Climate Change Impact Assessment and Species Distribution Model of a Critically Endangered Tree Using MaxEnt Modelling

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Abstract

Climate change is a key factor driving species extinction by altering their habitats and populations. We can already see its impact on ecosystems around the globe, especially at the species level. Using species distribution models helps us understand how climate change might shift where species live under different climate scenarios, which is crucial for protecting endangered plants and animals. This study focuses on predicting how climate change will affect the important tree species *Anisoptera scaphula* in Bangladesh's Chittagong division, using the Maximum Entropy (MaxEnt) model. Under the SSP2-4.5 (2021-2040) and SSP2-4.5 (2041-2060), as well as SSP5-8.5 (2021-2040) and SSP5-8.5 (2041-2060) scenario, our model predicts suitable habitats for this species in 2040 and 2060. The results show minimal changes in suitable habitats, suggesting that *A. scaphula*is quite resilient to climate change. These findings can guide policies for wildlife conservation and forest management, highlighting the species' importance to various animals.

1. Introduction

Bangladesh is a treasure trove of biodiversity, particularly within its lush forests that are home to an incredible variety of tree species (Islam et al., 2018; Pavel et al., 2016). The Chittagong division, in particular, is known for its diverse forest trees. As global warming becomes an increasingly pressing issue, Bangladesh has launched numerous initiatives to combat its effects. Universities and research institutions across the country are actively studying how climate change impacts various species (Islam et al., 2018; Masum et al., 2022; Maszura et al., 2018; Pavel et al., 2016). Many forest trees are now endangered or critically endangered due to the changing climate and the microclimate shifts necessary for their seed germination. Located along the Tropic of Cancer, Bangladesh benefits from a broad spectrum of sunlight and receives about 3000 millimeters of rainfall each year (Hossain et al., 2014). Among the 500 or so timber-producing tree species is *Anisoptera scaphula* (Roxb.) Kurz, a towering and endangered tree that grows between 32–45 meters high with an average trunk diameter of 3.4 meters. It’s known for its clear trunk and prominent buttresses, making it quite remarkable (Hossain et al., 2014; Saha et al., 2022).

A. scaphula is native to several Southeast Asian countries, including Bangladesh, Malaysia, Laos, Myanmar, and Thailand. This species is primarily deciduous or semi-deciduous, shedding its leaves seasonally (Islam et al., 2018; Maszura et al., 2018, 2018). The Bangladesh Forest Department has identified several reasons for the decline of *A. scaphula*'s habitat. These include habitat loss, the absence of mother trees needed for seed production, and poor microclimatic conditions on the forest floor. Additionally, the species' biological traits pose challenges for its survival. For example, *A. scaphula* produces seeds that cannot be stored for long, and its winged fruits, while aiding in seed dispersal, make natural germination difficult. Germination begins with a root emerging from the wing side and a shoot from the stalk end (Saha et al., 2022, Arman et al. 2024). The distribution of *A. scaphula* is significantly influenced by bioclimatic factors like rainfall, light, temperature, and day length. Conservationists increasingly use species distribution models to predict the future distribution of specific species under different climate scenarios (Masum et al., 2022). These models are essential tools for understanding how climate change might alter the habitats of endangered species and for developing effective conservation strategies.

Given the urgent need to address the impacts of climate change on biodiversity, it is essential to focus on species like *A. scaphula* that are particularly vulnerable yet crucial to their ecosystems. *A. scaphula*, (Hossain et al., 2014) with its unique ecological role and economic value, is a prime candidate for such studies (Miah et al., 2023). The species plays a critical role in maintaining the structure and function of tropical forests in Bangladesh and beyond (Alam et al., 2023). Its large size and extensive root system help stabilize the soil, preventing erosion, while its canopy provides habitat and food for various wildlife species. Despite its importance, *A. scaphula* faces numerous threats that are exacerbated by climate change (Islam et al., 2020). Deforestation for agriculture, illegal logging, and land conversion for infrastructure development are significant factors leading to habitat loss (Roy et al., 2015). The lack of mother trees for seed production is another critical issue (Imran et al., 2024), as it hampers natural regeneration processes (Rahman et al., 2022). Poor microclimatic conditions on the forest floor, influenced by changes in temperature and precipitation patterns, further challenge the species' survival (Mehta et al., 2021; Mitra et al., 2023; Saxena et al., 2013). The biological characteristics of *A. scaphula* also make its conservation more complex. The species produces recalcitrant seeds that are sensitive to drying and cannot be stored for long periods, complicating efforts to preserve its genetic material. Moreover, its winged fruits, while adapted for wind dispersal, often fail to settle in suitable germination sites, leading to low seedling recruitment rates (Das et al., 2020; Khan & Shankar, 2014; Mehta et al., 2021; Mitra et al., 2023; Saxena et al., 2013). In light of these challenges, it is crucial to use advanced tools like species distribution models to forecast the future distribution of *A. scaphula* and identify potential thread under various climate scenarios. Such models integrate bioclimatic variables, species occurrence data, and climate projections to predict changes in habitat suitability. By understanding these dynamics (Akter et al., 2020; Dwivedi & Chopra, 2014; Kuniyal et al., 2013), conservationists can develop targeted strategies to protect and restore habitats, ensuring the long-term survival of *A. scaphula*. The current and future scenarios for *A. scaphula* based on bioclimatic variables using the Maximum Entropy (MaxEnt) platform. MaxEnt is a powerful tool for modeling species distributions, especially for species with limited occurrence data. It estimates the probability distribution of a species presence based on environmental constraints and known occurrences. The study focuses on the Chittagong division of Bangladesh, an area that exemplifies the complex interplay of climatic factors influencing species distribution. By predicting suitable habitats for *A. scaphula* for the years 2040 and 2060 under the SSP2-4.5 (2021–2040) and SSP2-4.5 (2041–2060), as well as SSP5-8.5 (2021–2040) and SSP5-8.5 (2041–2060) climate scenario, this research provides critical insights into the species' resilience to climate change.

The study aimed to (i) assess the vulnerability of *A. scaphula* to global climate change using species distribution modeling (SDM) and (ii) project the potential risk of extinction resulting from climate impacts. The predictive models generated provide actionable insights for managing *A. scaphula*, offering evidence-based recommendations for its conservation. These findings will support policy development and conservation strategies, identifying key areas for protection and management. By safeguarding *A. scaphula*, the study also aims to enhance the resilience of the broader ecosystem, ensuring that the diverse plant and animal communities reliant on this species can continue to thrive amidst changing climatic conditions.

2. Materials and Methods

2.1 Study Site

The Chittagong division, which includes Chattogram, Bandarban, Rangamati, and Cox's Bazar, is a natural habitat for *A. scaphula*. This region features tropical evergreen and semi-evergreen forests, with *Tectona grandis* being a dominant species that provides habitat for large birds(Hossain et al., 2020), which have significant relationships with *A. scaphula*. The area is rich in biodiversity, and *A. scaphula* is considered a flagship species. The region experiences heavy to moderate rainfall, averaging 3000mm per year, and abundant sunlight, resulting in a wide range of temperatures, with an average of 26°C(Hossain et al., 2020;Rahman et al., 2018; Uddin et al., 2020). The study site is located at 22°22'0.001"N, 91°47'60"E, with an elevation of 29 meters above sea level.

2.2 Current Status of Boilam Trees in Bangladesh

In Bangladesh, a total of 21 Boilam trees have been identified across the country. Out of these, eight are still immature, meaning they haven't yet started flowering or fruiting. The remaining trees are either mature or over mature. Specifically, five of these trees are classified as mature, while six have reached an over mature stage (Islam et al., 2019; Saha et al., 2022). Unfortunately, two of the over mature trees are suffering from significant health issues: one is affected by root rot, and the other has heart rot disease. The two trees with these diseases are located in Faliar Para under Ukhia Upazila and in the Hazarikhil Wildlife Sanctuary within the Chittagong North Forest Division. The tree in Faliar Para is dealing with root rot, while the overmature tree in Hazarikhil Wildlife Sanctuary is struggling with heart rot disease. The six over mature trees are spread across various locations: Hazarikhil Wildlife Sanctuary, Sukhbilas Beat, Faliar Para, Shilkhali, and the Ukhia TV Station(Hossain et al., 2014). These older trees are particularly valuable as potential mother trees for seed collection, thanks to their advanced age and the genetic material they can provide. From July 2019 to June 2020, observations were made to study the phonological characteristics of the Boilam trees, including leaf shedding, flowering, and fruiting. During this year-long observation period, flowering was noted in only two trees: one located on the IFESCU campus and the other at the Ukhia TV Station.

Table 1
Bioclimatic and environmental variables considered for the MaxEnt model.

Variable	Description	Unit
Bio1	Annual mean temperature	°C
Bio2	Mean diurnal range	°C
Bio3	Isothermality ((Bio2/Bio7)∗100)	–
Bio4	Temperature seasonality (standard deviation∗100)	CV
Bio5	Maximum temperature of the warmest month	°C
Bio6	Minimum temperature of the coldest month	°C
Bio7	Temperature annual range (Bio5-Bio6)	°C
Bio8	Mean temperature of wettest quarter	°C
Bio9	Mean temperature of driest quarter	°C
Bio10	Mean temperature of warmest quarter	°C
Bio11	Mean temperature of coldest quarter	°C
Bio12	Annual precipitation	mm
Bio13	Precipitation of wettest period	mm
Bio14	Precipitation of driest period	mm
Bio15	Precipitation seasonality	CV
Bio16	Precipitation of wettest quarter	mm
Bio17	Precipitation of driest quarter	mm
Bio18	Precipitation of warmest quarter	mm
Bio19	Precipitation of coldest quarter	mm

2.3 Occurrence data

In the wilds of Chittagong, a team of passionate researchers embarked on a journey of discovery from January to February 2021. Armed with a trusty Garmin GPSMAP 62s device, they ventured into a variety of landscapes, from lush forests to the scientific grounds of the Bangladesh Forest Research Institute (BFRI), even exploring protected areas and rural homesteads. Led by their unwavering dedication (Hossain et al., 2014;Islam et al., 2020; Shome et al., 2022), they braved rugged terrain and unpredictable weather, determined to uncover the secrets of the critically endangered *A. Scaphula*. Despite the challenges they faced, the team's perseverance paid off as they meticulously documented 21 GPS occurrence data points for *A. Scaphula*. These precious data points are more than just coordinates; they represent invaluable insights into the species' distribution and habitat preferences in the Chittagong region. With each data point, they lay the foundation for future conservation efforts, ensuring the survival of *A. Scaphula* for generations to come.

2.4 Understanding Bioclimatic Variables and Climate Projections

To analyze how climate change might affect the distribution of the tree species *A. scaphula*, we used bioclimatic variables from the WorldClim 2.1 database (Accessed from https://www.worldclim.org/). These variables, such as temperature and precipitation (IPCC 2014), were collected as high-resolution raster files and processed using ArcMap 10.8 software. Climate scenarios from the IPCC (Machwitz et al., 2008; Mandal et al., 2022), including RCP2.6 (low greenhouse gas concentration) and RCP8.5 (high concentration), were used to understand potential future conditions. Updated scenarios (Hijmans et al., 2005), called Shared Socioeconomic Pathways (SSPs), align with these concentration levels and project conditions up to 2100. The analysis also used temperature data from the Coupled Model Intercomparison Project Phase 6 (CMIP6) to study the period from 1986 onwards. For future climate projections (2021–2040 and 2041–2060), we used the SSP2-4.5 and SSP5-8.5 scenario. The Met Office Hadley Centre (MOHC) HadGEM3-GC31-LL model was employed for downscaling and calibrating data, with current conditions as a baseline (Ridley et al., 2018).To simplify the data, Principal Component Analysis (PCA) was performed on the bioclimatic variables. MaxEnt, a machine learning algorithm, was then used for the analysis and projection, valued for its ability to handle various data types (Janekovi & Novak, 2012).

2.5 Modeling Species Distribution

The distribution model for *A. scaphula* was developed in two steps. First, researchers organized occurrence data into a CSV file (Fig. 2), detailing the species name, longitude, and latitude to map its locations accurately. Second, bioclimatic variables (BioClim 1–19) were prepared as raster files and processed using R version 4.4.0 for accurate representation. These datasets were combined in MaxEnt version 3.4.1, which calculates the probability of *A. scaphula's* presence based on environmental factors (Cord et al., 2009). MaxEnt's flexibility allowed researchers to produce a detailed probability distribution map of *A. scaphula* under various conditions (Thapa et al., 2018). The same method was applied to project future distributions for 2021–2040 and 2021–2060 under the SSP2-4.5 and SSP5-8.5 scenarios (Warton et al., 2013). This approach provided valuable insights into how climate change could impact the species, aiding in conservation planning and climate change mitigation strategies.

2.6 Validating the Model

To ensure the model's accuracy, researchers used the area under the curve (AUC) of the Receiver Operating Characteristic (ROC). The dataset was split, with 75% used for training and 25% for testing. Model performance by Thuiller et al. (2006) was assessed based on AUC values: a) AUC < 0.8: Poor or null model, b) 0.8 ≤ AUC < 0.9: Fairly good model, c) 0.9 ≤ AUC < 0.95: Good model, d) AUC ≥ 0.95: Excellent model

This evaluation method ensures reliable predictions, offering a strong foundation for understanding how *A. scaphula's* habitat might shift due to climate change (Phillips et al., 2006; Phillips and Dudík 2008). This information is crucial for developing adaptive conservation strategies to protect biodiversity in a changing climate.

3. Result and discussion

3.1 Present status

The study examined the distribution and maturity status of Boilam trees (*A. scaphula*) across various locations, revealing a total of 21 trees. The Hazarikhil Wildlife Sanctuary and the Chittagong University Campus (IFESCU) had the highest concentrations, each hosting 5 trees. Other locations like Dulahazra Safari Park and Sukhbilash Beat, Khurushia Range each contained 2 trees, while Bangladesh Forest Research Institute, Faliar Para, Shilkhali Beat, Ukhia TV Station, Saplapur, Lama, and the National Botanical Garden each had 1 tree.

During our survey, we found Boilam trees in various forest areas, including the Chittagong North and South Forest Divisions, Chittagong Hill Tracts North and South Forest Divisions, and Cox’s Bazar North and South Forest Divisions, as well as in homesteads (Hossain et al., 2014). The highest number of trees was observed in Hazarikhil Wildlife Sanctuary and the IFESCU area. However, we faced several challenges that limited our survey coverage. In some regions of the Chittagong and Cox’s Bazar forest divisions, we couldn't conduct surveys due to risks posed by elephants, difficult terrain (Pavel et al., 2016), and constraints in time and funding. Additionally, a lack of local knowledge about Boilam trees further complicated our efforts, as many local people were unaware of where to find this species. Despite these limitations, the data we collected provides valuable insights into the distribution of Boilam trees in the accessible areas (Hossain et al., 2014). This information is crucial for future conservation efforts and highlights the need for more comprehensive studies to fully understand the species' distribution.We also looked at the maturity state of these trees and found that 8 were immature, 5 were matured, 6 were over matured, and 2 were defected(Fig. 3). Understanding the distribution and maturity of Boilam trees is essential for their conservation and resource management.

3.2 Prediction Accuracy and Model Evaluation

The prediction accuracy for the distribution models of *A. scaphula* was remarkably high, with AUC values reaching 0.981 (Tables 1 and 2; **Figs. 4, 5 and 6**). This high AUC value indicates that the MaxEnt-derived distributions closely match the actual probability distribution of the species. Both the training and testing AUC values were over 90%(Islam et al., 2020), with very low standard deviations, suggesting consistent and reliable model performance. Since the AUC value is well above 0.5, it confirms that the models performed significantly better than random predictions. Figures 4 and 5 show high AUC values for both training data (red line, AUC = 0.968) and test data (blue line, AUC = 0.973), with the lines nearly coinciding, demonstrating excellent model reliability(Islam et al., 2019). The Jackknife test of leave-one-out cross-validation was used to evaluate the importance of bioclimatic and environmental variables. This test analyzed each predictor variable individually, when omitted, and in combination with all variables. The results highlighted that variables like bioclim11, bioclim13, bioclim16, bioclim4, and bioclim7 were the most significant in predicting species distribution. Interestingly, bioclim6 slightly outperformed bioclim7 in test gain. On the other hand, bioclim1, bioclim14, and bioclim18 contributed minimally and were excluded from the final predictions(Maszura et al., 2018).

This robust model performance underscores its effectiveness in predicting the distribution of *A. scaphula*, pinpointing the critical bioclimatic variables that influence its habitat. This information is essential for conservation planning and developing strategies to protect this species amid changing climatic conditions. The consistent AUC values between training and testing data further bolster confidence in the model's predictive capabilities, making it a reliable tool for future studies and conservation efforts.

Table 2
Prediction accuracy of the species distribution modeling.

	Training AUC	**Test AUC**	**Stander deviation**
SSP2-4.5(2021–2040)	0.968	0.973	0.0023
SSP2-4.5(2041–2060)	0.976	0.957	0.0028
SSP5-8.5(2021–2040)	0.981	0.951	0.0029
SSP5-8.5(2041–2060)	0.969	0.978	0.0027

3.3 Probable distribution of A. scaphula

The spatial distribution of *A. scaphula*, in terms of predictive probability, was segmented into 14 categories to represent the ranges of habitat suitability (Figs. 5 and 6). The probability values range from 0 to 1, with 0 indicating the lowest habitat suitability and 1 indicating the highest. Figure 6 suggests that the spatial distribution of *A. scaphula* across the Chittagong division might face increasing climate stress(Hossen & Hossain, 2018). However, the study's findings indicate that the likely distribution of *A. scaphula* under the SSP2-4.5 (2021–2040) and SSP2-4.5 (2041–2060), as well as SSP5-8.5 (2021–2040) and SSP5-8.5 (2041–2060) scenarios, would see only an insignificant decline due to the negative impacts of global climate change. Given these projections, it is recommended to concentrate conservation efforts in the southeastern region of Bangladesh. This area should be prioritized for habitat protection and restoration initiatives(Rahman et al., 2022). Additionally, continuous monitoring and updating of the habitat suitability model are essential to account for ongoing environmental changes and human activities. Engaging local communities and stakeholders in conservation activities can greatly enhance the effectiveness of these efforts and ensure the long-term survival of *A. scaphula* in Bangladesh. These findings have significant policy implications and should be reflected in the development of conservation strategies(Islam et al., 2018; Warton et al., 2013). Factors such as physiological characteristics, precipitation regimes, and habitat destruction are likely to influence the future distribution of this species. Therefore, a proactive and adaptive approach to conservation is crucial to mitigate the adverse effects of climate change on *A. scaphula's* habitat.

4. Discussion

This study found that *Anisoptera scaphula* exhibits a higher degree of climate resilience compared to other plant and animal species in Bangladesh (Alamgir et al., 2015; Sohel et al., 2016; Akhter et al., 2017; Deb et al., 2017). Previous research indicated that species like *Mangifera sylvatica* may face extinction by 2070 due to climate change (Akhter et al., 2017). Similar concerns have been raised for species such as *Hoolock hoolock* and *Panthera tigris* (Alamgir et al., 2015; Mukul et al., 2019). Additionally, the habitat for *Dipterocarpus turbinatus* and *Hopea odorata* is projected to decrease by 24% and 34%, respectively, in the South Asian region by 2070 (Deb et al., 2017). *Dipterocarpus turbinatus* in Bangladesh may see a dramatic reduction in suitable habitat under RCP2.6 and RCP8.5 scenarios by 2050 and 2070 (Islam et al., 2020). In China, *Pinus armandii* is expected to lose suitable habitat under similar scenarios (Ning et al., 2021), while in Burkina Faso, the habitat for *Ximenia americana* could decline by 15% and 25% under RCP4.5 and RCP8.5, respectively (Lompo et al., 2021). The comparative resilience of *A. scaphula* could be due to its extensive distribution and relatively stable conservation status, classified as of least concern both globally and in Bangladesh (IUCN 2020). Similar resilience has been observed in *Madhuca longifolia* in India (Yadav et al., 2021) and *Ammopiptanthus mongolicus* in northwest China, which may see an increase in suitable habitat under future climate scenarios (Du et al., 2021).

Temperature emerged as the dominant factor influencing species distribution in this study, with temperature-related variables like Bio11, Bio6, Bio7, and Bio9 playing significant roles. This contrasts with findings from Thailand, where precipitation was identified as the primary factor affecting *Dipterocarpus alatus* distribution (Kamyo and Asanok 2020). In other studies, both precipitation and temperature have been highlighted as key factors influencing the spatial distribution of species in China (Du et al., 2021; Ning et al., 2021) and Burkina Faso, where annual precipitation and temperature of the coldest quarter and coldest month were critical predictors (Lompo et al., 2021).

The study's limitations include a narrow geographical scope and a limited number of species geo-locations due to funding and time constraints. Despite these limitations, the research contributes to understanding climate-induced species redistributions in this region, which is highly vulnerable to climate change impacts. Future studies are recommended to expand geographical coverage and include more species geo-locations to provide a comprehensive understanding of these dynamics.

5. Conclusion

This study predicted possible responses of the two ecologically important but not yet endangered tree species - *A. scaphula* - in Chittagong districts of Bangladesh using the species distribution modeling approach. Our habitat suitability modeling based on present distribution data, bioclimatic and environmental variables, and under the SSP2-4.5 and SSP5-8.5 scenarios emission pathways for 2040 and 2060 showed insignificant change in case of the availability of suitable habitats for the *A. scaphula*. This study suggested that the future climate change trend may adversely affect the local habitat quality for selected tree species. However, none of the species will face extinction risk. Policymakers may use the outcome of this study in formulating policies regarding local level biodiversity conservation and forest management of these important wild fruit species. As *A. scaphula* will survive even in the harshest of climate change situations, Bangladesh Forest Department can think about these two species on a priority basis in plantation activities to enhance wildlife resilience. Planting these two species in augmented natural regeneration activities in denuded and degraded government forests will enhance the habitat resilience of the forests for wildlife conservation.

Declarations

Declaration of Competing Interest

The authors declare no potential conflicts of interest with respect to the research, authorship, and publication of this article.

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Figures

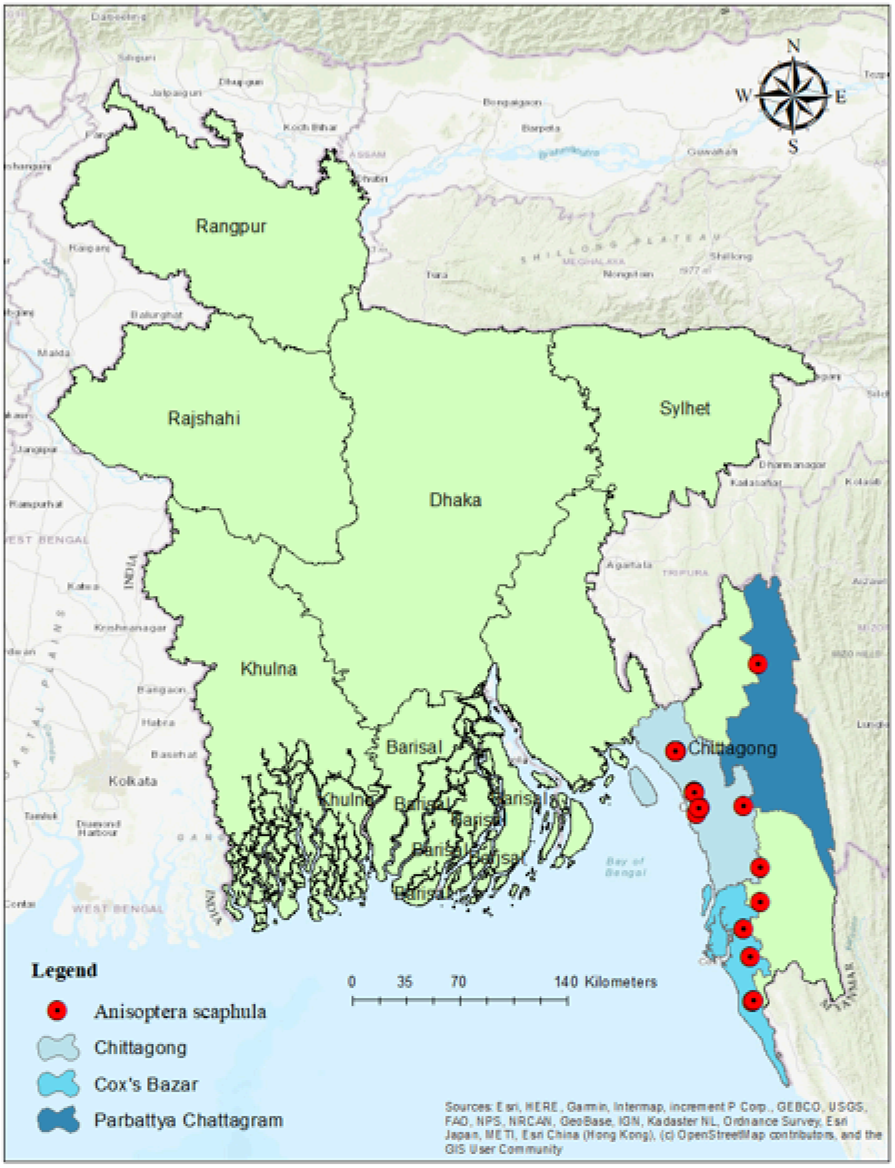

Figure 1

Species occurrence records of *Anisoptera scaphula* in Chittagong division of Bangladesh.

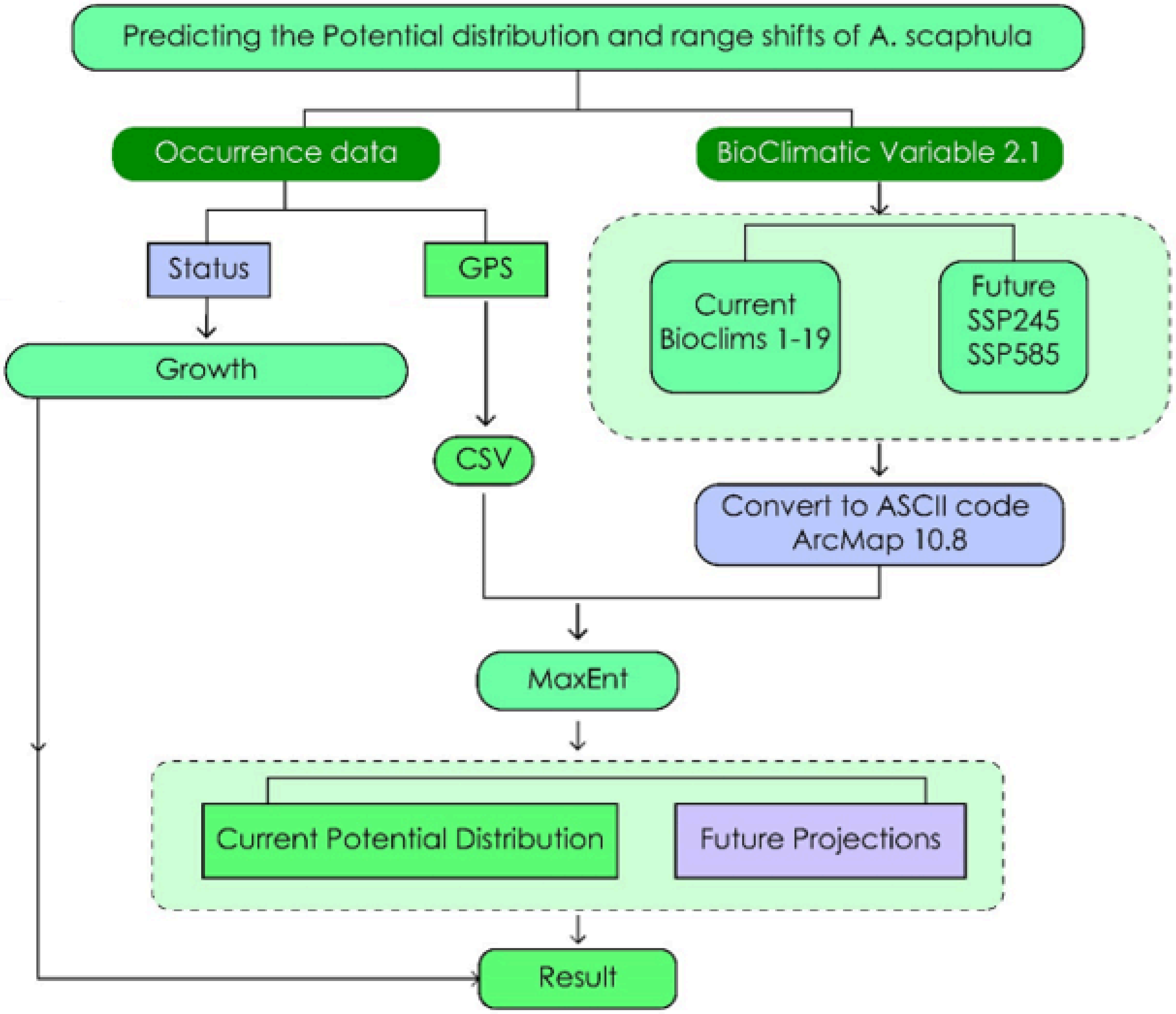

Figure 2

Flowchart of working processes for developing the species distribution model.

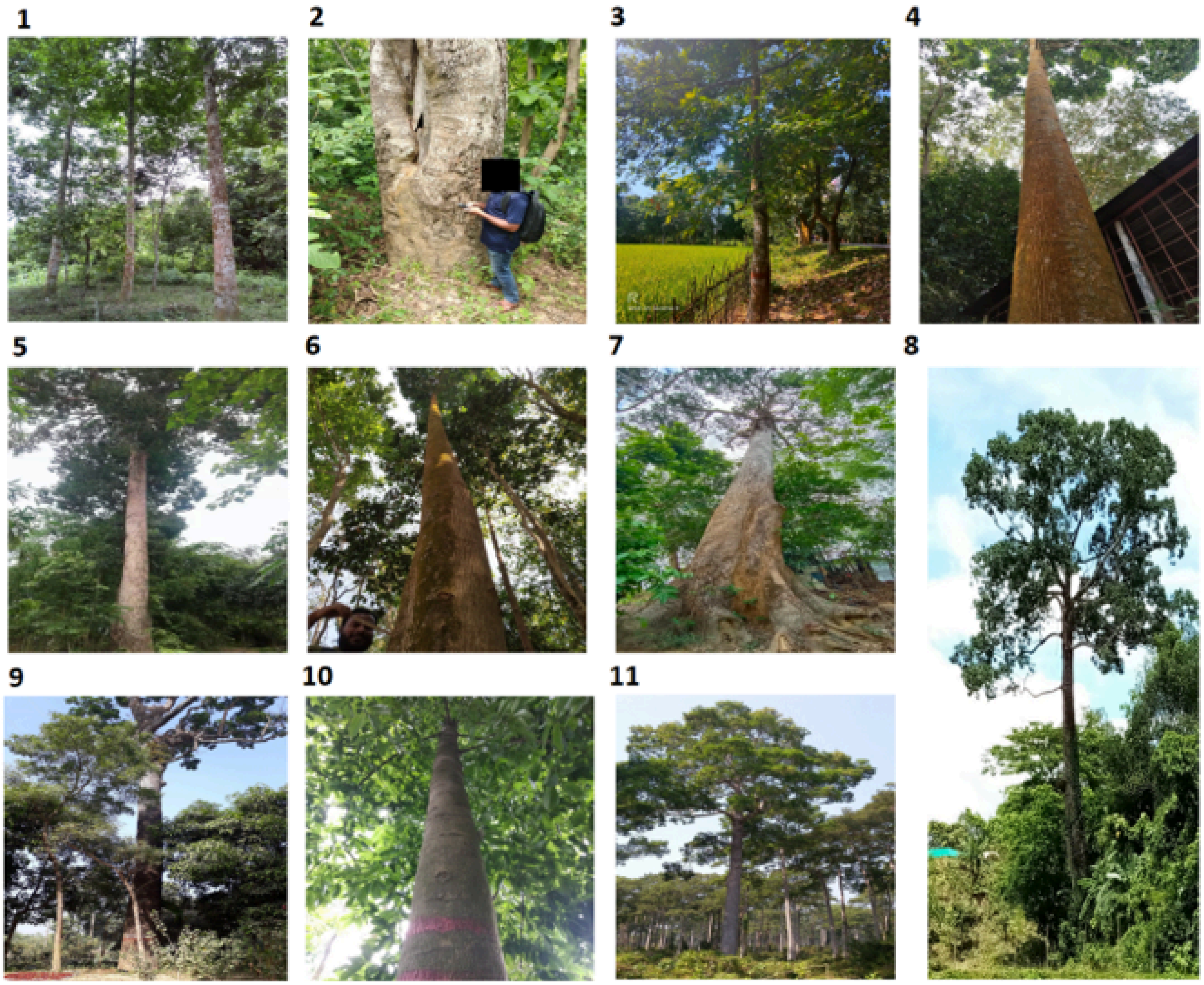

Figure 3

Physical Characteristics, and Present Status of Boilam Trees (*A. scaphula*) in 1. Hazarikhil Wildlife Sanctuary, 2. Hazarikhil Wildlife Sanctuary, 3. Dulahazra Safari Park Roadside, 4. IFESCU Campus, 5. Sukhbilas Beat, 6. National Botanical Garden, 7. Faliar Para, 8. Lama, 9. Ukhia TV Station, 10. Shilkhali Beat, and 11. Homestead of Dulahazra Safari Park Area

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Figure 4

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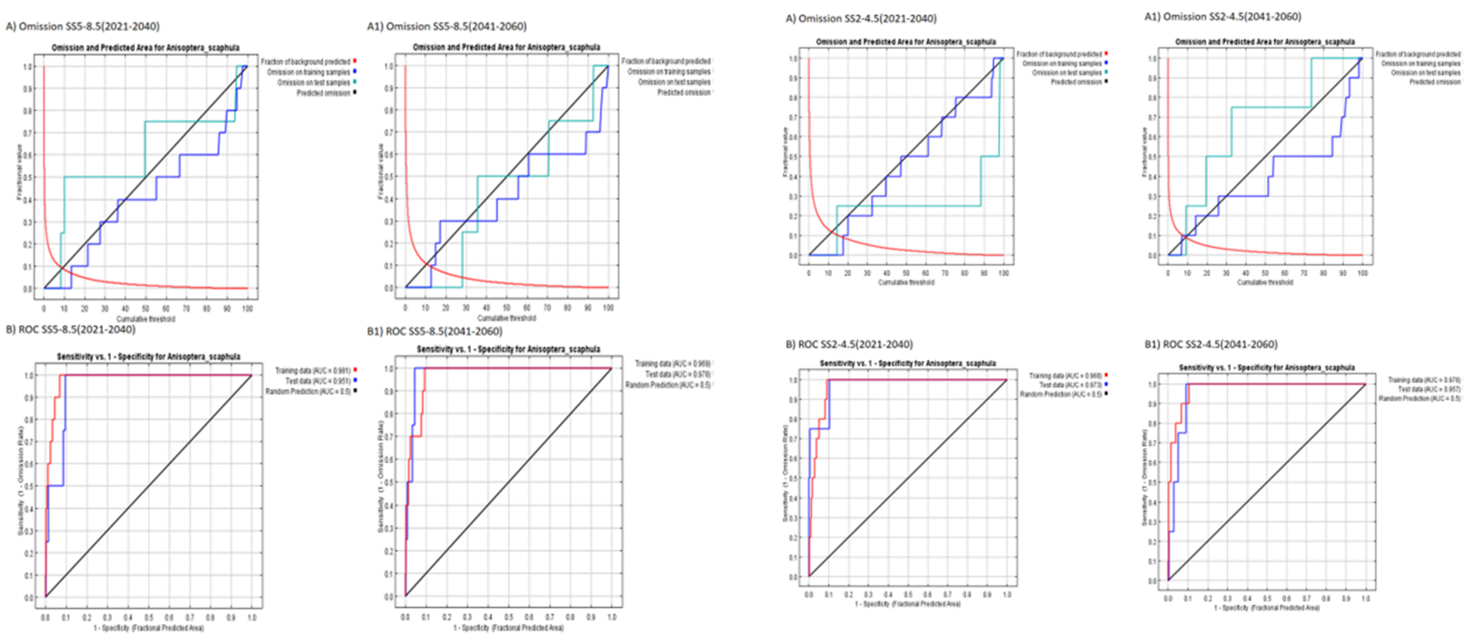

Figure 5a:

Figure 5

Omission, predicted area and sensitivity vs. 1 for *A. scaphula*, SSP5-8.5(2021-2040) and SSP5-8.5(2041-2060) scenarios.

a: Omission, predicted area and sensitivity vs. 1 for *A. scaphula*,SSP2-4.5(2021-2040) and SSP2-4.5(2041-2060) scenarios.

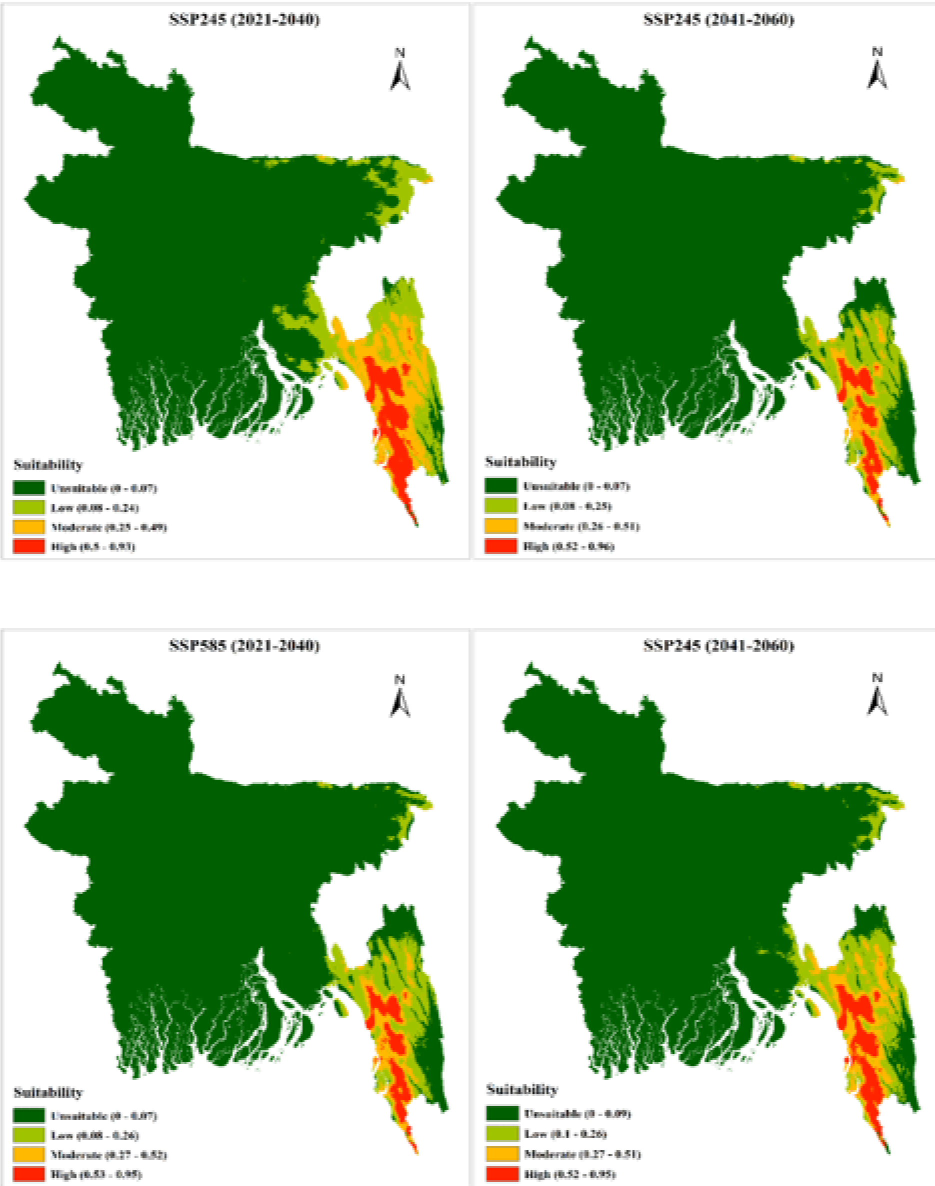

Figure 6

Predicted future distribution of *A. scaphula* in three selected Chittagong division under climate change scenario.