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RESEARCH ARTICLE

Habitat suitability modeling for the conservation of *Exacum bicolor* Roxb.: An endangered, medicinal and ornamental species of Kerala's lateritic hillocks under current and future climatic scenarios

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Abstract

Exacum bicolor Roxb. (Gentianaceae) is a perennial herb with striking flowers and medicinal beneficial properties. Endemic to Peninsular India, it is currently listed as endangered. Despite its aesthetic and therapeutic value, the species remains underexplored and underutilized. Preserving the genetic diversity through *in-situ* or *ex-situ* conservation is essential to meet the growing demand for its medicinal and ornamental uses. A Maximum Entropy (MaxEnt) modeling approach was used to estimate the potential distribution of *E. bicolor* in Kerala, India, considering both present and future climatic scenarios, due to its efficiency with presence-only data. The MaxEnt model predicted habitat suitability for *E. bicolor* with an area of approximately 1126 km^2, showing high probability zones concentrated in the northern parts of Kerala. To evaluate habitat suitability, 22 environment parameters - including bioclimatic variables, soil types, agroecological zones, topographical features - were incorporated into the MaxEnt model. The most influential variables were precipitation of driest quarter (Bio17), water vapour pressure (January), annual precipitation (Bio12), mean diurnal range (Bio2), solar radiation (July and March), Topographic Position Index (TPI) and slope. Habitat suitability for *E. bicolor* was projected under future climate scenarios (2020-2100) using Shared Socioeconomic Pathways (SSPs) 126, 245, 370 and 585. In the SSP585 scenario, highly suitable areas for *E. bicolor* are anticipated to decrease by 14.20 % during the period of 2080-2100 compared to the current scenario. This decline is likely attributed to rising temperatures and decreasing rainfall, underscoring the need for climate-resilient conservation planning.

Keywords: *Exacum bicolor* Roxb.; habitat suitability; MaxEnt model; Shared Socioeconomic Pathways

Introduction

Exacum bicolor Roxb., a herbaceous perennial belonging to the Gentianaceae family is native to the Indian peninsula. Commonly known as "country kreat" and "Kannanthali" in Malayalam, it is valued for its both ornamental and medicinal properties. The plant bears dichasial cymes, with attractive violet-blue flowers and glossy, dark green, sessile leaves arranged opposite. Flowering and fruiting occur from August to December. The flowers 4-5 cm in diameter, have a field life of 8-10 days and, making the species ideal for use in the garden beds and as a potted ornamental. It is seed-propagated and can be cultivated year-round (1). Naturally, it occurs in scrub savannas and grassy hill slopes of the Deccan Peninsula and particularly at elevations of 50 and 200 m above sea level. *E. bicolor* populations are severely impacted by laterite mining, soil excavation for highways and cashew and rubber plantations. As per the cited literature, Kasargod, Kannur, Malappuram, Kozhikode, Wayanad, Palakkad and Thrissur were the reported major localities of *E. bicolor* in Kerala while Idukki, Pathanamthitta and Kottayam were reported with sparse occurrence (2, 3).

Species Distribution Models (SDMs) have become a cornerstone in ecology, evolutionary biology and conservation science as they help predict the potential range of species based on environmental and spatial data (4). These models are especially valuable in understanding species' ecological requirements, habitat preferences and potential responses to environmental changes (5). A closely related framework, Ecological Niche Modeling (ENM) uses statistical, machine learning and geospatial techniques to model species-environment interactions (6, 7). ENMs are extensively applied in ecological and biogeographical research by understanding the complex interactions between species and their environment. ENM informs conservation strategies, climate change impact and biodiversity management (8). Geostatistical models and tools are extensively utilized to simulate global plant species distributions, analyse spatial diversity patterns and assess climate change impacts (9, 10). Notably, the Maximum Entropy (MaxEnt) model has emerged as the most reliable approach for species distribution modeling.

Maximum Entropy (MaxEnt) is a software utilizing machine learning algorithms grounded in entropy maximization principles to predict plant species' geographic distributions and optimal habitats from presence-only data (11, 12). Maxent is a widely utilized ENM tool, with numerous studies focusing on enhancing its efficacy (13). The MaxEnt model (Maxent (amnh.org) which produces a species presence probability estimate with a range of 0 to 1, where 0 represents the lowest probability and 1 represents the highest. The software is freely available through the American Museum of Natural History (https://biodiversityinformatics.amnh.org/open_source/maxent/).

To accurately predict how climate change will impact plant survival and biodiversity, scientists employ the Shared Socioeconomic Pathways (SSPs), which detail future socioeconomic development, mitigation and adaptation challenges. The Shared Socioeconomic Pathways (SSPs) link socioeconomic and land-use changes to their effects on local climates, while simultaneously representing the varying levels of challenge for climate change mitigation and adaptation (14). To establish these scenarios, each SSP uses socioeconomic, demographic and integrated assessment models to provide quantitative data and project future socioeconomic growth (15). The present study considered the following four SSPs:

SSP126 (Sustainability): A low-emission scenario aligned with sustainable development goals, emphasizing equity, environmental awareness and international cooperation (16, 17).

SSP245 (Middle of the Road): Represents a moderate-emission pathway, where development progresses unevenly and mitigation efforts are sporadic, resulting in moderate challenges to climate adaptation (17).

SSP370 (Regional Rivalry): Characterized by high greenhouse gas emissions and limited international cooperation, this scenario reflects a fossil fuel-intensive world with strong regional disparities (16, 17).

SSP585: This scenario depicts emissions high enough to produce a radiative forcing of 8.5 W/m^2 in 2100. It also explains a world that emphasizes the traditional, fast growth of developing nations, which is based on high energy utilization and carbon-emitting advancements (16, 17).

The present study aimed to examine the habitat suitability modeling of *E. bicolor* in the lateritic hillocks of Kerala under different climatic scenarios.

Materials and methods

Field study and site evaluation

Extensive field surveys were conducted between June and November 2023-2024, covering both the South-West and North-East monsoon seasons, to document the geographical coordinate points in four districts of Kerala namely Kasargod, Kannur, Malappuram and Thrissur. During this period, we observed the species in both vegetative and flowering stages. A total of 13 occurrence points were recorded (Table 1), which served as representative habitats for further ecological modeling. Species presence data were collected using a 1 × 1 m quadrat method (18).

Ecological niche modeling of *E. bicolor*

ENM was conducted using MaxEnt software (version 3.4.4; [https://biodiversityinformatics.amnh.org/open_source/maxent/], accessed January 19, 2024) to predict the potential distribution of *E. bicolor* across different environmental gradients.

The geographical coordinates of the study sites were recorded and integrated into the modeling process. Bioclimatic variables, solar radiation data (January to December) and water vapor pressure data (January to December) were sourced from WorldClim (https://www.worldclim.org/). Additionally, Normalized Difference Vegetation Index (NDVI) data (January to December) was obtained from the Bhuvan portal (Indian Geo Platform of ISRO (nrsc.gov.in)). The overall methodology is illustrated in Fig. 1.

Soil types of Kerala

The soils of Kerala are classified into nine categories: 1) Coastal Alluvium, 2) Alluvium, 3) Acid Saline, 4) Kari Soil, 5) Laterite Soil, 6) Red Soil, 7) Hill Soil, 8) Black Cotton Soil and 9) Forest Soil. The soil map of Kerala (2001) was obtained from the Soil Survey Organization, Department of Agriculture and Farmers' Welfare, Government of Kerala and was digitized and converted to ASCII format in QGIS for integration into the MaxEnt modeling process.

Agroecological zones

Kerala is geographically divided into 13 distinct agro-ecological zones, categorized based on factors such as altitudinal gradients, precipitation patterns, soil characteristics and topographical features (19). These zones include 1) Central Midlands, 2) Chittor Black Soils, 3) Coastal Sandy, 4) High Ranges, 5) Kuttanad, 6) Malappuram Type, 7) Malayoram, 8) Northern Midlands, 9) Onattukara, 10) Palakkad Plains, 11) Red Loam, 12) Southern Midlands and 13) River Bank Alluvium. The districts surveyed fall under the Malappuram Type, Northern Midlands, Central Midlands and Malayoram zones. The agroecological map of Kerala (2011) was sourced from the Cartography, GIS Processing

Table 1. Geographical locations of *Exacum bicolor* in various districts of Kerala

SI No	Place name	District name	Latitude (degrees)	Longitude (degrees)	Altitude (m MSL)
01	Thalakottukara	Thrissur	10.6217	76.135877	34.99
02	Puranattukara	Thrissur	10.558472	76.167518	20.99
03	Kumbla	Kasargod	12.582987	74.983635	80.99
04	Puthige	Kasargod	12.613948	75.008722	87.99
05	Dharmatadka	Kasargod	12.667981	75.024595	239.99
06	Kudalmarkala	Kasargod	12.669415	75.019698	239.99
07	Neerchal	Kasargod	12.57555	75.07017	107.9
08	Seethangoli	Kasargod	12.589287	75.010028	87.99
09	Nekreje	Kasargod	12.553546	75.070229	114.9
10	Pariyaram	Kannur	12.07653	75.290232	48.99
11	Kannamvettikavu	Malappuram	11.185527	75.905494	52.99
12	Vazhayur	Malappuram	11.201205	75.901138	52.99
13	Peringave	Malappuram	11.206067	75.902668	58.99

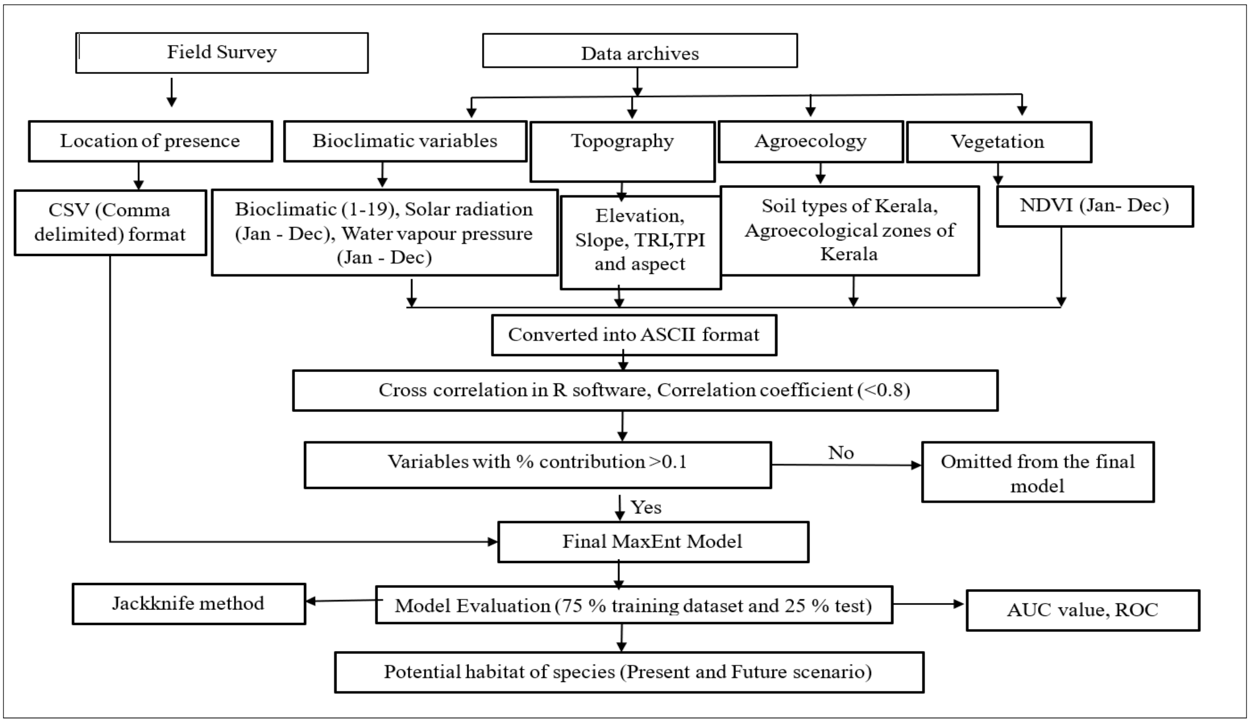

Fig. 1. Flow chart showing the methodology used in habitat suitability of *E. bicolor*.

and Production unit at the Centre for Land Resource Research and Management, KAU, Thrissur. This map was digitized and converted into ASCII format using QGIS for integration into the MaxEnt modeling process.

Slope

Slope refers to the rate of change in altitude in the direction of the steepest descent (20) and is expressed either in degrees or as a percentage.

Aspect

Aspect indicates the direction a slope faces or the line of steepest descent and it is measured in degrees (20).

Terrain Ruggedness Index (TRI)

Terrain Ruggedness Index (TRI) evaluates topographical heterogeneity by determining the mean elevation difference between a pixel and its eight adjacent pixels (21).

Topographic Position Index (TPI)

It indicates the variation between the elevation of a particular cell and the average elevation of its neighbouring cells. Positive values signify regions that are elevated compared to their surroundings, such as peaks and summits, whereas negative values indicate low-lying areas like valleys and depressions. Regions that are flat or exhibit a uniform slope are represented by values close to zero (21, 22).

Digital Elevation Model (DEM)

The SRTM Digital Elevation Model (DEM) was sourced from the WorldClim archive and used to derive additional topographic variables such as slope, aspect, Terrain Ruggedness Index (TRI) and TPI and converted to ASCII format using QGIS for use in MaxEnt modeling. This DEM provides a map-like representation of the Earth's surface, where each pixel corresponds to a specific elevation (21).

Model building and assessment

For MaxEnt data preparation, the geographic coordinates of 13 occurrence points were converted into CSV format using MS Excel. Environmental parameters, including bioclimatic variables such as monthly temperature (°C), precipitation (mm), solar radiation (kJ/m^2/day) and water vapor pressure (kPa), were sourced from the World Climate Data Portal (https://www.worldclim.org/). The bioclimatic data, available at a 30 arc-second resolution, was downloaded in GRID ('.grd') format and converted into ASCII ('.asc') format using QGIS 3.28 to ensure compatibility with the MaxEnt model.

Since including too many environmental variables may introduce multicollinearity and spatial autocorrelation—both of which reduce model accuracy and transferability (23, 24) - a pairwise correlation analysis was performed using R 4.3.3. To prevent overfitting, correlation analysis (r) was performed, eliminating one variable from pairs with correlation values (r > 0.80) (25). A correlation matrix of environmental variables was generated using R 4.3.3. From the initial 62 environmental variables, 40 highly correlated variables were discarded, leaving 22 variables with correlation coefficients below 0.8 to be used in the MaxEnt model (Table 2).

Model tuning and validation and evaluation of model performance

MaxEnt v3.4.4 was used to build the habitat suitability model using the species occurrence data and selected environmental variables. The dataset was randomly partitioned into 75 % for training and 25 % for testing (26). The Jackknife test was used to assess the percent contribution and permutation importance of each variable (25). Using the "leave-one-out" method, training gain was compared by systematically removing one variable at a time (27, 28). The MaxEnt output was an ASCII grid layer representing habitat suitability (0 = unsuitable, 1 = highly suitable) (29). We classified habitat as low suitable (0-0.6), moderately suitable (0.6-0.8) and highly suitable (0.8-1.0) based on the probability of suitability, with results visualized in QGIS.

Table 2. Environmental parameters with correlation <0.8

Sl. No	Environmental parameters	Unit
1.	Bio1 - Annual mean temperature	°C
2.	Bio2 - Mean diurnal range	°C
3.	Bio3 - Isothermality	°C
4.	Bio12 - Annual precipitation	mm
5.	Bio15 - Precipitation seasonality	mm
6.	Bio17 - Precipitation of driest quarter	mm
7.	Bio18 - Precipitation of warmest quarter	mm
8.	Srad_1 - Solar radiation (January)	$kJ/m^2/day$
9.	Srad_3 - Solar radiation (March)	$kJ/m^2/day$
10.	Srad_6 - Solar radiation (June)	$kJ/m^2/day$
11.	Srad_7 - Solar radiation (July)	$kJ/m^2/day$
12.	Srad_9 - Solar radiation (September)	$kJ/m^2/day$
13.	Srad_10 - Solar radiation (October)	$kJ/m^2/day$
14.	Water vapour pressure (January)	kPa
15.	Agro-ecological zones of Kerala 1) Central midlands, 2) Chittor black soils, 3) Coastal sandy, 4) High ranges, 5) Kuttanad, 6) Malappuram type, 7) Malayoram, 8) Northern midlands, 9) Onattukara, 10) Palakkad plains, 11) Red loam, l2) Southern midlands, 13) River bank alluvium	
16.	Soil types of Kerala 1) Coastal alluvium, 2) Alluvium, 3) Acid saline, 4) Kari soil, 5) Laterite soil, 6) Red soil, 7) Hill soil, 8) Black cotton soil, 9) Forest soil	
17.	Elevation (DEM)	m
18.	TRI - Terrain Ruggedness Index	m
19.	TPI - Topographic Position Index	m
20.	Slope	%
21.	Aspect	Degree
22.	NDVI - Normalized Difference Vegetation Index (August 31st)	Ratio

Model performance was evaluated using the area under curve (AUC) of the receiver operating characteristic (ROC) curve, which is a standard metric in MaxEnt for assessing model discrimination ability (30). Model performance was graded as poor (AUC < 0.8), fair (0.8 < AUC < 0.9), good (0.9 < AUC < 0.95) and very good (0.95 < AUC < 1.0) (31). In general, AUC values greater than 0.75 are significant and are thought to be reliable indicators of the suitability of a habitat. While AUC values <0.7 were considered as bad descriptors, values ranging from 0.7 to 0.9 showed fair predictive abilities and values >0.9 acted as strong descriptors (32, 33). AUC values between 0.9 and 1 indicated high accuracy (34).

To predict the potential future distribution of *E. bicolor*, environmental layers representing four Shared Socioeconomic Pathways (SSP126, SSP245, SSP370 and SSP585) were applied across four future timeframes: 2020-2040, 2040-2060, 2060-2080 and 2080-2100. These datasets were obtained from WorldClim CMIP6 projections, based on the MIROC6 global climate model, at a spatial resolution of 30 arc-seconds. The same set of 22 selected environmental variables was used for consistency and all raster layers were preprocessed in QGIS for compatibility with MaxEnt.

Results

Model evaluation and potential suitable habitat for *E. bicolor* under present scenario

The AUC value of the model was used to evaluate its prediction performance and it was observed to be 0.996 for training data and 0.990 for the test data (Fig. 2). In the current scenario the highly suitable habitats for *E. bicolor* are mainly distributed in the northern districts of Kerala namely, Kasargod, Kannur, Malappuram, Palakkad and Thrissur. Predicted area using the MaxEnt modeling for the current distribution of *E. bicolor* was to the tune of 1126 km^2(0.8-1.0 range). Moderately suitable zones (suitability index 0.6-0.8) were visualized in green on the habitat suitability map, while low suitability areas (<0.6) covered an estimated 37737 km^2 and were indicated in light yellow (Fig. 3). These results indicate that *E. bicolor* thrives best in central and northern parts of Kerala, particularly in hillocks and open lateritic zones.

Relative contribution of dominant environmental variables using Jackknife method

The estimated percentages of environmental variables that support the MaxEnt model in relation to one another are shown in Table 1. From the jackknife analysis, out of a total 22 environmental variables, eight variables namely, precipitation of driest quarter (Bio17), water vapour pressure (January), annual precipitation (Bio12), mean diurnal range (Bio2), solar radiation (July), TPI, solar radiation (March) and slope showed a significant role in predicting the current distribution of the *E. bicolor*. Their individual contribution was 20.8 %, 16.9 %, 16.6 %, 14.8 %, 11.8 %, 9 %, 8.8 % and 1.3 %, respectively (Table 3, Fig. 4). These results confirm that *E. bicolor* favors lateritic hillocks in northern Kerala with specific precipitation and radiation profiles, suggesting the importance of microclimate and topography in its habitat preference.

Range of environmental variables for the growth of *E. bicolor*

It was observed from the field survey that under the present scenario, *E. bicolor* could thrive in regions with annual precipitation (Bio12) ranging from 2938 mm to 4421 mm, precipitation of driest quarter (Bio17) ranging from 7 mm to 36

Table 3. Contribution of environmental variables in distribution modeling of *E. bicolor*

Variables	Percent contribution
Precipitation of driest quarter (Bio17)	20.8
Water vapour pressure (January)	16.9
Annual precipitation (Bio12)	16.6
Mean diurnal range (Bio2)	14.8
Solar radiation (July)	11.8
Topographic Position Index (TPI)	9
Solar radiation (march)	8.8
Slope	1.3

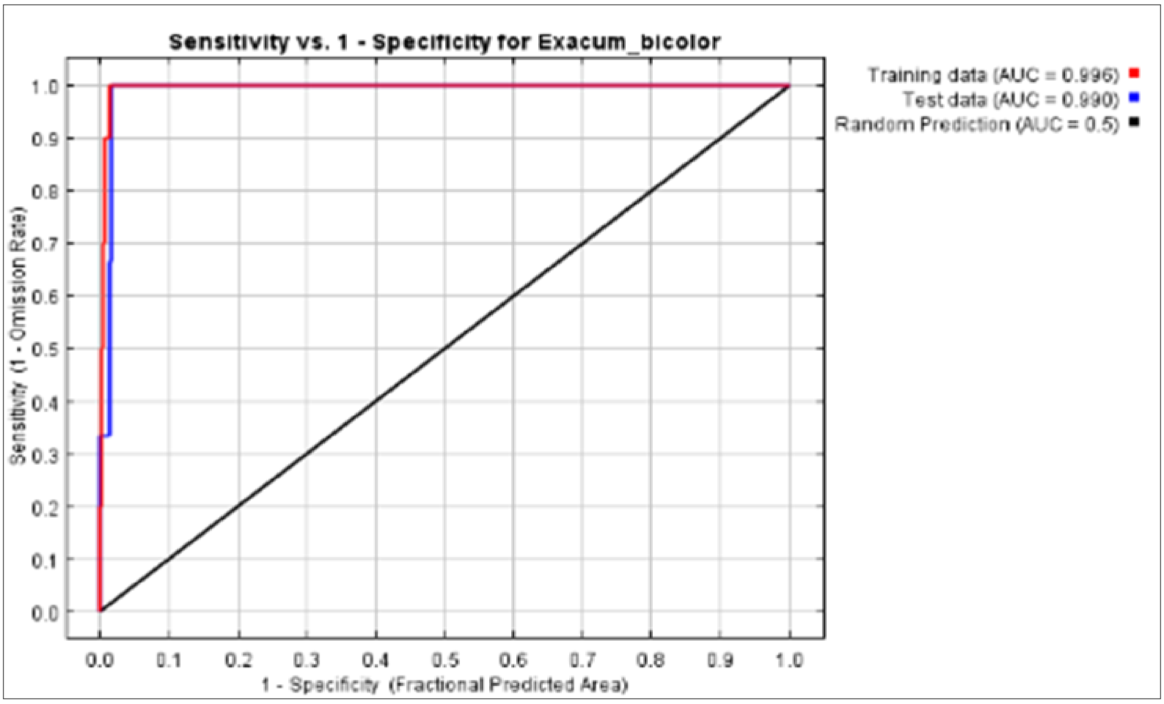

Fig. 2. Result of AUC in developing habitat suitability model for *E. bicolor*.

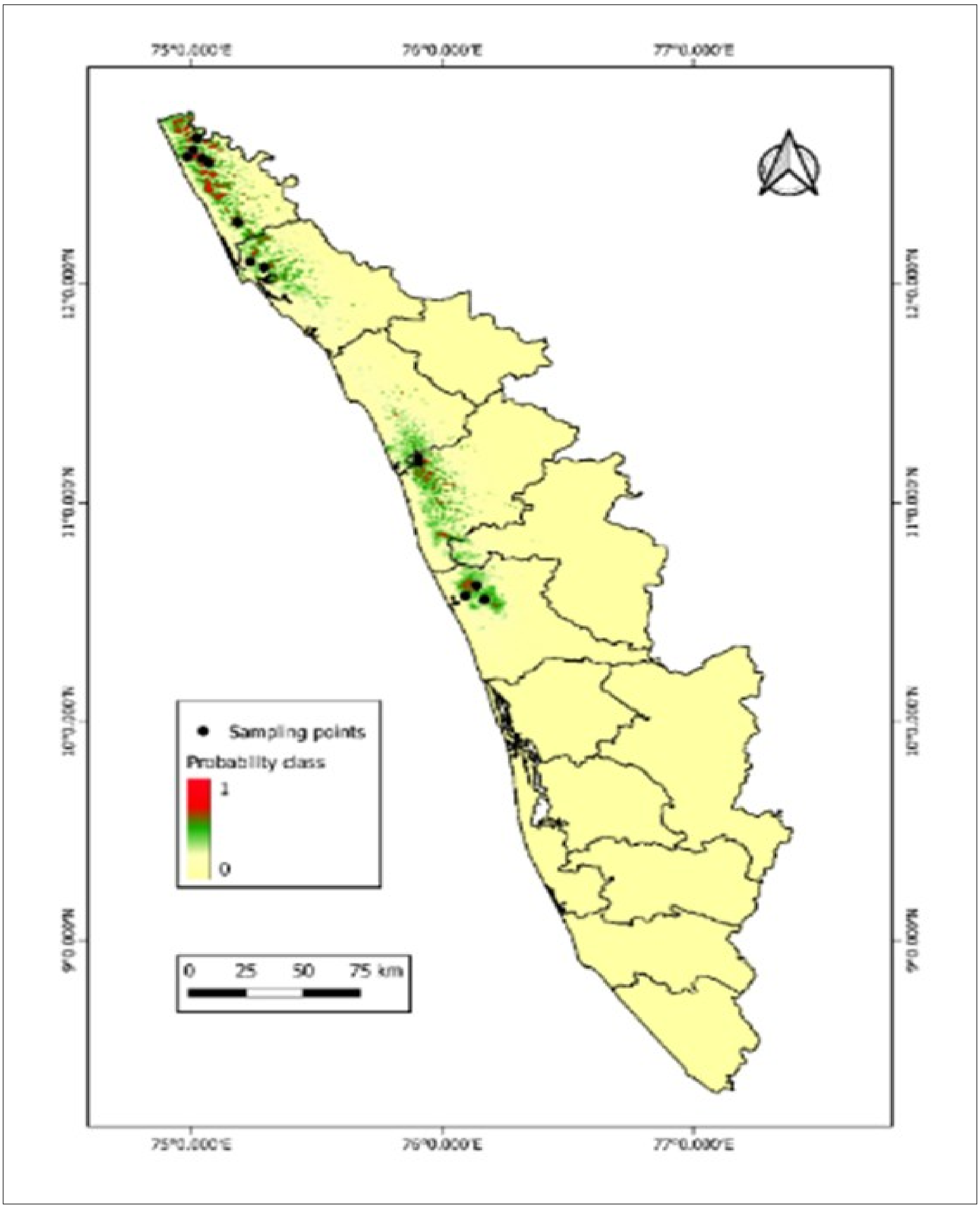

Fig. 3. Habitat suitability of *E. bicolor* in the state of Kerala, India.

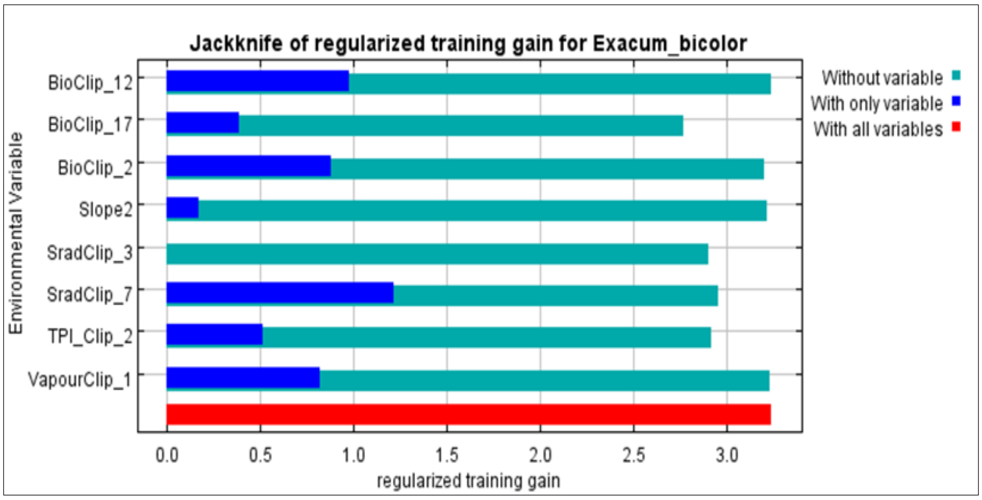

Fig. 4. Regularized training gain of dominant environmental variables using Jackknife method in *E. bicolor*.

mm, solar radiation (March) ranging from 23449 kJ/m^2/day to 24560 kJ/m^2/day, solar radiation (July) ranging from 16093 kJ/m^2/day to 16465 kJ/m^2/day, water vapour pressure ranging from 2.15 kPa to 2.41 kPa, maximum temperature ranging from 30.4 °C to 31.5 °C and minimum temperature ranging from 21.9 °C to 23.7 °C, TPI ranging from 5 m to 80 m.

These values represent the ecological envelope within which *E. bicolor* can persist and flourish (Table 4).

Marginal response curves

A marginal response curve shows how predicted habitat suitability or species occurrence shifts with incremental changes in a specific environmental variable, while all other variables are held constant at their average values. The marginal response curve for the environmental variables which were contributing to the model revealed that the areas of habitat suitability of *E. bicolor* were primarily influenced by annual precipitation (Bio12): ~ 4500 mm, precipitation of driest quarter (Bio17); ~ 20 mm, mean diurnal range (Bio2): ~ 6.0 °C, slope: ~ 5 %, solar radiation (March): ~ 21600 kJ/m^2/day, solar radiation (July): ~ 15300 kJ/m^2/day, TPI: ~ 50 m and water vapour pressure (January) :~ 2.5 kPa (Fig. 5). These values suggest that *E. bicolor* prefers moderately elevated, gently sloping areas with high annual rainfall and relatively stable temperature regimes.

Potential ecologically suitable distribution of *E. bicolor* under future climatic scenarios

To assess the potential future distribution of *E. bicolor* under varying climate conditions, the MaxEnt model was applied across four Shared Socioeconomic Pathway (SSP) scenarios-SSP126, SSP245, SSP370 and SSP585-covering the time periods 2020-2040, 2040-2060, 2060-2080 and 2080-2100. The four SSPs (Shared Socioeconomic Pathway) scenarios namely SSP126, SSP245, SSP370 and SSP585 were considered. The ecologically suitable distribution areas for *E. bicolor* were primarily concentrated in Kasargod, Kannur, Malappuram, Kozhikode, Palakkad and Thrissur under all Shared Socioeconomic Pathways (SSPs) scenarios. This consistent spatial pattern suggests that these regions may serve as long-term refugia for the species despite potential climatic fluctuations.

SSP126

Under SSP126, the MaxEnt model maintained strong predictive performance across future time slices. AUC values for the training dataset were 0.996 (present), 0.980 (2020-2040), 0.980 (2040-2060), 0.981 (2060-2080) and 0.980 (2080-2100). Corresponding AUC values for the test dataset were 0.990 (present), 0.995 (2020-2040), 0.990 (2040-2060), 0.970 (2060-2080) and 0.988 (2080-2100) (Table 5). These high values indicate the model's reliability in predicting future habitat suitability.

Under the SSP126 scenario, the area classified as highly suitable for *E. bicolor* increased consistently across most future periods. It expanded from 1126 km^2 in the present to 1169 km^2 (2020-2040; +3.8 %), 2280 km^2 (2040-2060; +102 %), 1999 km^2 (2060-2080; +77.5 %) and peaked at 2982 km^2 (2080-2100; +164 %) compared to the present (Fig. 6). Although a slight decline was noted between 2040-2060 and 2060-2080, the overall trend suggests a significant increase in suitable habitat under this low-emission, sustainability-focused scenario.

Table 4. Descriptive statistics of the environmental variables at the occurrence points of *E. bicolor* which were considered for the model run

Variables	Minimum value	Maximum value	Mean and SD
Annual Mean Temperature (°C)	26.2	27.6	26.9 ± 4.5
Maximum Temperature (°C)	30.4	31.5	31.09 ± 1.9
Minimum Temperature (°C)	21.9	23.7	22.94 ± 1.1
Annual precipitation (mm)	2938	4421	3685 ± 563
Precipitation of driest quarter (mm)	7	36	17.63 ± 11.17
Mean diurnal range (Bio2) (°C)	7.0	7.7	7.28 ± 2
Solar radiation (March) (kJ/m^2/day)	23449	24560	24053 ± 356
Solar radiation (July) (kJ/m^2/day)	16093	16465	16236 ± 123
Water vapour pressure (January) (kPa)	2.15	2.41	2.92 ± 0.08
Topographic Position Index (TPI) (m)	-1.1	80	25.5 ± 24.8

Table 5. AUC values of training and test data of the model for SSP126 scenario

Area under curve (AUC)	Present scenario	2020-2040	2040-2060	2060-2080	2080-2100
Training data	0.996	0.980	0.980	0.981	0.980
Test data	0.990	0.995	0.990	0.970	0.988

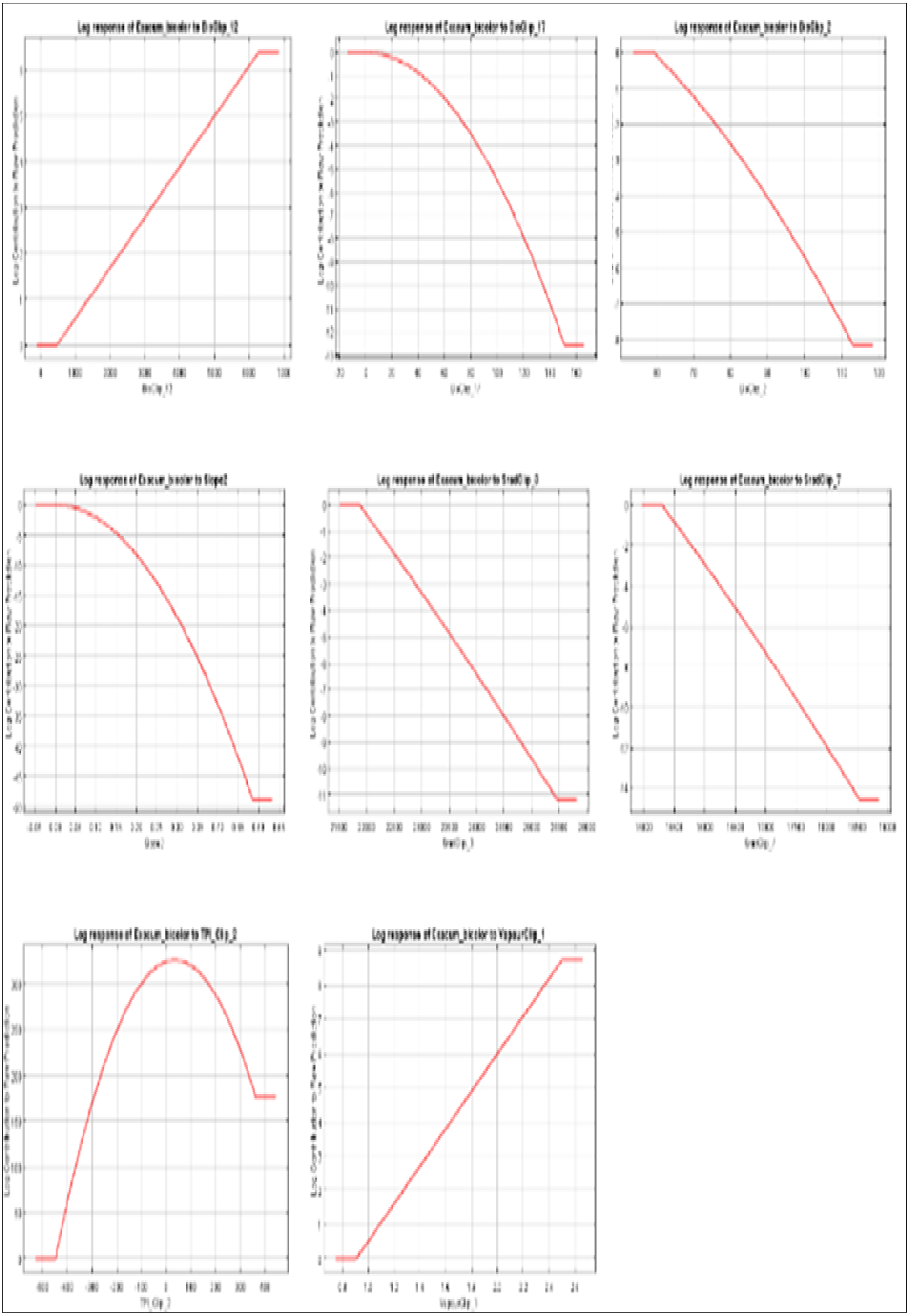

Fig. 5. Marginal response curves for important environmental variables affecting the distribution of *E. bicolor* in Kerala. (a) Annual precipitation (Bio12), (b) Precipitation of driest quarter (Bio17), (c) Mean diurnal range (Bio 2), (d) Slope, (e) Solar radiation (March), (f) Solar radiation (July), (g) Topographic Position Index (TPI), (h) Vapour pressure (January).

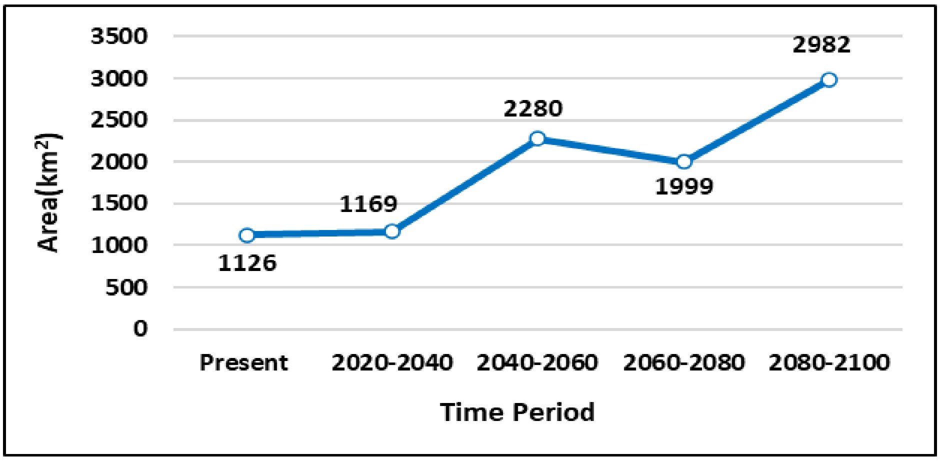

Fig. 6. Area under high suitability of *E. bicolor* as per SSP126 scenario.

The annual mean temperature extracted from the bioclimatic data set for *E. bicolor* varied from 26.9 °C (present scenario) to 27.6 °C (2020-2040), 27.8 °C (2040-2060), 27.8 °C (2060 -2080) and 27.9 °C (2080-2100). Maximum temperature extracted from the bioclimatic datasets varied from 31 °C (present scenario) to 31.6 °C (2020-2040), 31.8 °C (2040-2060), 31.9 °C (2060 -2080) and 31.9°C (2080-2100). The minimum temperature observed were 22.9 °C (present scenario) to 23.6 °C (2020-2040), 23.83 °C (2040-2060), 23.89 °C (2060-2080) and decreases to 23.85 °C (2080-2100). Rainfall increased from 3685 mm (present scenario) to 3718 mm (2020-2040), 3764 mm (2040-2060), decreased to 3744 mm (2060-2080) and again increased to 4232 mm (2080-2100). In general, there was an increase in rainfall and mean temperature (Fig. 7). These favorable shifts in climatic conditions likely contribute to the projected expansion of suitable habitats for *E. bicolor* under this scenario.

SSP245

The AUC value for training data was 0.996 (present scenario), 0.987 (2020-2040), 0.985 (2040-2060), 0.982 (2060-2080) and 0.997 (2080-2100). The AUC value for test data was 0.990 (present scenario), 0.953 (2020-2040), 0.983 (2040-2060), 0.966 (2060-2080) and 0.965 (2080-2100) (Table 6). Despite some fluctuation, the model performed consistently well across all projected periods.

The area of high suitability of *E. bicolor* increased from 1126 km^2 (present scenario) to 1274 km^2 (2020-2040), 1781 km^2 (2040-2060), 1557 km^2 (2060-2080) and 1833 km^2(2080-2100) with percentage increase of 13.1 %, 58.1 %, 38.2 % and 62.7 %, respectively with corresponding to present scenario (Fig. 8).

The annual mean temperature extracted from the bioclimatic data set for *E. bicolor* varied from 26.9 °C (present scenario) to 27.6 °C (2020-2040), 28.0 °C (2040-2060), 28.3 °C (2060-2080) and 28.64 °C (2080-2100). Maximum temperature extracted from the bioclimatic datasets varied from 31.09 °C (present scenario) to 31.7 °C (2020-2040), 32 °C (2040-2060), 32.4 °C (2060-2080) and 32.7 °C (2080-2100). The minimum temperature observed were 22.9 °C (present scenario) to 23.6 °C (2020-2040), 24 °C (2040-2060), 24.3 °C (2060-2080) and 24.6 °C (2080-2100). Rainfall decreased from 3685 mm (Present scenario) to 3660 mm (2020-2040) and increased to 3721 mm (2040-2060) and again decreased to 3671 mm (2060-2080) and 3659 mm (2080-2100). In general, there was a decrease in rainfall and increase in mean temperature during by the time period 2080-2100 (Fig. 9).

SSP370

The AUC value for training data was 0.996 (present scenario), 0.980 (2020-2040), 0.971 (2040-2060), 0.972 (2060-2080) and 0.982 (2080-2100). The AUC value for test data was 0.990 (present

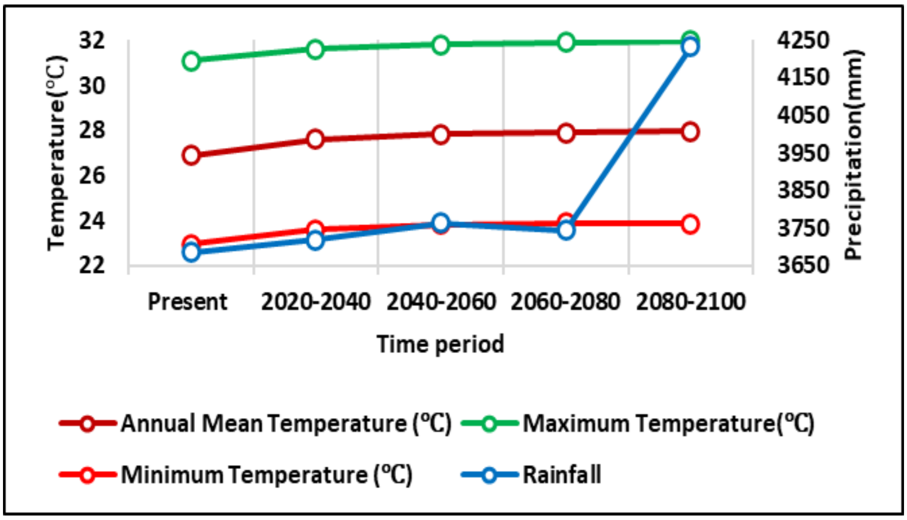

Fig. 7. Temperature and precipitation at the occurrence points of *E. bicolor* as per SSP126 scenario.

Table 6. AUC values of training and test data of the model for SSP245 scenario

Area under curve (AUC)	Present scenario	2020-2040	2040-2060	2060-2080	2080-2100
Training data	0.996	0.987	0.985	0.982	0.977
Test data	0.990	0.953	0.983	0.966	0.965

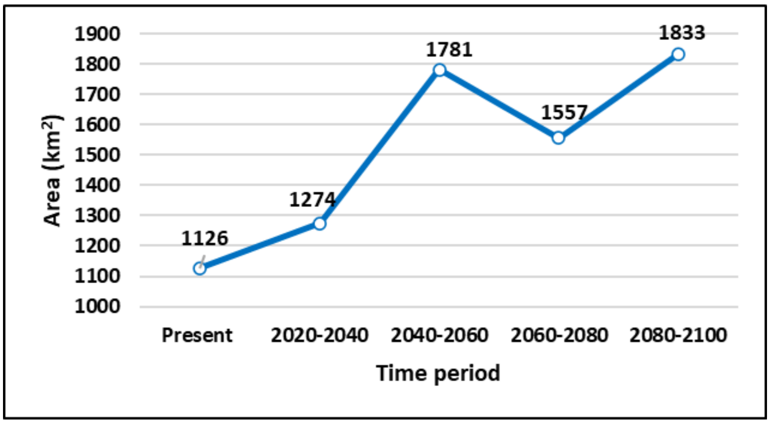

Fig. 8. Area under high suitability of *E. bicolor* as per SSP245.

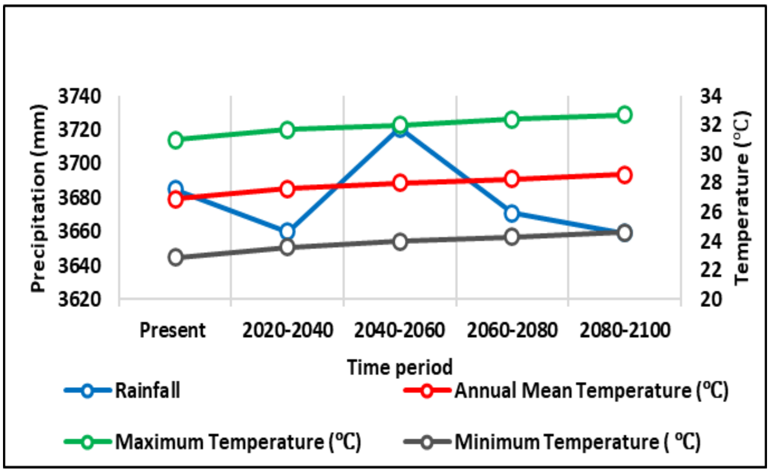

Fig. 9. Temperature and precipitation at the occurrence points of *E. bicolor* as per SSP245 scenario.

scenario), 0.988 (2020-2040), 0.994 (2040-2060), 0.958 (2060-2080) and 0.972 (2080-2100) (Table 7). Although a slight dip was observed in 2060-2080, the model remained highly accurate across all periods.

The area of high suitability of *E. bicolor* increased from 1126 km^2 (present scenario) to 1498 km^2 (2020-2040), 2109 km^2 (2040-2060), 1722 km^2 (2060-2080) and 1952 km^2 (2800-2100) with percentage increase 24.8 %, 87.3 %, 52.9 % and 73.35 %, respectively in corresponding to present scenario (Fig. 10).

The annual mean temperature extracted from the bioclimatic data set for *E. bicolor* varied from 26.9 °C (present scenario) to 27.6 °C (2020-2040), 28.1 °C (2040-2060), 28.8 °C (2060 -2080) and 29.3 °C (2080-2100). Maximum temperature extracted from the bioclimatic datasets varied from 31 °C (present scenario) to 31.6 °C (2020 -2040), 32.9 °C (2040-2060), 32.8 °C (2060-2080) and 33.6 °C (2080-2100). The minimum temperature extracted from the bioclimatic datasets varied from 22.94 °C (present scenario) to 23.5 °C (2020-2040), 24.1 °C (2040-2060), 24.7 °C (2060-2080) and 25.2 °C (2080-2100). Rainfall decreased from 3685 mm (present scenario) to 3682 mm (2020-2040), 3616 mm (2040-2060), 3566 mm (2060-2080) and 3507 mm (2080-2100). In general, there was an increase in temperature and decrease in rainfall (Fig. 11).

Table 7. AUC values of training and test data of the model for SSP370 scenario

Area under curve (AUC)	Present scenario	2020-2040	2040-2060	2060-2080	2080-2100
Training data	0.996	0.980	0.971	0.972	0.982
Test data	0.990	0.988	0.994	0.958	0.972

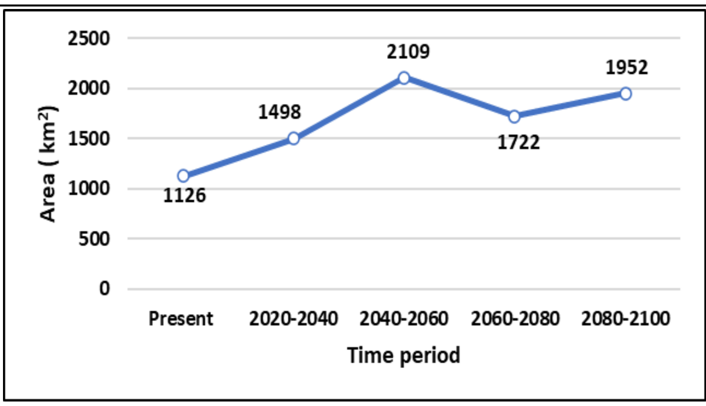

Fig. 10. Area under high suitability of *E. bicolor* as per SSP370 scenario.

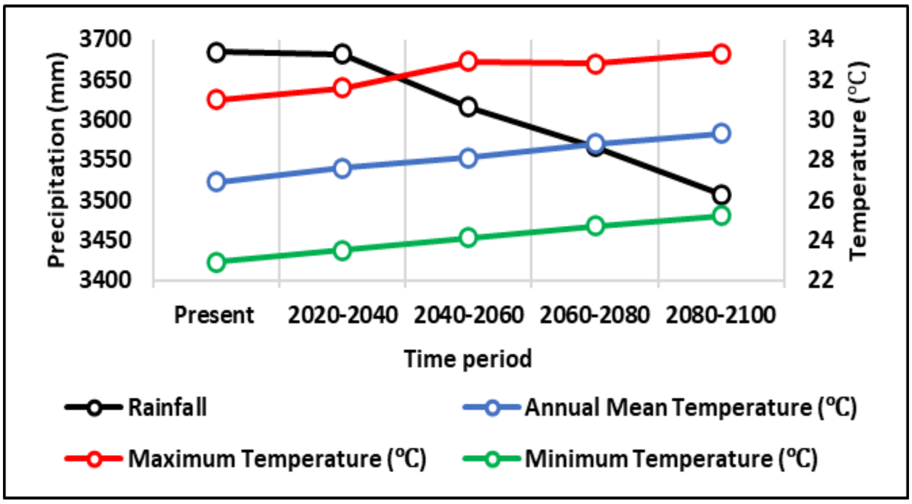

Fig. 11. Temperature and precipitation at the occurrence points of *E. bicolor* as per SSP370 scenario.

SSP585

The AUC value for training data was 0.996 (present scenario), 0.983 (2020-2040), 0.981 (2040-2060), 0.979 (2060-2080) and 0.990 (2080-2100). The AUC value for test data is 0.990 (present scenario), 0.996 (2020-2040), 0.988 (2040-2060), 0.961 (2060-2080) and 0.947 (2080-2100) (Table 8). This reduction may reflect increased uncertainty in the model under more extreme climate scenarios.

The area of high suitability of *E. bicolor* increased from 1126 km^2 (present scenario) to 2363 km^2 (2020-2040), 1670 km^2 (2040-2060) and 1135 km^2 (2060-2080) with percentage increase of 109 %, 48.3 %, 0.79 % the area of high suitability decreased with a value 966 km^2 (2800-2100) with percentage decrease of 14.20 % with corresponding to present scenario (Fig. 12). This trend suggests that the species may face critical habitat loss under high-emissions scenarios toward the century's end.

The annual mean temperature extracted from the bioclimatic data set for *E. bicolor* varied from 26.9 °C (present scenario) to 27.7 °C (2020-2040), 28.4 °C (2040-2060), 29.6 °C (2060-2080) and 30.3 °C (2080-2100). Maximum temperature extracted from the bioclimatic datasets varied from 31 °C (present scenario) to 31.8 °C (2020-2040), 32.5 °C (2040-2060), 33.3 °C (2060-2080) and 34.3 °C (2080-2100). The minimum temperature observed were 22.94 °C (present scenario) to 23.7 °C (2020-2040), 24.3 °C (2040-2060), 25.1°C (2060-2080) and 26 °C (2080-2100). Rainfall decreased from 3685 mm (present scenario) to 3640 mm (2020-2040), 3587 mm (2040-2060), 3533 mm (2060-2080) and 3413 mm (2080-2100) In general, there was a decrease in rainfall and increase in mean temperature throughout the period (Fig. 13).

Discussion

Ecological niche modeling

The present study utilized species distribution modeling (SDM) techniques to evaluate potential shifts in the distribution of suitable habitats for the medicinal native ornamental plant *E. bicolor* Roxb., in the lateritic hillocks of Kerala, India. SDM has emerged as a critical tool in ecological research and conservation, allowing researchers to predict how species' habitats may change under different environmental conditions, particularly in response to climate change. This approach not only helps identify key areas where species are vulnerable to habitat loss but also highlights gaps in current conservation and management strategies.

Table 8. AUC values of training and test data of the model for SSP370 scenario

Area under curve (AUC)	Present scenario	2020-2040	2040-2060	2060-2080	2080-2100
Training data	0.996	0.983	0.981	0.979	0.990
Test data	0.990	0.996	0.988	0.961	0.947

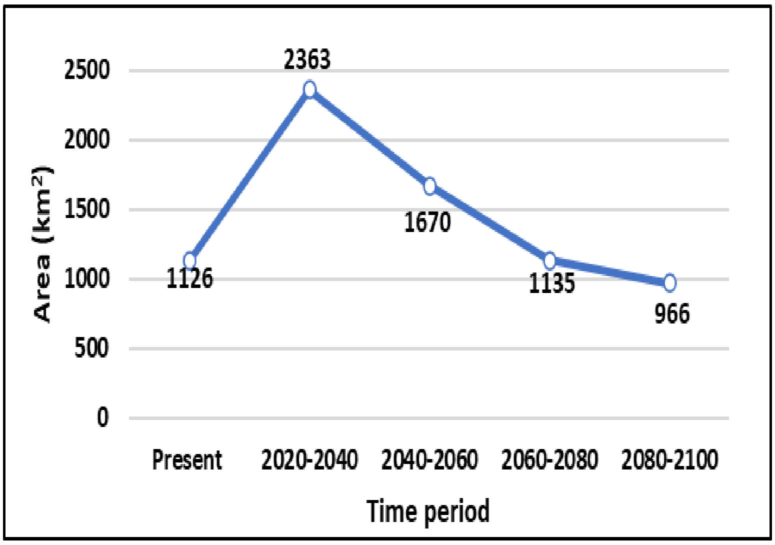

Fig. 12. Area under high suitability of *E. bicolor* as per SSP585 scenario.

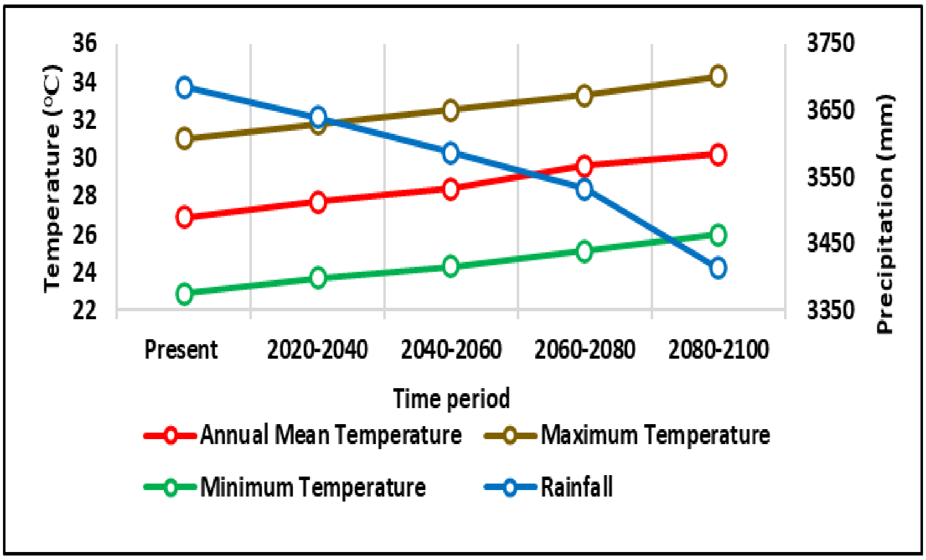

Fig. 13. Temperature and precipitation at the occurrence points of *E. bicolor* as per SSP585 scenario.

Populations of *E. bicolor* are facing severe threats due to activities such as laterite mining, soil excavation for highway construction and the expansion of cashew and rubber plantations. These activities lead to habitat destruction and degradation, significantly reducing the available suitable environments for the species to thrive (2).

Utilizing CMIP6 data, this study employed MaxEnt (3.4.4), QGIS (3.28) and R Studio (4.3.3) to model and map the potential distribution of *E. bicolor* in Western Ghats, Kerala, India, under current and future scenarios, highlighting cultivation planning and conservation efforts. The results not only help to inform site-specific conservation priorities but also support proactive planning for *in-situ* conservation and potential *ex-situ* cultivation in areas projected to remain climatically favorable.

Influence of environmental variables in species distribution modeling of *E. bicolor*

AUC values below 0.75 are generally considered to indicate poor model performance, while values above 0.75 suggest a good model fit (35). The model showed high predictive accuracy, with AUC value of 0.996 for training data and 0.990 for test data. Additionally, the predictions of model closely aligned with the actual geographical distribution of *E. bicolor* in Kerala.

The present results indicated that precipitation of driest quarter (Bio17), water vapour pressure (January), annual precipitation (Bio12), mean diurnal range (Bio2), solar radiation (July), TPI, solar radiation (March) and slope were the most influencing variables to generate habitat suitability map of *E. bicolor*.

Marginal response curves indicated that high suitability zones for *E. bicolor* were associated with TPI values ranging from approximately 50 m to 100 m. TPI values near zero represent flat terrains, values slightly above zero correspond to gentle, constant slopes and higher positive values indicate elevated features such as ridges or peaks (36). In this study, *E. bicolor* predominantly occurred in regions with TPI values greater than zero, suggesting its preference for moderately elevated or gently sloping terrains rather than flat lowlands.

Impact of climate change under future scenario

The Coupled Model Intercomparison Project (CMIP) is a collaborative initiative aimed at addressing emerging scientific questions related to climate change. Shared Socioeconomic Pathways (SSPs) are used as input parameters for climate prediction models, incorporating the effects of human activities. SSPs describe potential future emissions of greenhouse gases, reactive gases, aerosol particles and other atmospheric constituents, taking into account factors such as population growth, socioeconomic changes, advancements in science and technology, energy usage and land use patterns (37). Among the four SSP scenarios, SSP585 is identified as the worst-case climate change scenario, with severe consequences (38). Under the current climate, MaxEnt modeling estimated that the highly suitable habitats for *E. bicolor* are mainly distributed in Kasargod, Kannur, Malappuram and Thrissur, covering an area of 1126 km^2. In future climate scenarios under SSP126, SSP245 and SSP370, the area of high habitat suitability is expected to expand over the period from 2020 to 2100. However, under the SSP585 scenario, the high-suitability area is projected to shrink by 14.20 % during the 2080-2100 period. Climate modeling reveals contrasting impacts on suitable habitat of *E. bicolor* in Kerala. While SSP126, SSP245 and SSP370 show expanding high-suitability areas over the century (2020-2100), the SSP585 scenario indicates a decline, especially in the districts of Malappuram and Thrissur, by 2080-2100 as shown in Fig. 14.

Conclusion

This study employed the MaxEnt modeling approach to predict the habitat suitability of *E. bicolor* under present and future climate scenarios. The results indicated that the precipitation of driest quarter (Bio17), water vapour pressure (January), annual precipitation (Bio12), played a dominant role percentage contribution >15 % in survival and distribution of *E. bicolor*. Habitat suitability modeling under future scenario indicated that highly suitable area of *E. bicolor* is projected to expand under SSP126 (RCP2.6), SSP245 (RCP4.5) and SSP370 (RCP6.0) compared to current scenario. Conversely a potential decline in suitable habitat of *E. bicolor* could be observed under SSP585 (RCP8.5) scenarios. The findings reveal that anthropogenic activities, such as habitat destruction and land-use changes and the effects of climate change are having profound impacts on the distribution patterns of *E. bicolor* in the studied districts of Kerala. These pressures are altering the species' natural habitats,

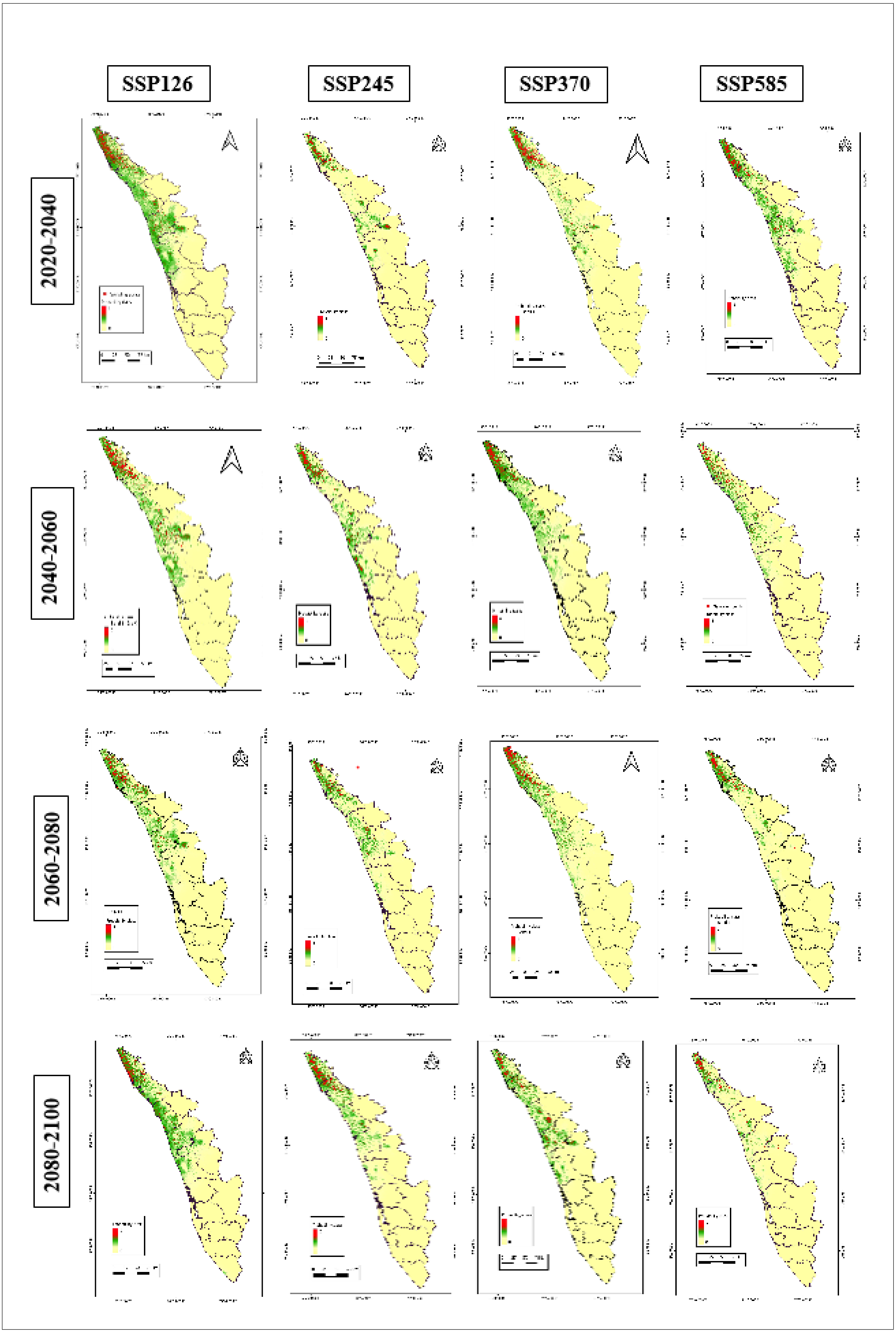

Fig. 14. Predicted future climatic habitat suitability of *Exacum bicolor* in Kerala under different SSP scenarios for 2021-2040, 2041-2060, 2061-2080 and 2081-2100.

reducing the availability of suitable environments and potentially threatening its long-term survival. The study underscores the urgency of implementing targeted conservation measures to address these challenges. Such actions may include habitat restoration, sustainable land management practices and climate adaptation strategies to mitigate the combined effects of human activities and changing environmental conditions. Recommended actions include habitat restoration, enforcing sustainable land-use policies and integrating climate adaptation strategies into regional conservation planning to ensure the persistence of *E. bicolor* in its native range.

Future scope of research

The present study provides a robust foundation for understanding the habitat preferences and distribution dynamics of *E. bicolor* under changing climatic conditions. Future research can focus on integrating finer-resolution climate models and land-use change data to enhance prediction accuracy. Additionally, field validation of predicted high-suitability zones would strengthen the applicability of the model in conservation planning. Further investigations on the reproductive biology, genetic diversity and propagation methods of *E. bicolor* are essential to support *in-situ* and *ex-situ* conservation efforts. Developing climate-resilient restoration protocols and community-based conservation models will also be vital to ensure the species' long-term survival in its native habitats.

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Authors' contributions

SH contributed to the research survey, data collection, statistical analysis, interpretation of results and original draft preparation; SF contributed to the research survey, data collection, interpretation of results and manuscript correction; SP contributed to statistical analysis, interpretation of results and manuscript correction; MS and SU contributed to the research survey, data collection and manuscript correction; and SAM contributed to manuscript correction. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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