Predicting current and future habitat suitability of *Cullenia exarillata* A. Robyns – An endemic and keystone species of the Western Ghats

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Abstract: Accurate prediction of habitat suitability is crucial for species of conservation importance. Predictive distribution models play a key role in conservation by identifying current and future suitable habitats. *Cullenia exarillata* A. Robyns is an endemic and keystone tree species of the tropical wet evergreen forests of the Western Ghats of India. This study used a species distribution model to predict the current and future distribution of *C. exarillata*. Various environmental variables and the MaxEnt model were used to assess the current potential distribution and shifts within different shared socio-economic pathways. The findings illustrate the potential reduction of the species ecological niche in certain landscapes of Karnataka, Kerala and Tamil Nadu under future climate change scenarios. The receiver operating characteristic area under the curve was used to evaluate the accuracy of the model. The Jackknife test was used to assess the significance of environmental factors. This study highlights the importance of targeted conservation and habitat management strategies for the conservation of *C. exarillata*. This spatial approach can be applied to other species facing similar threats, making it an essential tool for broader conservation efforts.

Keywords: Biodiversity, Species, Habitat, Climate change, Western Ghats

1. Introduction

Climate change has emerged as one of the most critical global challenges with profound implications for biodiversity and ecosystem services. Increasing concentrations of greenhouse gases, primarily due to human activity, have led to significant changes in global climate patterns. These changes include rising temperatures, altered precipitation patterns, and increases in the frequency and intensity of extreme weather events (IPCC, 2014). Such climate shifts cause widespread disruption of ecosystems, affecting species distribution, phenology and interactions (Thomas et al. 2017; Lang et al. 2024). Species have a limited ability to adapt to these rapid environmental changes, leading to shifts in their geographic ranges, population declines, and even extinction (Bellard et al. 2012). Understanding and predicting the impact of climate change on species distributions is critical to developing effective conservation strategies and mitigating biodiversity loss. Species distribution models (SDMs) have become indispensable tools in ecology and conservation biology for predicting the potential distribution of species in a landscape under current and future environmental conditions (Malik et al. 2022; Namitha et al. 2022). These models use occurrence data along with environmental variables to predict suitable habitats for species (Elith & Leathwick, 2009). SDMs are particularly valuable for identifying areas that are critical for conservation. Different modeling techniques such as maximum entropy (MaxEnt), generalized linear models (GLM) and random forests (RF) are used to build these predictive models (Elith et al. 2011). The accuracy of SDM depends on the quality of the input data and the selection of appropriate modeling techniques and environmental variables. SDMs are powerful tools for understanding species-environment relationships and for guiding conservation efforts in the face of climate change. Integrating climate change projections with species distribution models offers a robust framework for predicting future impacts of climate change on biodiversity. By integrating these methodologies, researchers can identify likely shifts in species' ranges and prioritize conservation efforts. Consistent with Thomas et al. (2017) and Saraf et al. (2024) climate change is predicted to cause significant range reductions and shifts in many species, requiring proactive conservation planning. This information is essential for designing protected areas, restoring degraded habitats, and implementing assisted migration or ex-situ conservation programs.

There are challenges in implementing SDM in the context of climate change. Significant challenges include the complexity of relationships between species and their environments, uncertainties in climate projections, and limitations of species occurrence data (Araújo & Peterson, 2012). However, advances in machine learning-based modeling techniques and the increasing availability of high-resolution environmental data are increasing the predictive power of SDM (Franklin, 2013). Integrating climate change research and species distribution modeling provides a powerful toolkit for addressing 21st century conservation challenges. *Cullenia exarillata* A. Robyns (Malvaceae) is an endemic and keystone species in the mid-elevation (between 400-1600 m) tropical wet evergreen forests of the central and southern Western Ghats, India. *Cullenia exarillata* has most recently been assessed for The IUCN Red List of Threatened Species in 2023 under Near Threatened status (https://www.iucnredlist.org/). The tree is known for its height (up to 40 m tall), massive canopy structure and unusual fruit and flowers that attract a variety of wildlife, including fruit-eating bats and arboreal mammals. Its cauliflorous flowering pattern has been identified as a significantadaptation for pollination. The flowers produce abundant nectar and are easily accessible for arboreal pollinators like bats and squirrels. It flowers between December and March, while its fruiting season occurs from March to July. It plays a key role in maintaining the structure and function of these ecosystems (Ganesh & Davidar, 2001). As a canopy dominant, it often co-occurs with other canopy species such as *Mesua ferrea* L. and *Palaquium ellipticum* (Dalzell) Baill., forming the *Cullenia exarillata – Mesua ferrea – Palaquium ellipticum* type of mid-elevation wet evergreen forests. Pascal et al. (2004) have identified a *Cullenia exarillata - Mesua ferrea - Palaqium ellipticum – Gluta travancorica* Bedd. (CMPG) type, confined to south of the Ariankavu Pass and defined by the altitudinal preference of *C. exarillata*. This specific type is limited to the Agasthyamala and Mahendragiri regions in the southern Western Ghats situated between latitudes 8° 20′N and 8° 50′N. At the canopy and subcanopy levels, major associated tree species include *Atuna travancorica*, *Diospyros barberi*, *Garcinia travancorica*, *Garcinia rubro-echinata*, *Nageia wallichiana* and *Calophyllum austroindicum*. Furthermore, species including *Octotropis travancorica*, *Goniothalamus rhyncantherus*, *Vernonia travancorica*, *Popowia beddomeana*, *Memecylon gracile*, and *Memecylon subramanii* are found at the undergrowth level. *C. exarillata* provides habitat and resources for a diverse array of organisms, making it a keystone species. The loss of *C. exarillata* could significantly reduce biodiversity in the forest, as it supports not only arboreal mammals but also other taxa, including plants and insects. Its distinct trunk, bark, and branch structure create niches in the forest that other species do not possess. It is harboured by many species of epiphytes such as *Eria*, *Peperomia* and *Bulbophyllum* (Devy, 2006). The majority of the trees range in height from 15 to 30 m. This large canopy tree provides essential resources, such as nectar and fruits, for a variety of fauna, including birds, mammals, and insects (Devy & Davidar, 2003).C. *exarillata* is the high-priority food species for lion-tailed macaque and Nilgiri langur which are endangered and endemic species. The seed dispersal is mainly through these frugivores, Malabar giant squirrels and bats (KFRI, 2016; Newport, 2022). The conservation of *C. exarillata* is critical for the overall health of the wet evergreen forest ecosystem. Therefore, utilizing SDM to predict the future distribution of *C. exarillata* under various climate scenarios can provide valuable insights for developing effective conservation strategies.

2. Study area

The Western Ghats, a UNESCO World Heritage site, is a mountain range that runs parallel to the western coast of India, stretching across six states (Figure 1). It receives the heaviest rainfall during the south-west monsoon period, June to September. The Western Ghats is recognized as one of the world's biodiversity hotspots, hosting a high level of endemism and species richness (Myers et al., 2000). However, the region is under significant threat from deforestation, habitat fragmentation, and climate change (Raman et al., 2010; Satish et al. 2014; Dutta et al. 2016; Reddy et al. 2016). The southern Western Ghats have the highest overlap of irreplaceable forest landscapes with vulnerability (Reddy et al. 2018).

3. Methodology

The methodology involves integrating species occurrence data with environmental variables using machine learning algorithm to predict suitable habitats.

3.1. Species Distribution Data

The geographic distribution data for *C. exarillata* in the Western Ghats were obtained from multiple sources (Roy et al. 2012; Vattakaven et al. 2016; Reddy et al. 2021). The latitude and longitude coordinates of the species from the collected samples were extracted and organized into a .csv file. To enhance the precision of our analysis, we identified and eliminated any duplicated distribution points within the dataset. This refinement process resulted in a final dataset comprising 254 unique distribution points for *C. exarillata*.

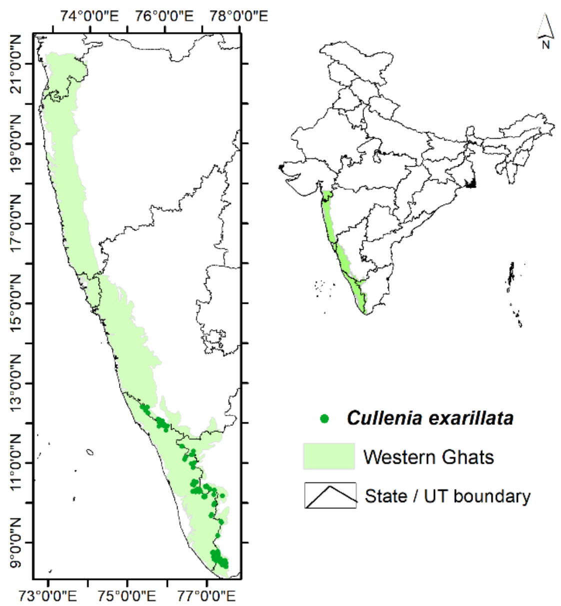

Figure. 1. Location map showing occurrence locations of *C. exarillata* in Western Ghats

3.2. Environmental variables

The present work made use of the WorldClim dataset, which offers an extensive collection of climate data for ecological and environmental research (Fick & Hijmans, 2017; https://www.worldclim.org).The current data on 19 bioclimatic variables at a 1 km spatial resolution was used to determine the potential distribution of the *C. exarillata* (Table 1). The Coupled Model Intercomparison Project Phase 6 (CMIP6) is a major international effort to provide a comprehensive set of climate model simulations that help researchers understand and predict climate change. Future environmental variables in this study were derived from the HadGEM3-GC31-LL climate model, part of the Hadley Centre Global Environment Model series developed by the UK Met Office (Andrews et al. 2019). HadGEM3-GC31-LL is recognized for its high-resolution simulations of atmospheric, oceanic, and terrestrial processes, offering critical insights into climate change impacts. The study analyzed specific scenarios under the shared socioeconomic pathways SSP-2 4.5 and SSP-5 8.5, which represent different greenhouse gas concentration trajectories. SSP-2 4.5 assumes moderate mitigation efforts, leading to intermediate greenhouse gas levels, while SSP585 represents a high-emission scenario with minimal mitigation. These scenarios were examined for two future periods: 2041–2060 (centered on 2050) and 2061–2080 (centered on 2070). By incorporating HadGEM3-GC31-LL within WorldClim, the study utilizes detailed climate projections to assess potential environmental changes and their impacts over the coming decades.

3.3. Data analysis

MaxEnt is a machine-learning method used for species distribution modeling, which estimates the probability distribution of a species' presence based on environmental constraints while making the fewest assumptions about the unknown factors (Phillips, 2005). It is particularly effective for predicting species distributions with limited occurrence data and has become a widely used tool in ecological niche modeling (Elith et al. 2011). The 19 selected environmental variables and species occurrence records of *C. exarillata* were loaded into MaxEnt. Of the 254 species occurrence locations, 70% were randomly chosen as testing data to create the prediction model, and the remaining 30% were used to validate the model's accuracy. The experiment was conducted using a total of five replicates to ensure sufficient data for statistical analysis and to enhance the reliability of the results.

The model was evaluated by computing the Area Under the Curve (AUC) of the receiver operating characteristic (ROC) plot. The "cloglog" (cumulative log-log) link function was used to relate the linear predictor (a combination of the input features) to the probability of the outcome. The AUC is a metric for determining how well a model can distinguish between two distinct classes, such as presence and absence, with values ranging from 0 to 1. A perfect model has an AUC of 1, meaning it can perfectly discriminate between the classes (Fielding and Bell, 1997). The AUC is particularly effective because it doesn't depend on any specific threshold for classification, making it a useful tool for evaluating model performance. AUC scores can be categorized: a score below 0.5 indicates a model worse than random guessing, while scores are classified as failing (0.5 to 0.6), bad (0.6 to 0.7), reasonable (0.7 to 0.8), good (0.8 to 0.9), and excellent (0.9 to 1) (Swets, 1988).

Table 1 List of bioclimatic variables

Variable	Variable name and Unit	Temporal Scale
Bio 1	Annual Mean Temperature (^{0}C)	Annual
Bio 2	Mean Diurnal Range (^{0}C)	Variation
Bio 3	Isothermality (Bio2/Bio7) (*100)	Variation
Bio 4	Temperature Seasonality (SD*100)	Variation
Bio 5	Maximum Temperature of the Warmest Month (^{0}C)	Month
Bio 6	Minimum Temperature of the Coldest Month (^{0}C)	Month
Bio 7	Temperature Annual Range (^{0}C) (Bio5-Bio6)	Annual
Bio 8	Mean Temperature of Wettest Quarter (^{0}C)	Quarter
Bio 9	Mean Temperature of Driest Quarter (^{0}C)	Quarter
Bio 10	Mean Temperature of Warmest Quarter (^{0}C)	Quarter
Bio 11	Mean Temperature of Coldest Quarter (^{0}C)	Quarter
Bio 12	Annual Precipitation (mm)	Annual
Bio 13	Precipitation of Wettest Month (mm)	Month
Bio 14	Precipitation of Driest Month (mm)	Month
Bio 15	Precipitation Seasonality (Coefficient Variation) (%)	Variation
Bio 16	Precipitation of Wettest Quarter (mm)	Quarter
Bio 17	Precipitation of Driest Quarter (mm)	Quarter
Bio 18	Precipitation of Warmest Quarter (mm)	Quarter
Bio 19	Precipitation of Coldest Quarter (mm)	Quarter

A Jackknife test was used to determine the relative importance of each variable on the distribution of this species in terms of percent contribution to the overall model fit (Yang & Zhao, 2013). Permutation importance was used to provide a straightforward interpretation of how much a variable contributes to the model's predictive performance by directly measuring the impact on performance metrics. To identify potential habitat changes from current to future data, we used a matrix model and image differencing techniques, applying a threshold to detect significant changes.

4. Results and Discussion

The current and future distribution areas of *C. exarillata* were predicted using the MaxEnt model (Figure 2). It shows high and moderate suitable habitats in central and southern Western Ghats of Karnataka (Kodagu district), Kerala and Tamil Nadu. The AUC value for the MaxEnt models was 0.978 (Figure 3), which signifies that the model's predictive performance is "excellent," indicating that the MaxEnt model is highly reliable for estimating the potential geographical distribution of *C. exarillata* in the Western Ghats. It is absent in the north of Brahmagiri Wildlife Sanctuary of central Western Ghats of Karnataka. Under the present climatic conditions, the species is predominantly found in habitats characterized by tropical wet evergreen forests, with the most favourable habitats located in the Anamalais (Anamalai Tiger Reserve), Periyar Tiger Reserve (Periyar National Park), Silent Valley National Park, Aralam wildlife sanctuary, Chimmony wildlife sanctuary, Kottiyoor wildlife sanctuary, Parambikulam tiger reserve, Agasthyamalai hills (Agasthyamala biosphere reserve) and Kanyakumari wildlife sanctuary. Among the non-protected areas, it was distributed mostly in Mannarkkad Division, Wayanad South Division, Nilambur North Division, and Nilambur South Division, of Kerala. This suggests that these areas provide optimal environmental conditions for the survival of *C. exarillata.*

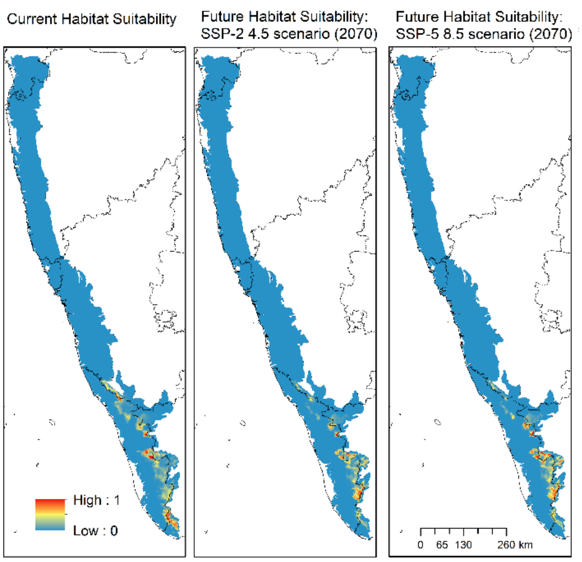

Figure 2. Habitat suitability maps of *C. exarillata*

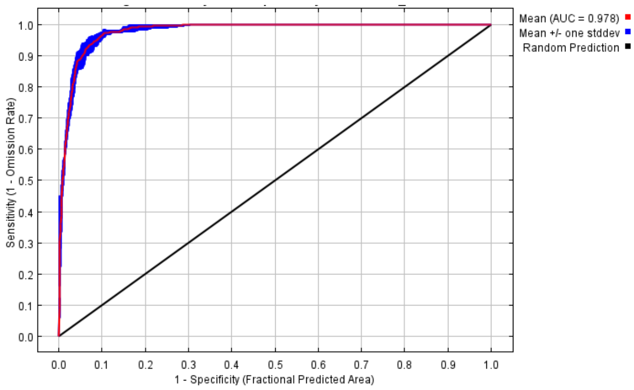

Figure 3. The averaged receiver operating characteristic (ROC) curve for *C. exarillata* (Mean (AUC = 0.978))

4.1. Contribution of each variable to the MaxEnt prediction model

The key environmental factors impacting the potential distribution of *C. exarillata* were identified based on their contributions to the modeling process, as assessed by the jackknife test (Figure 4). The test revealed that Annual mean temperature (24.8%), precipitation of driest quarter (Bio17 – 23.4%), precipitation during the driest month (Bio14 – 20.5%), precipitation of wettest month (Bio13 – 7.4%), and mean diurnal range (Bio2 – 5.8%) were the most significant contributors. The jackknife test identified the optimal value ranges for these environmental variables, which may indicate the correlation between the probability of presence and these factors. A probability of presence above 0.5 generally suggests that the environmental conditions are more favourable to species growth.

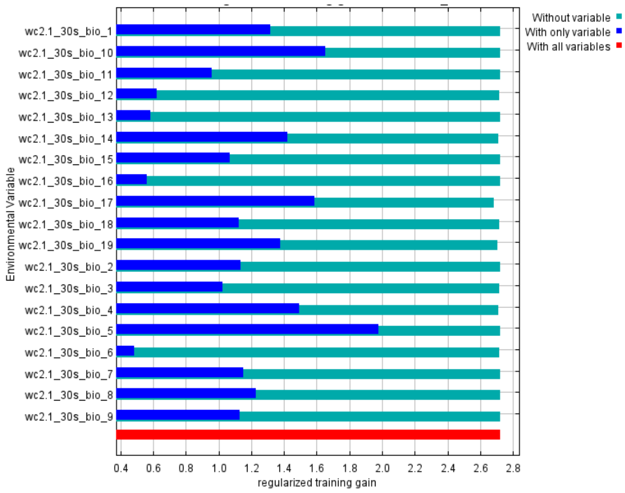

Figure 4. Jackknife test of regularized training gain for *C. exarillata*

4.2. Potential habitat changes of *C. exarillata* under future climate scenarios

The results, which are represented in the maps highlight the substantial influence that future climate change is anticipated to have on the ecological niche of *C. exarillata*. The potential habitat change maps are generated in terms of contraction, expansion, and persistence of the species (Figure 5). Contraction refers to the reduction in the habitat area of species as a result of climate change. Contraction is mostly represented in the Western Ghats of Karnataka, followed by Tamil Nadu and Kerala. Expansion describes the increase in the habitat area where a species can be found. Persistence refers to the continued presence of a species in its current habitat over time. Persistent potential habitats are found in Silent Valley, Anamalais, Parambikulam and Periyar region. Habitat fragmentation and changes in mammal populations can impact the success of this species in new habitats, emphasizing the importance of conservation strategies that support both tree species and their dispersers.

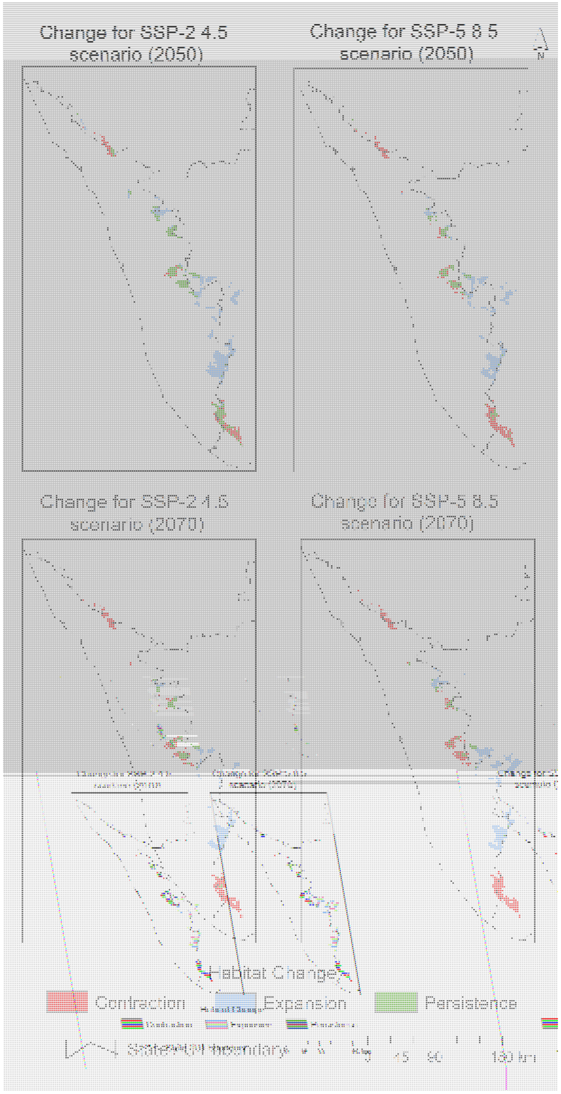

Figure 5. Future prediction maps of *C. exarillata* in climate change scenario showing change in potential distribution

The model shows a slight increase in total potential habitat areas in the future period 2041-2060 under the SSP2-4.5 scenario for *C. exarillata*. In the period 2061-2080, based on the SSP2-4.5 scenario, the area of total suitable habitat showed a decrease. Under the more extreme SSP5-8.5 scenario for the period 2061-2080, the situation is even more significant. Key drivers of habitat reduction include rising temperatures and altered rainfall patterns. The current mean annual temperature of 20–22 °C in most habitats of this species is expected to increase to around 25–26 °C in 2061–2080 under the SSP5-8.5 scenario. This significant decrease of habitat emphasizes how severely high-emission pathways affect *C. exarillata* niches. Overall findings of this study suggest that *C. exarillata* habitat expansion will be negatively affected by future climate change.

5. Conclusion

This study highlights the critical need for conservation strategies that are both adaptive and forward-thinking, capable of addressing the dynamic and evolving nature of environmental challenges. As ecosystems face increasing pressures from climate change, habitat fragmentation, and human activities, it is essential to design conservation plans that are flexible and proactive rather than reactive. The long-term survival of *C. exarillata* will depend on implementing a multi-faceted approach. Regular assessment of *C. exarillata* populations, their habitats, and associated ecological dynamics will provide up-to-date data on species trends, habitat conditions, and emerging threats. This information is crucial for making timely adjustments to conservation actions. Beyond focusing solely on *C. exarillata*, it is crucial to protect the broader ecosystem, including the species that contribute to seed dispersal, pollination, and overall ecological balance. This holistic approach will ensure the sustainability of habitats and the species that depend on them.

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