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Habitat Suitability Modelling of Canarium strictum Roxb. Using the Maximum Entropy (MaxEnt) Model for Conservation Planning in Periyar Tiger Reserve, Southern Western Ghats, India

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Research Article

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Habitat Suitability Modelling of *Canarium strictum* Roxb. Using the Maximum Entropy (MaxEnt) Model for Conservation Planning in Periyar Tiger Reserve, Southern Western Ghats, India

ABSTRACT

Canarium strictum Roxb. (Burseraceae), commonly known as Black Dammar, is an ecologically and economically important evergreen tree endemic to the Western Ghats of India. However, habitat degradation, forest fragmentation, climate variability, and poor natural regeneration threaten its long-term persistence. This study employed the Maximum Entropy (MaxEnt) model integrated with Geographic Information System (GIS) and remote sensing techniques to predict the potential habitat suitability of *C. strictum* in Periyar Tiger Reserve (PTR), Kerala, India. Species occurrence records collected through field surveys were modelled using environmental variables derived from Sentinel-2 imagery, the ALOS PALSAR Digital Elevation Model (DEM), climatic datasets, forest cover maps, and other spatial datasets. The MaxEnt model demonstrated excellent predictive performance, with a training Area Under the Curve (AUC) of 0.921 and a test AUC of 0.917 ± 0.005. Permutation importance analysis identified annual temperature as the most influential predictor, followed by elevation, Normalized Difference Vegetation Index (NDVI), annual precipitation, and proximity to perennial water sources, indicating that climatic, topographic, and vegetation-related factors collectively govern the distribution of *C. strictum*. The habitat suitability map classified 120.55 km² (13.04%) of the reserve as highly suitable, 172.88 km² (18.68%) as moderately suitable, 218.68 km² (23.64%) as low suitable, and 412.89 km² (44.64%) as unsuitable habitat. Together, the highly and moderately suitable classes accounted for 293.43 km² (31.72%) of environmentally favourable habitat within Periyar Tiger Reserve. Field investigations further revealed that indigenous communities continue to practice traditional, non-destructive harvesting of naturally exuded Black Dammar resin, demonstrating the compatibility of sustainable resource use with biodiversity conservation. The habitat suitability map developed in this study provides a scientifically robust spatial decision-support tool for

conservation prioritization, habitat restoration, assisted natural regeneration, and the sustainable management of *Canarium strictum* in the southern Western Ghats.

Keywords: *Canarium strictum*; Black Dammar; MaxEnt; Habitat Suitability; Species Distribution Model; Remote Sensing; GIS; Periyar Tiger Reserve; Western Ghats; Conservation Planning.

1. INTRODUCTION

The Western Ghats of India is internationally recognized as one of the world's eight "hottest" biodiversity hotspots because of its exceptional levels of species richness, endemism, and ecological heterogeneity (Myers et al., 2000). Extending for approximately 1,600 km along the western coast of the Indian peninsula, the mountain chain occupies less than six percent of India's land area while supporting nearly one-third of the country's flowering plant diversity (Nayar et al., 2014). The interaction of complex topography, diverse geology, high annual rainfall, and pronounced altitudinal gradients has resulted in the evolution of unique tropical evergreen ecosystems that harbour numerous endemic and threatened plant species (Pascal, 1988; Ramesh et al., 2010). Owing to its outstanding ecological significance, several landscapes of the Western Ghats have been designated as UNESCO World Heritage Sites and remain global priorities for biodiversity conservation.

Among the endemic evergreen tree species of the Western Ghats, *Canarium strictum* Roxb. (Burseraceae), commonly known as Black Dammar, occupies a prominent position because of its ecological, economic, and cultural importance (Sasidharan, 2013). The species occurs predominantly in tropical evergreen and semi-evergreen forests of Kerala, Tamil Nadu, Karnataka, and adjoining hill ranges, generally between 500 and 1,500 m above mean sea level (Matthew, 1999; Page & Harwood, 2013). Mature trees may attain heights exceeding 40 m and constitute an important component of mature evergreen forest canopies.

Canarium strictum produces a commercially valuable oleoresin known as black dammar, which has traditionally been utilized for incense manufacture, waterproofing materials, varnishes, traditional medicine, pharmaceutical preparations, and religious ceremonies (Ved & Goraya, 2008; Ravikumar & Ved, 2000). In addition to its economic value, the species contributes significantly to forest ecosystem functioning by enhancing carbon storage, nutrient cycling, canopy structure, and habitat availability for numerous birds, mammals, and insects inhabiting tropical evergreen forests (Page & Harwood, 2013).

Despite its ecological significance, natural populations of *C. strictum* have declined in several parts of the Western Ghats owing to habitat fragmentation, forest degradation, climate variability, invasive alien species, and inadequate natural regeneration (Ramesh et al., 2010; Ved & Goraya, 2008). Successful regeneration of the species depends on favourable moisture conditions, intact forest canopies, suitable soils, and effective seed dispersal, making it particularly sensitive to environmental change. Consequently, identifying environmentally suitable habitats has become an important priority for developing evidence-based conservation strategies.

Periyar Tiger Reserve, located in the southern Western Ghats of Kerala, supports one of the largest contiguous tracts of tropical evergreen forests in peninsular India. The reserve encompasses diverse environmental gradients including elevation, rainfall, geology, soils, hydrology, and vegetation, thereby providing suitable habitats for numerous endemic tree species. However, despite the ecological importance of *C. strictum*, comprehensive spatial information regarding its potential distribution and habitat suitability within Periyar Tiger Reserve remains limited.

One of the distinctive conservation features of Periyar Tiger Reserve is the continued coexistence of biodiversity conservation with indigenous communities. Tribal settlements such as Vanchivayal, Mannakkudy, Paliyakudi, and Moozhikal possess extensive traditional ecological knowledge regarding forest resources. During field investigations, it was observed that black dammar resin is collected primarily from naturally exuded deposits or through carefully managed traditional harvesting methods that do not cause significant injury to standing trees. These practices differ from destructive resin extraction reported elsewhere and demonstrate how indigenous knowledge can contribute to sustainable non-timber forest product management while maintaining healthy populations of Canarium strictum.

Recent advances in species distribution modelling have substantially improved the ability to predict potential habitats for rare and threatened species. Among the available modelling approaches, the Maximum Entropy (MaxEnt) algorithm has emerged as one of the most widely applied techniques because it performs reliably using presence-only occurrence records and consistently produces accurate predictions across diverse taxonomic groups (Phillips et al., 2006; Elith et al., 2011). MaxEnt estimates the probability distribution of a species by maximizing entropy while satisfying constraints imposed by environmental conditions at observed occurrence locations.

The integration of remote sensing and Geographic Information System (GIS) technologies with MaxEnt modelling has further enhanced habitat suitability assessment by enabling the incorporation of high-resolution environmental variables derived from satellite imagery and digital elevation models (Franklin, 2010). Variables describing vegetation condition, terrain, climate, hydrology, soils, geology, and forest cover collectively provide a comprehensive representation of ecological conditions influencing species occurrence

The specific objectives of the present study are to:

1. Develop and validate a habitat suitability model for *Canarium strictum* using the Maximum Entropy (MaxEnt) algorithm based on species occurrence records and environmental variables.
2. Assess the relative contribution of topographic, climatic, vegetation, geological, hydrological, and anthropogenic factors influencing the spatial distribution of Canarium strictum.
3. Predict and classify the spatial distribution of suitable habitats into different suitability zones within the Periyar Tiger Reserve.
4. Identify priority areas for conservation, restoration, and sustainable management of *Canarium strictum* based on habitat suitability predictions.
5. Demonstrate the application of geospatial technologies, species distribution modelling, and indigenous ecological knowledge for supporting evidence-based conservation planning of threatened forest tree species.

2. Study Area

2.1 Geographical and Environmental Setting

Periyar Tiger Reserve (PTR), located in the southern Western Ghats of Kerala, India (9°16′–9°43′ N, 77°01′–77°25′ E), covers approximately 925 km² and forms part of the Periyar Elephant Reserve and Periyar Biosphere Reserve (Figure 1). The reserve shares its eastern boundary with Tamil Nadu and is connected to adjoining protected areas, including Meghamalai Wildlife Sanctuary, Srivilliputhur Grizzled Giant Squirrel Wildlife Sanctuary, Ranni Forest Division, and Kottayam Forest Division, contributing to landscape-level ecological connectivity. Elevation ranges from approximately 100 to 2,019 m above mean sea level, creating diverse microclimatic conditions and supporting a wide range of forest ecosystems. The reserve experiences a humid tropical monsoon climate, receiving 1,800–3,500 mm of annual rainfall with mean annual temperatures ranging from 15°C to 31°C.

Geologically, the area is dominated by Precambrian crystalline rocks with deep, well-drained lateritic and forest loam soils. Periyar Tiger Reserve forms the upper catchment of the Periyar River and contains an extensive network of perennial streams that maintain high soil moisture and sustain tropical evergreen forests. Major vegetation types include tropical wet evergreen, semi-evergreen, moist deciduous, shola, montane grassland, and riparian forests, with evergreen forests representing the principal habitat of Canarium strictum. The reserve supports rich biodiversity, including flagship species such as the Bengal Tiger, Asian Elephant, Lion-tailed Macaque, and Great Hornbill. Within PTR, C. strictum predominantly occurs in undisturbed evergreen forests at elevations of approximately 600–1,500 m, where it is associated with dense canopy cover, deep soils, favourable moisture conditions, and proximity to perennial streams, making the reserve an important conservation landscape for this endemic Western Ghats tree species**.**

2.2 Indigenous Communities and Sustainable Black Dammar Collection

One of the distinguishing characteristics of Periyar Tiger Reserve is the coexistence of indigenous communities and biodiversity conservation. Tribal settlements including **Vanchivayal**, **Mannakkudy**, **Paliyakudi**, and **Moozhikal** have inhabited these forests for generations and possess extensive traditional ecological knowledge regarding forest resources.

Black dammar obtained from *Canarium strictum* represents one of the important non-timber forest products collected by these communities. Unlike destructive resin extraction practices reported from some parts of the Western Ghats, indigenous communities within Periyar Tiger Reserve generally collect **naturally exuded resin** or adopt traditional harvesting techniques that avoid excessive injury to standing trees. Resin is gathered only after natural hardening, thereby allowing trees to continue normal physiological growth without significant damage.

These sustainable harvesting practices demonstrate an effective balance between livelihood requirements and biodiversity conservation. Traditional knowledge regarding tree identification, seasonal resin collection, forest ecology, and sustainable resource utilization has been transmitted through generations and continues to support long-term conservation of *Canarium strictum* populations within the reserve.

The integration of indigenous ecological knowledge with modern geospatial technologies and habitat suitability modelling provides an opportunity to develop community-based conservation strategies that simultaneously promote biodiversity conservation and sustainable utilization of non-timber forest products.

Table 1. General characteristics of the study area

Parameter	**Description**
Study Area	Periyar Tiger Reserve
State	Kerala
Biogeographic Zone	Western Ghats
Geographic Coordinates	9°16′–9°43′ N, 77°01′–77°25′ E
Total Area	Approximately 925 km²
Elevation	100–2019 m above mean sea level
Climate	Tropical Monsoon
Annual Rainfall	1800–3500 mm
Temperature	15–31°C
Major Forest Types	Evergreen, Semi-evergreen, Moist Deciduous, Shola, Grassland
Dominant River	Periyar River
Major Conservation Status	Tiger Reserve, Elephant Reserve, Biosphere Reserve
Target Species	*Canarium strictum* Roxb.

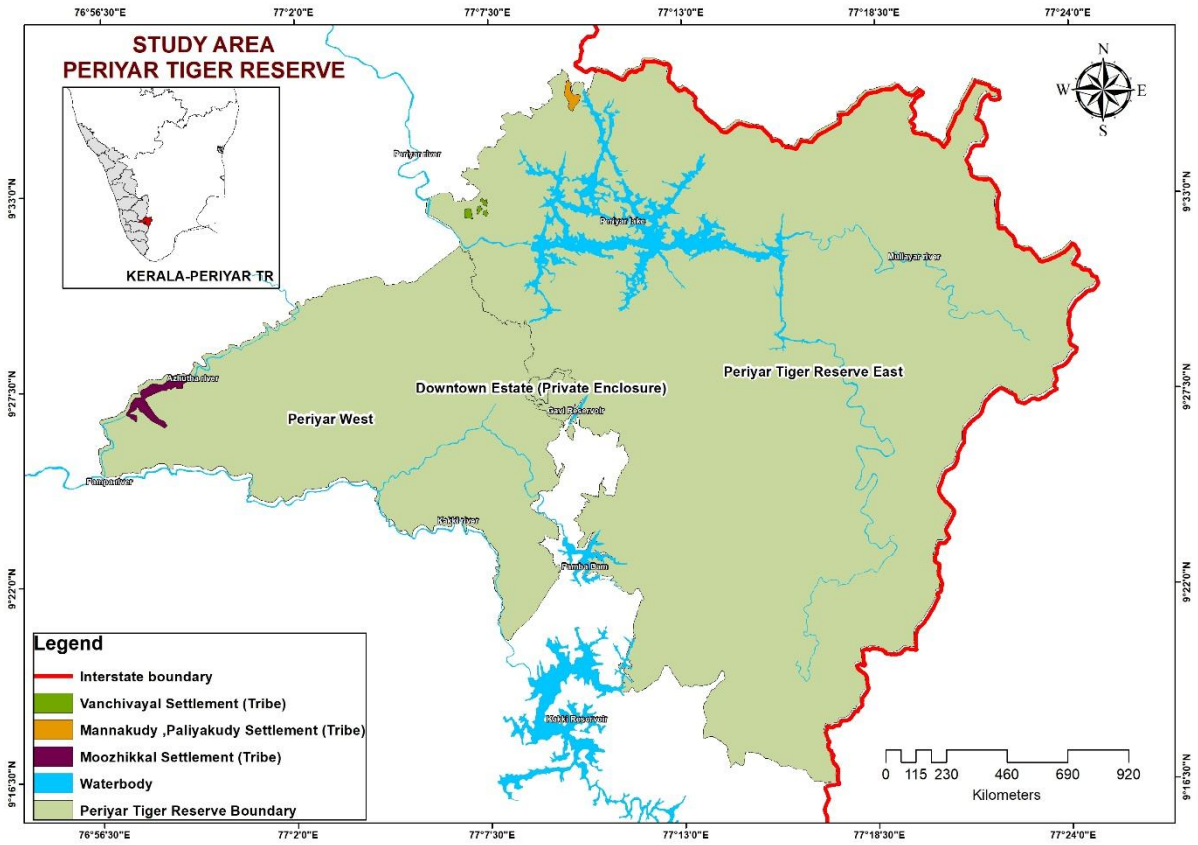


Figure 1. Location map of the study area showing Periyar Tiger Reserve

3. Materials and Methods

3.1 Overview of Methodology

The methodological framework adopted in this study integrates field-based species occurrence records, remote sensing datasets, environmental predictor variables, Geographic Information System (GIS) techniques, and Maximum Entropy (MaxEnt) modelling to predict the potential habitat suitability of *Canarium strictum* within Periyar Tiger Reserve. The workflow consisted of (i) collection and validation of species occurrence locations, (ii) preparation of environmental predictor layers, (iii) raster standardization and preprocessing, (iv) multicollinearity assessment and variable selection, (v) MaxEnt model development and calibration, and (vi) habitat suitability mapping and model evaluation.

The entire analysis was performed using ArcGIS 10.8, QGIS 3.x, SDM Toolbox v2.6, and MaxEnt version 3.4.4.

3.2 Species Occurrence Data

Occurrence records of *Canarium strictum* were collected through extensive field surveys conducted across different forest ranges of Periyar Tiger Reserve during April 2026 to July 2026. Species locations were recorded using handheld Global Positioning System (GPS) devices with an average positional accuracy of less than 5 m.

Additional occurrence records were obtained from:

- Kerala Forest Department vegetation records
- Periyar Tiger Reserve working plans
- Field verification surveys
- Forest range-level biodiversity monitoring records

For each occurrence location, the following information was documented:

- Geographic coordinates
- Elevation
- Habitat type
- Forest type
- Regeneration status
- Presence of resin collection activities
- Associated vegetation

Duplicate occurrence points located within the same raster grid cell were removed to minimize sampling bias and spatial autocorrelation. Spatial filtering was subsequently applied using SDM Toolbox to retain only ecologically independent occurrence locations for model development.

Table 2. Information collected during field surveys

Parameter	Description
Species Name	*Canarium strictum* Roxb.
Family	Burseraceae
GPS Coordinates	Latitude and Longitude
Elevation	m above MSL
Forest Type	Evergreen/Semi-evergreen

3.3 Environmental Predictor Variables

Species distribution is influenced by a combination of climatic, topographic, ecological, hydrological, geological, and anthropogenic factors. Therefore, multiple environmental predictor variables representing these conditions were prepared and incorporated into the MaxEnt model.

A total of thirteen environmental datasets were initially considered for analysis (Table 3).

Table 3. Environmental predictor variables used for habitat suitability modelling of *Canarium strictum* in Periyar Tiger Reserve

Sl. No	Data Description	Type	Source	Derived Layers
1	Sentinel-2 (10 m)	Raster	USGS Earth Explorer	NDVI
2	ALOS PALSAR DEM (12.5 m)	Raster	Alaska Satellite Facility	Elevation, Slope, Aspect, TRI, TPI, TWI, SPI, Plan Curvature, Profile Curvature, LS Factor
3	Annual Temperature	Raster	Kerala Forest Department	Annual Temperature
4	Annual Precipitation	Raster	Kerala Forest Department	Annual Precipitation
5	Forest Cover	Raster	FSI 2019	Forest Cover
6	Soil Suborder	Raster	FAO-UNESCO (2005)	Soil Classes
7	Lithology	Raster	Geological Survey of India	Lithological Units
8	Water Bodies	Vector	SOI Toposheets	Distance to Water Bodies

9	Settlements	Vector	SOI Toposheets	Distance to Settlements
10	Linear Networks	Vector	SOI Toposheets	Distance to Roads, Trek Paths, Power Lines
11	Faults	Vector	SOI Toposheets	Distance to Faults
12	Streams	Vector	SOI Toposheets	Distance to Streams
13	Livestock Density	Raster	Geo-Wiki Livestock Database	11 km Livestock Density Grid

3.4 Preparation of Environmental Layers

All environmental layers were projected to **WGS 1984 UTM Zone 43N** coordinate system and clipped to the Periyar Tiger Reserve boundary.

To ensure consistency during modelling:

- All raster layers were resampled to 10 m spatial resolution.
- Raster layers were converted into ASCII format.
- Cell alignment was standardized.
- Extent and coordinate systems were unified.

3.4.1 Vegetation Variable

The Normalized Difference Vegetation Index (NDVI) was generated from Sentinel-2 imagery to serve as a surrogate indicator of vegetation productivity, canopy density, and habitat quality using the following equation:

$$\text{NDVI} = \frac{\text{NIR} - \text{RED}}{\text{NIR} + \text{RED}}$$

where NIR represents Band 8 (Near-Infrared) and RED represents Band 4 (Red) of the Sentinel-2 sensor dataset.

3.4.2 Topographic Variables

Topographic variables were derived from the ALOS PALSAR DEM using Spatial Analyst and Hydrology tools in ArcGIS.
Derived variables included:

- Elevation
- Slope
- Aspect

These variables describe terrain complexity, moisture accumulation, runoff potential, and microclimatic variability influencing species distribution.

3.4.3 Climatic Variables

Annual temperature and annual precipitation layers were obtained from the Kerala Forest Department climate monitoring datasets. These variables represent long-term climatic conditions influencing growth, regeneration, and survival of *Canarium strictum*.

3.4.4 Hydrological Variables

Distance-to-water-body and distance-to-stream layers were generated from Survey of India topographic maps.

Hydrological variables are particularly important because *Canarium strictum* is frequently associated with moist evergreen forests and perennial water sources.

3.5 Multicollinearity Analysis

Prior to modelling, multicollinearity among environmental variables was evaluated using Pearson's Correlation Coefficient (r).
Correlation analysis was performed using the:
Raster Correlations and Summary Statistics Tool available in SDM Toolbox.

Highly correlated variables can inflate model performance and obscure ecological interpretation. Therefore:

- Variables with $|r| > 0.75$ were considered highly correlated.
- One variable from each correlated pair was removed.
- Ecologically meaningful variables were retained.

Following correlation analysis, the final set of independent variables selected for MaxEnt modelling included:

- Annual Precipitation
- Annual Temperature
- Elevation
- Slope
- Aspect
- NDVI
- Distance from Streams
- Distance from Water Bodies

- Forest Cover
- Soil Suborder
- Lithology

3.6 MaxEnt Habitat Suitability Modelling

Habitat suitability modelling was performed using **MaxEnt Version 3.4.4**, which applies the principle of maximum entropy to estimate species distribution using presence-only occurrence records.

The MaxEnt algorithm predicts habitat suitability by identifying the probability distribution that is closest to uniform while constrained by environmental conditions observed at known species locations.

Table 4. Model Settings

Parameter	Value
Software	MaxEnt 3.4.4
Replicates	10
Replicate Type	Cross Validation
Training Data	75%
Testing Data	25%
Maximum Iterations	5000
Background Points	10,000
Output Format	Logistic
Random Seed	Enabled
Response Curves	Enabled
Jackknife Test	Enabled

The logistic output generates habitat suitability values ranging from 0 to 1, where higher values indicate greater suitability.

3.7 Model Evaluation

Model performance was evaluated using the Receiver Operating Characteristic (ROC) curve and Area Under the Curve (AUC).

AUC values were interpreted as:

Table 5. **Model Evaluation**

AUC Value	**Model Performance**
< 0.70	Poor
0.70 – 0.80	Fair
0.80 – 0.90	Good
> 0.90	Excellent

The importance of predictor variables was assessed using:

- Jackknife Analysis
- Percent Contribution
- Permutation Importance
- Response Curves

4. Results

4.1 Model Performance

The Maximum Entropy (MaxEnt) model was successfully developed to predict the potential habitat suitability of *Canarium strictum* within Periyar Tiger Reserve using presence-only occurrence records and selected environmental variables. A total of **400 occurrence records** were used for modelling, of which **300 records** were used for model training and **100 records** for testing.

The model converged after **500 iterations** with a regularized training gain of **1.3953** indicating stable model optimization and effective characterization of the ecological niche of *C. strictum*. Receiver Operating Characteristic (ROC) analysis demonstrated excellent predictive performance, with a **training Area Under the Curve (AUC) of 0.921** and a **test AUC of 0.917 ± 0.005** (Figure 2). The close agreement between the training and testing AUC values indicates minimal model overfitting and excellent predictive capability.

Overall, the results confirm that the MaxEnt model reliably predicts the current distribution of environmentally suitable habitats for *C. strictum* within Periyar Tiger Reserve.

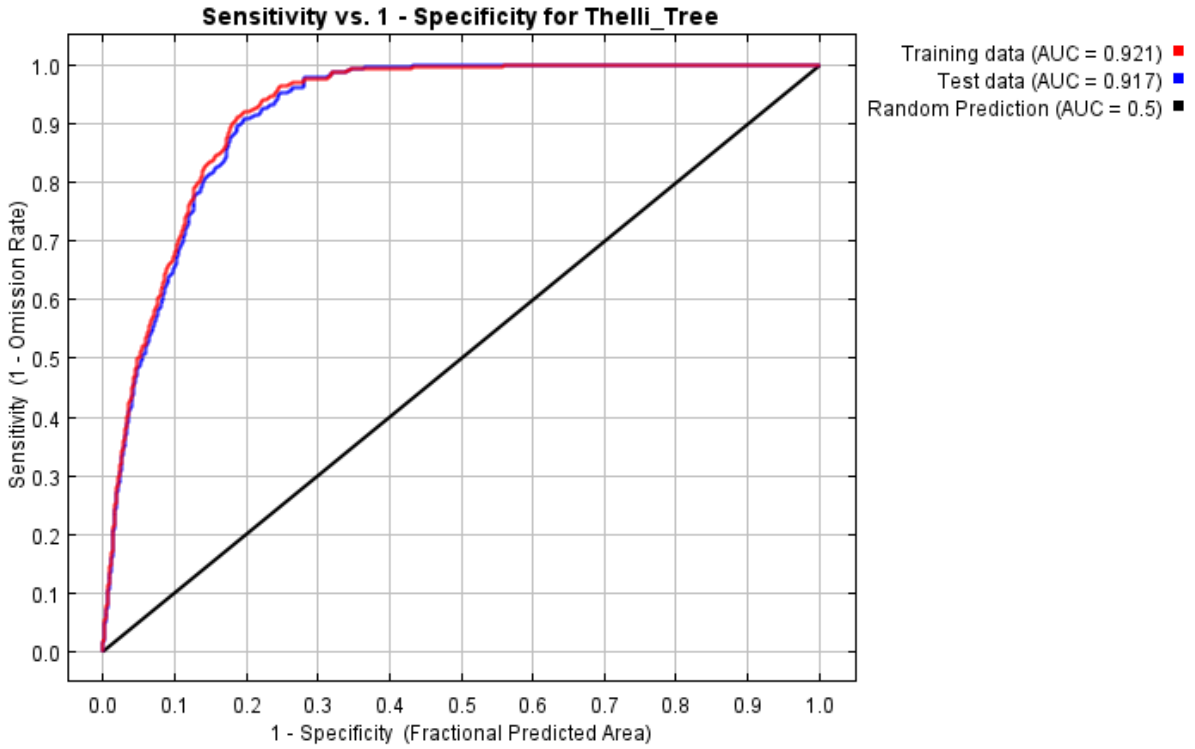


Figure 2. Receiver Operating Characteristic (ROC) curve showing the predictive performance of the MaxEnt habitat suitability model for *Canarium strictum* in Periyar Tiger Reserve.

4.2 Contribution of Environmental Variables

The MaxEnt model evaluated the relative influence of climatic, topographic, vegetation, hydrological, geological, edaphic, and anthropogenic variables on the distribution of *Canarium strictum*. The results indicate that climatic and environmental variables collectively govern the ecological niche of the species.

Permutation importance identified **annual temperature** as the most influential predictor (**29.6%**), highlighting the strong dependence of *C. strictum* on favourable thermal conditions. **Elevation (18.5%)** and **distance to streams (14.8%)** were the next most influential variables, indicating that topographic gradients and continuous moisture availability play a crucial role in determining suitable habitats. Among the remaining predictors, **annual rainfall (7.8%)**, **lithology (7.7%)**, and **Normalized Difference Vegetation Index (NDVI; 6.8%)** also made substantial contributions, reflecting the importance of precipitation, geological substrate, and vegetation productivity in shaping species distribution. **Slope (5.5%)**, **distance to water bodies (3.8%)**, and **soil suborder (3.6%)** showed moderate influence, whereas **aspect (1.4%)** and **forest cover (0.6%)** contributed relatively little to the final habitat suitability model.

Overall, the results demonstrate that the distribution of *C. strictum* is primarily controlled by climatic and topographic factors, followed by hydrological, geological, and vegetation-related variables. The ecological interpretation of this study focuses mainly on climatic, topographic, hydrological, geological, and vegetation variables because these factors are directly associated with the ecological requirements of *C. strictum*. Anthropogenic variables may partially represent sampling accessibility and correlated landscape characteristics rather than direct habitat preferences.

Table 6. Major environmental variables influencing habitat suitability of *Canarium strictum*

Environmental Variable	Permutation Importance (%)	Ecological Importance	Code
Annual Temperature	29.6	Very High	temp
Elevation	18.5	Very High	dem
Distance to Streams	14.8	High	stream
Annual Rainfall	7.8	Moderate–High	rainfall
Lithology	7.7	Moderate–High	litho
NDVI	6.8	Moderate	ndvi
Slope	5.5	Moderate	slope
Distance to Water Bodies	3.8	Low–Moderate	d2w
Soil Suborder	3.6	Low–Moderate	Soil
Aspect	1.4	Low	asp
Forest Cover	0.6	Very Low	fc

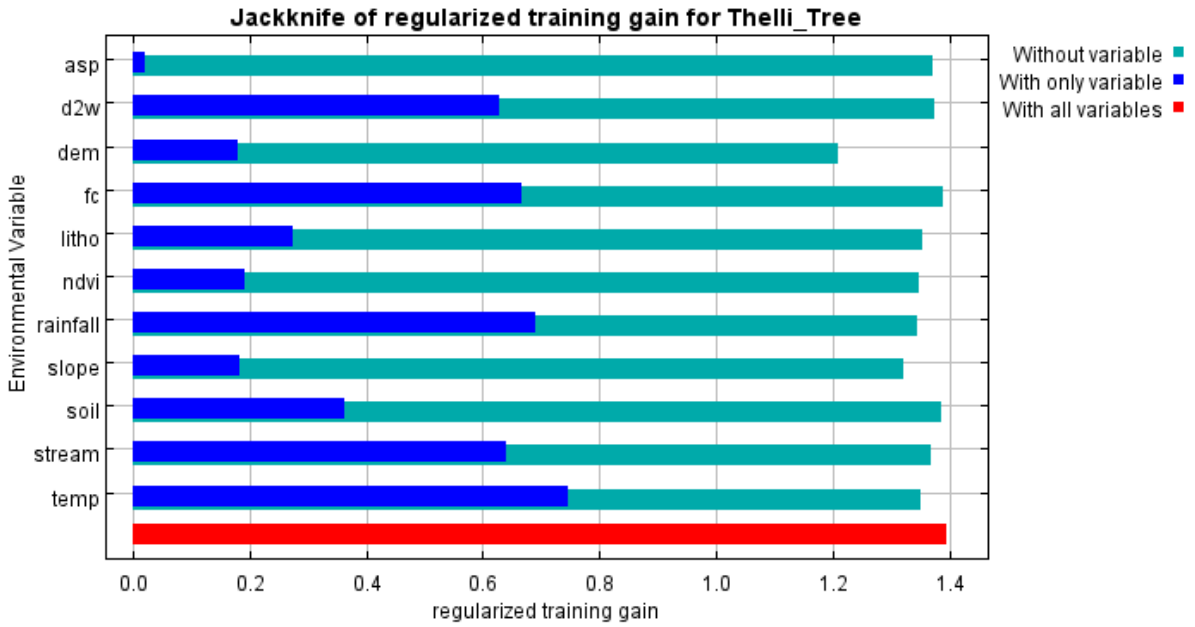
4.3 Jackknife Analysis

The jackknife test was used to assess the independent contribution of each environmental variable to the predictive performance of the MaxEnt model (Figure 3). The analysis demonstrated that climatic and topographic variables contained the greatest amount of unique ecological information for predicting the distribution of *Canarium strictum*.

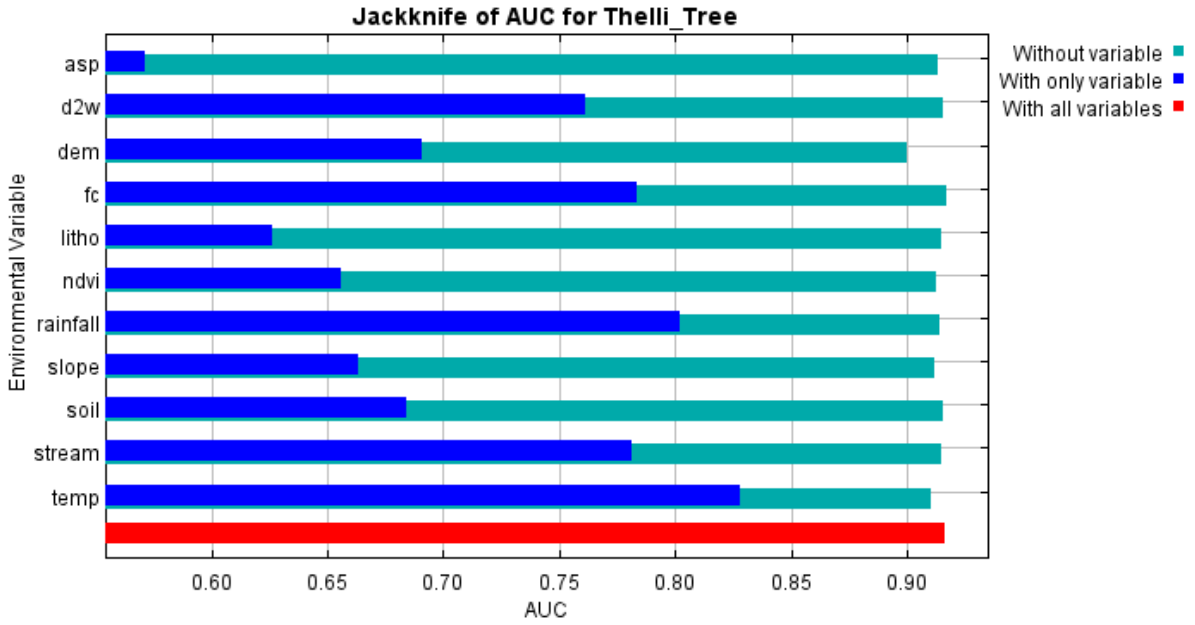
Annual temperature, elevation, vegetation condition (NDVI), and hydrological variables consistently produced higher training gains, indicating their significant contribution to defining

the ecological niche of the species. The omission of these variables resulted in noticeable reductions in model performance, demonstrating that each provides complementary ecological information essential for accurate habitat prediction.

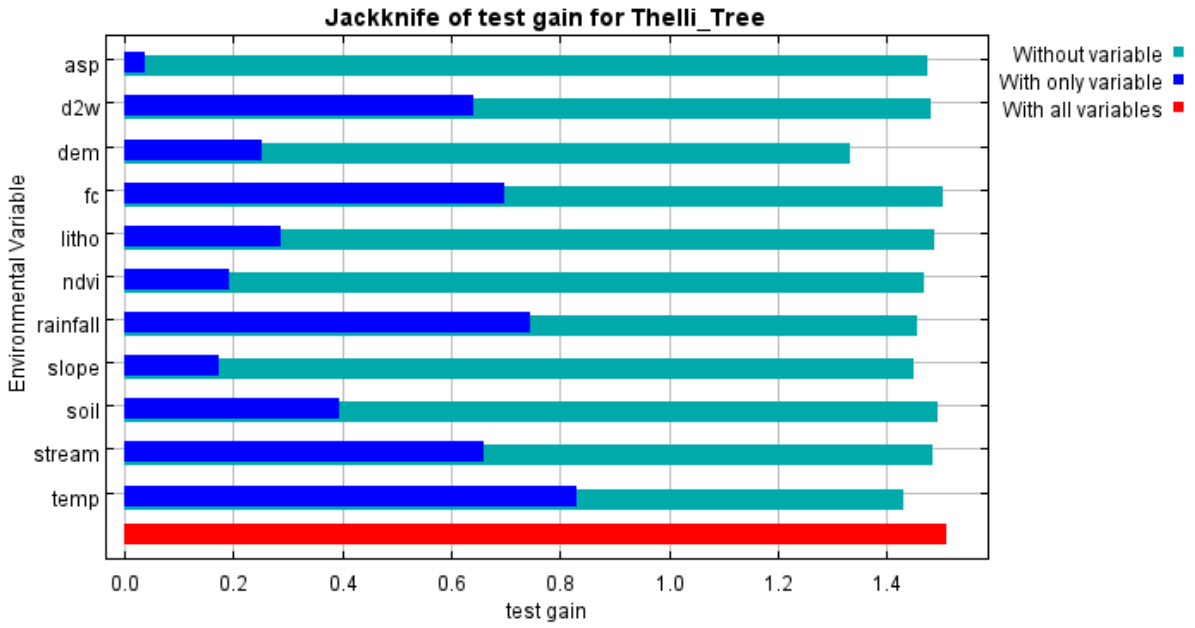
Forest cover, annual rainfall, and terrain characteristics further improved model performance by describing habitat structure and environmental conditions associated with tropical evergreen forests. Overall, the jackknife analysis confirmed that the distribution of *C. strictum* is controlled by the combined influence of climate, terrain, vegetation productivity, and moisture availability rather than by any single environmental variable.



(A)



(B)



(C)

Figure 3. Jackknife analysis showing the relative importance of environmental variables based on training gain (A), AUC (B), and test gain(C)

4.5 Habitat Suitability Distribution

The MaxEnt logistic model predicted a heterogeneous distribution of habitat suitability for *Canarium strictum* across Periyar Tiger Reserve (Figure 4). Habitat suitability values ranged from **0.00 to 1.00**, representing varying probabilities of species occurrence under current environmental conditions.

The continuous habitat suitability map was reclassified into four suitability classes based on logistic probability values (Table 7): Unsuitable (0.00–0.14), Low Suitable (0.14–0.37), Moderately Suitable (0.37–0.63), and Highly Suitable (0.63–1.00).

Table 7. Habitat suitability classes of *Canarium strictum* in Periyar Tiger Reserve.

Habitat Suitability Class	Logistic Value	Area (km²)	Percentage (%)
Unsuitable	0-0.14	412.89	44.64
Low Suitable	0.14-0.37	218.68	23.64
Moderately Suitable	0.37-0.63	172.88	18.68
Highly Suitable	0.63-1	120.55	13.04
Total	—	925	100

The habitat suitability assessment indicated that **120.55 km² (13.04%)** of Periyar Tiger Reserve was classified as **highly suitable** habitat for *C. strictum*, while **172.88 km² (18.68%)** was identified as **moderately suitable**. Collectively, these two categories account for **293.43 km² (31.72%)** of environmentally favourable habitat within the reserve. An additional **218.68 km² (23.64%)** was classified as **low suitable**, representing marginally favourable habitat where the species may occur under specific environmental conditions. The remaining **412.89 km² (44.64%)** was categorized as **unsuitable**, indicating areas where existing climatic, topographic, vegetation, and environmental conditions are less conducive to the occurrence of *C. strictum*.

Highly suitable habitats were predominantly concentrated within intact tropical evergreen forest ecosystems characterized by favourable temperature regimes, high annual rainfall, dense vegetation cover, suitable elevation, and consistent moisture availability. Moderately suitable habitats were generally distributed adjacent to these core evergreen forest regions, forming potential buffer zones for species expansion. In contrast, low suitable and unsuitable habitats were mainly associated with comparatively less favourable climatic conditions, lower vegetation density, altered topography, or disturbed landscapes.

Overall, the habitat suitability map provides a spatially explicit framework for identifying priority conservation areas, guiding ecological restoration and assisted natural regeneration programmes, and establishing long-term monitoring sites for *Canarium strictum* within Periyar Tiger Reserve. The predicted distribution also offers valuable baseline information for habitat management and conservation planning aimed at ensuring the long-term persistence of this ecologically and economically important endemic tree species.

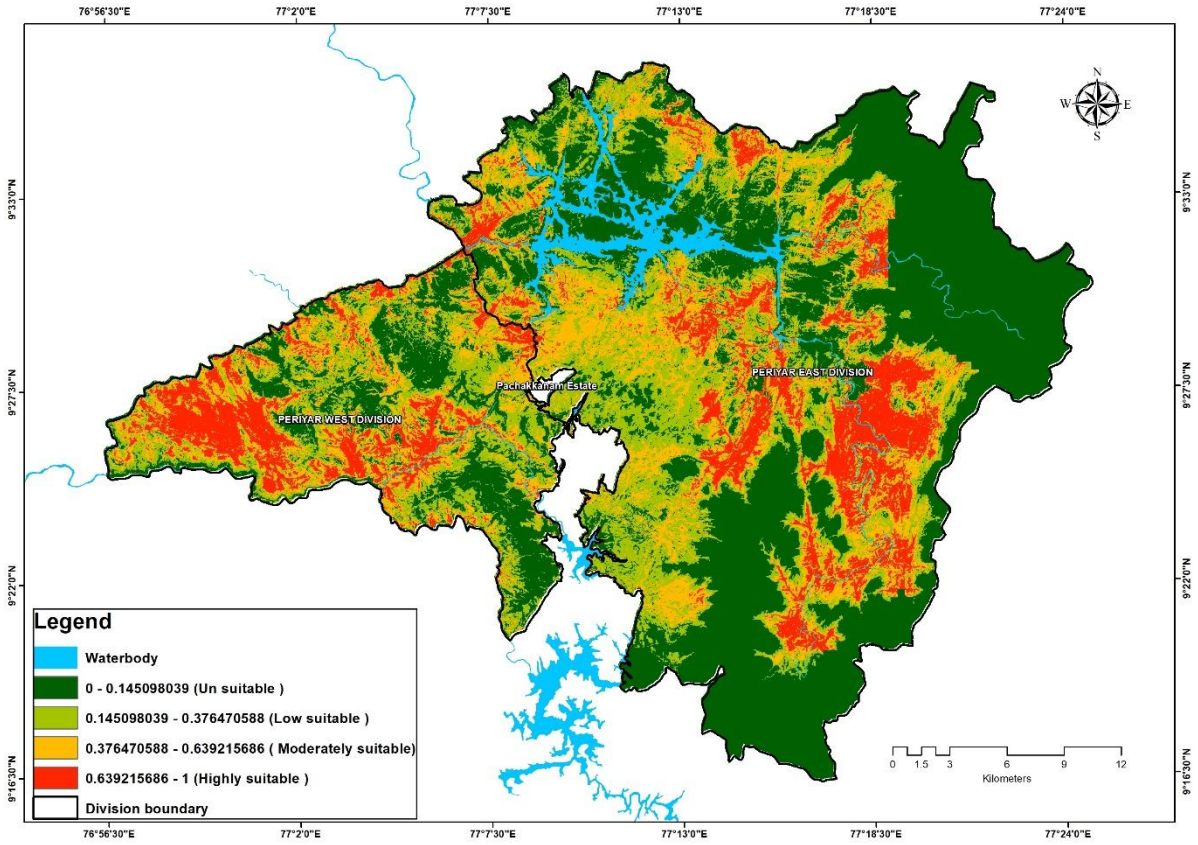


Figure 4. Habitat suitability map of *Canarium strictum* in Periyar Tiger Reserve generated using the MaxEnt model.

4.6 Conservation Priority Zones

The habitat suitability assessment identified **293.43 km² (31.72%)** of Periyar Tiger Reserve as **moderately to highly suitable habitat** for *Canarium strictum*. These areas represent the principal conservation zones that provide favourable environmental conditions for the occurrence, persistence, and natural regeneration of the species. In contrast, **218.68 km² (23.64%)** was classified as low suitable habitat, while **412.89 km² (44.64%)** was identified as unsuitable under the prevailing environmental conditions.

Highly suitable habitats were predominantly associated with intact tropical evergreen forests characterized by dense canopy cover, favourable temperature regimes, high annual rainfall, suitable elevation, and reliable moisture availability. These areas should be prioritized for long-term habitat protection, conservation management, enrichment planting, assisted natural regeneration, and periodic ecological monitoring to ensure the sustained persistence of *C. strictum* populations.

Field observations further indicated that several highly suitable habitats coincide with areas traditionally used by indigenous communities for the collection of naturally exuded Black Dammar resin using non-destructive harvesting practices. The coexistence of sustainable resin harvesting and healthy tree populations underscores the importance of integrating traditional ecological knowledge with scientific habitat management to promote both biodiversity conservation and sustainable livelihood practices.

The habitat suitability map generated in the present study provides a robust spatial decision-support framework for identifying conservation priority areas, guiding ecological restoration programmes, supporting assisted natural regeneration, planning long-term monitoring, and promoting the sustainable management of Black Dammar resources within Periyar Tiger Reserve. The results also provide a scientific basis for developing species-specific conservation strategies and adaptive forest management plans for *Canarium strictum* under changing environmental conditions.

5.Discussion

5.1 Habitat suitability of *Canarium strictum* in Periyar Tiger Reserve

The present study successfully employed the Maximum Entropy (MaxEnt) model to predict the potential habitat suitability of *Canarium strictum* within Periyar Tiger Reserve. The model demonstrated excellent predictive performance, achieving a training Area Under the Curve (AUC) of **0.921** and a test AUC of **0.921 ± 0.005**, indicating high reliability in distinguishing suitable from unsuitable habitats. These results are consistent with previous studies that have demonstrated the effectiveness of MaxEnt for modelling species distributions using presence-only occurrence data (Phillips et al., 2006; Elith et al., 2011).

The habitat suitability assessment revealed that **120.55 km² (13.04%)** of the study area was classified as **highly suitable**, while **172.88 km² (18.68%)** was identified as **moderately suitable**, together accounting for **293.43 km² (31.72%)** of the reserve. In addition, **220.20 km² (23.80%)** was classified as **marginally suitable**, whereas the remaining **413.08 km² (44.48%)**

was categorized as **unsuitable** for *C. strictum*. The relatively limited extent of highly suitable habitat reflects the species' narrow ecological niche and its dependence on specific environmental conditions. The concentration of suitable habitats within intact evergreen forests highlights the ecological significance of Periyar Tiger Reserve as an important refuge for this endemic tree species.

The heterogeneous distribution of suitable habitats observed in this study reflects the considerable environmental variability within the reserve. Spatial differences in climate, topography, vegetation structure, and hydrological conditions collectively influence the occurrence and persistence of *C. strictum*, resulting in a patchy distribution pattern that is characteristic of many endemic tree species in the Western Ghats. These findings underscore the importance of conserving ecologically intact evergreen forest ecosystems and prioritizing habitat management in areas identified as highly and moderately suitable to ensure the long-term survival of *C. strictum* populations.

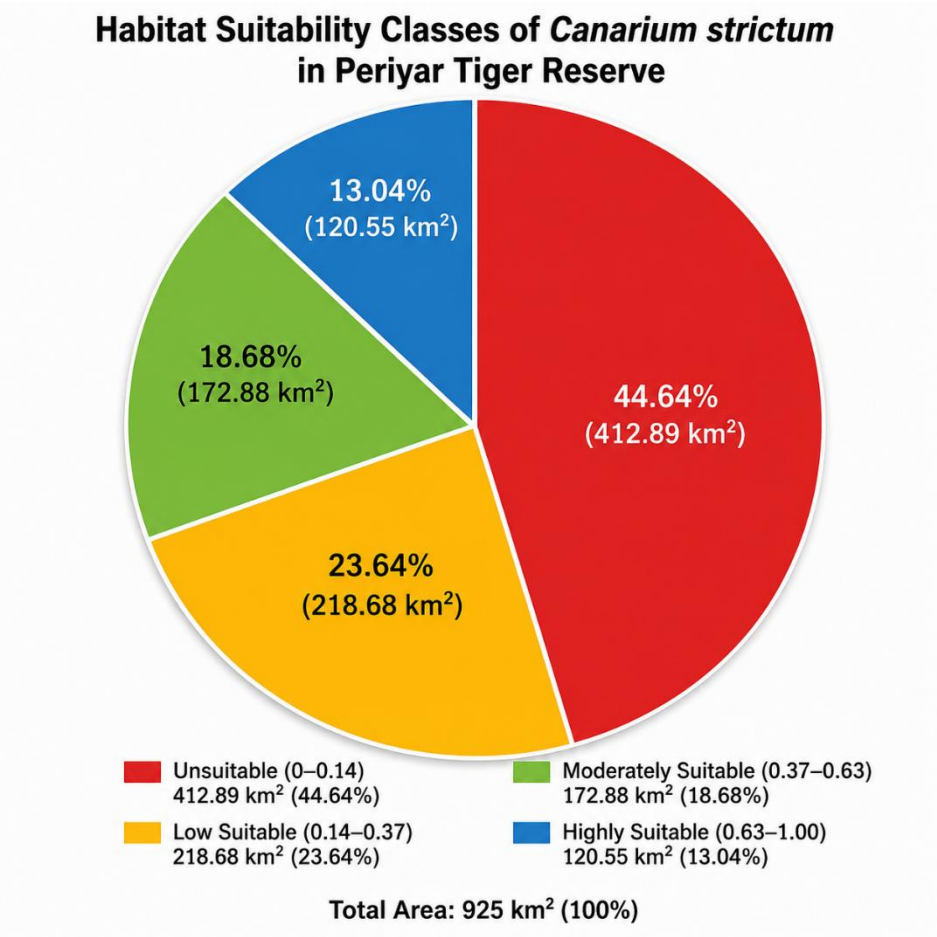


Figure 5. Area statistics of habitat suitability classes of *Canarium strictum* in Periyar Tiger Reserve

5.2 Influence of climatic variables

Climatic variables emerged as the primary determinants of habitat suitability, with annual temperature showing the greatest influence on model performance. Temperature regulates several physiological processes, including photosynthesis, respiration, flowering, fruit development, seed maturation, and seedling establishment. Consequently, even small variations in temperature can significantly affect the distribution of evergreen tree species.

The response curves indicated that *C. strictum* is associated with moderate temperature regimes typical of tropical evergreen forests. These findings agree with previous ecological studies that describe *C. strictum* as a moisture-loving species adapted to humid tropical environments with relatively stable climatic conditions. Annual precipitation also played an important role by maintaining favourable soil moisture, reducing drought stress, and supporting continuous forest productivity.

Projected changes in temperature and rainfall under future climate scenarios may alter the distribution of suitable habitats for *C. strictum*. Long-term monitoring and climate-adaptive conservation strategies will therefore be essential to safeguard existing populations within the Western Ghats.

5.3 Role of topography

Topographic variables derived from the ALOS PALSAR Digital Elevation Model significantly contributed to habitat prediction. Elevation was identified as one of the most influential environmental variables, reflecting its role in controlling local climate, cloud formation, humidity, soil development, and vegetation composition.

The results indicate that *C. strictum* is predominantly associated with mid-elevation evergreen forests where favourable microclimatic conditions persist throughout the year. These environments typically experience lower temperature fluctuations, higher relative humidity, and greater moisture availability than surrounding landscapes.

Slope also influenced habitat suitability by providing well-drained yet moisture-retentive soils favourable for root development and seedling establishment. Similar relationships between topography and species distribution have been reported for numerous evergreen tree species across the Western Ghats, highlighting the importance of terrain characteristics in maintaining forest biodiversity.

5.4 Importance of vegetation condition

Vegetation condition, represented by the Normalized Difference Vegetation Index (NDVI), emerged as one of the major environmental predictors. NDVI provides an indirect measure of vegetation productivity, canopy density, and photosynthetic activity and therefore serves as an effective indicator of habitat quality.

Higher habitat suitability was consistently associated with areas exhibiting high NDVI values, indicating a preference for dense evergreen forests with closed canopy conditions. Mature forest stands provide moderated temperatures, higher humidity, improved litter accumulation, and favourable soil conditions that promote successful regeneration of *C. strictum*.

The close relationship between NDVI and habitat suitability highlights the importance of maintaining intact forest canopies. Forest degradation and canopy opening can alter microclimatic conditions, reduce soil moisture, and ultimately decrease habitat quality for the species.

5.5 Hydrological influences

Hydrological variables also played a significant role in determining habitat suitability. Areas located close to perennial streams and water bodies exhibited higher probabilities of occurrence, reflecting the dependence of *C. strictum* on continuously moist environments.

Perennial drainage systems help maintain stable soil moisture throughout the year, supporting physiological processes, seed germination, and natural regeneration. During field surveys, mature individuals of *C. strictum* were frequently recorded in valleys, lower hill slopes, and stream-associated evergreen forests where moisture availability remained relatively high even during dry periods.

These findings indicate that water availability is an essential ecological requirement and should be considered when identifying priority areas for restoration and assisted natural regeneration.

5.6 Conservation significance of indigenous knowledge

An important outcome of this study is the documentation of sustainable Black Dammar resin harvesting by indigenous communities residing within Periyar Tiger Reserve. Tribal settlements such as Vanchivayal, Mannakkudy, Paliyakudi, and Moozhikal continue to collect naturally exuded resin using traditional non-destructive harvesting practices.

Unlike destructive tapping methods reported from some parts of the Western Ghats, resin collection within Periyar Tiger Reserve does not involve deliberate injury to standing trees.

This traditional practice allows continued resin extraction while maintaining tree health and supporting long-term population persistence.

These observations demonstrate that traditional ecological knowledge can effectively complement scientific conservation strategies. Incorporating indigenous knowledge into forest management plans can enhance biodiversity conservation while simultaneously supporting sustainable livelihoods and the long-term management of non-timber forest products.

5.7 Conservation and management implications

The habitat suitability map developed in the present study provides a valuable decision-support tool for conservation planning within Periyar Tiger Reserve. The identification of **293.43 km²** of moderate to highly suitable habitat enables forest managers to prioritize areas for long-term protection and ecological restoration.

Priority management actions should include:

- Protection of existing mature seed-bearing trees within highly suitable habitats.
- Assisted natural regeneration and enrichment planting using locally adapted planting material.
- Restoration of degraded evergreen forest patches adjacent to suitable habitats.
- Long-term ecological monitoring to assess changes in habitat quality and population dynamics.
- Sustainable management of Black Dammar resources through community participation.
- Integration of habitat suitability maps into forest management and conservation planning.

Site-Specific Conservation Prioritization: The habitat suitability analysis, supported by field observations, identified several locations with a high occurrence of *Canarium strictum* within Periyar Tiger Reserve. These areas should be recognized as priority conservation zones for focused protection, monitoring, and habitat management. Major high-suitability locations include **Mukkar, Karangal Thodu, Aladimala, Inchipara Thodu, Thalamala Mettu, Kottakavala, Manadikala, Erichil, Undaviduthi, Bommachi Mukku, and Churakotta Thodu** in **Periyar Range**; **Thellithodu, Kavanthi, Meenmutti, Orangekanam, and Pachamudi** in **Azhutha Range**; **Kallidam Kunnu, Manjapodithattu,**

Oliyan Puzha, Valiyanavattam, Podanpulavu, and Sannidhanam area in **Pamba Range**; **85 Plantation, Irukutty, and Paravalavu Kandam** in **Vallakkadavu Range**; and **Medhakanam mala, Kulaloodhi, and Palkachimala** in **Thekkady Range**. These sites should receive priority for habitat protection, prevention of anthropogenic disturbances, population monitoring, and natural regeneration initiatives to ensure the long-term conservation of *C. strictum*

Because *C. strictum* is endemic to the Western Ghats and exhibits a relatively restricted ecological niche, conserving these priority habitats is essential for ensuring the long-term persistence of the species. The integration of species distribution modelling, remote sensing, GIS, and indigenous ecological knowledge provides a robust framework for evidence-based conservation planning in protected landscapes.

6. Conclusion

The present study demonstrates the effectiveness of the Maximum Entropy (MaxEnt) modelling approach integrated with Remote Sensing and Geographic Information System (GIS) techniques for predicting the potential habitat suitability of *Canarium strictum* within Periyar Tiger Reserve, Southern Western Ghats, India. The MaxEnt model exhibited excellent predictive performance, achieving a training Area Under the Curve (AUC) of **0.921** and a test AUC of **0.917 ± 0.005**, confirming its robustness and reliability for species distribution modelling and conservation planning.

The habitat suitability assessment revealed a heterogeneous spatial distribution of suitable habitats across the reserve. The model classified **120.55 km² (13.04%)** as **highly suitable** habitat and **172.88 km² (18.68%)** as **moderately suitable** habitat, together accounting for **293.43 km² (31.72%)** of environmentally favourable habitat for *Canarium strictum*. In addition, **218.68 km² (23.64%)** was identified as **low suitable** habitat, whereas **412.89 km² (44.64%)** was classified as **unsuitable** under the prevailing environmental conditions. These findings indicate that nearly one-third of Periyar Tiger Reserve provides favourable ecological conditions for the long-term persistence and natural regeneration of the species.

Among the environmental variables, annual temperature emerged as the most influential predictor of species distribution (29.6%), followed by elevation (18.5%), distance to streams (14.8%), annual rainfall (7.8%), and lithology (7.7%). These variables collectively define the ecological niche of *C. strictum*, emphasizing the critical importance of favourable thermal conditions, suitable topography, and immediate proximity to flowing water sources, alongside

broader regional precipitation patterns and geological substrates in determining habitat suitability.

Highly suitable habitats were predominantly concentrated within intact tropical evergreen forests that provide stable microclimatic conditions and favourable ecological environments for species survival. These areas represent high-priority conservation zones and should receive focused attention through habitat protection, enrichment planting, assisted natural regeneration, and long-term ecological monitoring to ensure the continued persistence of *C. strictum* populations.

Field investigations further confirmed that indigenous communities residing in **Vanchivayal, Mannakkudy, Paliyakudi, and Moozhikal** continue to practice traditional, non-destructive harvesting of naturally exuded Black Dammar resin. The coexistence of healthy *C. strictum* populations with sustainable resin harvesting practices demonstrates the value of integrating traditional ecological knowledge with scientific conservation approaches. Community participation can therefore play a significant role in promoting sustainable resource utilization while supporting biodiversity conservation within protected areas.

Overall, the habitat suitability map generated in this study provides a scientifically robust spatial decision-support tool for identifying conservation priority areas, guiding ecological restoration and assisted natural regeneration programmes, supporting long-term biodiversity monitoring, and promoting the sustainable management of Black Dammar resources within Periyar Tiger Reserve. The integration of species distribution modelling, geospatial technologies, field validation, and indigenous ecological knowledge offers a comprehensive framework for the conservation and sustainable management of *Canarium strictum* and other threatened endemic tree species across the Western Ghats. This study also establishes a valuable baseline for future assessments of climate change impacts and adaptive conservation planning in tropical forest ecosystems.

6.2 Future Scope

Future research should focus on integrating high-resolution climate projections (e.g., CMIP6 scenarios) to assess potential distributional range shifts under shifting climate pressures. Incorporating structural metrics derived from LiDAR or high-resolution radar (e.g., NISAR), alongside finer-scale edaphic parameters, could improve model sensitivity. Additionally, multi-model ensemble frameworks comparing MaxEnt with machine learning algorithms like Random Forest or Boosted Regression Trees would limit algorithmic uncertainty. Finally,

landscape genetic assessments are necessary to determine the genetic diversity and connectivity among remaining populations across the Western Ghats network

References

1. Elith, J., Graham, C. H., Anderson, R. P., Dudík, M., Ferrier, S., Guisan, A., Hijmans, R. J., Huettmann, F., Leathwick, J. R., Lehmann, A., Li, J., Lohmann, L. G., Loiselle, B. A., Manion, G., Moritz, C., Nakamura, M., Nakazawa, Y., Overton, J. McC., Peterson, A. T., … Zimmermann, N. E. (2006). Novel methods improve prediction of species' distributions from occurrence data. *Ecography*, **29**, 129–151.
2. Elith, J., Phillips, S. J., Hastie, T., Dudík, M., Chee, Y. E., & Yates, C. J. (2011). A statistical explanation of MaxEnt for ecologists. *Diversity and Distributions*, **17**, 43–57.
3. Hijmans, R. J., Cameron, S. E., Parra, J. L., Jones, P. G., & Jarvis, A. (2005). Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology*, **25**, 1965–1978.
4. Myers, N., Mittermeier, R. A., Mittermeier, C. G., da Fonseca, G. A. B., & Kent, J. (2000). Biodiversity hotspots for conservation priorities. *Nature*, **403**, 853–858.
5. Phillips, S. J., Dudík, M., Elith, J., Graham, C. H., Lehmann, A., Leathwick, J., & Ferrier, S. (2009). Sample selection bias and presence-only distribution models. *Ecological Applications*, **19**, 181–197.
6. Forest Survey of India (FSI). (2019). *India State of Forest Report 2019*. Dehradun.
7. Survey of India. (2018). *Topographical Maps*. Survey of India, Dehradun.
8. Brown, J. L. (2014). SDMtoolbox: A Python-based GIS toolkit for landscape genetic, biogeographic and species distribution model analyses. *Methods in Ecology and Evolution*, **5**(7), 694–700. https://doi.org/10.1111/2041-210X.12200
9. Nayar, T. S., Beegam, A. R., & Sibi, M. (2014). *Flowering Plants of the Western Ghats, India*. Jawaharlal Nehru Tropical Botanic Garden and Research Institute.
10. Page, T., & Harwood, C. (2013). Tropical tree domestication and conservation. *Forest Ecology and Management*, **310**, 1–10.
11. Sasidharan, N. (2013). *Flowering Plants of Kerala*. Kerala Forest Research Institute.
12. Franklin, J. (2010). *Mapping Species Distributions: Spatial Inference and Prediction*. Cambridge University Press.
13. Kumar, S., & Stohlgren, T. J. (2009). MaxEnt modeling for predicting suitable habitat. *Ecological Modelling*, **220**, 2783–2791.
14. Ved, D. K., & Goraya, G. S. (2008). *Demand and Supply of Medicinal Plants in India*. FRLHT, Bengaluru.
15. Pearson, R. G. (2007). Species distribution modeling for conservation educators and practitioners. *Lessons in Conservation*, **3**, 54–89.

16. Peterson, A. T., Papeş, M., & Eaton, M. (2007). Transferability and model evaluation in ecological niche modelling. *Ecography*, **30**, 550–560.
17. Phillips, S. J., Anderson, R. P., & Schapire, R. E. (2006). Maximum entropy modeling of species geographic distributions. *Ecological Modelling*, **190**, 231–259.
18. FAO. (2005). *Digital Soil Map of the World*. Food and Agriculture Organization, Rome.
19. Guisan, A., & Thuiller, W. (2005). Predicting species distribution: Offering more than simple habitat models. *Ecology Letters*, **8**, 993–1009.
20. Phillips, S. J., Dudík, M., & Schapire, R. E. (2004). A maximum entropy approach to species distribution modeling. *Proceedings of the Twenty-first International Conference on Machine Learning*, 655–662.
21. Matthew, K. M. (1999). *The Flora of the Palni Hills*. Rapinat Herbarium.
22. Pascal, J. P. (1988). *Wet Evergreen Forests of the Western Ghats of India*. Institut Français de Pondichéry.
23. IPCC. (2021). *Climate Change 2021: The Physical Science Basis*. Cambridge University Press.