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MaxEnt modeling for predicting impacts of climate change on the suitable habitat of *Morus indica* in Tamil Nadu, India

Manickavasagam Mithilasri*[1], Shankar S. M[2], R. Nandha Kumar[3]

[1]Centre for Climate Change and Disaster Management (CCC&DM), Anna University, India
[2]Department of Physics, Don Bosco Arts and Science College, Dharamapuri, India
[3]Department of Sericulture, Forest College and Research Institute, Mettupalayam, India

ABSTRACT

This study assesses the habitat suitability of Morus indica under current and future climate scenarios (2050s, 2070s, and 2090s) using MaxEnt modeling. Habitat suitability was classified into non-suitable (< 0.3), medium (0.3-0.5), and high (> 0.5) categories. Under current conditions, medium suitability areas cover the largest extent (17,445.44 sq. km), followed by non-suitable (5,045.22 sq. km) and high suitability (3,463.806 sq. km) areas. Future projections indicate substantial alterations: by the 2050s, non-suitable areas increased by 36.75%, with medium and high suitability areas decreasing by 7.54% and 15.54%, respectively. This trend intensifies by the 2070s and 2090s, with non-suitable areas expanding dramatically and high-suitability areas declining by up to 65%, suggesting habitat fragmentation and decreased species viability. Challenges in this study include the complexity of modeling habitat suitability under diverse climate scenarios and the potential for data limitations affecting accuracy. Despite these challenges, the study contributes valuable insights into the future distribution of Morus indica and underscores the urgent need for targeted conservation strategies to address the adverse impacts of climate change on its habitats. Key predictors of habitat suitability include Bio 4 (Temperature Seasonality), Bio 12 (Annual Precipitation), Bio 2 (Mean Diurnal Temperature Range), and Bio 18 (Precipitation of the Warmest Quarter).

Keywords: *Morus indica, Habitat suitability, Climate change, Bioclimatic variables, Conservation, Species distribution modeling, MaxEnt, Future climate scenarios, Habitat fragmentation.*

Introduction

Morus indica, commonly known as Indian mulberry or silkworm mulberry, holds significant ecological and economic importance in India due to its role as a primary food source for silkworms and its potential in various agricultural and medicinal applications [3]. These trees thrive in diverse climates and terrains within an ecological environment. Over time, the germplasm resources of mulberry trees have been meticulously selected through artificial means [14,20]. One common variety is known as round leaf or hairy vein mulberry, which is deciduous [7,12]. This species thrives in various habitats, including forests, grasslands, and scrublands, and can be found in both rural and urban environments.Current research on *M. indica* primarily focuses on its biological characteristics and genetic improvement, with no available research predicting its potential distribution [4,11,15]. Understanding the spatial distribution of a species is crucial for ecological and evolutionary studies. In addition to traditional field investigations, species distribution studies have opened new research avenues [20]. By establishing an ecological niche model based on niche theory, we can better understand and apply this species. The niche model predicts a species' future distribution by examining the relationship between its existence and environmental variables, thereby determining its potential future distribution area [8.18].Among various niche models, the MaxEnt model stands out for its advantages, such as its small sample size requirements and accurate predictions [16]. The model's short run time, ease of operation, and high accuracy are also significant reasons for its selection [2]. The MaxEnt model has been used for different species in various countries; for example, Thakur *et al.*[13] predicted suitable distribution areas for Elwendia persica (Boiss.) in the Indian Himalayan region, and Ji *et al.* [5] predicted suitable distribution areas for Daktulosphaira vitifoliae (Fitch) globally.

In this study, we use the MaxEnt model along with ArcGIS technology to predict both current and future potential suitability distribution areas for *M. indica* under different climate conditions [1,17]. This analysis aims to elucidate how environmental changes impact the distribution patterns of *M. indica*, providing a solid foundation for further research on this species.

2. Materials and Methods

Study area

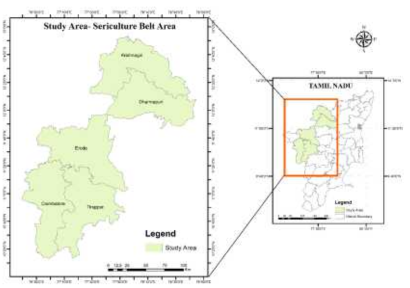

Figure 1. Study Area

*Corresponding Author: **Manickavasagam Mithilasri***

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Data preparation

The present study recorded 80 geographical locations of the *M.indica* orchid using Trimble Juno 3B Global Positioning System (GPS). Environmental (categorical) layers like the Shuttle Radar Topographic Mission (SRTM) Digital Elevation Model (DEM) having 90 m spatial resolution, downloaded from the USGS website (www.srtm.usgs.gov). Using the nearest neighbor re-sampling technique, the categorical layers were resampled into 1 km x 1 km spatial resolution in Arc GIS. In addition, 19 bioclimatic variables (Table 1) for the current period were also derived from the World Clim data set (https://www.worldclim.org/). These bioclimatic variables represent annual trends, seasonality, and extremities of temperature and rainfall parameters. They were extracted for the study area and converted to ASCII files. To avoid the cross-correlation within the selected environmental variables multi-collinearity test was conducted using Pearson's correlation coefficient in R software (R studio 3.4.2) The variables with r-value ≥ 0.8 were eliminated to minimize the effect of multi-collinearity and model overfitting [6,15]. Eight bioclimatic variables were selected to assess the current and future habitat suitability of *M. indica*.

Table 1 Bioclimatic variables used for habitat suitability species distribution model

Variable code	Description	Unit
Bio 01	Annual mean temperature	°C
Bio 02	Mean diurnal range (Mean of monthly (T_{max}-T_{min})	°C
Bio 03	Isothermality	°C
Bio 04	Temperature seasonality	°C
Bio 05	Maximum temperature of warmest month	°C
Bio 06	Minimum temperature of coldest month	°C
Bio 07	Temperature annual range	°C
Bio 08	Mean temperature of wettest quarter	°C
Bio 09	Mean temperature of driest quarter	°C
Bio 10	Mean temperature warmest quarter	°C
Bio 11	Mean temperature of coldest quarter	°C
Bio 12	Annual precipitation	mm
Bio 13	Precipitation of wettest month	mm
Bio 14	Precipitation of driest month	mm
Bio 15	Precipitation of seasonality (Coefficient of variation)	mm
Bio 16	Precipitation of wettest quarter	mm
Bio 17	Precipitation of driest quarter	mm
Bio 18	Precipitation of warmest quarter	mm
Bio 19	Precipitation of coldest quarter	mm

Modeling procedure

Among numerous species distribution models, the maximum entropy (MaxEnt) distribution model was the most effective [9]. It needs information on the species being modeled as well as the corresponding environmental (categorical) and climatic variables. The habitat suitability modeling of *M.indica* was done using the freely accessible MaxEnt model, version 3.3.10 k (http://www.cs. princeton.edu/). 30% of the 24 *M.indica* presence locations were used as test data, while 70% of them were used for model training. In the replicate run, cross-validation was preserved, and the iterations were set to 5000. The current study chose 0.1 as the regularisation value to prevent the test data from being overfitted [10]. The receiver operating curve's area under the curve was employed for the 0.5 (random) to 1.0 (perfect discrimination), model rating scale. Additionally, this study evaluated the significance of variables in the final model using the Jackknife method [10]. Current bioclimatic variables were used to train the model, and future bioclimatic variables were used to project it. The present study used clamping while the model was running to see the shift in the bioclimatic suitability range in the future prediction. The model's final outputs were exported to ArcGIS 10.8 for additional analysis.

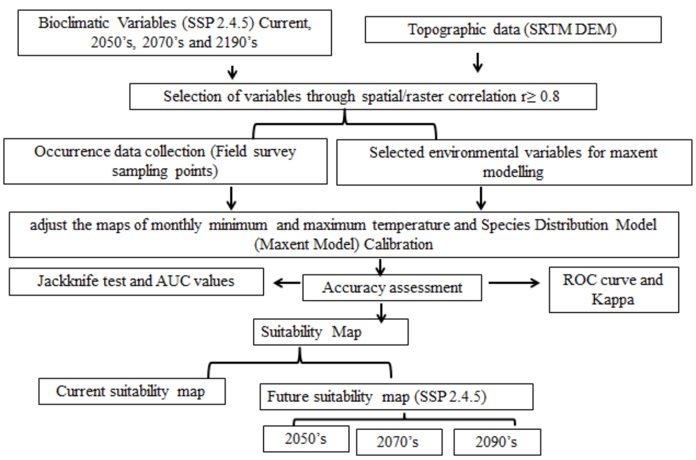

Figure 2. Habitat Suitability Prediction Mapping Methodology

Results and Discussion

The present study focused on assessing the habitat suitability of *M. indica* tree species under current conditions and future climate scenarios (2050s, 2070s, and 2090s). We classified habitat suitability into three categories: non-suitable (< 0.3), medium (0.3-0.5), and high (> 0.5), and quantified the corresponding suitability areas in square kilometers.

Furthermore, the present study compared the projected suitability areas with the current distribution to ascertain changes over time.

Under current conditions, *M. indica* habitats exhibit varying degrees of suitability, with medium suitability covering the largest area (17,445.44 sq. km), followed by non-suitable (5,045.22 sq. km) and high suitability (3,463.806 sq. km) areas. However, the projections suggest substantial alterations in habitat suitability across future periods. In the 2050s, we observed a moderate increase in non-suitability areas (36.75%) compared to the current distribution. Medium suitability areas experience a slight decrease (-7.54%), while high suitability areas also decline (-15.54%). These changes indicate a potential redistribution of suitable habitats, with some areas becoming less favorable for *M. indica* tree species. By the 2070s, the trend intensifies, with a significant expansion of non-suitability areas (80.12%) and notable contractions in medium (-17.06%) and high suitability (-30.78%) areas. This suggests a considerable reduction in suitable habitats, potentially leading to habitat fragmentation and decreased species viability. In the 2090s, the situation worsens, with non-suitability areas continuing to increase (55.5%) and medium suitability areas showing a slight decrease (-3.14%). High suitability areas experience the most substantial decline (-65%), indicating a severe reduction in suitable habitats. This scenario poses significant challenges for *M. indica* tree species' survival and underscores the urgency of conservation efforts (Table 2 &Figure 3).

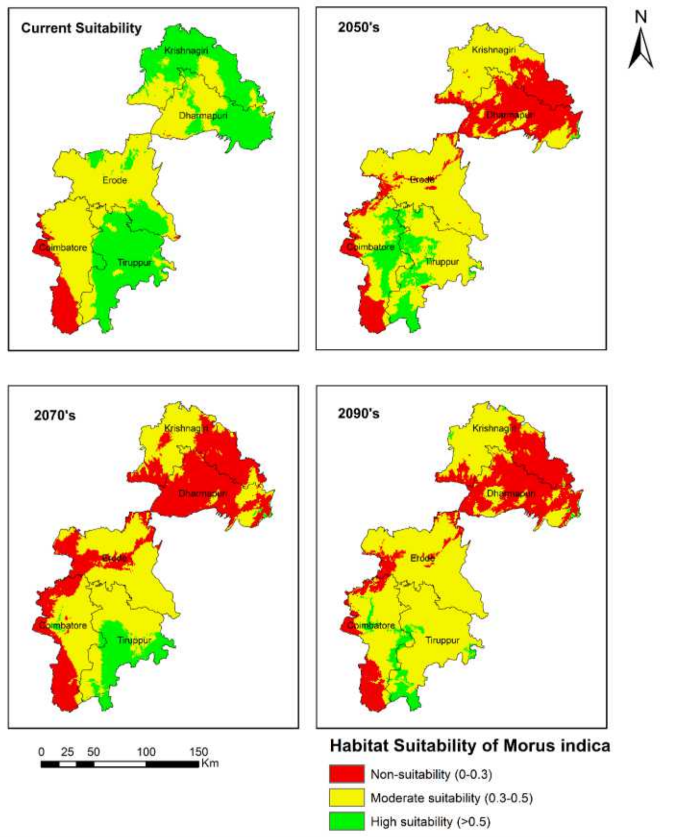

Figure 3. Habitat Suitability of M.indica

Table 2 Habitat suitability of M.indica

Projection year	Suitability Classification	Suitability Area (Sq.Km)	Comparison with current Distribution (%)
Current	< 0.3 (Non-suitable)	5045.22	-
	0.3-0.5 (Medium)	17445.44	-
	>0.5 (High)	3463.806	-
2050’s	< 0.3 (Non-suitable)	6899.233	36.75
	0.3-0.5 (Medium)	16129.74	-7.54
	>0.5 (High)	2925.488	-15.54
2070’s	< 0.3 (Non-suitable)	9087.46	80.12
	0.3-0.5 (Medium)	14469.51	-17.06
	>0.5 (High)	2397.49	-30.78
2090’s	< 0.3 (Low)	7845.158	55.50
	0.3-0.5 (Medium)	16896.8	-3.14
	>0.5 (High)	1212.504	-65.00

Factors influencing the habitat suitability of *M. indica*

The present analysis among 19 bioclimatic variables Bio 4, Bio 12, Bio 2, and Bio18 are the important predictors or major contributors to habitat suitability of *M. indica*, with temperature and precipitation variables (Bio 4, Bio 12, Bio 2) emerging as major contributors. Bio 4 emerges as the most influential variable, with a substantial percentage contribution (29.2%) and permutation importance (33.2%). This variable represents the temperature seasonality, which likely plays a pivotal role in shaping the habitat suitability of *M. indica*. Temperature fluctuations throughout the year can affect various aspects of species physiology, phenology, and ecological interactions, ultimately influencing habitat suitability. Bio 12 follows closely, contributing 20.8% to habitat suitability predictions, with a permutation importance of 7.2%. Bio 12 represents annual precipitation, a crucial factor for determining water availability and ecosystem productivity. Changes in precipitation patterns can significantly impact vegetation dynamics, affecting the suitability of habitats for *M. indica* tree species. Bio 2 ranks third in terms of contribution (17.1%) and permutation importance (12.4%). This variable represents the mean diurnal temperature range, which influences the thermal conditions experienced by species within their habitats. Fluctuations in diurnal temperature can affect physiological processes such as photosynthesis, growth, and reproduction, thereby influencing habitat suitability. Bio 18 contributes to habitat suitability predictions with 8.2% and a permutation importance of 5.5%. This variable represents precipitation of the warmest quarter, reflecting the availability of water during the critical growing season. Adequate moisture during this period is essential for supporting vegetation growth and maintaining suitable habitat conditions for *M. indica* tree species. Bio 14 and Bio 1 exhibit comparable contributions to habitat suitability, with percentages of 6.6% and 6.1%, respectively. However, they differ in permutation importance, with Bio 14 at 16% and Bio 1 at 17.3%. Bio 14 represents the precipitation of the driest month, while Bio 1 represents the annual mean temperature. Both variables are essential for assessing the climatic conditions that *M. indica* species can tolerate within their habitats. Bio 3 and Bio 15 contribute relatively less to habitat suitability predictions, with percentages of 6.4% and 5.6%, respectively.

These variables represent isothermality and precipitation seasonality, which may have indirect influences on habitat suitability through their interactions with other bioclimatic factors (Table 3).

Table 3. Primary contribution percent of the bioclimatic variables impacting the distribution of M.indica (%)

Variable	Percent contribution	Permutation importance
Bio 4	29.2	33.2
Bio 12	20.8	7.2
Bio 2	17.1	12.4
Bio 18	8.2	5.5
Bio 14	6.6	16
Bio 3	6.4	0.9
Bio 1	6.1	17.3
Bio15	5.6	7.7

Table 4. Key bioclimatic variables impacting the suitability of M.indica

Bioclimatic Variables	Temporal Scale	Current Period	2050s	2070s	2100
Bio4	Variation	204.90±3.06	210.23±29.39	215.98±29.93	216.01±29.88
Bio12	Annual	860.54±304.30	894.45±315.51	907.25±317.82	959.22±326.16
Bio1	Annual	26.59±1.92	27.14±1.91	27.67±1.91	27.90±1.90
Bio3	Variation	56.89±3.06	56.38±3.05	55.74±3.12	54.54±3.23
Bio18	Quarter	165.65±30.50	168.55±31.27	164.59±30.26	178.21±33.02
Bio14	Month	7.70±3.38	7.72±3.34	7.67±3.32	8±3.62
bio2	Variation	9.94±0.69	9.84±0.70	9.74±0.96	9.51±0.69
bio15	Variation	82.42±6.36	82.40±6.34	83.67±6.67	81.97±6.63

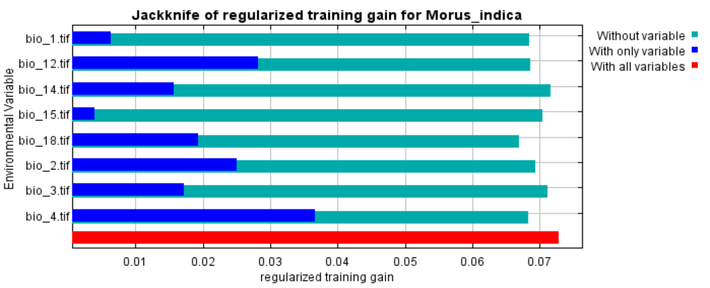

Figure 4. Jackknife test for variable importance of M.indica habitat suitability distribution

The optimum range of each bioclimatic variable varies across temporal scales (current period, 2050s, 2070s, and 2100), indicating how habitat suitability might change in the future due to climate change. Bio4

(Temperature Seasonality) shows an increasing trend in its optimum range over time, suggesting that species may need to adapt to greater temperature variations between seasons whereas Bio12 (Annual Precipitation) also shows an increasing trend in its optimum range, indicating potential changes in precipitation patterns that could impact habitat suitability (Table 4).

Conclusion

The present study highlights the need for proactive conservation measures to mitigate the adverse effects of climate change on *Morus india* tree species and their habitats. Adaptive management strategies that consider projected changes in habitat suitability and bioclimatic variables are essential for promoting species resilience and ensuring their long-term survival in a changing environment. By integrating spatial modeling techniques with bioclimatic analyses, we contribute to the evidence-based conservation planning necessary for preserving biodiversity and ecosystem integrity in the face of ongoing environmental changes.

Scope of the Study

This research explores the habitat suitability of *Morus indica* in Tamil Nadu, India, by utilizing MaxEnt modeling to examine current and future climate scenarios for the 2050s, 2070s, and 2090s. The study categorizes habitat suitability into non-suitable, medium, and high classifications and evaluates how these categories shift under varying climate projections. It highlights critical factors influencing habitat suitability, such as Temperature Seasonality, Annual Precipitation, Mean Diurnal Temperature Range, and Precipitation of the Warmest Quarter. The research addresses challenges in modeling these suitability parameters, including data constraints and the intricacies of predicting future climate impacts. Additionally, the study considers the implications for conservation strategies, emphasizing the need for proactive measures to address the negative effects of climate change on *Morus indica* habitats. By focusing on Tamil Nadu, the study offers insights relevant to similar ecological areas and aids in developing effective conservation strategies and policies.

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Data availability

The BIOCLIMATIC variables and Topographic data (SRTM DEM) were downloaded from the World Clim webpage (https://www.worldclim.org/data/index.html).

Declarations

Competing interests: The authors declare no competing interests.

Ethical approval

All authors have read, understood, and complied with the statement on "Ethical Responsibilities of Authors" as outlined in the Instructions for Authors.

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