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Research Article

Global range extension of bioclimatic zone of *Bruguiera hainesii* C.G.Rogers 1919 (Rhizophoraceae)

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Abstract

Bruguiera hainesii is a rare mangrove species with limited populations worldwide, but there is lack of detailed knowledge about its population size and distribution in Vietnam. Its regeneration capacity is notably low, raising concerns about its long-term survival. This study aims to model the bioclimatic niche of *B. hainesii* to identify potential ecological regions in Vietnam suitable for its conservation and survival under current and future climate scenarios. Occurrence data were collected from the global GBIF database and recent field surveys in Vietnam conducted during 2023–2024. The Maxent model was used to predict bioclimatic suitability, with projections extended to future climate scenarios using ACCESS-CM2 under SSP2-4.5 (medium-emission scenario) for 2080–2100. The study identified Vietnam as a highly suitable region for *B. hainesii* despite its small population size. Projections indicate a potential expansion of ideal habitats under future climate conditions, highlighting the species' adaptability. The findings provide valuable insights into the conservation of *B. hainesii*, emphasising the importance of preserving existing populations and managing suitable habitats to ensure the species' long-term survival and regeneration. This research also underscores the role of bioclimatic niche modelling in guiding conservation strategies for endangered mangroves.

Keywords

Bruguiera hainesii, climate change, new records, ecological modelling, Maxent

Introduction

Vietnam lies within the Indo-Burma Region, recognised as one of the 36 global biodiversity hotspots. The country's significant habitat loss and the presence of numerous rare species make it a critical area that demands high priority in biodiversity conservation efforts (Duke et al. 2010,Habel et al. 2019). *Bruguiera hainesii* C.G.Rogers 1919, has a very limited distribution in coastal areas of Southeast Asia and belongs to the Rhizophoraceae family (Tran et al. 2023). Despite the species being situated within a protected forest area, where it faces less impact from human activities like agricultural development and shrimp farming, climate change is accelerating the loss of mangrove habitats. Elevated temperatures and rising sea levels are worsening coastal erosion. For many years, *B. hainesii* has not been studied for its ecological characteristics due to its narrow distribution on Con Dao Island, which is located more than 100 km from the mainland (Tran et al. 2023). Although *B. hainesii* is thought to be a narrow-range species, efforts must continue to balance the development and preservation of this species' ecosystem, as biodiversity in mangrove forests plays a crucial role in maintaining the health of coastal ecosystems. This can be particularly achieved through scientific research to better understand its growth, facilitating the propagation of *B. hainesii* and other threatened species (Hoang 2013)

Research indicates that, under high-emission scenarios, the presence and relative density of mangrove forests are likely to increase significantly in the northern Gulf of Mexico and along the south-eastern coast of the United States (Bardou et al. 2024). Research suggests that warming temperatures and changing precipitation patterns could create favourable conditions for mangroves to expand their range and density in these areas. This expansion could lead to shifts in local ecosystems, influencing coastal biodiversity, carbon storage and shoreline protection in regions that historically have not had extensive mangrove forests (Smee et al. 2017). Understanding these changes is essential for anticipating the broader impacts on coastal communities, infrastructure and fisheries, making this research critical for future environmental and policy planning.

Another study hypothesises that black mangroves will expand their range to higher latitudes in the 21st century due to global climate change (Osland et al. 2019). The main factor driving this change is the decrease in both the frequency and intensity of coastal cold spells, which historically constrained the growth of mangrove stands and the size of individual trees. This reduction in cold spells has allowed mangroves to expand their range. One potential area for such expansion is the Gulf of Mexico, situated at the northern edge of the black mangrove's habitat. The Gulf's relatively milder temperatures could facilitate the northward movement and growth of black mangrove populations, which were previously limited by colder conditions (Comeaux et al. 2012). Over approximately 35 years, mangrove coverage increased by 4.3% from 1980 to 2015, with the most significant expansion in Texas and southern Florida, owing to mild winters without subzero temperatures (Giri and Long 2016).

An important factor that conservationists might find crucial for assessing a species' adaptation to climate change is the ability to identify specific indicators (Pham et al. 2024). These indicators can provide valuable insights into how a species responds to shifting environmental conditions, such as changes in temperature, precipitation or habitat availability (Pham et al. 2024). By monitoring these indicators, conservationists can better understand the species' resilience and vulnerability to climate-related impacts. This information is vital for developing effective conservation strategies and management plans aimed at mitigating the effects of climate change on biodiversity and ensuring the long-term survival of the species in question. In the past decade, the rapid development of machine-learning has provided significant benefits, serving as an effective tool for creating potential species distribution maps, which are essential in biodiversity conservation programmes (Beery et al. 2021). These maps help identify areas where species may survive and thrive in the future, thereby supporting more effective ecosystem management and protection. In Vietnam and some neighbouring countries, ecological modelling studies have been successfully conducted, offering clearer insights into the potential habitats of wildlife species (Pham et al. 2024). These models use machine-learning algorithms to analyse environmental and biological data, predicting species distributions (ENM) under changing environmental conditions. This is particularly important in the context of climate change and altering natural landscapes, where species need to adapt to new conditions to survive (Crego et al. 2022).

This study aims to present new findings on the total number of *B. hainesii* individuals in Vietnam. Using a machine-learning algorithm (Maxent), the research analyses and selects an optimal modelling approach to identify suitable areas for the species, based on 19 bioclimatic factors. The analysis results include both current and future predictions for the period 2080–2100, based on the ACCESS-CM2 climate change scenario. The research process helps identify parameters affecting species distribution, providing crucial information for effective conservation measures in the context of climate change.

Material and methods

Occurrence and environmental data

Field surveys were carried out at Con Dao National Park, located in the Con Dao Islands of Ba Ria-Vung Tau Province, Vietnam. The occurrence of *B. hainesii* was individually measured for several parameters, including height, trunk diameter and crown diameter, to obtain a comprehensive dataset on the population structure of species in this region; the geographic coordinates and elevation data were gathered using a Garmin GPSMAP 64s receiver, with all measurements recorded according to the WGS 84 coordinate system. After examining the morphology and photographing the habitat, the specimens were numbered according to the individual trees. The specimen photos have been stored in the photo archive of the Institute of Tropical Ecology, Vietnam-Russia Tropical Center. Specimen identification was based on the documents by Tran et al. (2023).

Additionally, we used species distribution data from the GBIF biodiversity database. In total, data from 13 population distribution areas were collected from all countries where they are found worldwide, including Vietnam, Thailand, Indonesia, Malaysia, Singapore, Australia and Papua New Guinea (Fig. 1).

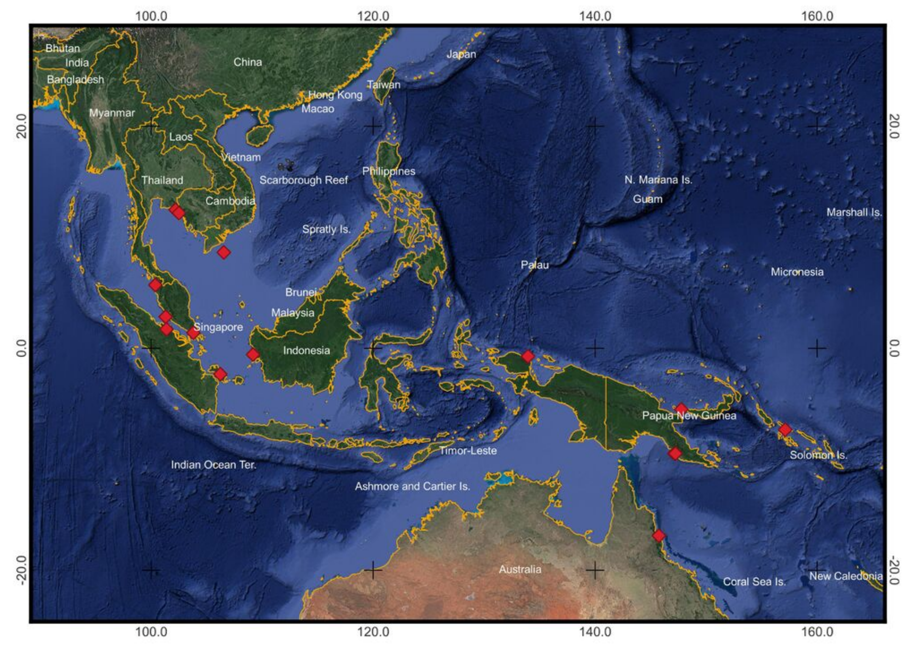

Figure 1.

Distribution location of *B. hainesii*.

Nineteen bioclimatic variables were collected from Worldclim (version 2.1) for modelling and are considered to influence the distribution of species in natural environments (Phillips et al. 2006, Fick and Hijmans 2017). Correlations between environmental variables greater than 0.8 were removed to avoid overfitting the model. Finally, the remaining environmental parameters were used in the model, including seven variables (bio1: annual mean temperature; bio2: mean diurnal range (mean of monthly (max temp - min temp)); bio8: mean temperature of the wettest quarter; bio9: mean temperature of the driest quarter; bio10: mean temperature of the warmest quarter; bio12: annual precipitation; bio15: precipitation seasonality, coefficient of variation).

Ecological Niche Model (ENM)

Two models were developed to predict the distribution of *B. hainesii* using Maxent software on both a desktop platform and Google Earth Engine (GEE), a cloud computing platform. By analysing the current and projected ecological niche models (ENMs) of this species, critical areas requiring protection can be identified to support its survival. Additionally, the anticipated changes in optimal ecological zones provide valuable insights, contributing to conservation strategies for *B. hainesii*.

In the first model, species occurrence data and environmental variables were utilised to create the ENM using Maxent software (version 3.4.4). The model was executed 10 times with a test data proportion configured using a "random seed" option. The cross-validation method was applied as the run type, with maximum iterations set to 500. A Jackknife test was employed to evaluate the significance of climatic variables and response curves were generated to assess their impact on the distribution of *B. hainesii* (Pham et al. 2024). The output format was set to logistic, while other settings remained at their default values.

In the second model, environmental variables and data on species presence and pseudo-absence were added to the Maxent algorithm that was run on the GEE platform. We also extracted the contribution of each environmental variable to the Maxent model. A FeatureCollection was created to facilitate the visualisation and analysis of the contribution values of environmental variables on the JavaScript platform.

Predicted future distribution of suitable habitats of *B. hainesii*

We used climate scenarios (ACCESS-CM2) downloaded from WorldClim v.2.1 (1 km resolution). ACCESS-CM2 (Australian Community Climate and Earth-System Simulator) is an advanced climate model with high accuracy in predicting climate change for large regions. This model is developed to forecast long-term trends in climate variables, such as temperature and precipitation, with better spatial resolution, especially for the Asia region and surrounding seas (Bi et al. 2020). ACCESS-CM2 scenario includes 19 bioclimatic variables under the medium emission scenario SSP2-4.5. Each SSP (Shared Socioeconomic Pathway) represents a different trajectory for future social, economic and environmental conditions, affecting the level of climate change mitigation and the adaptation challenges we may face. SSP2-4.5 is a scenario that predicts a future where global social and economic development is moderate, with coordinated efforts to reduce greenhouse gas emissions.

Validation of a model

This is a critical step in model development to ensure its accuracy, reliability and generalisability. Area Under the Curve (AUC) was used as a metric that measures the performance of a classification model (Muschelli 2019) . In the context of ecological modelling and machine-learning, AUC is commonly used in the evaluation of the ROC curve (a chart illustrating a classifier's performance across multiple threshold settings). AUC = 1 indicates that the model operates with precision. AUC ≤ 0.5 indicates that the model performs no better than random guessing. AUC from 0.5 to 1 indicates that the model demonstrates classification abilities surpassing random chance, with higher AUC values reflecting improved performance. AUC is a way to assess the accuracy and discriminatory power of a model, indicating how well the model can correctly classify positive and negative cases.

Reliability of the analysis results

The jackknife test was implemented as a statistical technique employed to evaluate the precision of estimates derived from a data sample (Dixon 2001) . It is primarily employed to evaluate the stability and reliability of statistical indices. Specifically, in a jackknife test, we systematically removed one observation at a time from the dataset and recalculated the statistical estimate (such as the mean, standard deviation etc.) with each remaining sample. These are estimated to assess their variability and sensitivity to changes in the data. This method is very useful for detecting unwanted influences from specific data points and provides information about the reliability of the analysis results.

Mapping suitable distribution zones

On the GEE platform, the predicted results were standardised into the Habitat Suitability Index (HSI), with values ranging from 0 to 1, where 0 denotes unsuitable habitat and 1 indicates highly suitable habitat. The predictions are presented for both current and future conditions and all these raster files were exported to Google Drive and then reclassified to create HSI maps using ArcGIS Pro software (Pham et al. 2024).

On the Desktop platform, ASCII map layers (.ascii) generated from the Maxent model were converted to raster format (.tif) using ArcGIS Pro software. The "10th percentile training presence logistic threshold" was used to determine the suitability threshold for the habitat of *B. hainesii*. Four classification levels were defined: unsuitable (< 0.45), low suitability habitat (0.45–0.60), moderate suitability habitat (0.6–0.75) and high suitability habitat (> 0.75).

Results

Based on the results of the ecological survey conducted in November 2013, we recorded seven individuals of *B. hainesii* on the Con Dao Islands. For the first time, a study on the biological and ecological characteristics of *B. hainesii* has been conducted, with the following results:

Description

This is the first time the coordinates of all seven individuals have been documented, along with the biological characteristics of the species. The average height of the individuals is 15 m, with a trunk diameter of 84 cm. This species has a distinctive aerial root system, which helps the tree resist erosion and stabilises the soil. The aerial roots typically develop robustly, forming a network of secondary roots that rise above the ground and water, aiding in oxygen absorption in the muddy environment. *B. hainesii* has small flowers, usually clustered in groups of 2–3 on a single inflorescence. The flowers predominantly bloom from January to March and it is uncommon to encounter a tree bearing fruit. This parameter is similar to our other study at Con Dao (Tran et al. 2023).

Ecological notes

In Vietnam, this species primarily grows in mangrove forests on a small island (Hon Ba Island, part of the Con Dao Archipelago). The habitat of *B. hainesii* here is characterised by saline water, partially submerged by tides, with seasonal variations in seawater levels. The mangrove forests where *B. hainesii* thrives are noted for their soft, thick mud layer and frequent inundation. The trees often grow in shallow water areas where there is an exchange of water between the sea and the land. Analysis of 24 soil samples from areas where this species is distributed showed that the soil composition is predominantly sandy (> 89%), with minimal clay and silt (Fig. 2). The soil pH_{KCl} ranges from slightly acidic to neutral (4.62-6.77). Organic matter content is moderate (OM = 3.27%). The total nitrogen (N) content is moderate (0.12%), phosphorus (P) is low (0.04%) and potassium (K) ranges from moderate to high (0.38%) (Fig. 3).

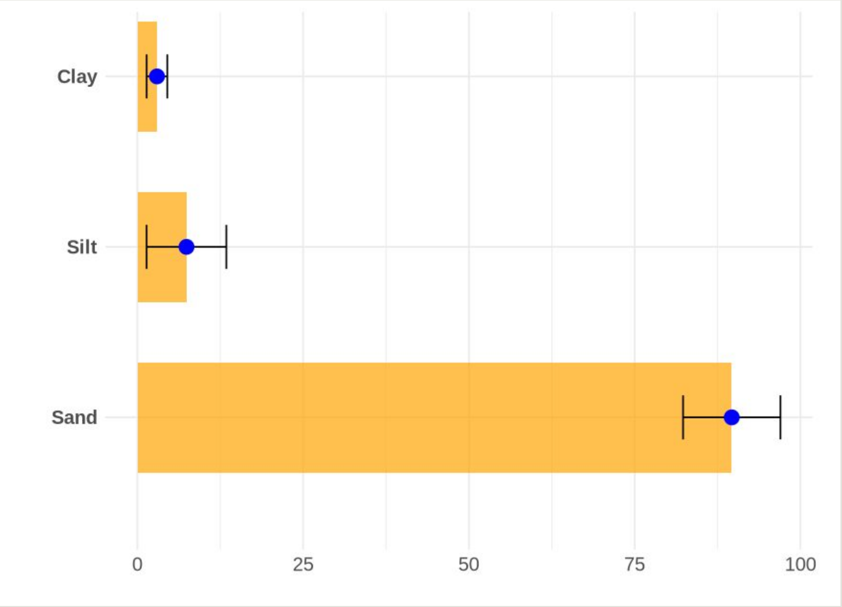

Figure 2.

Soil properties (min/max, standard deviation) around the *B. hainesii* distribution site, Vietnam.

Conservation status

The species is categorised as " Critically Endangered" by the IUCN Red List (Duke et al. 2010). This species has a very restricted distribution, found in Con Dao, Vietnam and a few neighbouring countries, such as Thailand, Malaysia, Singapore, Indonesia and Australia (GBIF). The conservation status of the species in Vietnam faces significant challenges, primarily due to the absence of fruiting in recent years, the lack of observed regenerating seedlings and the species' exposure to declining area and quality of habitat in mangrove forests. The main threats to this species include coastal erosion, sea level changes due to climate change and the expansion of tourism activities in the mangrove areas, which places additional pressure on its habitat.

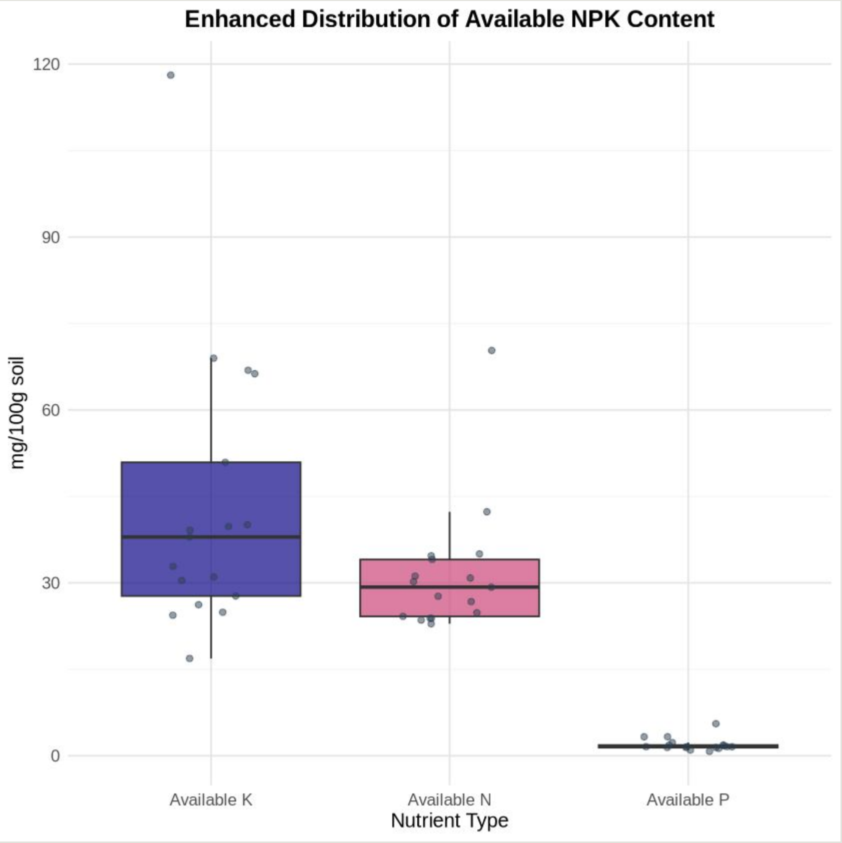

Figure 3.

NPK content (min/max, standard deviation) around the *B. hainesii* distribution site in the soil layer at a 10 - 30 cm depth, Vietnam.

Current and future appropriate bioclimate zone of *B. hainesii*

Based on the Maxent algorithm for *B. hainesii*, the model generated using Maxent software achieved an AUC of 0.862, which outperforms the model created with GEE (AUC: 0.66). The high AUC value (Fig. 4) from Maxent indicates that the bioclimatic variables used in the model effectively explain the distribution range of *B. hainesii*, highlighting the critical role of climatic factors in shaping and maintaining its habitat. In contrast, the model generated using GEE, which incorporated both presence and pseudo-absence data, exhibited a lower AUC, potentially due to inaccuracies or the random distribution of pseudo-absence data. This finding suggests that the use of pseudo-absence data should be approached with caution, particularly for species with limited presence data or those inhabiting specialised environments such as mangrove forests.

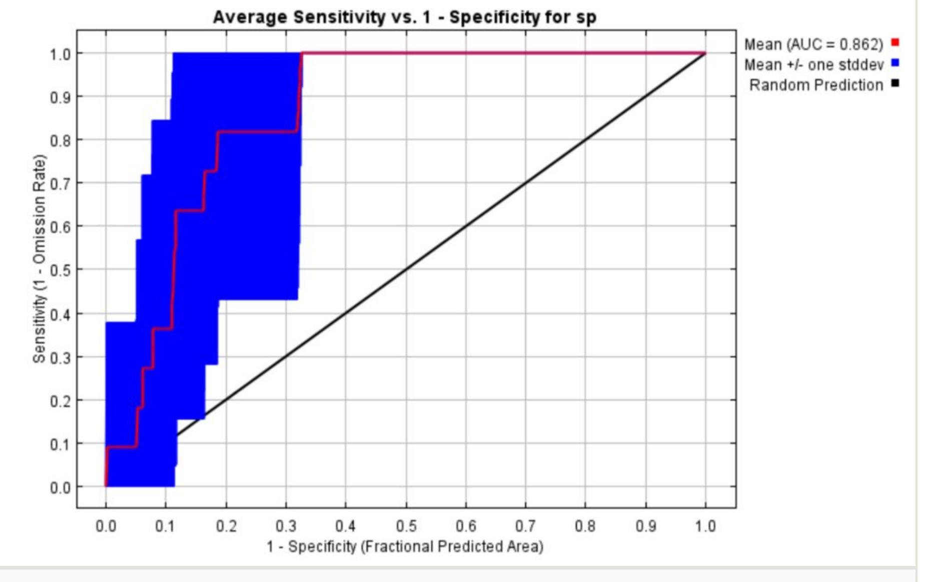

Figure 4.

AUC curve.

Consequently, the Maxent software model was selected for analysis and evaluation of both current and future scenarios. The predictions suggest that the most suitable habitat for *B. hainesii* is primarily located in Southeast Asia. This region includes countries such as Vietnam, Thailand, Indonesia, Malaysia, the Philippines, Singapore and Papua New Guinea. Additionally, parts of northern Australia are also predicted to offer suitable conditions for this species (Fig. 5). This information is valuable for conservation efforts, as it helps identify and prioritise regions where habitat protection and restoration activities are most needed to support the survival and growth of *B. hainesii*.

In the model used to assess the habitat suitability for *B. hainesii*, three specific climatic variables played a crucial role in determining its performance. These factors include the mean diurnal range (bio2), which represents the difference between the maximum and minimum temperatures within a day; the mean temperature of the driest quarter (bio9), which indicates the average temperature during the least rainy season of the year; and the annual mean temperature (bio1), which is the average temperature throughout the entire year. Together, these factors contributed to the model's effectiveness in predicting habitat suitability (Table 1).

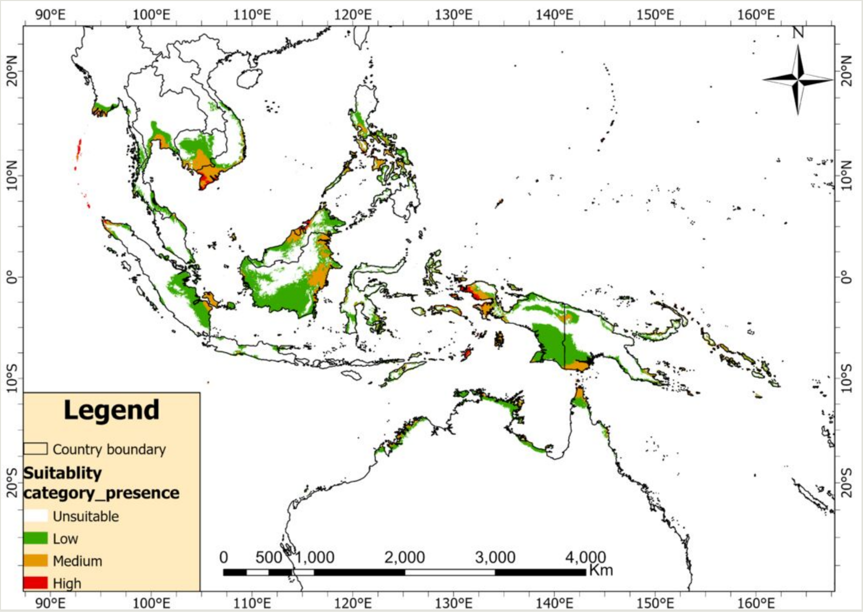

Figure 5.

Habitat Suitability Index of *B. hainesii* at present.

Table 1.

Percent contribution and permutation importance of the variables. (bio1: annual mean temperature, bio2: mean diurnal range (mean of monthly (max temp - min temp)), bio8: mean temperature of wettest quarter, bio9: mean temperature of driest quarter, bio10: mean temperature of warmest quarter, bio12: annual precipitation, bio15: precipitation seasonality, coefficient of variation).

Variables	Percent contribution	Permutation importance
bio2	76	62.5
bio9	10.3	5.6
bio1	10.1	0
bio8	2.8	30.8
bio15	0.7	0
bio12	0	1.1
bio10	0	0

The study's results indicate that the potentially suitable distribution area for *B. hainesii* under future scenarios (ACCESS scenario SSP2-4.5 for period: 2080-2100) is predicted to expand, with a significant increase in the total area of high habitat suitability index (HSI) across the entire region. The results of the Jackknife test on the importance of environmental variables show that the variable that achieves the highest gain when analysed independently is bio2, suggesting that this variable provides the most useful information when considered independently. The environmental variable that caused the greatest reduction in model gain when excluded was also bio2, this suggesting that it holds the most distinct information not found in other variables. These values represent averages over multiple models run (Figs 6, 7).

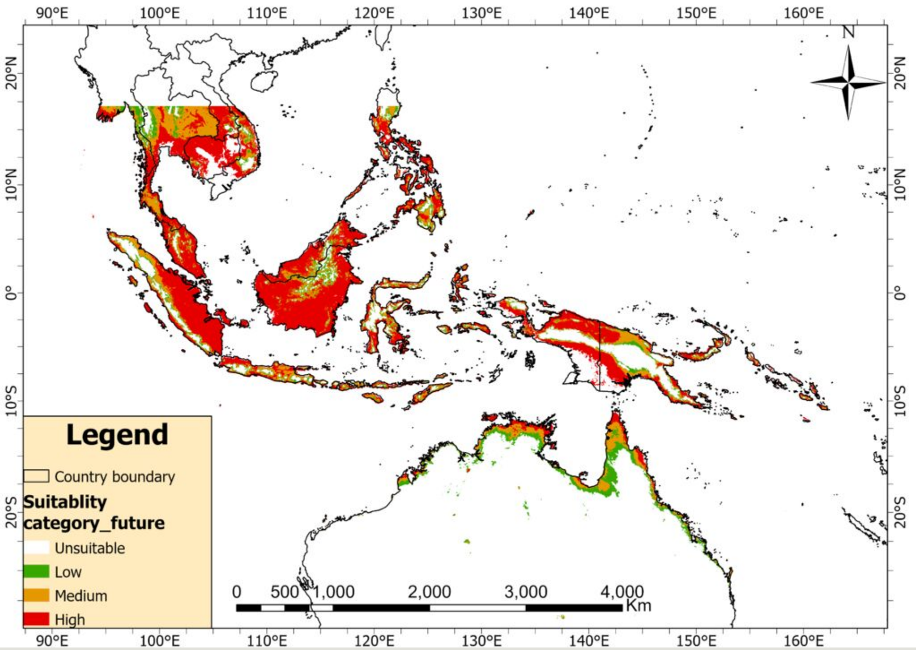

Figure 6.

Habitat Suitability Index of *B. hainesii* in the future (2080-2100) using the ACCESS scenario SSP2-4.5.

Discussion

Mangroves are capable of adapting to climate change due to their ecological characteristics and crucial role in coastal ecosystems. These ecosystems are resilient to high salinity conditions, fluctuating water levels and tidal flows. Mangrove species have generally developed complex adaptive mechanisms in morphology, anatomy, physiology and molecular biology that enable them to thrive in stressful environments (Srikanth et al. 2016).

There has been no study on the adaptive capacity of *B. hainesii* under significant climate change impacts. However, recent local assessments suggest that *B. hainesii* might have expanded to Vietnam due to ocean currents transporting it to the Con Dao Islands. Another reason that the distribution of *B. hainesii* and mangroves, in general, might adapt well to climate change is their mobility. Mangroves can naturally expand and colonise new areas as conditions become more favourable. In western Jamaica, mangrove ecosystems were able to persist during the mid-Holocene as their sedimentation rates outpaced the rising sea levels (Hendry and Digerfeldt 1989). Suppose migration or inland expansion does not occur rapidly enough to counteract rising sea levels. In that case, mangroves may become increasingly diminished and potentially face extinction. The suitable climatic zones for *B. hainesii* are likely to expand significantly, which also shows that the regions such as Vietnam, Indonesia, Singapore and Malaysia, where high temperatures and precipitation, support their habitats. However, mangrove expansion is not a straightforward process. Despite potentially favourable climatic conditions, other factors such as land loss due to urbanisation, resource extraction and marine ecosystem changes could create barriers to this expansion (McLeod and Salm 2006).

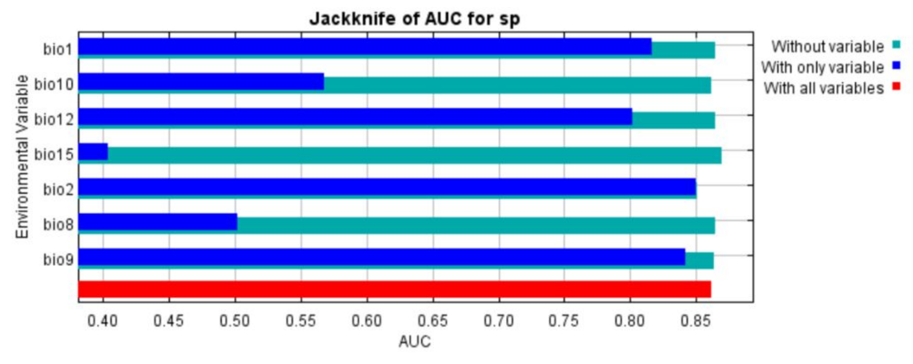

Figure 7.

Jackknife test of the model.

Different mangrove species have distinct tolerances for the duration, frequency and depth of flooding (Semeniuk 1994). *B. hainesii*, as a tree species found in high tidal zones, has stable adaptations to coastal shape, soil and salinity and changes in these factors could alter the species' tolerance (Hoang 2013). Given the very small population of this species and the lack of research on its potential for relocation (replanting) to new areas, further studies are necessary. To evaluate the impact of rising sea levels on the *B. hainesii* habitat, it is important to consider factors affecting ecological balance, including coastal processes, local geomorphology and salinity of soil.

Climatic changes can exacerbate impacts on mangroves before sea-level rise, sediment and nutrient supply, as well as salinity regimes. In examining the effects of sea-level rise on river estuaries, Kennish (2002) highlighted the crucial influence of local environmental conditions. He stressed that factors such as tidal range and sediment supply play a fundamental role in shaping how mangrove ecosystems respond to rising sea levels. According to his analysis, mangrove communities situated in regions with high tidal ranges and abundant sediment, such as northern Australia, exhibit greater resilience to sea-level rise compared to those in areas with lower sediment availability and smaller tidal ranges, such as the Caribbean islands. This contrast is evident from studies like those of Woodroffe (1995), who observed the enhanced stability of mangrove systems in sediment-rich environments and Parkinson et al. (1994) who documented the vulnerability of mangroves in sediment-poor areas with limited tidal fluctuations. Understanding these local conditions is essential for predicting the potential impacts of sea-level rise on mangrove habitats and for developing targeted conservation strategies to protect these vital coastal ecosystems (Ward et al. 2016).

Although the global distribution of *B. hainesii* may increase in the future, mangroves often experience stress beyond their survival thresholds due to various factors (e.g. hydrological changes, artificial sedimentation, subsidence, climate change). We recommend that rising sea levels are likely to reduce the geographical distribution of this species in Con Dao NP due to the island's small size and limited sediment conditions, making it difficult to access external sediment sources. Compared to riverine mangroves, mangroves on small islands are less likely to withstand sea-level rise effectively, compared to those with external sediment sources (Pernetta 1993).

Conclusions

B. hainesii demonstrates significant potential to adapt to climate change, with projections indicating that its climatic range could expand due to increases in temperature and precipitation between 2080 and 2100. This suggests that the species may be resilient to some aspects of climate change, particularly those affecting temperature and rainfall. As such, *B. hainesii* might be able to colonise new areas that become more suitable under future climatic conditions, which could potentially enhance its distribution and ecological role. These findings highlight the species' ability to adjust to changing environmental conditions, which is critical for its long-term survival in the face of global climate challenges. However, the results of this study also suggest that climatic factors alone are not responsible for the global rarity of *B. hainesii*. Despite the potential for adaptation, the species' low regeneration capacity remains a significant limiting factor. This limitation could be linked to physiological constraints, such as poor seed viability, limited pollination or challenges in seedling establishment, which could hinder its ability to recover and expand. These issues are more critical than climate-related factors in determining the species' population dynamics. Therefore, addressing these physiological barriers is essential for improving the regeneration and overall survival of *B. hainesii*. In light of these findings, conservation efforts for *B. hainesii* should prioritise habitat protection, particularly in regions where the species already exists. This can provide a stable environment for the remaining populations, ensuring their survival in the short term. Simultaneously, research into overcoming the physiological barriers to regeneration should be a central focus. Strategies such as enhancing seedling establishment, improving pollination rates or exploring genetic approaches could help increase the species' regeneration capacity. By addressing both habitat preservation and physiological limitations, we can ensure the long-term sustainability of *B. hainesii* and the critical coastal ecosystems it supports.

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Conflicts of interest

The authors have declared that no competing interests exist.

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