

Conservation of forest genetic resources in eastern India amidst climate change and abiotic stress

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Abstract

Eastern India's forest ecosystems, dominated by *Shorea robusta* Gaertn., are increasingly threatened by abiotic stressors and climate change, posing significant risks to species survival, regeneration dynamics, and forest genetic resources. This study evaluated the current distribution, population structure, and regeneration status of *S. robusta* and its major associates and their response to climate change in eastern India. The potential distribution range of *S. robusta* and its major associates were modelled for current and future climate scenarios using CMIP6 climate models (INM-CM5-O, IPSL-CM6A-LR, MIROC6) proxied through Shared Socioeconomic Pathways (SSP126, 245, 370, 585). Presently, suitable habitat ranges cover approximately 11.21%, of the study area for *S. robusta* and 7.35%, 11.79%, 9.42%, 11.11%, and 12.13% for its major associates; *T. alata*, *P. marsupium*, *L. parviflora*, *D. melanoxylon*, and *M. longifolia*, respectively. The future projections indicate contraction in suitable habitat range of *S. robusta*, *P. marsupium*, and *L. parviflora*, with northward shifting. The study predicted ~ 7.75–65% potential decline in the suitable habitat of *S. robusta* by 2050. For a business-as-usual scenario the suitable habitat range for all the species is predicted to decline with a maximum ~ 84% for *L. parviflora*. The study found *S. robusta*, *M. longifolia*, *P. marsupium*, *T. alata*, and *D. melanoxylon*, showed good regeneration, indicating favorable conditions for forest regeneration in the study region. Notably, *P. marsupium* and *M. longifolia* exhibit resilience to climate stress, supported by favorable regeneration status. We recommend location and species-specific intervention strategies to conserve and manage the integrity of the forest ecosystem in the eastern Indian region.

Highlights

- Current suitable habitats for *S. robusta* and its major associates are concentrated in the southern and western parts of eastern India, with promising regeneration status for most species except *L. parviflora*.
- Future climate projections indicate a potential northward shift and contraction in the suitable habitat of *S. robusta*, reflecting broader ecological transitions in the region.
- Among associated species, *M. longifolia* and *P. marsupium* show the highest resilience to climate change.

1. Introduction

Forests play a crucial role in maintaining ecological balance, regulating the climate, and providing essential resources to mankind (Chen et al., 2022). They provide habitat for over 50% of terrestrial biodiversity and are a major source of the world's biomass for energy (Gorain and Malakar, 2020). Habitat fragmentation and degradation has been a persistent issue among research communities globally (Wu, 2013; Haddad et al., 2015). A growing body of published work provides evidence of potential shift in species habitat due to climate change (Sharma et al., 2022; Zhang et al., 2022; Maharjan et al., 2023). Other factors such as logging, land use and land cover (LULC) conversion,

extending range of invasive species, and wildfire events are further contributing to fragmentation of forests (Armenteras et al., 2019; Tiwari et al., 2022). Recent studies have shown potential species migration towards higher altitude due to climate change (Manish et al., 2016). Climate change may lead to shifts in species habitats, altering forest structure and composition (Abolmaali et al., 2018), resulting in compromised biodiversity and ecosystem services (Tan et al., 2024). Thus, understanding the potential habitat scenarios amidst climate change scenario is critical, to planning effective conservation and management strategies to protect a forest's sanctity.

Evidence from previous studies show that tropical forests will be more vulnerable to climate change induced habitat degradation (Brodie et al., 2012). India is placed third among the top ten nations with the highest annual net gain of 266,000 ha year⁻¹ in forest areas (FAO, 2024). Given its tropical climate, India has the largest abundance of tropical deciduous forests, accounting for approximately 65.6% of the country's total forest cover (ISFR, 2023). *Shorea robusta* Gaertn. along with *Terminalia alata* B.Heyne ex Roth, *Pterocarpus marsupium* Roxb., *Lagerstroemia parviflora* Roxb., *Madhuca longifolia* (J.Koenig ex L.) J.F.Macbr., *Diospyros melanoxylon* Roxb., *Buchanania cochinchinensis* (Lour.) M.R. Almeida, *Anogeissus latifolia* (Roxb. ex DC.) Wall. ex Guill. & Perr., and other associates, is the dominant species in this forest type (Mishra et al., 2021; Garai et al., 2023; Pradhan et al., 2024). However, the completeness of a forest ecosystem lies with the region- dominant species along with its major associates, as together they form a community in the region (Murthy et al., 2020). Because of intense anthropogenic pressures, and climate change scenarios, it is also most susceptible to deterioration (Kumar and Saikia, 2020).

Among the different predictive aspects, climate is one of the most important factors which play a vital role in determining the probable distribution of any species (Pearson and Dawson, 2003; Raxworthy et al., 2003). Presently Shared Socio-economic Pathways (SSPs) are being used as a vital input for the recent climate model, which was published under the Intergovernmental Panel on Climate Change (IPCC) in the sixth assessment report. Although climate-driven impact on habitat fragmentation is well established, the majority of these studies focussed to study the habitat shift concerning a single species only. A very limited number of studies have used SSPs with a single climate model to determine the habitat distribution of *Shorea robusta* (Kaur et al., 2023). Nevertheless, we were unable to find any related research that used SSPs to map out the habitat distribution of *S. robusta* along with its major associates in tropical deciduous forests of India. The habitat distribution for all these associate species therefore needs to be determined for offering an insight to the ecological balance among them.

To assist explain the distribution patterns, we employed three climate models in order to bridge the gaps in previous studies. Maximum Entropy (MaxEnt) model is a machine learning based algorithm to estimate the eco distribution modeling of any kind of species based on the occurrence data and different environmental factors (Phillips et al., 2006). It is a crucial programme or tool, developed to identify the ideal distribution of the species (Wisz et al., 2008). Maxent combines presence-only data and a user-defined number of randomly selected points with bioclimatic variables to provide a habitat suitability score for each pixel ranging from 0 (least suitable zone) to 1 (most suitable zone) (Gormley et al., 2011).

In this present study, the MaxEnt model was used to determine the distribution of *S. robusta* along with its associates *T. alata*, *P. marsupium*, *L. parviflora*, *D. melanoxylon*, and *M. longifolia* in tropical deciduous forests of three states of Eastern India - Jharkhand, Bihar and West Bengal. Further, the simulated results have been verified through analyzing the population density and regeneration status of these species across three states at each forest division level. This study aims to focus on the following three aspects: i) Habitat distribution pattern of the six species in Jharkhand, Bihar and West Bengal under the present and future climatic conditions, ii) What is the present population and regeneration status of these species, and iii) How climate change will affect the geographical distribution of species in the future. The study's findings will provide improved insights into the present vegetation pattern and their future distribution under the different climate models in eastern India.

2. Data and Methodology

2.1 Study area

The three states that comprise the study area are Jharkhand, West Bengal, and Bihar. These states are situated between 83° E and 90° E latitudes and 21° N and 28° N longitudes (Fig. 1). The total geographical area of the study region is 262631 sq km (ISFR, 2023). The study area is bounded by Bhutan, Nepal on the north and Bangladesh on the east. The area of this study is composed of three basic landforms: hilly, plateau, and flat. Sandakphu, the highest mountain in the study region, is situated at an elevation of 3636 meters (Sinha et al., 2018). The study area is divided into three sections: the hilly northern side, which is bordered by the great Himalayan range; the center plateau area and the southern side, which traces the lowlands of the Sundarbans biosphere reserve. The center region is predominantly a plateau with a large tribal population and it is also a mineral hotspot. As a result, this region of the country has undergone significant land degradation (Thakur et al., 2022). The study region is home to about 1.5 million tribal people (ISFR, 2023), and forest products serve as the principal source of income for these rural and indigenous inhabitants. The predominant forest types in this research region include the Dry Peninsular Sal Forest (5B/C1c), the Northern Dry Mixed Deciduous Forest (5B/C2), the East Himalayan Sal Forest (3C/C1a(i)), and the Moist Mixed Deciduous forests (3C/C3) (Champion and Seth, 1968). The targeted six species of this study are naturally distributed in the forests of the study area.

2.2 Survey method and Species locational information

Stratified random sampling was used to gather the locational information of the selected species during the tenure of 2020–2023. GPS (Garmin etrex 30x) was used to collect the species geo coordinate with an accuracy of ± 8 m. To document the species' natural range, the majority of field surveys have been focused on the recorded forest areas (RFAs) of the study regions as per Forest Survey of India (FSI). The nested quadrat technique (Mishra, 1968) with 10 m $\times$ 10 m quadrats was employed at the forest range level. In each quadrat laid, population structure and regeneration status of the target species was also assessed. The occurrence data spatially rarified to minimize the sampling bias (Aiello-Lammens et al., 2015). After spatial thinning of occurrence data, 122 locational points for *T. alata*, 113 points for *P.*

marsupium, 133 points for *L. parviflora*, 122 points for *D. melanoxyton*, 130 points for *M. longifolia* and 314 points for *S. robusta* were utilized for this study. Latitude and longitude values were taken in the form of decimal degree (DD) and saved in comma-separated values format (.csv). The overall flow diagram of the methodology is given below (Fig. S1).

2.3 Environmental variables

We acquired bioclimatic variables (Bio_1 to Bio_19) from the Worldclim site to model the potential distribution range of selected species (Fick and Hijmans, 2017). Three Global Climate Model (GCM) models; Institute of Numerical Mathematics (INM-CM5-0), Institut Pierre-Simon Laplace (IPSL-CM6A-LR) and Model for Interdisciplinary Research on Climate (MIROC6) under the Coupled Model Intercomparison Project phase 6 (CMIP6) were employed to model the potential distribution range of *S. robusta* and its associates for the future. These climate scenarios were proxied through Shared Socio-Economic Pathways (SSP), 126,245,370, and 585. Additionally, soil layers acquired from the Food and Agriculture Organization of the United Nations (FAO, 2023), and slope (Chakraborty et al., 2016, Zhang et al., 2023) derived from elevation data were also employed.

We used multicollinearity tests to eliminate highly correlated variables, applying the SDM Toolbox in ArcGIS (Liu et al., 2021). Of the 19 bioclimatic variables, 15 showed no autocorrelation at Pearson's $R \geq 0.9$ (Gilani et al., 2020). To model the potential distribution range of *S. robusta* and associates we used MaxEnt version 3.4.4 (Phillips et al., 2022), an open-source tool widely recognized for its robustness and accuracy (Chitale and Behera, 2012; Deb et al., 2017; Kumar et al., 2020).

2.4 Model Training and Evaluation

For model assessment, 75% of species occurrence data were used for calibration and 25% for testing (Liu et al., 2019). MaxEnt evaluates model performance using the AUC (Area Under Curve) under the ROC (Receiver Operating Characteristic) curve, which reflects model accuracy based on trial data (Peterson, 2006; Lobo et al., 2008). An AUC value below 0.5 indicates poor performance, while values closer to 1 suggest high accuracy (Swets, 1988). The average test AUC from 15 replicate runs was: *S. robusta* – 0.888, *T. alata* – 0.905, *P. marsupium* – 0.899, *L. parviflora* – 0.905, *D. melanoxyton* – 0.895, and *M. longifolia* – 0.881 (Fig. S2). Jackknife test to determine most significant contributing variables showed soil and slope, mean temperature of wettest quarter (Bio_8) and precipitation of coldest quarter (Bio_19) were the most important bio-climatic factors for distribution of the species (Fig. S3).

2.5 Assessment of population structure and regeneration status

For each targeted species, the density of seedlings, saplings, and mature trees were used to evaluate the population structure. In each forest division of each state, 10 quadrats of 10m X 10m were laid out at forest range level. Various girth classifications based on their girth at breast height (GBH) were assigned to the total number of individuals that were registered in each quadrat. These categories included seedlings (< 10 cm GBH), saplings (10–30 cm GBH), young trees (31–60 cm GBH), adults (61–90 cm

GBH), mature trees (91–120 cm GBH), and old trees (> 120 cm GBH). The total number of individuals per division in each girth class was counted to establish the population structure (Nandy et al., 2024). To evaluate the natural regeneration status of each tree species, the density of seedlings (< 10 cm GBH), saplings (10–30 cm GBH), and adults (> 30 cm GBH) of each species was calculated per hectare during the phytosociological study (Sasidharan et al., 2020). The regeneration status was then classified into four categories (Shankar, 2001), i.e., good regeneration (seedlings > saplings > adults), fair regeneration (seedlings > saplings ≤ adults), poor regeneration (species found only as saplings or saplings < adults), and no regeneration (species found only as adults).

3. Results

3.1 Habitat distribution range of the species under present climatic condition

The habitat distribution of *S. robusta* and its associates under the current scenario is shown in Fig. 2. The southern and western portions of the research area were found to have the most suitable climate for all the species. Major areas under the most suitable climate were located in the state of Jharkhand followed by West Bengal and Bihar. A closer look at the suitable climatic region found a dense forest cover that included several protected forests and wildlife reserves. Nonetheless, the northern portion of the study area was found to be the least suitable for these species.

The study found a wide distribution of *S. robusta* and was the most dominating species in the region (Fig. 3). *S. robusta* also exhibits significant coverage (~ 10%), reaffirming its dominance in sal forest formations. In contrast, *T. alata* has the most limited suitable habitat area among all species examined. *T. alata* with ~ 6% suitable habitat area predominantly occupied the western portion of the research region, with sporadic occurrences observed throughout the remaining area. The low suitable habitat area of *T. alata* highlighting its sensitivity to climatic thresholds and narrower niche requirements.

P. marsupium and *D. melanoxylon* follow closely (~ 11% and ~ 10%), suggesting their adaptability to diverse bioclimatic and topographic conditions. *P. marsupium* exhibited a dispersed distribution, primarily concentrated in the southern part of the study area. Suitable habitat of *D. melanoxylon* was found to be largely confined to the western part of the study area in comparison to the other species studied, *M. longifolia* shows the highest suitability (~ 12%), indicating its broad ecological tolerance and drought resilience. In order to determine the most appropriate elevation for each species, we further divided the suitable class into four classes (Fig. S4) and extracted the elevation for each.

3.2 Habitat distribution range for the future climatic condition

We employed three different climatic models i.e. INM-CM5-0, IPSL-CM6A-LR and MIROC6 to simulate the future potential distribution range of *S. robusta* and its associates (Fig. S5 to Fig. S10). The suitable area

of the studied species is shown in Fig. 4. Future projections indicated significant changes in the distribution patterns of these species within the study area (Table 1). Interestingly, the study demonstrated potential expansion in suitable habitat range for all the studied species, but *L. parviflora*. The potential suitable range for *T. alata* is expected to expand its population and migrate northward. *P. marsupium* is anticipated to decrease in abundance in the eastern zone while shifting towards the north and west. The suitable habitat for *D. melanoxylon* is projected to contract from the eastern portion of the study area and relocate to the south-western region. In accordance with the least current distribution, the suitable habitat area for *L. parviflora* is predicted to decrease across the entire study area in future scenarios.

S. robusta demonstrated a potential northward shift under future climatic conditions, with the highest density expected to be supported only in the southwestern region of the research area. *M. longifolia* is projected to experience the most significant habitat gain by 2050, with its distribution range shifting northward. Most of the species noted their suitable soil condition classes as follows Bh18-2b, Rd30-2b, Je75-2a, Bc25-2c, Lf10-1bc, Lf92-2a, Ne56-2b, Lf92-1a, Bc26-2c, l-Lc-2bc, l-Ne, Lo50-2a, Lf96-2ab; suitable slope varies from 0° to 14°; mean temperature of wettest quarter is 12° to 29° and precipitation of coldest quarter was 35 mm to 65 mm (Fig. 5).

Table 1
Percentage of area changed in the future, compared to the present scenarios

Different Shared Socioeconomic Pathways	<i>S. robusta</i> (%)	<i>T. alata</i> (%)	<i>P. marsupium</i> (%)	<i>L. parviflora</i> (%)	<i>D. melanoxylon</i> (%)	<i>M. longifolia</i> (%)
126	-32.76	-9.98	23.89	-79.93	-28.45	5.11
245	-31.46	24.59	44.29	-76.67	-9.85	31
370	-7.75	43.33	14.41	-72.21	-5.36	15.56
585	-65.34	-26.65	-3.04	-84.59	-53.9	-34.07

3.3 Assessment of population structure and regeneration status

The population structure was evaluated using the density of the individuals per hectare (Fig. 6), which is a measure of dominance and is connected to the availability of individuals per unit area. Forests of three distinct agroclimatic zones (ACZs) were assessed, comprising ACZ III (West Bengal), ACZ IV (Bihar) and ACZ VII (Jharkhand). ACZ VII exhibited the highest population density for all six species across the different girth classes. These girth classes correspond to the age groups of these species in natural forests. Interestingly, across all three ACZs, *S. robusta* emerged as the dominant species, exhibiting the highest density in most girth classes, with the highest density of 796.29 individuals ha⁻¹ in the < 10 cm girth class and 85.03 individuals ha⁻¹ in the > 120 cm girth class from ACZ VII. *M. longifolia* also exhibited exemplary population density across all girth classes in every ACZs. Substantial variations

were seen across the ACZs for species such as *T. alata* and *P. marsupium*. They exhibited substantially higher population density in ACZ VII compared to the other two ACZs. Conversely, as compared to the other four species, *D. melanoxylon* and *L. parviflora* tend to have lower densities. *D. melanoxylon* a sharp decline in ACZ III, where only 397.11 individuals ha⁻¹ in the < 10 cm girth class were documented, with no individuals in the > 120 cm girth class. Whereas, *L. parviflora* maintained a gradual decline as we moved towards the eastern portion of our study area from ACZ VII to ACZ III.

The majority of species exhibited constant regeneration capacity across the three ACZs (Fig. S11). *S. robusta*, *M. longifolia*, *P. marsupium*, *T. alata*, and *D. melanoxylon*, showed good regeneration in all three ACZs, indicating favorable conditions for forest regeneration in the study region. The number of their seedlings consistently exceeded saplings, which in turn exceeded adults (seedlings > saplings > adults). Nonetheless, *L. parviflora* provided an intriguing instance of regeneration status. It showed poor regeneration in ACZ VII, where adults outnumbered both seedlings and saplings (seedlings, saplings < adults). On the other hand, in the rest of the two ACZs, it showed somewhat fair regeneration with seedlings > saplings ≤ adults.

4. Discussion

For the current climate scenario, the suitable habitat range of *S. robusta* and its associates primarily occur in western and southern regions and are likely to shift northward by 2050. The lower latitudes of the planet are seeing an alarming pace of temperature rise due to global climate change. In response, any species has a natural propensity to migrate to higher latitudes with lower temperatures (Guo et al., 2012). This study supports previous research on plant species habitat modeling, which consistently indicates a northward shift in species distribution. (Shitara et al., 2021; Li and Huang, 2022; Zhang et al., 2022, Malakar et al., 2025). The study further revealed gradual decline of *S. robusta* and its associates from the eastern region. In the future, the central and south western part of the study area encompassing Chhota Nagpur Plateau promise a better spread of vegetation (Garai et al., 2021). The projected expansion in distribution range of *M. longifolia* and *P. marsupium* indicates robust adaptability of these species to the future climatic conditions. This finding aligns with earlier studies on *M. longifolia* (Yadav et al., 2022, Pradhan et al., 2024) and *P. marsupium* (Ghosh et al., 2021), further reinforcing the observed distribution patterns. However, the population of *L. parviflora* may decline significantly from the projected part of the eastern region.

Slope was the major factor limiting the distribution of *S. robusta*, *L. parviflora*, *D. melanoxylon*, and *M. longifolia*, whereas soil contributed most for the *T. alata* and *P. marsupium* distribution range. A study by Wu et al. (2021) also noted soil and slope are important factors for species diversity. Another study by Zhao et al. (2025), found Soil and temperature variables shaped *Leymus secalinus* distribution under SSP scenarios. Mean temperature of the wettest quarter (Bio_8) and precipitation of the coldest quarter (Bio_19) were the major factors that contributed most in limiting the distribution range of *S. robusta* and its associates (Duan et al., 2022; Gebrewahid et al., 2020). One interesting finding of the study indicated

that for all species the pattern of distribution range will gradually increase for SSP 370, and abruptly fall for SSP 585 (Shi et al., 2023).

Population structure and regeneration analysis exhibited a general trend of decreasing density with increasing girth class. This inverse relationship between tree size and abundance is a typical characteristic of forest ecosystems, reflecting natural mortality and competition processes (Stephenson et al., 2011). *S. robusta* and its associates barring *L. parviflora*, exhibited an inverse-J population structure throughout the study area, with higher densities in smaller girth classes and lower densities in larger classes. This structure is representative of a population that is healthy and self-sustaining. This outcome corroborates with the findings reported by Kumar and Saikia (2020) that reported a reverse J-shaped girth class distribution of *S. robusta* in the eastern Indian region.

Across the study area, the seedling numbers of these species were also consistently higher than saplings and adults, exhibiting good regeneration. A similar study on dry deciduous forests in eastern India encompassing West Bengal found that *S. robusta* populations were dominated by individuals in lower diameter classes, forming a reverse J-shaped curve (Nag and Gupta, 2014). This suggests good seed production and germination potential, crucial for long-term forest sustainability. The simulation also predicted the same increasing distribution range for these species in future. On the other hand, poor regeneration of *L. parviflora* in northern and western parts of the study area, may be due to the nonfavourable edaphic conditions concerning *L. parviflora* ecological requirements. *L. parviflora* requires well-drained loamy soils and moderate light for successful seedling establishment (Ramakrishna, 2007). Poor performance of *L. parviflora* in marginal zones may reflect habitat mismatch, as supported by SDM predictions showing contraction in its distribution range.

The study revealed ~ 260 to 400 meters as the most suitable elevation range for *S. robusta* and its associated species. Field surveys further confirmed that their distribution was predominantly confined to this elevation range. The population structure analysis revealed a very sparse density of the individuals along higher altitudes, specifically in the northern sub-Himalayan part of the study area.

The LULC-wise analysis showed most of the suitable habitat range for *S. robusta* and its associates occurred within the vegetation, rangeland and cropland classes. During the field surveys too the distribution of these species were observed mainly within protected and reserved forests. This could be attributed to stringent legal regulations that prevent human interference in the protected areas and help natural ecosystems to thrive (Ghosh-Harihar et al., 2019). Protected regions serve as genetic diversity repositories, which is essential for a species' long-term resilience and survival in response to environmental changes (Salgotra and Chauhan, 2023).

Overall, the study offers great insightful details on potential distribution range, regeneration status, and potential population structure of *S. robusta* and its major associates in the eastern Indian region amidst the climate change scenarios. Many researchers argue the validity and practicality of simulated sites modelled through machine learning tools mostly due to the lack of validated source of species occurrence data (Fois et al., 2018). According to Horton et al. (2021), while predictive modeling is a

feasible method for determining potential migratory hotspots in the future, taking into account local physical features would yield a very feasible and location-specific methodology. Additionally, MaxEnt's approach is limited by the use of a present-only data algorithm, which does not address absent data scenarios (Phillips and Dudík, 2008). These limitations impact model performance since the quality of the training dataset is the only factor that determines how well predictive models work.

One of the strengths of our study was extensive field surveys to observe and record species occurrence records. The extensive field surveys not only provide validated sources of information on location-wise population distribution of studied species but also compliments the results of modelled habitat sites with regeneration studies. The LULC-wise assessment of species distribution provides its response for diverse land cover and supports planning conservation and management strategies to promote these species particularly for the tree outside forests (TOF) areas.

The outcome of the study has several implications. One of the major implications of the current study is availability of updated information on distribution and regeneration status of *S. robusta* and its associates in the eastern Indian region. *S. robusta* and its associates constitute a very important sub-set of Forest Genetic Resources (FGRs) in the study area. This study offers to be the very first location-specific knowledge base concerning high potential regeneration sites of *S. robusta* and its associates in eastern India. This information helps to identify high and low potential sites which can be of great help to formulate conservation strategies through germplasm collection of these FGRs and promoting *ex-situ* and *in-situ* practices (Singh, 2025). However, conventional conservation methods alone are not sufficient to restore the forest cover and its biodiversity in India, due to rapid climate change and severe anthropogenic pressures (Gorain et al., 2025). These conservation programs need reliable and up-to-date monitoring of prevailing biodiversity, and can be aligned with innovative approaches like remote sensing and geographic information system (RS-GIS) (Lock et al., 2021; Kerry et al., 2022). Recent advances in machine learning (ML) algorithms have empowered researchers to integrate RS-GIS data with ecological field data to effectively map the distribution of different rare, endangered and threatened (RET) FGR species (Matyukira and Mhangara, 2024; Li et al., 2024; Moharir and Pande, 2025). A similar integrated approach was adopted in this study which offered holistic insights into understanding the distribution ecology of *S. robusta* and its associates. This serves a diverse category of stakeholders globally through data-driven approaches to manage and conserve the depleting FGRs sustainably for future.

5. Conclusion

The study found significant variations in the current and future potential distribution scenarios of *S. robusta* and its major associate species in the eastern region of India. The southern and western part of the study area were the most suitable habitats of *S. robusta* and its associates in the current climate scenario. Barring *L. parviflora*, the regeneration status of *S. robusta* and its remaining associates was found promising. Future projections suggest a northward shift with potential contraction in the suitable habitat range of *S. robusta*, accompanied by a similar directional shift in the potential distribution of its associated species, indicating a broader ecological transition. Among associates, *M. longifolia* and *P.*

marsupium exhibited the highest resilience to climate change. We recommend location and species-specific conservation strategies supported by community participation, and strong policy frameworks for preserving and restoring the forest ecosystem.

Declarations

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Authors contribution

All the authors of this manuscript contributed to its conceptualization, design and implementation. The first draft of the manuscript was prepared by Sanjoy Garai and Ayushman Malakar. Data curation, formal analysis, investigation, methodology and validation were carried out by Sanjoy Garai, Ayushman Malakar, Rikesh Kumar, Manjuel Jojo, Sonu Choudhary, Surojit Konar, and Aryan Mishra. Yogeshwar Mishra contributed to funding acquisition and project administration. Sharad Tiwari supervised the overall study and manuscript preparation. All authors contributed to reviewing and editing the manuscript. The final version of the manuscript was read and approved by all the authors.

Conflict of interest

The corresponding author, on behalf of all authors, declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Data Availability Statement

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Figures

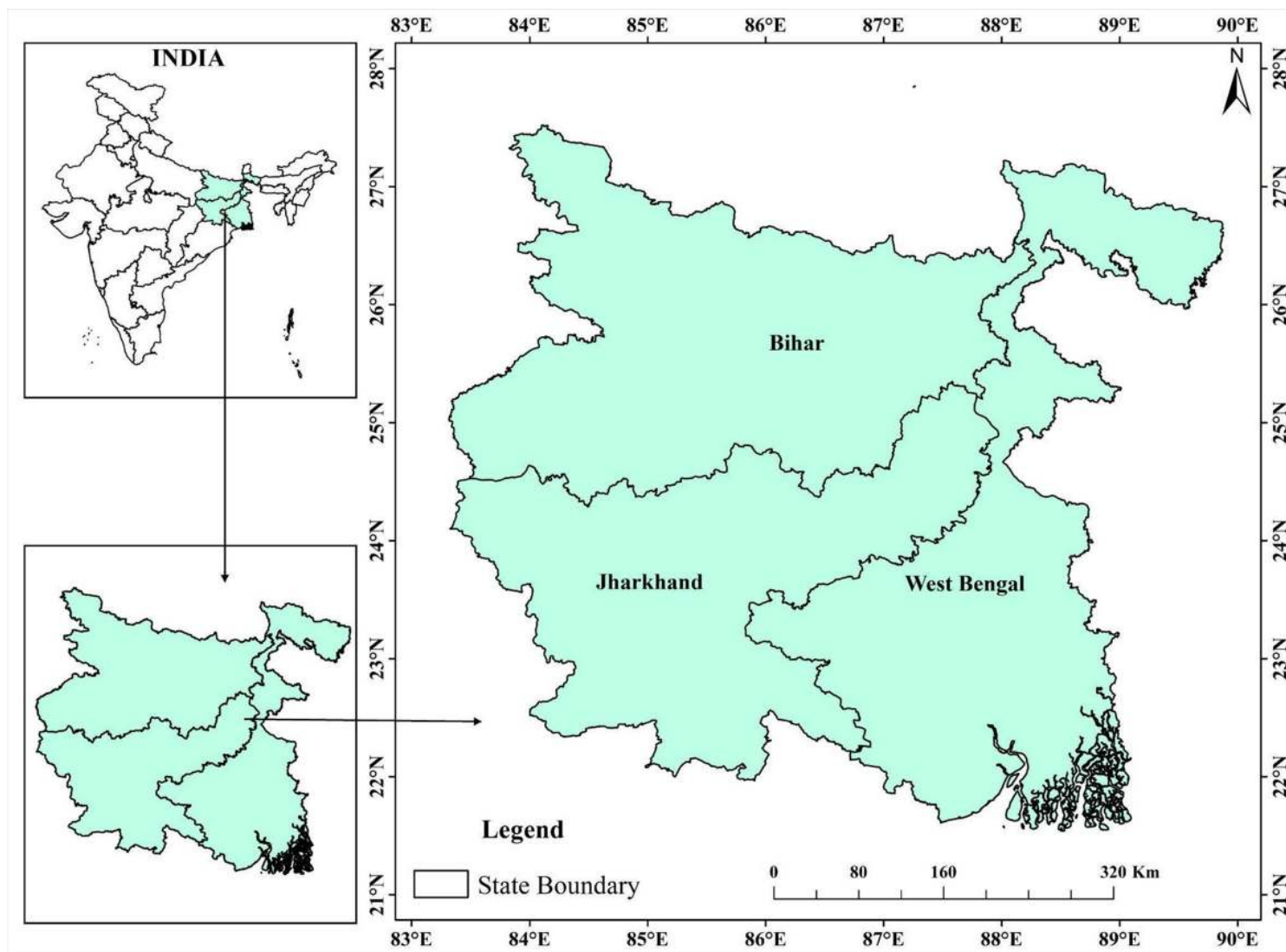


Figure 1

Locational map of the study area depicting the states of Jharkhand, Bihar and West Bengal

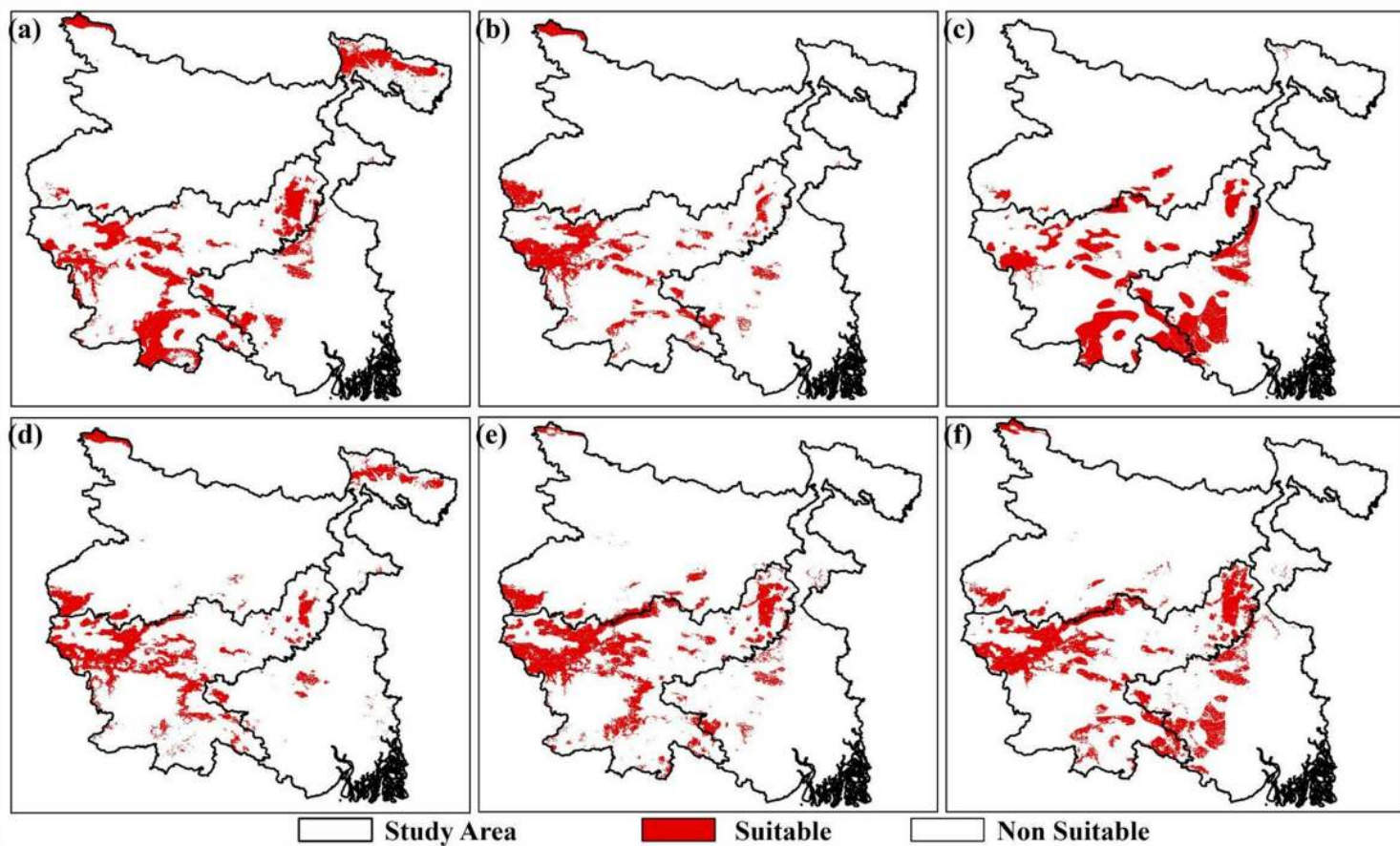


Figure 2

Suitable habitat distribution maps of a) *S. robusta* b) *T. alata* c) *P. marsupium* d) *L. parviflora* e) *D. melanoxylon* f) *M. longifolia*

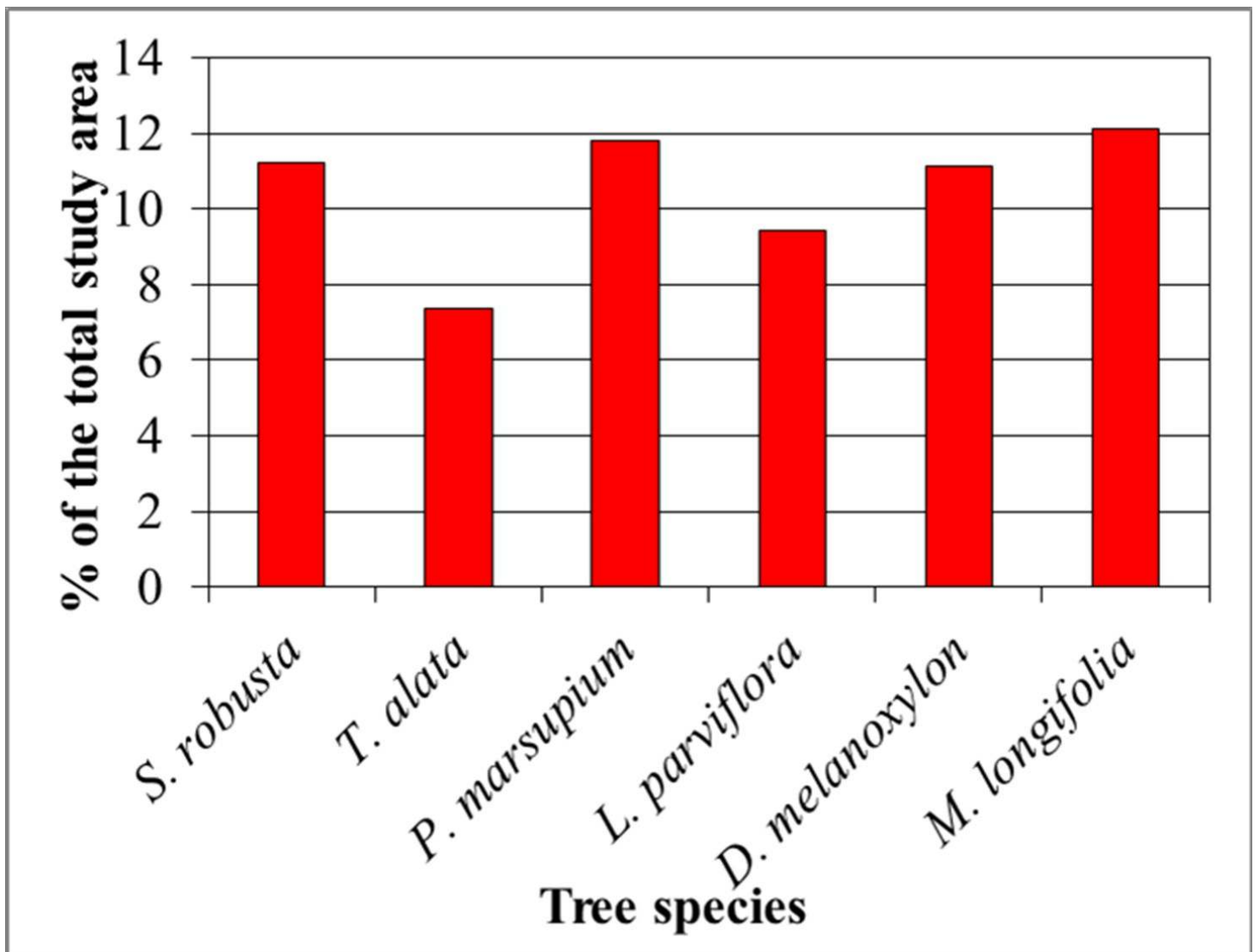


Figure 3

Graph shows the distribution area (%) of different species for the present scenario

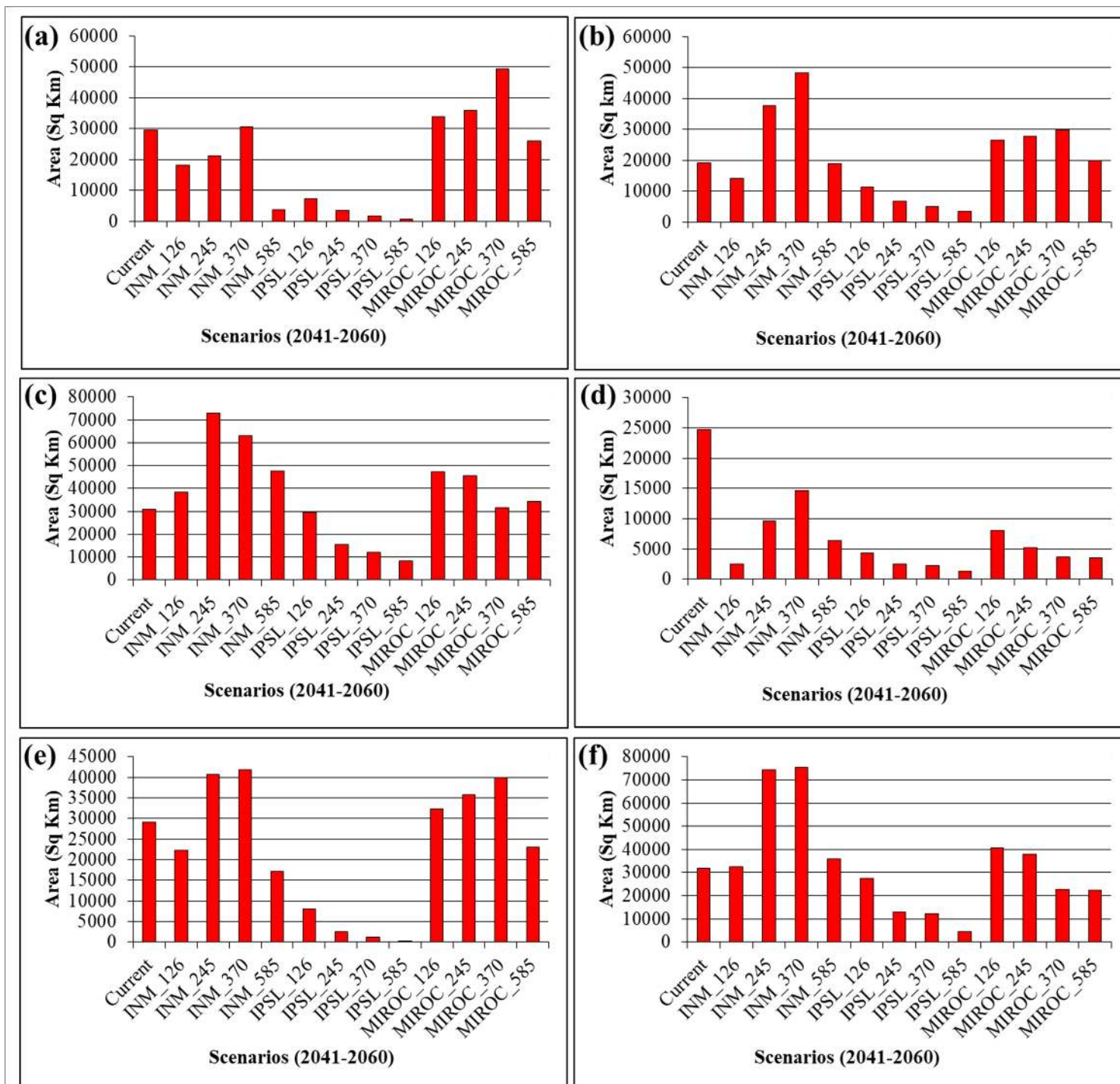


Figure 4

Suitable habitat area of a) *S. robusta* b) *T. alata* c) *P. marsupium* d) *L. parviflorae* e) *D. melanoxyton* f) *M. longifolia* under various climatic models and scenarios. On averaging it was found that the projected suitable habitat range for *S. robusta* and its two major associates *L. parviflora* and *D. melanoxyton* will decrease across all the proxied climate scenarios. Under the business-as-usual scenario, the potential suitable habitat range will decline for all the species. Although the predicted habitat range for *M. longifolia* and *P. marsupium* is projected to increase across all proxied scenarios except for SSP 585, but, the distribution pattern of these two species was mostly found in association with other species. Thus,

despite having suitable habitat range the physiological traits of these two species might get compromised in absence of or decline of other associated species mentioned in this study

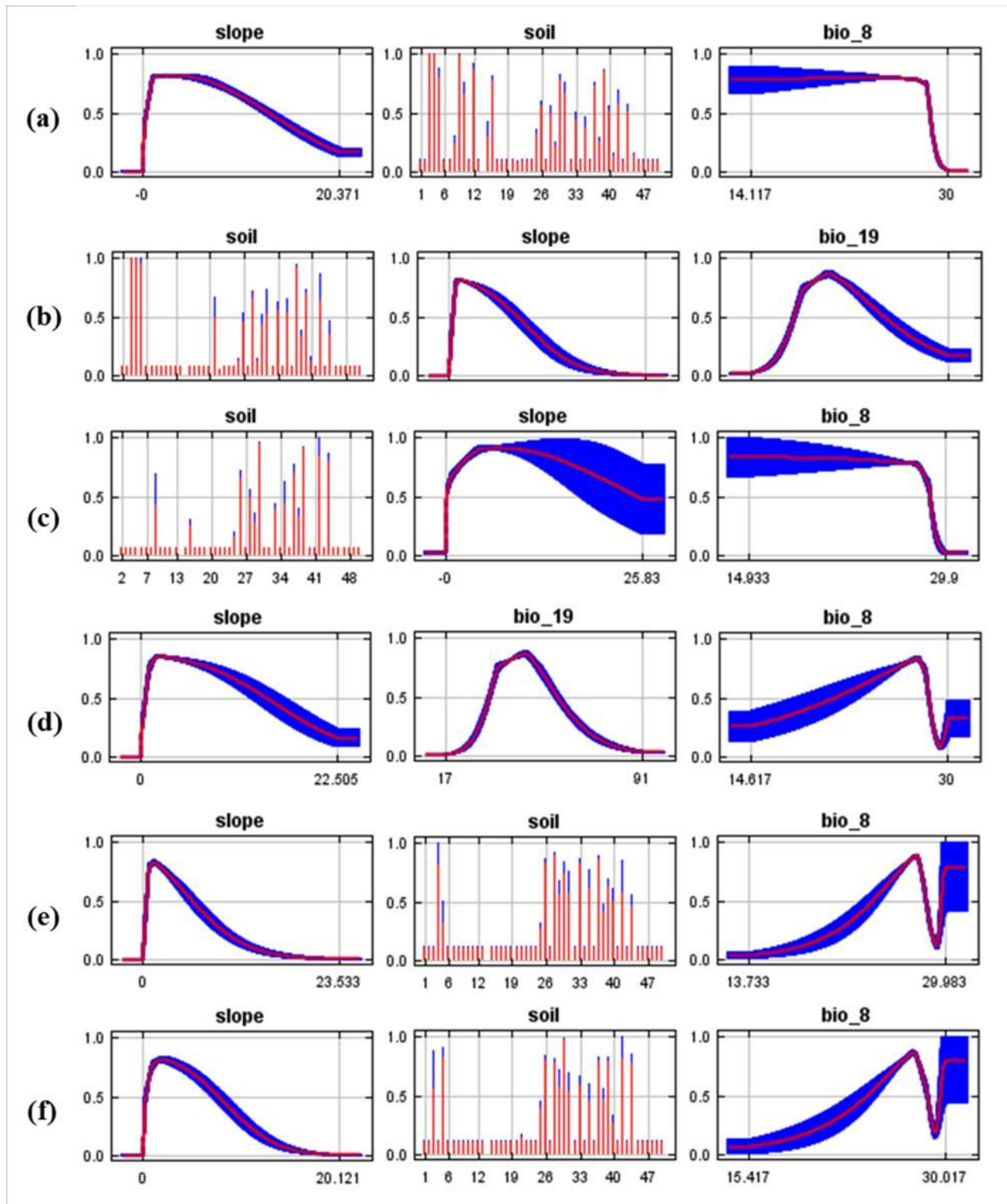


Figure 5

Graph shows the ROC curve for most significantly contributing variables limiting the distribution of a) *S. robusta* b) *T. alata* c) *P. marsupium* d) *L. parviflorae* e) *D. melanoxylon* f) *M. longifolia*. Slope and Bio_8

repeatedly emerge as major factors, indicating the role of topography and seasonal temperature in limiting the distribution range of *S. robusta* and its major associates in the eastern region. Impact of Soil varies across species, indicating its potential role in microhabitat specificity and might be the major factor in regulating species regeneration

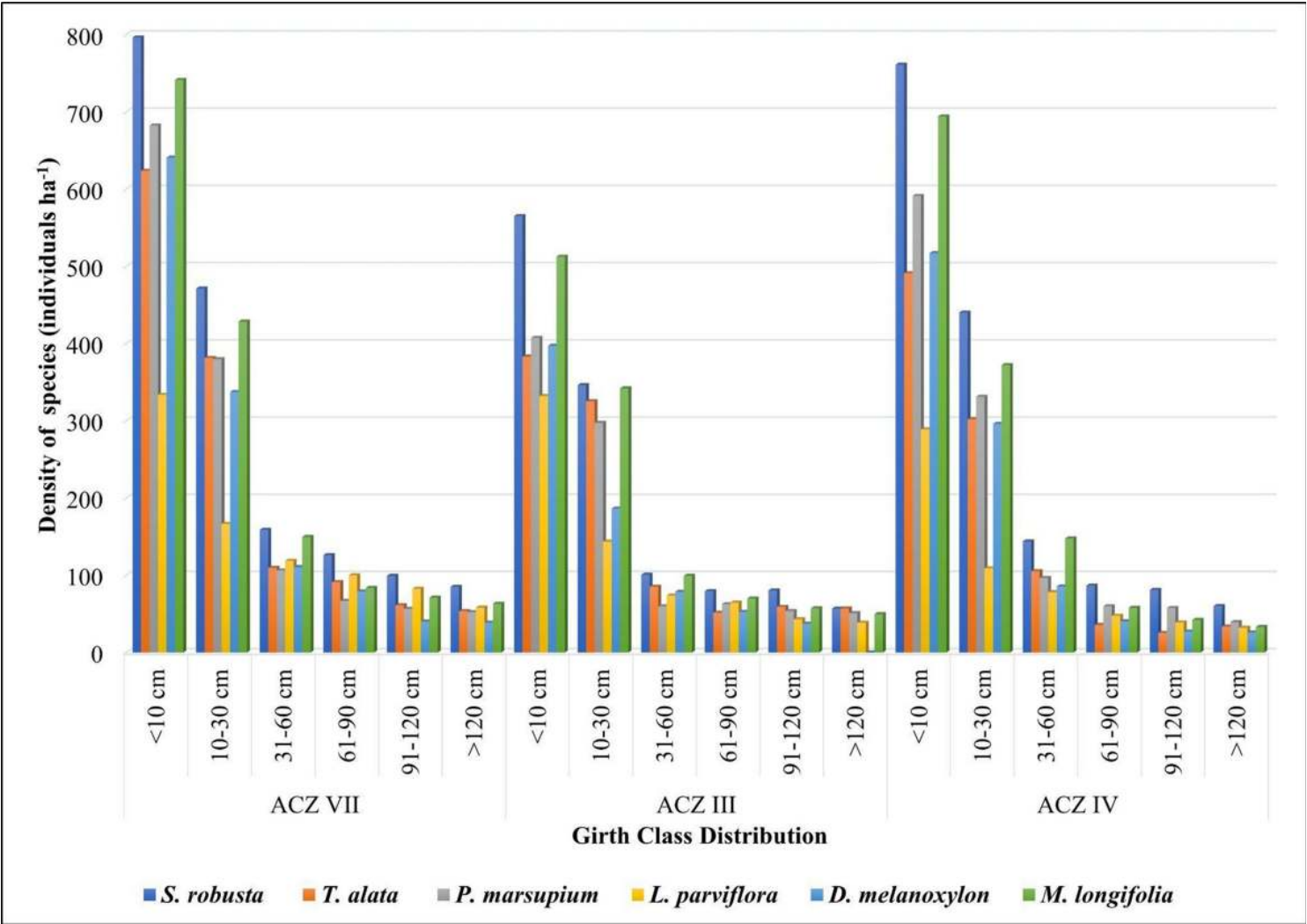


Figure 6
Assessment of population structure of the six studied species across three different agro-climatic zones (ACZs) in the study area through girth class distribution