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# Predicted distribution of the endemic fern *Elaphoglossum beddomei* reveals threats to rainforests of Western Ghats of India

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**Research Article**

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## Abstract

Pteridophytes are excellent ecological indicators of habitat quality. In this study, we built a model that predicts the habitat suitability of *Elaphoglossum beddomei* Sledge, an epiphytic or lithophytic and endemic pteridophyte in Southern Western Ghats, by using the technique of species distribution modelling. The occurrence data of *E. beddomei* from field explorations as well as from various herbaria were collected during 2018–2022. These occurrence data along with climatic data were processed by R packages. The processed data were further analysed using MaxEnt software to project the distribution of *E. beddomei* in future climatic scenarios. After correlation analysis, five bioclimatic variables – Mean Temperature of Wettest Quarter (bio8), Precipitation of Driest Quarter (bio17), Precipitation of Warmest Quarter (bio18), Precipitation of Wettest Quarter (bio16) and Temperature Annual Range (BIO5-BIO6) (bio7) – were selected from 19 bioclimatic variables with less correlation. Precipitation of Warmest Quarter (bio18) had the most influence in determining the distribution of *E. beddomei*, with a permutation importance of 83%. Conversely, Temperature Annual Range (BIO5-BIO6) (bio7) and Precipitation of Driest Quarter (bio17) showed least influence in determining the distribution of *E. beddomei*, and hence, the models created without these variables are considered for prediction. The habitat suitability predictions of the model indicate that the potential habitats of the species may get reduced in Southern Western Ghats in future climatic scenarios. It is in tune with the predicted expansion of drier climatic zones in Southern Western Ghats, which may reduce the suitable habitats for the *E. beddomei* in near future. So, it demands formulating suitable strategies for reducing the emission of greenhouse gases, regenerating forests and conserving forests by implementing more stringent policies on the environment to protect such highly habitat-specific evergreen elements.

## Introduction

Pteridophytes play significant roles in ecosystems by providing suitable microhabitats for other plants and animals, preventing nutrient leaching and soil erosion, in succession and as gap fillers in most habitats (Holttum 1938; Walker 1994; Sharpe *et al.* 2010; Walker and Sharpe 2010; Walker *et al.* 2010). They prefer specific environments with definite habitat traits to thrive and establish. Due to these differential preferences for specific ecological conditions, many of them are endemic to certain bio-geographic regions and habitats (Sharpe *et al.* 2010; Pouteau *et al.* 2016; Karger *et al.* 2021b).

There are two major centres of diversity of pteridophytes in India – Western Ghats and North East India – and approximately 10% of Indian pteridophytes are endemics. Majority of the taxa are confined to the Western Ghats of the Peninsular India, due to high degree of habitat diversity, as a result of its unique geographical location and climatic features (Fraser-Jenkins, 2008).

Expansion of drier areas at a higher rate and associated changes are expected in the immediate future (Antão *et al.* 2020) and the Western Ghats of Peninsular India is also not an exception (Munoz *et al.* 2021). The alterations in climatic conditions specifically affect the existence of endemics. Large-scale climatic changes due to an increase in average temperature and its influence on the vegetation of the Earth were predicted by various climate change models (Masson-Delmotte 2018).

As endemics have restricted distribution in small geographical areas, they usually face serious threats to their existence. By analysing the known geographical locations of a taxon, many studies made use of Maximum Entropy (MaxEnt) modelling to get insights into patterns of species distribution, including potential areas (Bose *et al.* 2016; Chaitanya and Meiri 2021; Ferreira *et al.* 2021; Karger *et al.* 2021a). This warrants development of specific conservation strategies for such species and this is possible only through the basic know-how on its pattern of distribution in different habitats.

The MaxEnt modelling has been widely used in India and elsewhere to predict the changes in distribution of species in response to climate changes (Phillips *et al.* 2006; Phillips *et al.* 2017; Munoz *et al.* 2021). It ranged from analysing the future prospects of crops such as rubber (Ray *et al.* 2014), pepper (Sen *et al.* 2016), *Kaempferia* (Raina *et al.* 2015), tea (Potom and Nimasow 2019), *Zingiber* (Huang *et al.* 2019), medicinal plants – Asclepiads in Africa (Khanum *et al.* 2013), *Coscinium fenestratum* and *Embelia ribes* (Pownitha *et al.* 2022), *Garcinia indica* (Palkar *et al.* 2020) in Western Ghats, *Taxus contorta* in Himalayan region (Chauhan *et al.* 2022), *Bauhinia vahlii* in Indian subcontinent (Thakur *et al.* 2022), *Terminalia chebula* (Kailash *et al.* 2022), to predict the expansion of invasive plants like *Mimosa diplotricha*, *Mikania micrantha* (Choudhury *et al.* 2016), *Parthenium* (Arogoundade *et al.* 2020), etc., and animals such as African snail (Sarma *et al.* 2015), pests (Choudhary *et al.* 2019), diseases (Escobar *et al.* 2014), and for conservation planning of threatened (Sreekumar *et al.* 2016) and endemic taxa – *Calamus* spp. (Joshi *et al.* 2017), *Rosa arabica* (Abdelaal *et al.* 2019), etc. Species distribution modelling (SDM) studies of pteridophytes, however, are comparatively less frequent (Sharpe 2019; Della and Falkenberg 2019). SDMs of pteridophytes have been attempted in the island of Taiwan (Hsu *et al.* 2012; Hsu *et al.* 2014; Hsu *et al.* 2014), Neotropical region (Brummitt *et al.* 2016) and Mesoamerican region (Syfert *et al.* 2018). Shreshta and Zhang (2015) used SDM to predict the extent of distribution of *Huperzia hamiltonii*, a Himalayan endemic.

In the present study, the distribution of endemic fern species *Elaphoglossum beddomei* is predicted by using the bioclimatic variables for two time periods – current climatic regime and one future climatic regime (2041–2070). It was categorised as least concern (LC) in an earlier assessment (Kumar 2011). Later assessments (Chandra *et al.* 2008; Ebihara *et al.* 2012; Fraser-Jenkins *et al.* 2021) treated the taxon as near threatened (NT). According to Karger *et al.* (2021b), loss of tropical cloud forest biodiversity is at its fastest rate now, due to worldwide climate change and limited protection actions. Such loss of biodiversity in montane evergreen forests may adversely affect the existence of endemics inhabited in such specific ecosystems, like *E. beddomei*.

*E. beddomei* is a high-altitude, evergreen-shola element in the Western Ghats of Peninsular India. So, the present study is focused on finding out the potential habitat for *E. beddomei* in the current climatic scenario. This study also aims to find out the important bioclimatic variables that determine the habitat suitability of *E. beddomei* in Southern Western Ghats and an attempt is being made to figure out the habitat suitability change that should occur in the light of climate change.

## Materials and methods

Distribution data of *E. beddomei* Sledge was tabulated from the available literature (Fraser-Jenkins *et al.* 2021; Hassler 2024; Manickam and Irudayaraj 1992; Nayar and Geevarghese 1993), herbaria (CALI, KFRI, MH, ZGC) and field observations (Table S 1). It is an endemic fern with simple fronds, crowded on the short creeping (0.5 cm thick) rhizome and growing in the evergreen and shola forests of the Western Ghats of Peninsular India as epiphytes or lithophytes at an elevation of 900–2200 m (see supplementary data for description of the species S1). It is sparsely distributed in the Western Ghats of the Peninsular Indian states of Kerala, Tamil Nadu and Karnataka. GPS data points were obtained from the field observations during 2018–2021 (Figure 1). Position coordinates, latitude and longitude, were recorded using a mobile phone geopositioning application. Co-located or nearby locations (Phillips *et al.* 2017), within 2 km, were avoided for better results, totalling 31 records of *E. beddomei*, including primary collection records (Figure 1).

### Environmental data

High-resolution climatic data of 19 bioclimatic variables for two time periods – 2011–2040 (current) and 2041–2070 – from the CHELSA (Climatologies at high resolution for the Earth's land surface areas) CMIP6 by Karger *et al.* (2017) were selected, as environmental predictors. Two scenarios of future climate were selected as SSP126 and SSP585 representing seasonality, annual trends in climate and limiting environmental factors (Qi *et al.* 2004). The Shared Socio-economic Pathways (SSP) derive the emission scenarios under different climate policies. SSP126 stands for SSP1-RCP2.6 climate as simulated by the GCMs. Here, RCP is the Representative Concentration Pathway, which is a greenhouse gas emission trajectory by the IPCC. SSP126, RCP2.6 is the lowest in the RCPs; it assumes a decreased emission of greenhouse gases after 2100. Conversely, SSP585, SSP5-RCP8.5 climate as simulated by GCMs, represents a more pessimistic scenario of future gas emission. RCP8.5 represents the concentration of carbon, which delivers global warming at an average of 8.5 Watts/sq. metre across the earth (Karger *et al.* 2021a). We eliminated the highly correlated – both positively and negatively correlated variables – with a Pearson correlation coefficient $> 0.75$, for avoiding overprediction and confounding effects in the model (Elith *et al.* 2011; Merow *et al.* 2013; Bose *et al.* 2016).

### Background selection

The first and most crucial step in SDM is the choice of background points, or landscape selection, which should represent a broad array of possible habitats for the species (Sreekumar and Nameer, 2021, 2022). So in this study, the background has been selected within the evergreen and shola forest vegetation of Southern Western Ghats – representing a potential habitat for *E. beddomei* – from the vegetation map of Indian Institute of Remote Sensing Biodiversity Information System, Government of India (Roy *et al.* 2016).

### MaxEnt modelling

We used MaxEnt version 3.4.1 (Phillips and Dudik, 2008) to perform a species distribution model of *E. beddomei*. The best model was evaluated based on True Skill Statistics (TSS) and overall accuracy, calculated using R package ENMTools (Chaitanya and Meiri, 2021), and Area Under the receiver operating characteristic Curve (AUC) from MaxEnt output. The model that showed highest values for AUC, TSS and overall accuracy was selected as the best MaxEnt model for analysis (Table S 2).

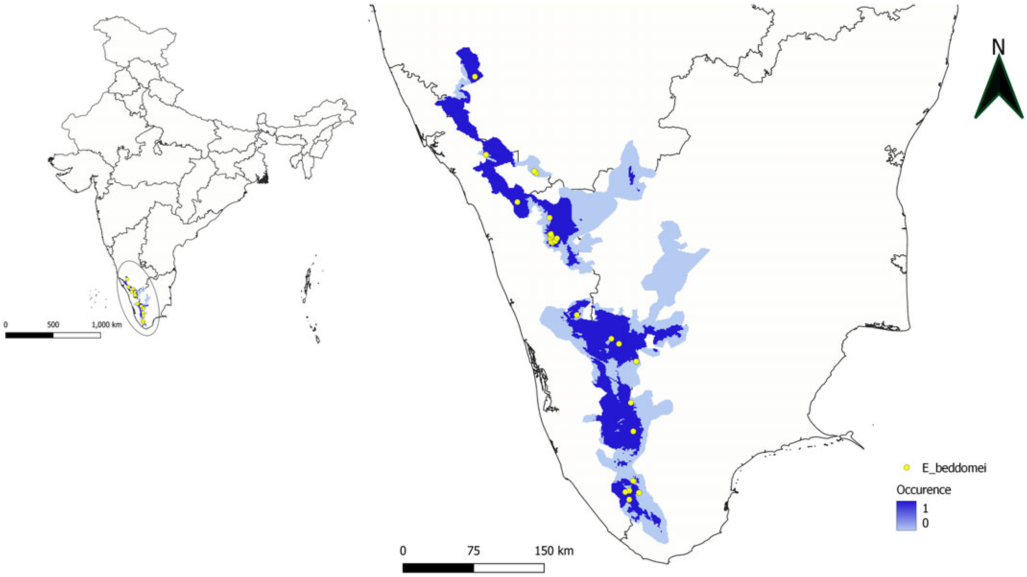


**Figure 1.** The background map generated based on the evergreen forest patches in Southern Western Ghats (Indian Biodiversity Information System https://www.indiaobservatory.org.in/tool/ibis) showing the distribution locations of *Elaphoglossum beddomei* in Southern Western Ghats (yellow dots); predicted potential habitat of *E. beddomei* in current climatic regime (dark blue regions); the background with existing evergreen forest patches (light blue regions).

The initial model was created using MaxEnt based on the regularisation multiplier value (rm value = 3) as calculated by the ecological niche modelling (ENM) evaluation tool. Then, based on jackknife analysis in the MaxEnt output, we calculated the contribution permutation importance of each variable and discarded the lowest valued variable (Zurell *et al.* 2020) and again ran MaxEnt to get the best model with highest AUC, TSS and overall accuracy. The MaxEnt settings were given as 10-fold of cross-validation, number of background points of 10,000 and iterations of 5,000. The output file format was set as complementary log-log (c-loglog).

### *Future distribution prediction of E. beddomei*

The current study predicted the distribution of *E. beddomei* in future climatic regimes (2041–2070) under different climatic change scenarios – such as SSP126 and SSP585 for 2041–2070. Here, we used five Earth System Models (ESMs) under CMIP6 (Coupled Model Intercomparison Project Phase-6) – including GFDL-ESM4, UKESM 1-OLL, MPI-ESM 1-2HR, IPSLL-CM6A LR and MRI-ESM 2-0. Then we calculated the average of these ESMs.

### *Evaluation of the MaxEnt model*

We evaluated the MaxEnt models based on the AUC, which plots sensitivity against 1-specificity. It ranges from 0 to 1; the value near one indicates the best prediction. We also considered TSS, which is 'sensitivity + specificity – 1', and the overall accuracy for model performance, using R package ENMTools.

### *Habitat loss and gain in future simulations*

We mapped suitable and unsuitable habitats of *E. beddomei* by considering the threshold value of maximum test sensitivity plus specificity c-loglog threshold (Max SSS) (Liu *et al.* 2013) on the predicted probabilities, using the Raster reclassification tool in Q-GIS v. 3.61. Then, we used the raster calculator tool of Q-GIS v. 3.61 to calculate changes in suitable habitats of *E. beddomei*, as the difference between the current binary map and future binary maps under different conditions in future climatic regimes. Based on the prediction of potential habitats, we calculated the habitat loss and gain in the future time periods, by comparing the predicted suitable area under two climatic scenarios – SSP126 and SSP585 – of 2041–2070 and the prediction in the current time period. From this calculation, we obtained the gain of suitable habitat, loss of suitable habitat and unchanged habitats of *E. beddomei* in future climatic conditions.

## Results

### *MaxEnt modelling and influenced bioclimatic variables*

After correlation analysis, five bioclimatic variables – Mean Temperature of Wettest Quarter (bio8), Precipitation of Driest Quarter (bio17), Precipitation of Warmest Quarter (bio18), Precipitation of Wettest Quarter (bio16) and Temperature Annual Range (BIO5-BIO6) (bio7) – were selected from 19 bioclimatic variables with less correlation. As per the jackknife analysis, Precipitation of Warmest Quarter (bio18) had the most influence in determining the distribution of *E. beddomei*, with a permutation importance of 83% (Table 1). Temperature Annual Range (BIO5-BIO6) (bio7) and Precipitation of Driest Quarter (bio17) showed least influence in determining the distribution of *E. beddomei*, and hence, the models created without these variables were considered for prediction.

### *MaxEnt modelling*

The predicted model had an AUC value of 0.838, TSS value of 0.6852 and overall accuracy of 0.9346. Predicted distribution in current climatic regimes represented its potential distribution along the Western Ghats (Figure 1). The results showed that the predicted suitable area for *E. beddomei* at present is approximately about 11,181.6 square km in Southern Western Ghats.

### *Predicted changes in future climatic scenarios*

Here, Table 2 summarises the potential habitat gain and loss or Niche shift in the future climatic period – 2041–2070 – compared with the current climatic regime. Here in all climatic scenarios, habitat loss was more than that of habitat gain in future time

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**Table 1.** Contribution of selected bioclimatic variables to the distribution of *E. beddomei* in current climatic regime

| Selected bioclimatic variables | Description | Percent contribution (%) | Permutation importance (%) |
|---|---|---|---|
| Bio18 | Precipitation of Warmest Quarter | 47 | 83 |
| Bio8 | Mean Temperature of Wettest Quarter | 27.5 | 14 |
| Bio16 | Precipitation of Wettest Quarter | 25.5 | 3.1 |

**Table 2.** Habitat loss and gain in 2041–2070 time period

| | 2041–2070 | |
|---|---|---|
| | SSP126 | SSP585 |
| Habitat loss (sq. km) | 6049.8 (20.718%) | 5495.4 (18.820%) |
| Unchanged habitats (sq. km) | 23077.8 (79.03%) | 23472 (80.384%) |
| Habitat gain (Niche shift) (sq. km) | 72 (0.246%) | 232.2 (0.795%) |

periods, such as in the 2041–2070 climatic period, the average loss of suitable habitat in two scenarios was 19.769% and the average gain of suitable habitats in two scenarios was only 0.5205%. The loss of suitable habitat was greater in SSP126 (20.718%) climatic scenario of 2041–2070 time period. Niche shift of *E. beddomei* is very negligible in future climatic periods, as average habitat gain is 0.5205%. (Table 2).

## Discussion

At present, *E. beddomei* is known to occur in a narrow zone of the Western Ghats of Kerala, Tamil Nadu and Karnataka with specific cool, evergreen, climatic parameters (Manickam and Irudayaraj, 1992; Benniamin and Sundari, 2020; Benniamin *et al.* 2020). *E. beddomei* is known to be endemic to Southern Western Ghats of India. As per earlier IUCN Red List assessment (Kumar, 2011), it was considered as LC and demanded further studies to clarify its geographic distribution, and in recent assessments, the status was redesignated as NT (Benniamin *et al.* 2020; Fraser-Jenkins *et al.* 2021). The global trend in forest ecosystems showed that the concentration of the evergreen forests is confined more to higher altitudes and shows drastic decline at higher rates (Laurance *et al.* 2012), causing severe loss of tropical cloud forest ecosystems (Murugan *et al.* 2009; Karger *et al.* 2021b), which may adversely affect most of the high-altitude evergreen endemic species (Munoz *et al.* 2021). So, *E. beddomei,* a species inhabiting evergreen habitat, may become more threatened in future climatic regimes due to lack of suitable habitats.

The predicted potential habitats in current climatic regimes showed a possibility of recording *E. beddomei* from other potential habitats of the Western Ghats. There are similar reports of rediscoveries and extended distribution records found by the analysis of occurrence of species like *Micromeria serbaliana* and *Veronica kaiseri* (Omar and Elgamal 2021) in Egypt, and ferns under Rare, Endangered and Threatened (RET) categories (Williams *et al.*, 2009) in the United States through distribution models. Predicted potential distribution in the future climatic regime – 2041–2070 – showed a trend of decline for *E. beddomei* in Southern Western Ghats (Figure 2a and b), as the average loss of potential habitats in the 2041–2070 is 19.796%. Whereas, the average gain of potential habitats or niche shifts in the climatic period – 2041–2070 – is only 0.5205%.

By analysing the influence of bioclimatic variables, the distribution of *E. beddomei* proved limited by precipitation (Table 1). As *E. beddomei* is an evergreen high-altitude fern species, the temperature and precipitation characteristics of high-altitude evergreen forests determine the growth and distribution. So, the predicted future distribution reflects a change in precipitation pattern in Southern Western Ghats, which in turn should affect the existence of *E. beddomei* in Southern Western Ghats. It can be concluded that the suitable habitat for *E. beddomei* will progressively decline in future due to the variations in global temperature and precipitation.

Although the forcing level differs between the 126 and 585 SSP scenarios, it does not mean that the predicted rainfall patterns should differ much between the two scenarios. For instance, under the CNRM-CM6-1 model, we found that the variation of bio12 (annual rainfall) and bio18 (rainfall of the warmest quarter) in 2060 between the two SSP scenarios should only be about 0.8% and 5.3% on average, respectively. This is why our predictions of occurrences of *Elaphoglossum* are quite similar between SSP scenarios (Munoz *et al.* 2021).

The study of endemics in Western Ghats by Bose *et al.* (2015) mentioned that the variation in precipitation patterns from past climatic regimes to current climatic conditions might be the reason for higher endemicity in Western Ghats, especially in Southern Western Ghats. So, the predicted future decline of *E. beddomei* from Southern Western Ghats points to a drastic change in precipitation pattern in Southern Western Ghats regions. Fluctuating rainfall patterns are due to increased global warming (Murugan *et al.* 2009) and it may affect the existence of evergreen species like *E. beddomei* of Western Ghats. Increase in temperature and fluctuating or decreasing precipitation may act as limiting factors for such strict evergreen taxa. The changes in the distribution pattern of animals, birds or plants have been used to predict the trend in future environmental conditions in India and other countries (Jose and Nameer 2020; Sony *et al.* 2018; Li *et al.* 2019). The expansion of the Peafowl (*Pavo cristatus*) population in the Peninsular Indian state of Kerala (Jose and Nameer 2020) has been taken as an indication of desertification and increase in temperature regimes in the state of Kerala. Similarly, a reduction in suitable habitat due to climate change is anticipated for the endemic ungulate mammal, Nilgiri Tahr (*Nilgiritragus hylocrius*) population in the Western Ghats (Sony *et al.* 2018). The studies on plants, especially the impact of climate change on endemics and threatened category taxa, warn for establishing proper conservation strategies, *in situ* as well as *ex situ,* for the maintenance of threshold minimum population sizes globally. The potential distribution and impact of climate change on the endangered pteridophyte genus *Isoetes* (Yang *et al.* 2022) in

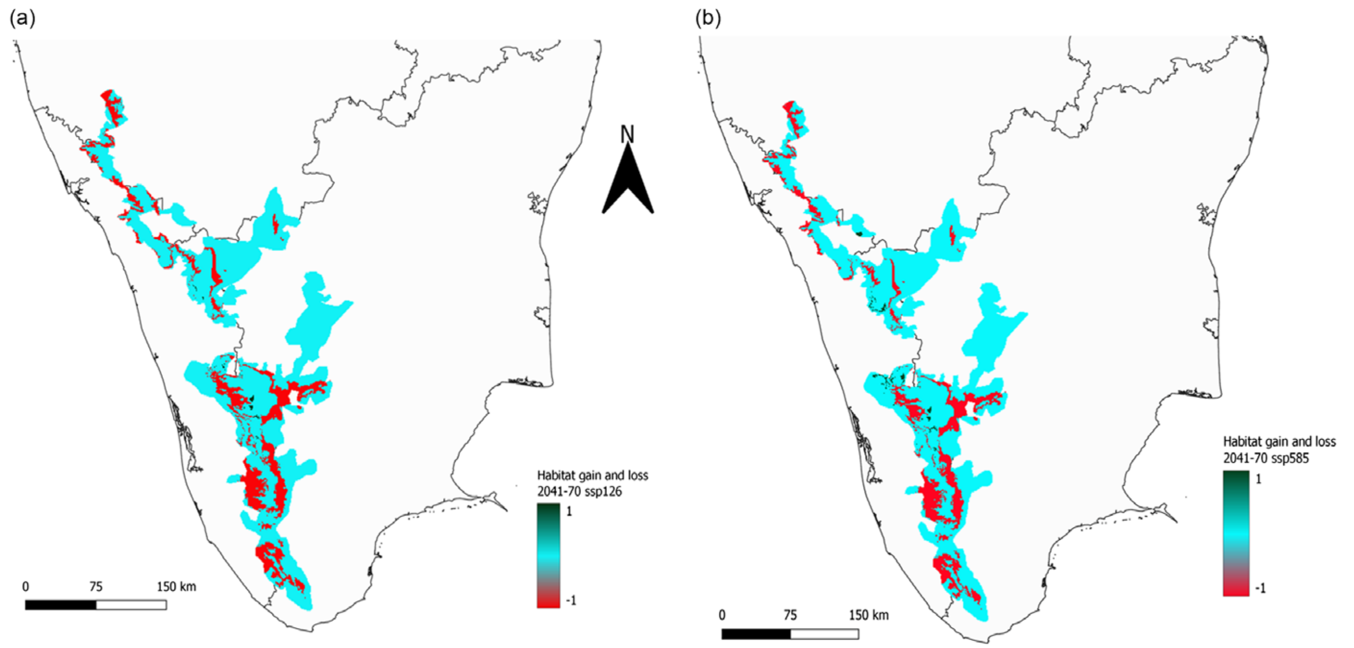


**Figure 2.** Habitat gain-unchanged-loss map of *E. beddomei* in 2040–2071; a. SSP126 scenario and b. SSP585 scenario – black (1) indicated habitat gain; blue (0) indicated unchanged habitat; and red (–1) indicated habitat loss.

China, the rare and endangered fern species *Brainea insignis* (Wanga *et al.* 2012) in Taiwan and the micro-endemic plant species *Cistus ladanifer* subsp. *sulcatus* (Ferreira *et al.* 2021) in Portugal showed the reduction of potential habitats in future climatic regimes due to drastic changes in climatic conditions. Along with these predictions addressing the impact of climate change on species existence and distribution, there are studies that predict suitable habitats for endangered lycophytes and fern species for designing suitable conservation strategies (Wang *et al.* 2016; Li *et al.* 2019). These strategies will include *in situ* conservation by locating potential habitats and re-establishment of the species, as well as *ex situ* methods like procurement of such species from natural habitats and maintaining them in botanical gardens, along with germplasm conservation through cryobanks and spore banks. Likewise, *E. beddomei* is a NT, endemic species to the Western Ghats (Ebihara *et al.* 2012; Chandra *et al.* 2008; Benniamin *et al.* 2020; Fraser-Jenkins *et al.* 2021). The decrease in potential habitats of *E. beddomei* in future climatic regime is an indication of the decline in evergreen forest patches in Southern Western Ghats. So, if the climate changes to an unfavourable condition, it may adversely affect the survival of the NT species – *E. beddomei*.

The present study provides deep insights on the trend of distribution of Pteridophytes and warrants for formulating suitable conservation strategies for taxa such as *E. beddomei*. Except for some preliminary attempts of *in vitro* spore germination and gametophyte development studies (Benniamin *et al.* 2020), the protocols for mass propagation and field trials for re-introduction of this species are yet to be formulated. Suitable strategies, both short-term and long-term, such as *in situ* strategies targeting conservation of the endemic species in their natural habitat using the support of local people and forest personnel, raise awareness to the public about the importance of the local biodiversity and its role in their life and future generations. *Ex situ* conservation methods like growing the plant in gardens by providing appropriate habitat conditions are essential to ensure the conservation of this species. The case of *E. beddomei* is also an indication of the trend of endemics of the Southern Western Ghats in the age of climate change (see also Munoz *et al.* 2021).

## Conclusion

The predicted species distribution and ENM of the species – *E. beddomei* – carried out in the present study reveal trends in climatic variations in the near future in India, especially in the Western Ghats. The distribution model predicted that there will be subsequent increase in temperature and dryness in Southern Western Ghats due to climate change, and change in precipitation pattern will lead to drastic decline of suitable habitats for evergreen taxa such as *E. beddomei*. It is similar to the trends predicted for Peafowl (Jose and Nameer, 2020) and Nilgiri Tahr (Sony *et al.* 2018) in southern India. Hence, suitable conservation strategies are essential to reduce the rate of degradation of critical habitats such as evergreen forests in Peninsular India along with protecting the micro habitats of taxa that serve as ecological indicators.

**Supplementary material.** The supplementary material for this article can be found at https://doi.org/10.1017/S0266467424000154

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**Competing interests.** The author(s) declare none.

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