/or

a shift in the spatial distribution of habitats of local and introduced fishes in up- or downstreams of mountain rivers (Lenoir et al., 2010; Comte and Grenouillat, 2013; Sharma et al. 2021).

Despite the long history of trout in India, hardly any information exists on the ecology of the fish species under environmental drivers which may predict the success and limitation of its distribution and habitat expansion. The changing environmental parameters due to climate change or changing ecological conditions of the Himalayan aquatic ecosystem (Kattel, 2021) may form extended habitat for any introduced species in the space as a consequence of changes in environments. Ecological and environmental information are important for understanding spatial and temporal variability in distribution of any introduced alien fish species and also for providing the necessary feedback to guide policy options in the context of fish invasions which are recognized as the major threats to biodiversity (Singh & Lakra, 2011; Thapliyal et al., 2016; Araujo, et al., 2019; Hosegawa, 2020; Johal et al., 2021; Sharma et al., 2021; Singh, 2021). Freshwater ecosystems in Himalaya present unique challenges to its fish diversity due to their linear spatial orientation and their association with upland habitat variables (Kattel, 2021).

Recognizing the environmental variables responsible for habitat expansion of introduced trout, this study was undertaken to determine how trout population's distribution would deduce management action need in the Himalayan ecosystem especially in the context of their extended distribution and propagation. Therefore, the objective of this study was to predict future expansion of brown trout and rainbow trout by using MaxEnt algorithm for future management action. In this study, we attempted to clinch key environmental variables that were highly connected with brown trout and rainbow trout distribution in the Indian Himalaya. Information generated in this paper will identify the environmental driver(s) responsible for future habitat expansion of trout in the Himalaya in the context of ecological changes and climate change. This study is our first attempt to identify critical knowledge gaps towards bioclimatic factors assisted ecosystem approach to sustainably manage trout and to protect Himalayan ecosystem from the possible threats.

Materials And Methods

The spatial data in this study represent the naturalized distribution of *S. trutta fario* and *O. mykiss* in the Himalayan region. A total of 48 locations with *Oncorhynchus mykiss* and 33 locations with *Salmo trutta fario* occurrences were recorded during the period of 2018 to 2021 using the Global Positioning System (GPS) and field surveys. All generated data were entered into Microsoft Excel 2007 and saved as format "CSV." The most significant factors in identifying environmental niches of each species were environmental variables. To avoid the biased sampling, we applied spatial filtering and used only 1 sample from a locality in such a way that no two samples lay within 5 km radius (Kramer et al., 2013). Finally, the error free presence only dataset of the two species was used in the study to develop the distribution model for trout (Hernandez et al., 2008). For climate data, World Clim Version 2.0 (Fick and Hijmans, 2017) was used which is a database of high spatial resolution for global weather and climate. The new release was used in this study which had a set of global climate layers (gridded climate data) and the data were used for mapping and spatial modeling. The monthly climate data for minimum, mean, and maximum for temperature, precipitation, solar radiation, wind speed, water vapor pressure, and

total precipitation were used. There are 19 bioclimatic variables each of which was downloaded as a 'zip' file containing 12 GeoTiff (.tif) files one for each month of the year (January -01 to December -12). The 19 bioclimatic variables were the average for the years 2018 to 2021. In the present study, all the environmental data with 7 climatic (7*12 month = 84) and 19 bioclimatic variables at a spatial resolution of 30 seconds (~ 1 km²) were used (Table 1). For hydrology, Global Multi-Resolution Terrain Elevation data GMTED 2010 database was used to derive data for entire India with a spatial resolution of 30 m on different hydrological and topographical variables. This product suite provided coverage of all land areas in the Indian Himalaya. In the present study, only the mean dataset available in GMTED for India was used for deriving the values of different hydrological parameters. The values of the hydrological parameters listed in Table 1 were derived by applying the AT Search Algorithm developed by Ehlschlaeger (1989) using GRASS GIS (Version 7.8.1) software. From the prepared dataset of the hydrological variables, the two topographical variables 'landscape slope' and 'aspect' were derived using the above-mentioned GIS software. The basin and drainage maps were overlaid on the Google maps for identification of river reaches. The river reaches were isolated by digitizing and annotating (Singh et al., 2021).

The MaxEnt software, version 3.1 was used with 4-fold cross validation method on the occurrence datasets prepared for *O. mykiss* and *S. trutta fario*. The environmental variables comprising of climate, hydrology and topography were calibrated for developing distribution modeling of brown and rainbow trout to estimate the presence probability of these species varying from 0 to 1, where 0 was the lowest and 1 the highest probability (100%). Sample radius of 5 pixels (150 meter) was used with 25% random test percentage for each replicate run (Phillips and Dudik, 2008). We used the area under the Receiving Operator Curve (AUC) to evaluate model performance. The value of AUC ranges from 0 to 1 (Fielding and Bell, 1997). An AUC value of 0.50 indicates that model did not perform better than random, whereas a value of 1.0 indicates perfect discrimination (Swets, 1988). The model with the highest AUC value was considered as the best performer. For display and further analysis, we imported the results of the MaxEnt model for predicting the presence of both the trout species (0–1 range) into Arc GIS 9.3. with a reference to the classification proposed by Yang et al. (2013). Five classes of potential habitats were regrouped: unsuitable habitat (<50%); barely suitable habitat (50-65%); suitable habitat (65-80%); highly suitable habitat (80-95%); very highly suitable habitat (>95%). For MaxEnt model, we calculated the area of the optimal distribution, classified as highly or very highly suitable habitat (65->95%).

Results

Trout distribution was estimated using MaxEnt model, which overlaid presence data onto environmental layers and characterized those conditions which were most suitable for the trout species expansion. AUC mean value observed for *Salmo trutta fario* was 0.919 and for *Oncorhynchus mykiss* it was 0.881 which showed that the Maxent model was highly accurate with statistically significant AUC values which were higher than 0.5 of a null model. The calibration of the model for both the brown trout and rainbow trout was found satisfactory (Fig. 1A and 1B). The results of this study indicated that the distribution of *Salmo trutta fario* and *Oncorhynchus mykiss* were based mainly on precipitation of driest quarter (Bio_17)

followed by altitude variables (GMTED_DEM) and precipitation seasonality (Bio_15). MaxEnt distribution model indicated that Bio_17 contributed 71.4% for *Salmo trutta fario* and 61.1% for *Oncorhynchus mykiss* respectively (Fig. 2a & Fig. 3a). The *Salmo trutta fario* habitat model also cumulatively contributed by other two important layers of environmental variables which were above 5%. These were altitudinal variables (GMTED_DEM) having value of 7.9% and Bio_15 value of 10.9% (Fig. 2b & 2c). While other nine layer of environmental variables were found to contribute less than 5% cumulatively representing 9.8% for all such variables (Fig. 4a). In case of *O. mykiss*, the contributed three layer of permutation importance above 5% were mean temperature of driest quarter (Bio_9) having value of 10.8%; precipitation (Prec_03) 9.6% and length_slope 7% (Fig. 4b, c & d). The other eight layer of environmental variables cumulatively contributing less than 5% accounted for 11.5% and was not of permutation importance (Fig. 4b). Species response curve depicted relationship between environmental variables and the probability of species distribution incidence. The environmental variables also showed biological tolerances of the brown trout and rainbow trout for habitat preferences.

The Jackknife test of different environmental variables for both the trout species depicted their potential habitat distribution. The Jackknife test of environmental variable importance using regularized training gain are presented as graphs (Fig. 5a & 5b). The blue bars indicated the gain using solo environmental variable, the green bars indicated the gain excluding the single variable from the full model, and the red bars indicated the gain considering all variables. In *Salmo trutta fario*, permutation importance variables were Bio_17, Bio_15 and GMTED_DEM which provided very high gains when used independently, indicating that Bio_17, Bio_15 and GMTED_DEM contained more useful information than the other variables did. Slope_steepness, Srad_05, Prec_03, had moderate gain when used independently in case of *S. trutta fario* while other variables including Srad_08, length_slope, Prec_04, Prec_05, Bio_02 and Srad_06 had low gains when used in isolation. On the other hand, *Oncorhynchus mykiss* had permutation importance variables of Bio_17, Bio_19, Prec_03 and length_slope which provided extreme gains autonomously indicating that Prec_04 and Sard_09 variables contributed moderately with defined probability at the threshold of 5% (Fig. 4.). The common variables in both the species was Bio_17 which was the significant predictor for distribution (Fig. 2a & 3a). The MaxEnt prediction model for *O. mykiss* showed that its distribution rested more towards length_slope of the Indian Himalaya. As far as data availability were concerned, it also showed that the bioclimatic variables in the present study were chosen to reflect physiological needs of *Salmo trutta fario* which were Bio_17, Bio_15 and elevation tolerance to extreme temperatures or amount of precipitation required.

The species richness of *Salmo trutta fario* and *Oncorhynchus mykiss* in Himalayan region are shown (Fig. 6a & 6b.), which predicted trade-off between the environmental variables of permutation importance and their habitat expansion. The occurrence map of *Salmo trutta fario* delineated that it was more spread in four Himalayan states i.e., the J&K, Himanchal Pradesh, Uttarakhand, and Arunachal Pradesh. The *O. mykiss* species rich areas were J&K, HP, Uttarakhand, Sikkim and Arunachal Pradesh. The *O. mykiss* species rich areas were found spread from the north western to the north eastern areas (lower altitude richness in Indian Himalaya).

Discussion

The distribution of brown and rainbow trout in natural habitats has been found to be derived by the climatic and ecological factors such as precipitation of driest quarter (Bio_17), altitudinal variables (GMTED_DEM) and precipitation seasonality (Bio_15) in this study. Environmental variables have been reported to exert important effects on the distribution of species within their habitat (Shuai et al., 2017; Carlson et al., 2019). The MaxEnt model-based distribution prediction delineate that bioclimatic variations (Bio_17, Bio_15, GMTED_DEM) are significant factors for the habitat expansion of brown trout whereas Bio_17, Bio_09, precipitation and length_slope have been important factors for expansion of rainbow trout. Moreover, the distribution patterns of rainbow trout have been found to be affected by precipitation and slope degrees corroborating with the earlier report (Williams et al. 2015; Carlson et al., 2019). However, there is little response of solar radiation for the distribution of rainbow trout because of length_slope. Due to the geophysical and the biological interactions within the Himalayan ecosystem, Bio_17 has been common for both the trout fish. Brown trout thrive at high levels of nutrients for growth and these areas tend to have significant trophic conditions hence there exist more fish species diversity such as local snow trout in these areas (Singh et al., 2017; Johal et. al. 2021). Our results delineate that introduced trout richness in these areas support the reported ecological and environmental conditions required for each of the trout species (Singh et al., 2017; Johal et. al. 2021). In the developed distribution maps of brown and rainbow trout, such environmental variables are illustrated by the grid cells. The four states in India namely the J&K, Himachal Pradesh, Uttarakhand and Arunachal Pradesh have shown 95% predicted areas to have more habitat expansion (Fig. 6A&B). The trout species habitat will further expand due to climate change when the above said bio-climatic variables precipitate. While the use of non-native trout species has an indispensable importance for Himalayan region, the findings of the study pose considerable risk management need for the native biodiversity, as escapee trout may become invasive in certain environments (Sharma et al., 2021). A detailed study should be planned to develop management action for the trout species in the Himalayan region to make them sustainable in years to come.

In future, the scenario of the gain in the distribution area of both the trout species will be most extensive, which may happen because of the pessimistic climate change scenario (Carlson et.al., 2019; Sabin et al. 2020). Distribution of trout species will also vary according to an array of biological and physical conditions underlying the fundamental niche and correlative species distribution that will enhance our understanding on the niches to be invaded by the introduced trout in new geographic spaces (Thapliyal et al. 2016; Sharma et al. 2021; Johal et al. 2021). The areas which gain species in future, considering the existed distribution, may have more suitable habitat available for the respective trout species (Varela et al., 2014; Johal et al. 2021). Based on the findings of this study, *in situ* conservation with sustainable utilization of the local resources is recommended. All the predicted areas are suitable for long term *in situ* conservation of the local fish species while promoting both the introduced trout species being economical and lucrative (Singh, 2020).

Conclusion

In this study, an independent assessment of suitable environmental variables associated with the current distribution of trout in Himalaya has been conducted and future habitat expansion is predicted using MaxEnt model. Our results delineate the potential impacts of environmental variables on the future distribution of brown and rainbow trout. Our results on environmental variables clearly demonstrate habitat specificity for the introduced trout in Himalayan region. One of the most concerning aspects of environmental variables due to climate change on habitat expansion of introduced trout in the Himalaya is the likelihood of changes in the distribution of not only the trout but also local fish species. Since introduced alien trout share characteristics with endemic trout species, they have been documented to disrupt natural ecosystem interactions, and in severe cases cause extinction. This species has been shown to displace native species, compete for food, or directly predate on species of concern. These changes are more likely to modify the availability and quality of habitats particularly concerning the local species in the actual ranges of trout distribution. Reports are now available displaying opinion that a decline in catches of schizothoracine species notably *Schizothoracichthys esocinus*, *S. progastus*, *Schizothorax richardsonii*, *S. longipinnis*, *S. nasus* and *S. hugelii* in the Himalayas as the result of brown trout habitat expansion. It is important to mention that Schizothoracines, are the most important endemic fish species existing in the Himalayan trout waters. Successfully established wild populations of non-native brown trout (*Salmo trutta fario*) in higher altitude of Himalaya raise concerns for conservation of native snow trout (*Schizothorax richardsonii*) species over the past years. As such, assessing the way invasive-alien species and native fish would respond to changing climate in vulnerable Himalayan riverscapes is of utmost importance. Considering how habitat expansion of trout in future may comprehensively harm local fish biodiversity, conservation planning must start considering cultural significance and the importance of introduced trout in the Himalaya. Planning for Himalayan region local fish diversity conservation should also succeed sustainable management of trout farming at the same time. It is therefore, propagation of freshwater trout in Himalayan ecosystem must be enforced by including social, cultural, and governance factors. In summary, spatially optimized solutions to meet local fish biodiversity conservation can support efforts to propagate sustainable trout production in the region. However, there are many challenges to effective conservation outcomes for local fish species in the region, from competing land-use demands to mounting climate change vulnerabilities. The trout distribution areas in Indian Himalaya having the large gain in habitat expansion as observed in this study should be considered opportunity for *ex situ* and *in situ* management planning in the context of trout angling perspectives, fishery and management of local fish diversity in view of possible invasiveness of the introduced trout in the newer areas.

Declarations

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Consent to publish - Not Applicable

Ethical Approval - the study did not require any ethics approval

Funding Agency - Not Applicable

Data availability statement - Not applicable

Authors contribution

Both the authors contributed to the study conception & design; material preparation, data collection and analysis. The first draft of the manuscript was written by Dr Atul K Singh and both the authors (AKS and SCS) approved the final manuscript.

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Tables

Table1. Climate, bioclimatic variables available in World Clim Version 2.0 database. The hydrological variables derived from the mean dataset available in GMTED for India and the topographical variables used in the study.

Climate variables	Minimum temperature (°C)
	Average temperature (°C)
	Maximum temperature (°C)
	Precipitation (mm)
	Solar radiation ($\text{kJ m}^{-2} \text{ day}^{-1}$)
	wind speed (m s^{-1})
	water vapour pressure (kPa)
Bioclimatic Variables	BIO1 = Annual Mean Temperature
	BIO2 = Mean Diurnal Range (monthly (max temp – min temp)
	BIO3 = Isothermality (BIO2/BIO7) ($\times 100$)
	BIO4 = Temperature Seasonality (standard deviation $\times 100$)
	BIO5 = Max Temperature of Warmest Month
	BIO6 = Min Temperature of Coldest Month
	BIO7 = Temperature Annual Range (BIO5-BIO6)
	BIO8 = Mean Temperature of Wettest Quarter
	BIO9 = Mean Temperature of Driest Quarter
	BIO10 = Mean Temperature of Warmest Quarter
	BIO11 = Mean Temperature of Coldest Quarter
	BIO12 = Annual Precipitation
	BIO13 = Precipitation of Wettest Month
	BIO14 = Precipitation of Driest Month
	BIO15 = Precipitation Seasonality (Coefficient of Variation)
	BIO16 = Precipitation of Wettest Quarter
	BIO17 = Precipitation of Driest Quarter
	BIO18 = Precipitation of Warmest Quarter
	BIO19 = Precipitation of Coldest Quarter
Hydrological variables	max_slope_length = Maximum length of surface flow
	accumulation = Number of cells that drain through each cell
	log_accumulation = Absolute logarithmic value of accumulation

	tci = Topographic index $\ln(a / \tan(b))$ (Quinn et al., 1991)
	spi = Stream power index $a * \tan(b)$ (Moore et al., 1991)
	drainage = Drainage direction (numbered from 1 to 8)
	basin
	stream
	length_slope = Slope length (Weltz et al., 1987) slope_steepness = Slope steepness (McCool et al., 1987)
Topographical variables	Landscape slope
	Landscape aspect

Figures

Figure 1

Area under curve (AUC) between average sensitivity and specificity for (A) *Salmo trutta fario* (B) *Oncorhynchus mykiss*

Figure 2

Important predictor variables and their response curve for *Salmo trutta fario* (a) Bio_17, (b) GMTED_DEM, (c) Bio_15

Figure 3

Important predictor variables and their response curve for *Oncorhynchus mykiss* (a) Bio_17, (b) Bio_09, (c) Prec_03 and (d) Length_slope.

Figure 4

Signed environmental variables having permutation importance but insignificant role in spread of (a) *Salmo trutta fario* and (b) *Oncorhynchus mykiss*

Figure 5

Relative Jackknife based environmental variables displaying regularized training gain in MaxEnt model for (a) *S. trutta fario* and (b) *O. mykiss*

Figure 6

Average distribution values for raster maps predicted by the MaxEnt model (A) *Salmo trutta fario* (B) *Oncorhynchus mykiss*