

Prediction of Suitability of Red Mangrove (*Rhizophora mangle*) in North America with MaxEnt

Qindong Wang

Annie Wright Schools, Tacoma, Washington, the U.S.

qindong_wang@aw.org

Abstract. Mangroves are essential intertidal species that play a critical role in ecosystems, serving as carbon sinks, protectors against tsunamis, and habitats for valuable and endangered species. Species distribution models (SDMs), such as MaxEnt, are effective tools for predicting habitat suitability, but their application to red mangroves (*Rhizophora mangle*) in North America has been limited. This research addresses this gap by using MaxEnt to model red mangrove distribution based on occurrence data and environmental variables (geographical and bioclimatic). The findings contribute valuable data for future research on mangrove SDMs and provide insights for conservation decision-making in North America. Results show that the most suitable habitats for red mangroves are along the eastern Gulf of California, the southern coast of Florida in the U.S., Yucatán, Tabasco, and Quintana Roo in Mexico, eastern Nicaragua, and western Cuba. Key environmental variables influencing the model are elevation, minimum temperature of the coldest month, isothermality, and maximum temperature of the warmest month.

Keywords: *Rhizophora mangle*, mangrove, MaxEnt, suitability, North America.

1. Introduction

Mangroves are halophytic trees or shrubs thriving in tropical and subtropical intertidal zones [1]. As keystone species, they play vital roles in maintaining ecosystem stability. First, mangroves act as natural coastal barriers, reducing the energy of tsunamis and large ocean waves by dissipating wave force [2]. Using GIS, researchers evaluated the impact of the Indian tsunami and found that regions with mangrove forests experienced significantly less damage than bare areas. [3]. Additionally, mangroves support economically valuable species. For example, researchers in the Gulf of California estimated that each hectare of mangroves contributes 37,500 USD annually through fisheries. Furthermore, mangroves act as significant carbon sinks. Current studies have shown that mangroves can store 650 billion tons of blue carbon through their extensive root system and high biomass density [6]. According to estimates by environmental organizations, carbon emissions caused by mangrove deforestation could contribute up to 10% of global carbon emissions in the future, despite mangroves covering only 0.7% of the total area of global tropical forests [7], and numerous species loss alerts have been issued by the environmental organization Global Mangrove Watch over the past five years [8]. According to Donato [9], the coverage of global mangrove forests has declined 30-50% in the past five decades due to factors such as coastal development, rising sea levels, and deforestation. As mangrove forests are confronting the risks of severe decline, SDMs can be helpful in outlining suitable habitats based on bioclimate and

geographical factors [10,12]. This paper aims to identify the suitability of red mangroves (*Rhizophora mangle*) in North America and discuss how the migration of these suitable habitats may be the consequence of climate change.

This research aims to (1) estimate the habitat suitability of red mangroves in North America using MaxEnt; (2) analyze the contribution of environmental factors via the jackknife method; (3) explore how climate change drives habitat migration.

This paper is structured as follows: the first section provides an overview of mangrove species and their ecological significance. The second section reviews existing literature and identifies gaps in suitability data. The third section describes the data collection and MaxEnt model setup, followed by an analysis of the results and a discussion of future implications.

2. Literature review

2.1. Overview of existing literature

Species distribution models (SDMs) are ecological niche models that predict suitable areas for species. Common examples of SDMs include GARP, DOMAIN, BIOCLIM, and MaxEnt [10,12]. Among the various SDMs, MaxEnt is considered one of the most user-friendly and accurate models for predicting species distribution [11,12]. MaxEnt has been widely used to study multiple species, including Brazilian tobacco, stipa, and coral reefs [10,13,14]. Additionally, MaxEnt aids researchers in achieving various ecological and environmental goals, ranging from identifying invasive species [15] to outlining conservation areas [10,11]. Regionally, a study in Guangdong, China, reports that 25% of the mangrove forests are not well-preserved, and MaxEnt model suitability results are used to outline conservation areas [11]. Similarly, in Mozambique, the MaxEnt model was employed to assess the vulnerability of near-coastal mangrove forests to flooding and hurricanes by calculating the exposure index (EI) [16]. This demonstrates the versatility of the MaxEnt model in addressing diverse environmental challenges. Nonetheless, the application of the MaxEnt model for predicting mangrove suitability is rare in North America. Mangrove forests face numerous threats: sea-level rise, hurricanes, and habitat destruction [17]. Field and literature research indicate that red mangroves are among the most common mangrove species in North America [17,18]. This research will focus on red mangroves and predict suitable areas in North America under the SSP5-8.5 pathway-the regular development pathway that controls climate change under 5 degrees Celsius [10]. Studies of mangroves highlight that climate change can lead to large-scale shifts in species distribution, and red mangroves are undergoing transitional processes in salt marshes within tropical-subtropical zones [19], which can be validated using the MaxEnt model.

2.2. Identification of gaps in the literature

Although the MaxEnt model has been widely used to predict mangrove distribution in regions such as China and Mozambique [10,16], studies on mangrove distribution in North America, particularly in regions with significant populations like Mexico and Florida, remain limited.

2.3. Relevance to current studies

Previous studies with MaxEnt model have demonstrated its interactivity along with high accuracy and reliability in predicting species distribution. The current study builds on this foundation by employing the MaxEnt model specifically for red mangroves in North America, filling a critical gap in geodata that may be useful for future regional conservation.

3. Methodology

3.1. Research design

This research employs the MaxEnt model to predict the suitability of red mangroves in North America. The research design involves data collection, processing environmental factors, model training, and

verification. The habitat suitability results from the model will be produced based on the occurrences of red mangroves and environmental layers, providing a theoretical foundation for future conservation.

3.2. Material and equipment

The primary software and materials used for this research are ArcGIS v10.8, Excel, and MaxEnt model. ArcGIS is used to process environmental data of bioclimate and geological layers. Excel is used for filtering out repetitive or missing occurrences in the initial stage. Lastly, MaxEnt model is used to predict suitable areas of mangrove forests through the input of occurrence coordinates and environmental layers. The results from the MaxEnt model include the receiver operating characteristic (ROC) curve, maps showing the probability distribution of red mangroves' suitable areas, response curves, and variable contribution ratios, which are significant for analysis and evaluation.

3.3. Data collection

The data obtained in this research can be categorized into occurrence and environmental factors. Specifically, the occurrence of red mangroves in North America is downloaded from the Global Biodiversity Information Facility. Repetitive and missing coordinates in the initial occurrence data were removed, and the remaining occurrence data were rarefied to a 20km resolution using the SDM toolbox in ArcGIS to reduce spatial autocorrelation [10]. Environmental data were obtained from WorldClim, and landscape data were collected from the Etopo global relief model of NOAA. The layer of Euclidean distance to coasts is processed from the landscape layer by using the spatial analysis tools in ArcGIS 10.8. All of the environmental data were processed into five arcminutes (around 9-kilometer resolution) and converted into ASCII files for importing into the MaxEnt model. All the environmental layers are restrictive conditions of the MaxEnt model, which is crucial for the model to predict the most accurate (with the most entropy/randomness) suitability.

3.4. Model setup and parameters

To set up the simulation, rarefied occurrences of red mangrove and processed environmental layers are imported into MaxEnt 3.4.4. Since using bioclimate data of similar categories might incur over-correlation [10], this research has run a trial modeling with all 19 bioclimate variables. By considering the overall relevance (contribution) and correlation issue, the environmental variables used in this research are presented in Table1.

Table 1. Chosen Environmental Data for MaxEnt

Data Type	Abbreviation	Environmental Variable	Units
Bioclimate	bio2	Mean diurnal range	°C
	bio3	Isothermality	--
	bio5	Max. temperature of warmest month	°C
	bio6	Min. temperature of coldest month	°C
	bio18	Precipitation of warmest month	mm
	bio19	Precipitation of coldest month	mm
Topographic	etopo	Elevation	--
	eudis	Euclidean distance to coast	M

This research allocates 75% of occurrences for training and the rest 25% for testing, ensuring the model's generalization and reliability [10,12]. Response curves are drawn to evaluate the model's overall accuracy, and the jackknife method is chosen for analyzing variable contribution. Setting the replicates to 10 and using a random seed generates multiple outcomes for higher accuracy, with the rest of the parameters remaining at default [11].

3.5. Data analysis techniques

ROC and area under this curve (AUC) are used to evaluate the accuracy of the model, with AUC values above 0.9 indicating high predictive power [11]. According to previous studies, the AUC value between “0.9 – 1.0” indicates “high very accurate,” “0.8 – 0.9” indicates “accurate,” “0.7 – 0.8” indicates “moderate,” and “<0.7” indicates “inaccurate” [10,11]. Additionally, the jackknife method is used to identify the most influential variables in model construction, with response curves demonstrating the most optimal ranges of the variables. Lastly, this research will categorize suitable regions as follows using equal-interval classification [20]: 'highly suitable' (0.8–1.0); 'suitable' (0.6–0.8); 'moderately suitable' (0.4–0.6); 'slightly suitable' (0.2–0.4); and 'non-suitable' (0.0–0.2).

4. Results

4.1. Accuracy analysis of MaxEnt

The ROC curve (Figure 1) shows that both the mean training and test data of 10 replicates have AUC values above 0.90, indicating high predictive accuracy of the MaxEnt model for red mangroves. An AUC value greater than 0.90 reflects excellent model performance in distinguishing between suitable and unsuitable habitats.

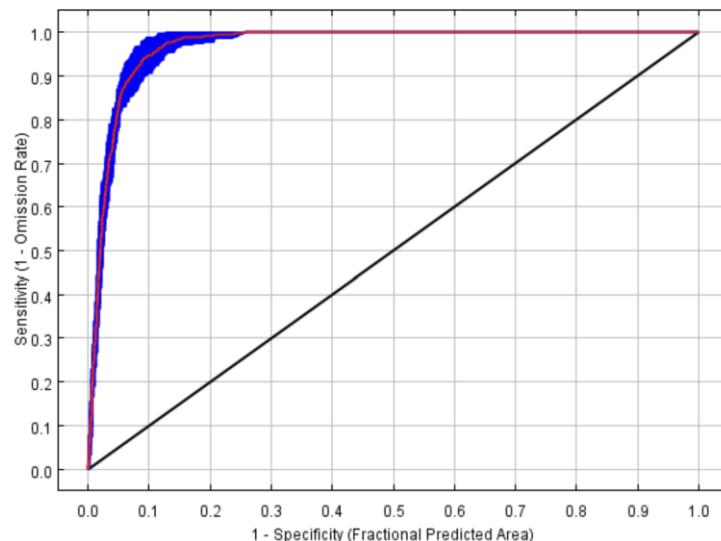


Figure 1. Receiver Operating Characteristic Curve and Mean AUC of Training (red) and Test (blue, $\pm$ one SD) Data AUC of 10 Replicates

4.2. Contribution of individual environmental variables on MaxEnt model construction

According to Table 2, minimal temperature of coldest month (bio6) is the most influential variable of eight variables, contributing 52.0% to the overall model results. This value indicates that red mangroves are particularly sensitive to cold temperature, which may restrict their suitability. Elevation (etopo) and precipitation of warmest month (bio18) contribute 16.8% and 17.5%, respectively; the remaining variables together contribute 13.7% of the overall model. Therefore, the minimum temperature of the coldest month, elevation, and precipitation of the warmest month are the top three crucial variables in model building, as they play significant roles in determining habitat suitability.

Table 2. Chosen Environmental Data for MaxEnt

Variables	Contribution Rate (%)
Mean diurnal range (bio2)	0.7
Isothermality (bio3)	6.1
Max. temperature of warmest month (bio5)	1.7

Table 2. (continued).

Min. temperature of coldest month (bio6)	52.0
Precipitation of warmest month (bio18)	17.5
Precipitation of coldest month (bio19)	4.0
Elevation (etopo)	16.8
Euclidean distance to coast (eudis)	1.3

4.3. Jackknife test

The jackknife test (Figure2) reveals that minimal temperature of the coldest month (bio6) has the highest independent contribution (with-only-variable score) to model's regularized test, which is higher than 1.3. This method evaluates each variable's contribution by excluding others, highlighting bio6 as a critical influencer of the overall red mangrove distribution. Additionally, isothermality (bio3), and maximal temperature of warmest month (bio5) score higher than 1.2, and elevation (etopo) scores higher than 1.1. These three variables are also significant individual contributors to the suitability prediction. In contrast, the regularized gain, test gain, and AUC, the with-only-variable scores of mean diurnal range (bio2), precipitation of coldest month (bio19), and Euclidean distance to coast (eudis) are significantly lower than other variables, indicating these three variables contain more special environmental information [10]. In summary, elevation (etopo), minimal temperature of coldest month (bio6), isothermality (bio3), and maximal temperature of warmest month (bio5) are the most influential variables for red mangrove suitability in North America.

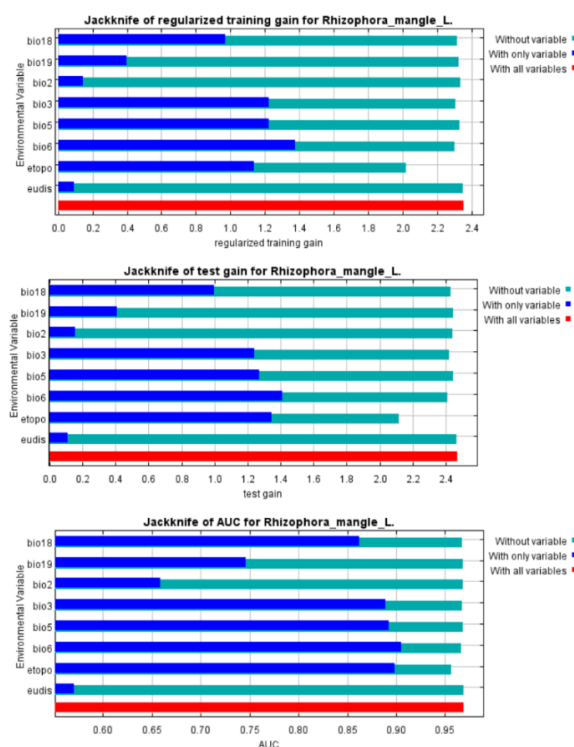


Figure 2. Variable Contribution to the MaxEnt Model of red mangroves Based on Jackknife Test

4.4. Response curves of most influential variables

Figure 3 shows how variations in key variables, such as isothermality (bio3) and minimum temperature of the coldest month (bio6), impact the likelihood of red mangrove presence. The optimal ranges for red mangrove presence are: isothermality between 67 – 79; minimum temperature of the coldest month

between 10 – 20 °C; precipitation of the warmest month between 250 – 750 mm; and elevation between -3000 – -1000 meters. These curves provide critical insights for the environmental conditions necessary for red mangrove survival.

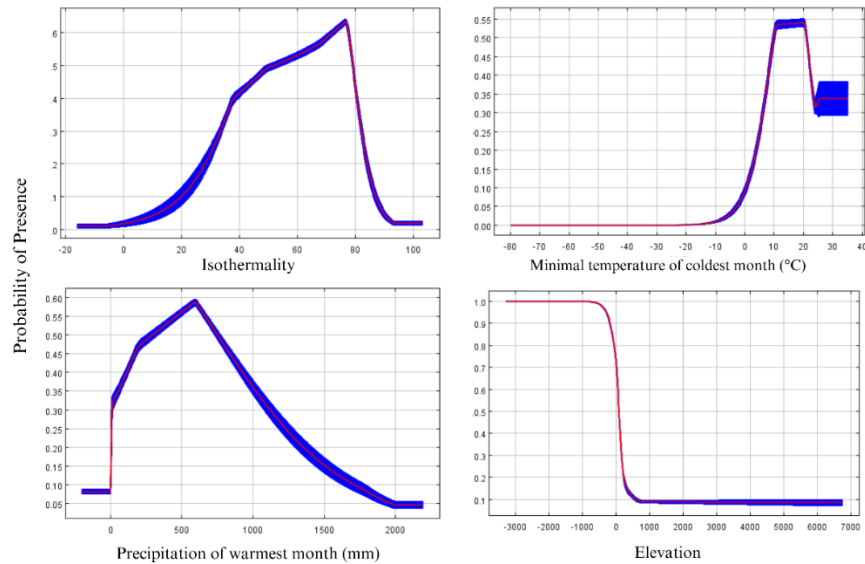


Figure 3. Response Curve of Probability of Presence of Red Mangroves and Four Key Environmental Variables (red: mean response from 10 replicates; blue: mean $\pm$ 1 standard deviation)

4.5. Suitable areas and equal-interval classification of red mangroves in North America

Figure4 below demonstrates the suitability outcome from MaxEnt, and Figure5 is produced by applying the equal-interval classification mentioned in Section 3.5.

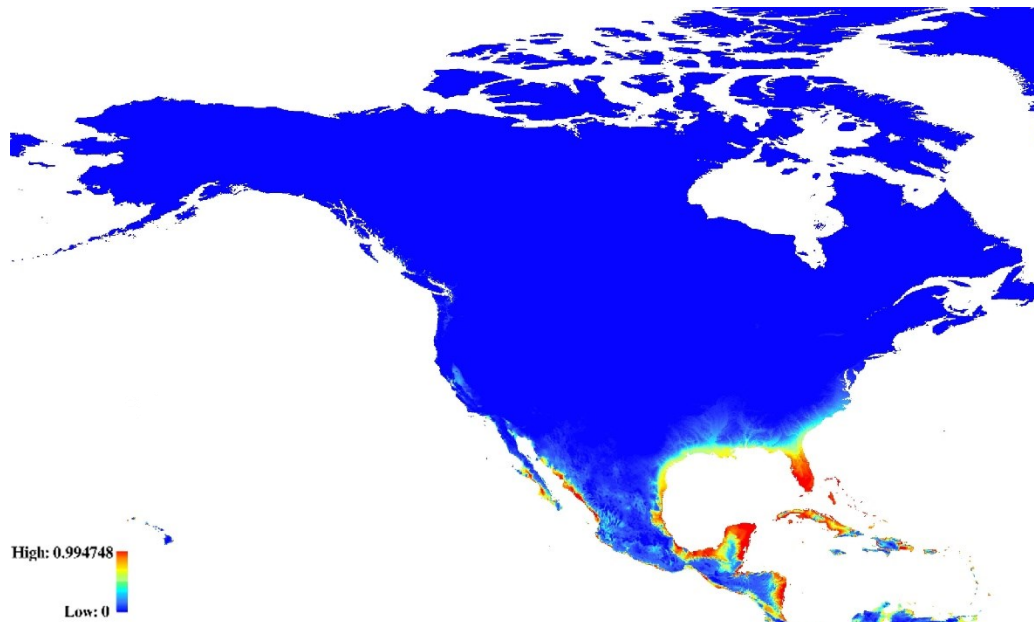


Figure 4. Logistic Probability of Distribution of Red Mangroves in North America

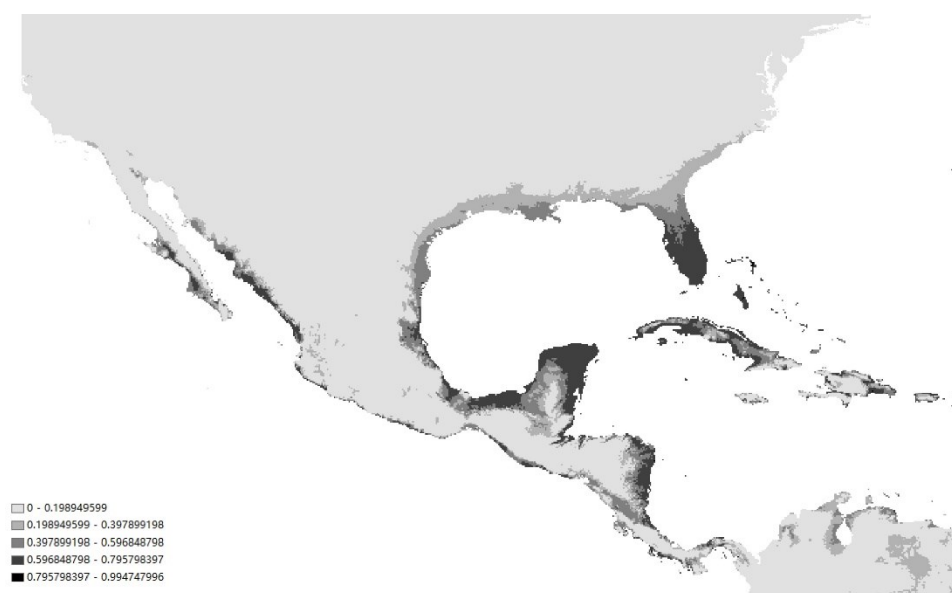


Figure 5. Equal-interval Classification of Red Mangroves Suitability in North America

Figure 5 highlights regions of the eastern Gulf of California, the southern coast of Florida in the U.S., Yucatán, Tabasco, and Quintana Roo in Mexico, eastern Nicaragua, and western Cuba as 'highly suitable' and 'suitable' habitats for red mangroves in the near future. These results offer valuable guidance for future conservation efforts, helping policymakers prioritize these regions for in-situ conservation. Additionally, “moderately suitable” and “slightly suitable” areas, such as the northern Gulf of Mexico, could be targeted for habitat restoration to ensure the long-term survival of red mangroves under the pressure of climate change.

4.6. MaxEnt results and connection to previous studies

The results of this research corroborate findings from previous research on red mangrove habitat suitability, particularly regarding the significant influence of environmental variables such as minimal temperature of the coldest month (bio6) and elevation. These variables have consistently been identified as key limiting factors in the distribution of red mangroves in this research [14]. This research further supports the theory that climate change may drive a poleward shift in mangrove populations, as indicated by the lower suitability of habitats in higher latitudes. For instance, the range limitations observed between 26°48' N to 30°18' N in regions like California and Mexico are closely tied to rising temperatures [21], affirming the role of temperature in mangrove migration. Moreover, recent research on the epigenetic patterns of mangrove species offers a promising avenue for understanding how genetic diversity may influence red mangrove adaptability to changing environmental conditions [22]. Future studies could integrate epigenetic data with environmental models to further enhance predictions of habitat suitability and inform conservation strategies.

5. Conclusion

In conclusion, this research applies the MaxEnt model, alongside bioclimatic and geographical data, to predict the suitable habitats for red mangroves (*Rhizophora mangle*) in North America, filling the gaps left by previous studies. The high AUC values (>0.90) confirm the model's reliability in identifying these areas. This research also highlights the critical environmental factors contributing to the distribution of red mangroves through the jackknife method, highlighting isothermality, minimal temperature of coldest month, precipitation of warmest month, and elevation. “Highly suitable” and “suitable” areas are located in the eastern Gulf of California, Florida, Mexico, Nicaragua, and Cuba. These regions are potential in-situ conservation areas in the 2040s. In North and Central Mexico, where

mountain ranges are present and altitude increases, 'moderately suitable' regions shift to 'slightly suitable' areas toward the interior. These lower-suitability regions at higher latitudes (northern Florida) or higher altitudes (Mexico) suggest that red mangrove habitats tend to shift to regions with cooler temperature ranges, which may be a result of accelerating global warming. Previous studies have pointed out that “mangrove species have proliferated at or near their poleward limits,” confirming that mangrove populations tend to migrate to higher latitudes and revealing the environmental stress that they face. It is essential to realize how the habitats of red mangroves shift corresponding to climate change as mangroves can only survive in the intertidal zones or salt marshes, signifying that the habitats of red mangroves are harsher and more significant risks can be brought once mangroves are enforced to migrate.

The limitations of this research lie in the selection of environmental variables. First, key environmental variables, such as sea salinity and average annual sea level, were not included in this research, which may undermine the model's accuracy. In addition, integrating oceanic and terrestrial data can create a buffer region in environmental raster that offers a more comprehensive and accurate view of mangrove habitat dynamics. Third, although isothermality (bio2) and Euclidean distance to the coast (eudis) contribute only a minor percentage to model construction, further investigation is required to determine their relevance before considering their exclusion from future SDMs. These variables may still provide critical information in different ecological contexts or when combined with other factors.

Future research should focus on refining species distribution models by incorporating additional variables, such as sea surface salinity and sea level, that can influence mangrove survival. Such improvements will enhance the accuracy of MaxEnt outcomes. Thus, subsequent studies can explore integrating epigenetic data to better comprehend how red mangroves evolve to adapt to climate change, which is beneficial for making more targeted conservational policies at both regional and global scales.

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