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Modelling mangrove dynamics in Mauritius: Implications for conservation and climate resilience

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A R T I C L E I N F O

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A B S T R A C T

Mangroves are vital ecosystems offering services such as coastal protection and carbon sequestration. However, climate change will substantially impact these ecosystems, especially on island states. Currently, there is a lack of detailed studies that predict changes in mangrove distribution under future climate scenarios and those that exist rarely address the unique vulnerabilities and challenges faced by island ecosystems. The present study aimed to fill in this gap by using MaxEnt to predict mangrove distribution at Le Morne, Mauritius, under two climate change scenarios (SSP126 and SSP245) across four time periods: 2021–2040, 2041–2060, 2061–2080 and 2081–2100. Key predictors used were LULC, temperature seasonality, DEM and slope. All AUC values were in the range of 0.89–0.9 indicating robust model performance. Results indicated mangrove inward migration constrained by existing land uses, potentially reducing ecosystem services such as carbon sequestration and biodiversity support. These findings are crucial for conservation efforts at Le Morne, a famous tourist site, where mangroves sustain local livelihoods. The study also supports SDGs 6, 8, 13 and 14 and the methodology can be scaled and replicated globally. Decision makers, researchers and relevant stakeholders can leverage these findings to guide proactive conservation strategies and effective planning efforts to increase climate change resilience.

1. Introduction

Climate change is one of the most pressing issues that the world is currently facing. According to the Intergovernmental Panel on Climate Change (IPCC, 2023), human induced global warming is already affecting many weather and climate extremes in every area of the world resulting in widespread adverse impacts on communities and nature. Coastal zones, home to billions of people (Broom, 2022), very often heavily laden with built infrastructure and providing a range of resources, are severely at risk (Sandifer and Scott, 2021). For many Small Island Developing States (SIDS) where the coastal zone is in fact the whole island, climate change impacts, especially those related to the ocean, could be devastating (UNDP, 2022). Jennerjahn et al. (Jennerjahn et al., 2021) further remark that tropical coastal zones are especially severely threatened by both climate change and human activities including sea level rise, shifting ocean currents, changing patterns of land and water use which collectively impact the ocean's environmental, economic and social functions Table 1.

One of the most important and diverse coastal ecosystems are mangrove forests which work closely with other marine ecosystems like coral reefs and seagrass beds to ensure the overall health of oceans and coasts. These unique ecosystems thrive in the global tropical and subtropical intertidal regions where local conditions are suitable and provide a range of benefits including coastal protection, shoreline stabilization, carbon capture, as pollutant sinks and directly support the livelihoods of millions of people as income from fishing, tourism and raw materials. However, their particular dynamic habitat between the land and the sea coincides with regions projected to experience some of the worst effects of climate change (Ellison, 2015; Friess et al., 2022) such as sea level rise, increased storminess, changes in ocean currents and rainfall pattern and increased temperature and carbon dioxide levels (Ward et al., 2016). Recent studies in fact highlight the urgency of

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Table 1
Predictors deemed suitable for climate change analysis on the mangroves at Le Morne; predictors in italics were the actual predictors used in the MaxEnt model.

S/N	Variable	Unit	Importance	Reference
1	monthly average minimum temperature	°C	Mangroves are sensitive to variations in temperature. Changes in temperature can result in thermal stress, reduced regeneration and growth and increased vulnerability to pests and diseases.	49,51
2	monthly average maximum temperature			
3	monthly total precipitation	mm	Precipitation plays a key role in mangrove growth, maintaining the hydrological balance of mangrove environments, flushing salts, and facilitating seed dispersal.	51,52
4	*Bioclimatic variables*	*°C/mm*	*Bioclimatic variables, derived from monthly temperature and rainfall values representing yearly trends in seasonality and extreme environmental factors, are important indicators that describe how climate affect ecosystems and are widely used in ecological modelling and climate change studies.*	*53*
5	Seawater salinity	psu	Salinity is an important factor that affects the growth, distribution, productivity and health of mangroves with moderate salinity (10–50 %) encouraging leaf growth, height, root length, total dry mass weight and leaf area.	33
6	Soil salinity	$cmol_c kg^{-1}$	Soil salinity directly influences mangrove distribution, physiological processes, productivity, seedling establishment and is critical to predict future mangrove distribution under changing climatic conditions.	54
7	Tidal average	m	Mangrove distribution is affected by a combination of tidal range and surface elevation which creates distinct inundation regimes influencing several abiotic factors that are needed for mangrove growth and development.	55
8	*LULC*	*9 types*	*LULC maps support mangrove management interventions as they help identify different land uses such as deforestation.*	*56*
9	*DEM*	*m*	*Mangrove zonation is closely associated to elevation above mean sea level and elevation values help make the distinction between mangroves and other vegetation.*	*57,58*
10	*Slope*	*degree*	*Slope of an area relative to the surrounding land and its proximity to water bodies together with elevation determine the frequency of flooding and salinity of any area.*	*57*
11	*Mangrove height*	*cm*	*Height generally indicates the overall health and productivity of mangroves such as taller mangroves correlating with favourable conditions for growth; this data can thus help identify potential areas conducive for mangrove survival and growth.*	*59*

understanding and mitigating these impacts. For example, the Global Mangrove Alliance's 'Mangrove Breakthrough' (IUCN, 2022) initiative emphasises the need for unified global action to restore and protect mangroves at a scale necessary to secure their future. Similarly, the World Wildlife Fund's 'Mangroves for Community and Climate' (Wwf, 2020) initiative aims to protect and restore millions of acres of mangroves, protecting local communities and safeguarding significant carbon stocks as part of the Bezos Earth Fund.

Climate change impacts on global mangroves will be different from place to place based on local geographical features, regional climate patterns and variations in local environmental conditions such that some forests may shrink, others may adapt and some even expand. For instance, Ghosh et al. (Ghosh et al., 2020) note an upstream migration of mangroves in India as a result of changing environmental conditions including sea level rise, Whitt et al. (Whitt et al., 2020) report that mangroves were encroaching into southern Australia's saltmarsh interior along creeks due to rising temperatures and Gholami and Jaafari (Gholami and Jaafari, 2020) state that there was a landward decrease in mangrove cover in Iran post 1998 due to long term droughts. These examples illustrate the regional variability of mangrove dynamics in the tropics under environmental stressors such as warming temperatures, prolonged droughts and sea level rise. While the effects of climate change on mangroves have typically been considered of secondary importance compared to more severe issues like deforestation (Alongi, 2008), massive mangrove death in Australia during the period 2015–16 suggest that climate change risks for mangroves may have been underestimated (IPCC, 2023). As a result, climate change risks in relation to mangroves are now projected to be moderate if the global temperature reaches 1.3 °C above pre-industrial levels (IPCC, 2023). The above mentioned case studies thereby inform the present analysis by providing a framework to explore the potential climate-induced shifts in mangrove ecosystems in Mauritius, tailored to their unique regional characteristics.

In this respect, species distribution models (SDMs) have become an important tool to understand the relationship between species and their environment, map their potential geographic distribution and are today widely used to predict changes in species distribution under different climate change scenarios (Santini et al., 2021; Samal et al., 2023). Species distribution modelling is a methodology based on ecological and biogeographical concepts about the relationship between species distribution and the physical environment; SDMs are typically developed using species location data and variables believed to influence species distributions (Elith et al., 2024). In climate change forecasting studies using SDMs, models are trained using current data to predict the likelihood of species potential distribution under present and future conditions (Santini et al., 2021). Several SDM techniques have been used to assess climate change impacts on mangroves such as Maximum Entropy Models (MaxEnt) (Wang et al., 2022), Generalized Linear Models (GLM) (Guo et al., 2013; Cavanaugh et al., 2015), Generalized Additive Models (GAM) (Quisthoudt et al., 2013), Artificial Neural Networks (ANN) (Ahmad et al., 2024) and ensemble models using several algorithms from the sdm package in R software such as MaxEnt and GLM (Samal et al., 2023; Quisthoudt et al., 2013). While the choice of model for climate change forecasting depends on several factors such as data availability, computational resources and technical capacity, MaxEnt has been recommended as a robust model that can handle complex ecological relationships using presence-only data (Phillips et al., 2006; Phillips & AT&T Research, 2021).

Despite mangroves' importance in SIDS and high vulnerability to climate change impacts (Veitayaki et al., 2017) research and information on future climate suitability of mangroves is limited even more so using SDMs. There remains a gap in localised studies that predict how specific mangrove species such as *Rhizophora mucronata* in Mauritius, will respond to various climate scenarios. Addressing this gap is crucial for developing targeted conservation strategies and informing policymakers on how to enhance the resilience of these ecosystems and the communities that rely on them. To address these research gaps, the aim of this study was to assess the potential impacts of climate change on a mangrove forest in Mauritius using MaxEnt. This was chosen for its strong performance with presence-only data thus making it ideal for ecological studies where absence data is limited (Phillips et al., 2006). It also has the ability to model complex relationships between environmental variables and species presence with visualisation and evaluation tools thereby ensuring robust and interpretable outputs for conservation planning under changing climate scenarios (Elith and Franklin, 2013). Thus, using presence-only data, the study modelled the current and future habitat suitability of *Rhizophora Mucronata* at Le Morne from 2021 to 2100 based on SSP126 and SSP245, examines the factors that drive such change and discuss the implications of resulting change. The present study is highly innovative in the context of Mauritius as it is believed to be the first assessment of mangroves' response to climate change impacts using a Maximum Entropy Model which incorporates multiple environmental variables and addresses local specificities which are often overlooked in larger-scale models. The study's results will therefore provide key information to inform tailored management and conservation strategies in Mauritius which can be adapted to regions of similar ecosystems and provides evidence-based information to policy makers aimed at mitigating climate change impacts on coastal ecosystems.

2. Methodology

2.1. Case study area

Mauritius, centred on coordinates 20°15′ S and 57°35′ E, is a Small Island Developing State (SIDS) found in the south-west Indian Ocean around 900 km off the east coast of Madagascar. Mauritius island covers a land surface area of 1865 km^2 consisting mainly of a central flat zone and several peaks with highest elevation of 828 m and has an Exclusive Economic Zone (EEZ) of 2.3 million km^2 of which 400,000 km^2 is jointly managed with Seychelles. The coastline of Mauritius extends for 322 km, mainly bordered by fringing reefs except near river mouths, estuaries and the southern part of the island. As of December 2023, Mauritius had a population of 1.3 million people and is today known as an economic success in Sub-Saharan Africa having moved from a sugarcane based low-income country to an upper-middle-income country rooted in a diversified economy composed of tourism, manufacturing, fisheries, ICT and financial services.

Mauritius was chosen as the case study as it is characterized by a narrow coastal zone highly exposed to coastal threats such as storm surges, sea level rise and coastal erosion. It also forms part of the Western Indian Ocean global biodiversity hotspot making mangrove ecosystems ecologically significant. Mangrove ecosystems are also vital for the livelihoods of thousands of coastal populations by providing a wide range of ecosystem services, especially in supporting local fisheries and ensuring food security. Coastal ecosystems including mangrove forests are integral to the island's tourism industry, which contributes significantly to the economy. Currently, a large proportion of the population resides along the coast, increasing the dependency on and pressure on coastal resources like mangroves. In the last decades, Mauritius has been facing rising temperatures, altered precipitation patterns and an increased frequency of extreme weather events such as cyclones directly affecting coastal populations. Mauritius has made significant strides in coastal zone management and conservation policies making it a suitable case study for understanding the integration of mangrove conservation into climate adaptation strategies.

2.2. Climatic conditions in Mauritius

Mauritius experiences a mild tropical maritime climate year round which is influenced by several weather systems. South East Trade Winds blow over the island for the large part of the year due a sub-tropical high-pressure belt to the south of Mauritius. Summer in Mauritius, which is also the rainy season, lasts from November to March and winter, which is cool and dry, is from June to October.

The InterTropical Convergence Zone (ITCZ), which is based on the latitude of maximum insolation, influences climatic conditions in tropical regions. Every year, the ITCZ is driven northward during the northern hemisphere summer and southward during the southern hemisphere summer by the seasonal shift of the sun. Climate change in tropical areas is a result of the Earth's precessional cycle operating on an orbital timescale with a frequency band in the range of 19 and 23 ka. The African and Indian monsoon systems, further divided into the northern and southern hemisphere components, and driven by solar insolation, influence rainfall in the Western Indian Ocean. The southwest monsoon, including the Indian Summer Monsoon (ISM) and Asian Summer Monsoon (ASM), prevail during the boreal summer and the northeast monsoon prevails during the austral summer. The primary source of moisture for the southwest monsoon is the southern equatorial Indian Ocean as a result of cross-equatorial moisture transport. Since Mauritius is found in the southern equatorial Indian Ocean, it is affected by both ISM and ASM systems. Mean rainfall precipitation thus ranges from 800 mm on the west coast to 1200 mm on the east coast and exceeding 4000 mm on the central plateau. Warm, low salinity Pacific water brought along the Indonesian flow also feeds the western equatorial Indian Ocean through the westbound south equatorial current of the Indo-Pacific warm pool. The Indian Ocean Dipole (IOD) is another crucial climate driver in the region that causes anomalous sea surface temperature variability thereby influencing regional atmospheric circulation and precipitation. Extratropical cyclones are also common in the region with cyclones originating in the mid-latitudes of the southern Indian Ocean and travelling south-eastwards followed by anticyclones that travel towards the north of Mauritius during summer.

Two species of mangroves grow in Mauritius namely *Rhizophora mucronata* Lam. and *Bruguiera gymnorrhiza* (L.) Lam. of which *Rhizophora* is the dominant species forming almost pure stands. In the past, some 2000 ha of mangroves used to cover most of the island's coastline, but due to several anthropogenic activities such as coastal development, and acts of vandalism, as of 2022, 181 ha of mangroves remain (Reef Conservation, 2022). Mangroves typically grow in estuaries and sheltered lagoons occurring in thin belts as the land topography does not allow for adequate tidal flooding while the tidal range of 0.5 m itself is low.

2.3. Field surveys

Field surveys were conducted at the selected site, Le Morne in Mauritius, to collect mangrove presence points to train and test the model (Fig. 2). Mangroves in Mauritius typically occur in very small patches that effective modelling is not feasible; Le Morne however is one of the largest mangrove forest of Mauritius and is easily accessible. Active afforestation has been ongoing at the site for decades making it an excellent case study due to long-term commitment to ecological restoration and the potential insights into the effectiveness and impact of

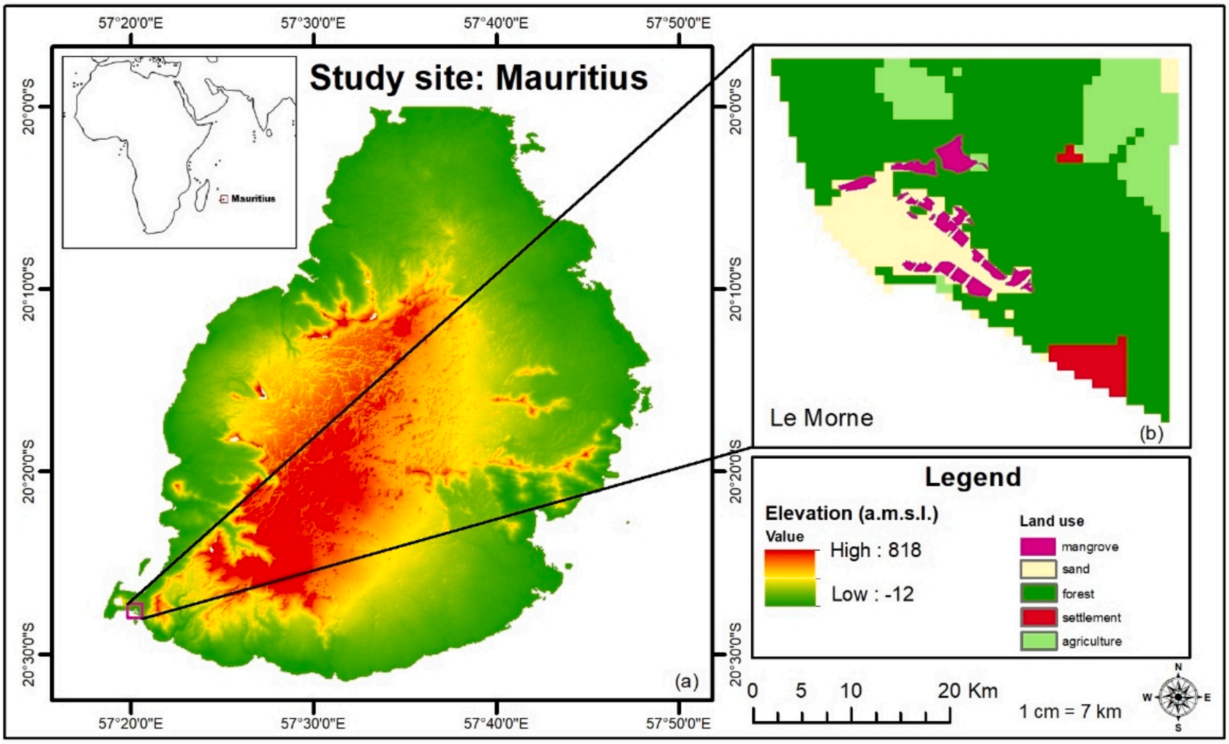

Fig. 1. (a) Study site Mauritius island in relation to Africa (b) Selected area for the assessment, Le Morne, as LULC (Land Use Land Cover) map and distribution of mangroves.

these activities. Le Morne, positioned on coordinates 20°27′ S and 57°20′ E, is a 5 ha mangrove area found in the south of the island. It is dominated by *R.mucronata* which grows in sandy saline shores and flooded by mean high tides of 0.6–0.75 m and mean low tides of 0.2–0.4 m. The average amount of rainfall recorded is around 726 mm, highest mean temperature is 28 °C (January to March) and lowest mean temperature is 22 °C. Salinity typically ranges from 32 to 37 psu, decreasing during the rainy season.

The site was surveyed on 05 May 2024 and Google Earth Pro imagery was used as baseline map to create a transect to capture GPS coordinates using the mobile application GPS Waypoints version 3.10 with an accuracy level of 5 m. In this way, 101 GPS points were collected at Le Morne. Next, mangrove tree heights were measured manually using a marked pole. 10 m x 10 m quadrats were set up using the baseline Google Earth pro image and trees were measured randomly in each quadrat. The data was then interpolated using the IDW (Inverse Distance Weighted) interpolation technique in ArcGIS Desktop (ESRI, Redlands, California) version 10.6 to estimate mangrove heights at the site.

2.4. Environmental variables

To build SDMs, environmental variables believed to influence species distributions are used (Phillips et al., 2006). Hence to assess the potential impacts of climate change on the distribution of mangroves at the site, 29 environmental variables considered to influence mangrove coverage at Le Morne were used as listed below. Future climate data were retrieved from WorldClim at a spatial resolution of 30 s ($\sim$ 1 km^2) for two Shared Socio-economic Pathways (SSPs) namely SSP126 and SSP245 for the periods 2021–2040, 2041–2060, 2061–2080 and 2081–2100. According to Vargas Zeppetello et al. (Vargas Zeppetello et al., 2022), global mean temperature could increase by 3.0 °C in 2100 leading to disastrous conditions for nations in the tropics and subtropics. An increase to 3.0 °C was thus deemed suitable for the study as SSP1-2.6 represents a temperature rise of 0.40—2.05 °C and SSP2-4.5 a rise of 1.27–3.00 °C by the end of the 21st century (2081–2100) compared to the 1995–2014 average (Tebaldi et al., 2021). Data was retrieved from the latest HadGEM3-GC31-LL climate model developed by the UK Met Office as part of the Hadley Centre Global Environment Model (HadGEM) series as it has contributed in understanding how climate change might affect the Indian Ocean e.g. Met Office Hadley Centre (Met Office Hadley Centre, 2019); Long and Li (Long and Li, 2021); Katzenberger et al. (Katzenberger et al., 2021).

Climate variables used were monthly average minimum temperature and maximum temperature, monthly total precipitation and 19 bioclimatic variables. Since seawater salinity is one of the most important factors that influence mangrove growth (Ball, 2002), seawater salinity data was extracted from the EU Copernicus Marine Service Information at spatial resolution of $\sim$ 30 km^2. Soil salinity also affects microbial community compositions in mangrove soils which can influence tree development and soil productivity (Van Tang et al., 2020). Soil salinity data was retrieved from the International Soil Reference and Information Centre (ISRIC) with spatial resolution of $\sim$ 1 km^2 (Batjes, 2016). As wetland vegetation, tides play a critical role in mangrove development and growth (Adame and Lovelock, 2011) so average tidal data was also retrieved from the Global Marine Environment Dataset (Basher et al., 2014).

A 2023 land use land cover (LULC) map at 10 m resolution was retrieved from ESRI's ArcGIS Living Atlas (Esri Land Cover - ArcGIS Living Atlas, 2023). A 30 m resolution Digital Elevation Model (DEM) was retrieved from USGS Earth Explorer (USGS Earth Explorer, 2014) and slope was calculated using ArcGIS. All environmental datasets were then resampled to a 10 m pixel size, projected into the same Geographic Coordinate System WGS 1984 (which is convenient to produce prediction maps) and converted into ASCII format to run the model as required by MaxEnt (Phillips et al., 2006). While MaxEnt uses machine learning techniques and is relatively unaffected by collinearity among factors (Elith et al., 2011), Merow et al. (Merow et al., 2013) emphasize the importance of careful selection and pre-processing of predictor variables if the study aims to predict the future potential distribution of species based on environmental variables. In this respect, a multi-collinearity

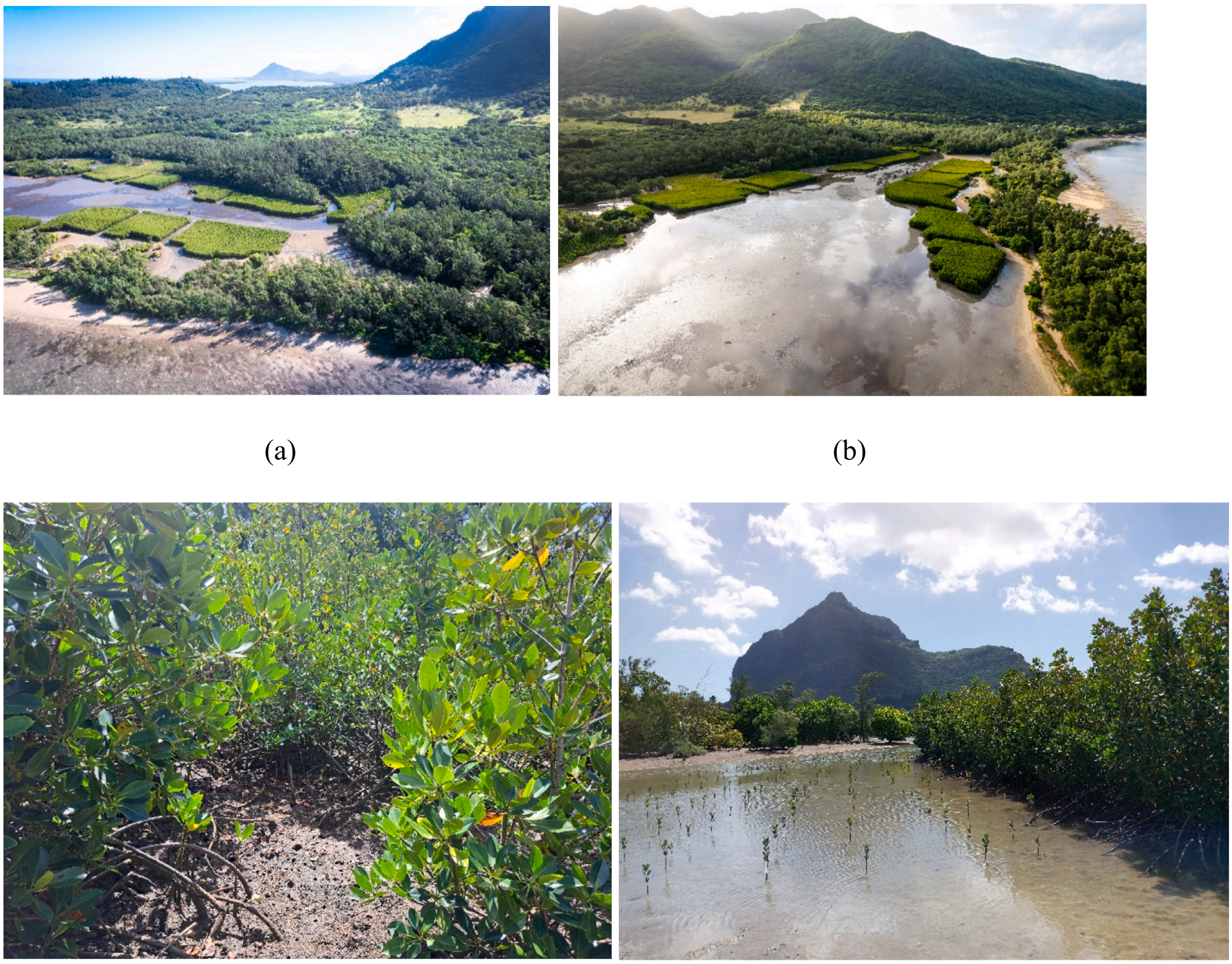

Fig. 2. (a). Aerial image of the mangrove forest at Le Morne highlighting the ecosystem nestled along the coastline (b). Aerial image of the mangrove forest from the seaward perspective and backdrop of current land uses (c). Young adults of *R.mucronata* capturing the intricate network of roots and lush greenery (d). Seedlings of *R. mucronata* growing alongside young adult trees. (Source: Main Author, R.S.).

test was conducted in SPSS (version 25) using the VIF and variables with values less than 10 were retained.

2.5. MaxEnt modelling

MaxEnt is a widely used standalone Java application that was designed for species distribution modelling (Phillips and Dudík, 2008; Phillips et al., 2017) and has demonstrated stronger performance compared to other species distribution models (Phillips et al., 2006; Phillips and Dudík, 2008). MaxEnt estimates a species potential distribution by identifying the distribution with maximum entropy that is closest to a uniform distribution, while adhering to environmental constraints at the recorded occurrence points (Elith et al., 2006). For this study, MaxEnt version 3.4.3 was used (Phillips et al., 2024). A number of runs was conducted with varying features for model evaluation until the top performing model was identified. The data was split into a 70 % training and 30 % for testing the model; the regularization multiplier was set to 1, maximum number of background points to 1000 and replication to 10 as subsamples and iterations to 500.

Model accuracy was measured using the AUC (Area under the Receiver Operating Characteristic Curve or ROC) which is a robust measure to assess the performance of score classifiers as its calculation is based on the entire ROC curve, including all possible classification thresholds (Melo et al., 2013). While there are different guidelines to interpret measures of agreement between observed and predicted values (Araujo et al., 2005), Swets (Swets, 1988) suggests interpreting AUC values as $AUC > 0.90$ excellent, $0.80 > AUC < 0.90$ good, $0.70 > AUC < 0.80$ fair, $0.60 > AUC < 0.70$ poor and $0.50 > AUC < 0.6$ failed.

3. Results

The results section presents the key findings of the study, focusing on the environmental contributions of environmental variables to mangrove distribution in Mauritius and the projected suitability patterns under different climate scenarios. The present section provides an overview of how the selected predictors influence mangrove habitats and highlights the spatial and temporal changes observed across scenarios. These results form the basis for understanding the ecological responses of mangroves to climate change in the context of the island of Mauritius which are further analysed and interpreted in the discussion section.

The results of the collinearity test are shown in Table 2.

From the table, it can be noted that out of 26 predictors, only four variables (BIO4 – temperature seasonality –, DEM, Slope and LULC) were included in the multicollinearity assessment while the rest was excluded due to singularity. Based on the R^2 value (0.694) of the model,

Table 2
Results of the multicollinearity test conducted in SPSS based on VIF.

Variable	Coefficient (B)	t-value	Significance	Collinearity Statistics	
				Tolerance	VIF
BIO4	−2.80	−0.34	0.74	0.81	1.23
DEM	−15.13	−3.90	0.00	0.32	3.10
Slope	20.36	1.63	0.13	0.32	3.12
LULC	−4.23	−0.73	0.48	0.84	1.20

the VIF for mangrove height, which was the independent variable in the analysis, was calculated yielding a VIF of 3.27. As the VIF values for these four predictors were all below 10, they, along with mangrove height, were included in all subsequent modeling exercises.

Fig. 3 illustrates the current prediction analysis of *R.mucronata* at Le Morne using these variables. The model effectively predicts the distribution of mangroves as reflected by the alignment between the high suitability areas on the map and the actual mangrove cover at the site. The ROC curve also confirms the model's strong performance, with a high AUC value of 0.89 thereby indicating accurate predictions.

Fig. 4 shows the future predicted distribution of mangroves at Le Morne, Mauritius, using MaxEnt models under two different climate scenarios (SSP126 and SSP245) across four time periods: 2021–2040, 2041–2060, 2061–2080, 2081–2100. Each panel represents the habitat suitability for mangroves categorized into low (blue), moderate (yellow) and high (red) suitability zones. For the period 2021–2040, in SSP126, there is a mix of low, moderate and high suitability areas, with high suitability areas concentrated near the current mangrove regions; a similar distribution can be observed under SSP245, but with slightly reduced high suitability areas compared to SSP126, indicating early signs on environmental stress. For the period 2041–2060, under SSP126, high suitability areas start to shrink slightly, with moderate suitability areas expanding; there is more pronounced reduction in high suitability areas and a significant increase in moderate suitability areas under SSP245, reflecting greater environmental changes. For the period 2061–2080, under SSP126, high suitability areas continue to shrink with further expansion of moderate suitability areas while under SSP245, high suitability areas are notably reduced with most areas now categorized as moderately suitable. For the period 2081–2100, under SSP126, high suitability areas become very limited, with moderate suitability dominating the region and very few high suitability areas remain under SSP245 with moderate suitability regions further expanding and low suitability areas becoming more prominent.

ROC curves for the future predicted MaxEnt models averaged over the replicate runs are shown in Fig. 5. AUC value for SSP126, 2021–2040 (a) was 0.89; SSP245, 2021–2040 (b) 0.89; SSP126 2041–2060 (c) 0.89; SSP245, 2041–2060 (d) 0.88; SSP126, 2061–2080 (e) 0.90; SSP245, 2061–2080 (f) 0.90; SSP126, 2081–2100 (g) 0.90 and SSP245, 2081–2100 (h) 0.89. Slight variations in the AUC values can be noted which reflect changes in model performance due to different emission scenarios and time periods. But in general, all the ROC curves consistently show high AUC values across all time periods and scenarios suggesting that the MaxEnt models have strong predictive power for mangrove distribution at Le Morne, Mauritius under changing climate conditions.

Table 3 shows the estimates of relative contributions of the environmental variables to the MaxEnt models. It can be observed that LULC significantly contributes to model performance across all time periods and scenarios, indicating that land use and land cover are crucial in determining mangrove distribution at Le Morne. Notably, under SSP245 in the 2021–2040 period, it has quite a high permutation importance of 52.7 % emphasizing its critical role in that scenario. BIO4 (temperature seasonality) has a consistent high contribution and permutation importance across all periods especially under SSP126 thus suggesting that temperature variations significantly influence mangrove suitability. DEM demonstrates substantial contribution and permutation importance thereby highlighting the importance of elevation in mangrove distribution. Height is also important in model performance but to a lesser extent compared to LULC, BIO4 and DEM; the contribution and permutation importance of height remains relatively stable across both scenarios and time periods. Slope shows the least contribution and

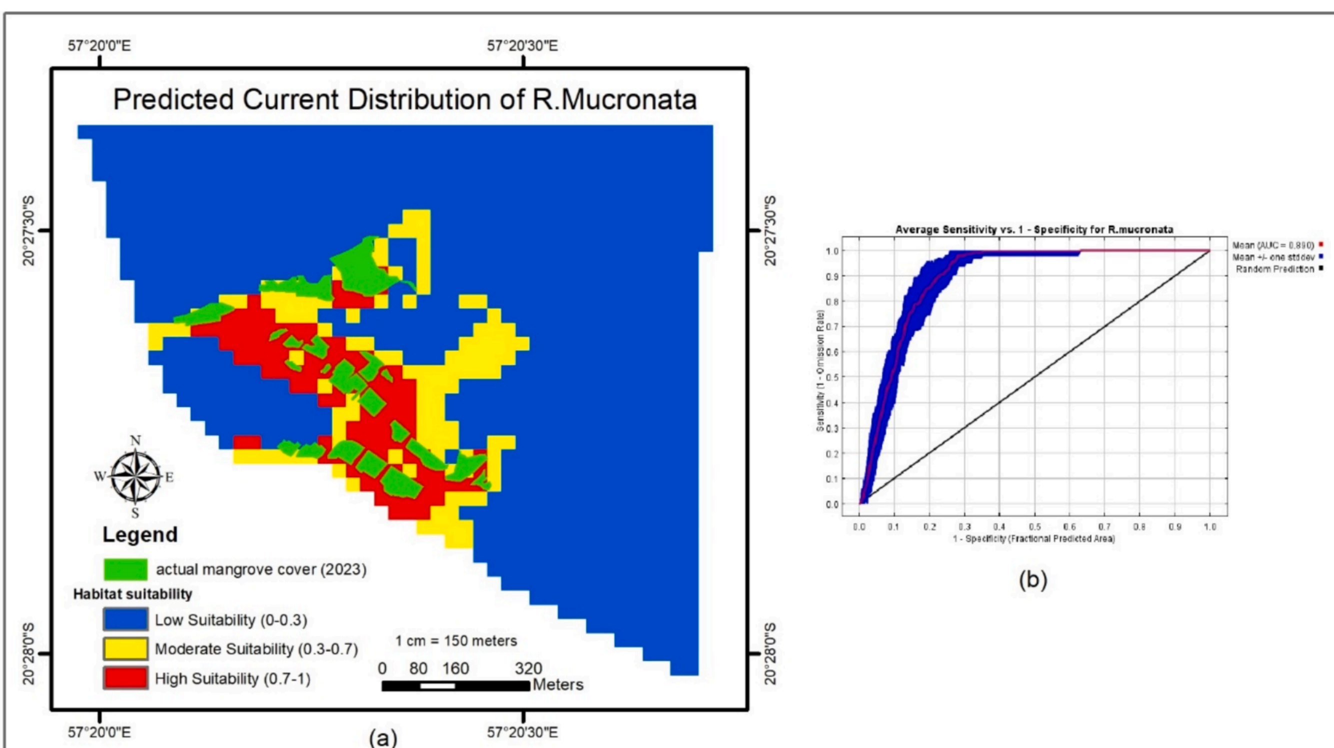

Fig. 3. (a) Predicted current distribution of *R.Mucronata* at Le Morne overlain with current mangrove stands (b) ROC plot of model with AUC value of 0.89.

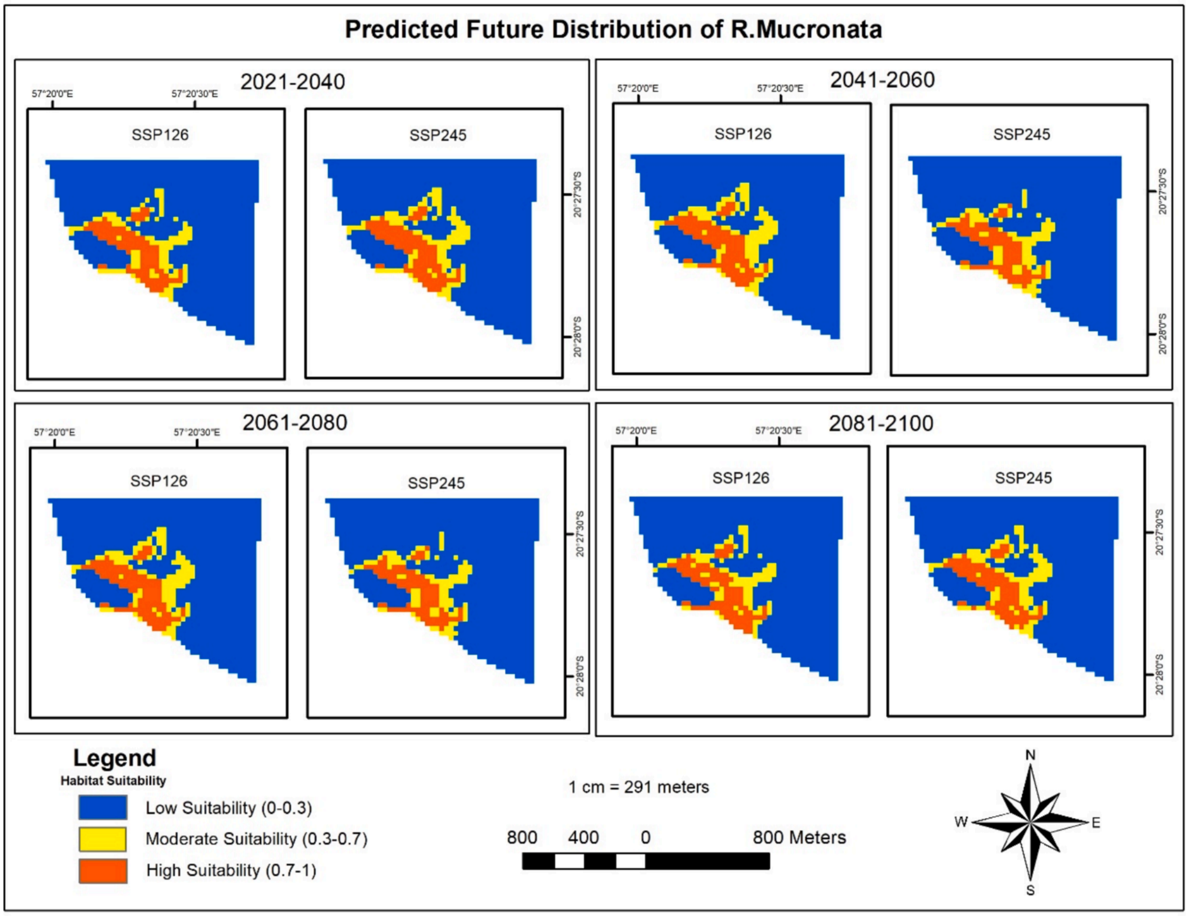

Fig. 4. Predicted future distribution of *R.Mucronata* at Le Morne under different climate change scenarios (SSP126, SSP245) for the period 2021–2040, 2041–2060, 2061–2080, 2081–2100; the habitat suitability are based on a range of 0 to 1, with 0 having the lowest suitability and 1 the highest.

permutation importance indicating that terrain steepness at Le Morne is less influential in predicting mangrove distribution compared to the other variables. In terms of climate change scenarios, it can be observed that under SSP126, variables like BIO4 and DEM play a more dominant role in model performance while under SSP245, LULC shows higher permutation importance suggesting that land use changes might have a more immediate and significant impact on mangrove distribution.

Fig. 6 shows the results of the Jackknife test of variable importance in the MaxEnt models, Jackknife test based on test gain only and Jackknife test using AUC on test data. It can be observed that under SSP126 and SSP245, for the period 2021–2040, LULC and BIO4 are the most significant variables; when used alone they show high gains indicating strong predictive power. When they are excluded, a notable drop in gain is observed, particularly in SSP245, thus showing their importance in the model. DEM also contributes significantly to the model and height and slope have lower importance. The patterns remain similar under both climate change scenarios for the period 2041–2060, with LULC and BIO4 being the top contributors, DEM slightly less important and height and slope maintain lower contributions. LULC and BIO4 still dominate under SSP126 and SSP245 for the period 2061–2080 but the difference between these variables and others slightly decreases; DEM's contribution is still consistent with previous periods while height and slope show minor fluctuations in their importance. For the period 2081–2100, under SSP126 and SSP245, LULC and BIO4 remain the most influential variables with slight variations in their contributions, DEM's importance remains steady showing it is a critical factor over time and height and slope continue to have lower importance compared to the other predictors.

4. Discussion

4.1. Evaluation of the MaxEnt models

From Figs. 4 and 5, it can be observed that all the MaxEnt models produced to evaluate climate change impacts on mangrove distribution at Le Morne under SSP126 and SSP245 for the periods 2021 to 2100 show high accuracy levels in the range of 90 % thus indicating a good model performance according to Swets (Swets, 1988). While initially 29 predictor variables were deemed appropriate to build the models, the collinearity test however revealed significant collinearity among the different predictors used. As mentioned above, Merow et al. (Merow et al., 2013) cautioned to pre-process predictor variables for future prediction studies with Dormann et al. (Dormann, 2013) stating that reducing collinearity is a key step in building SDMs so as to improve the accuracy and robustness of the models. This study also confirms these statements as several models were tested until the best fit model was achieved. It was noted that when using all the predictor variables (29 plus different combinations of predictors), model processing time was significantly prolonged and collinear values affected model coefficient estimates. However, using the four predictors only, all the models performed well (Table 3). It is believed that this high collinearity is likely due to the small sample area resulting in minimal variation in environmental conditions across the site (Dormann, 2013; Guisan, 2002).

In the present study, LULC and temperature seasonality were particularly influential in creating the MaxEnt models for predicting mangrove distribution at Le Morne. The contributions of these variables as highlighted in Table 3 showed the significant impact across different time periods and climate scenarios. The Jackknife plots (Fig. 6) further

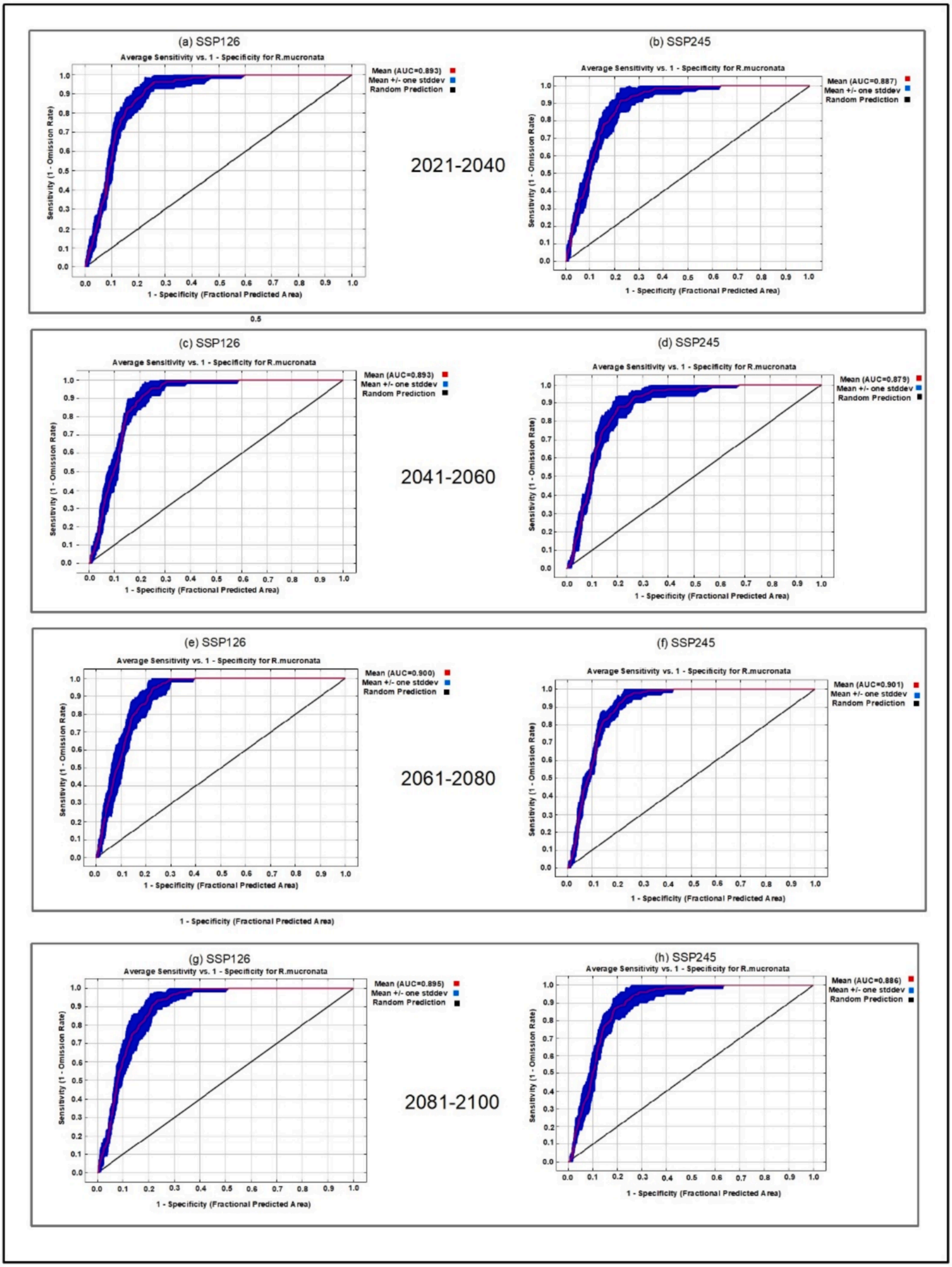

Fig. 5. Accuracy of MaxEnt models based on ROC.

Table 3
Contributions of estimates of relative contributions of the environmental variables to the MaxEnt models.

Variable	Percent contribution								Permutation importance							
	2021–2040		2041–2060		2061–2080		2081–2100		2021–2040		2041–2060		2061–2080		2081–2100	
	SSP126	SSP245	SSP126	SSP245	SSP126	SSP245	SSP126	SSP245	SSP126	SSP245	SSP126	SSP245	SSP126	SSP245	SSP126	SSP245
LULC	35.7	32.9	34.2	36.9	31.9	32.2	36.2	35.2	1.4	52.7	1.5	2.6	49	1.1	2.1	1.2
Bio4	28.8	32.7	33.6	29.9	31.5	31.3	30.6	29.1	56.2	1.5	55.2	57.5	0.4	43.7	54.5	42.7
DEM	20.9	20.4	18.9	18.7	20.5	20.4	17.6	19.1	24.6	29.9	23.9	22	31.1	36.4	24.7	40.9
Height	14	13.4	12.9	14.1	15.3	14.7	15.1	15.9	17.4	15.2	18	17	18.5	17.7	16.8	14.3
Slope	0.6	0.6	0.4	0.4	0.8	1.4	0.6	0.7	0.4	0.7	1.5	0.9	0.9	1.1	1.9	0.9

corroborate this finding by demonstrating that LULC and temperature seasonality were consistently the most critical variables in predicting mangrove distribution at Le Morne, Mauritius, across all modelled scenarios and time frames. As it is, mangrove distribution is not only affected by environmental conditions, but by different types of land use and cover as well (Wang et al., 2022; Krauss et al., 2014; Wang et al., 2021; Faruque et al., 2022). In fact, McIvor et al. (McIvor et al., 2013) state that land use changes are more likely to affect mangroves compared to climate induced changes. Mangroves can migrate landward provided there are no physical barriers such as infrastructure, buildings, seawalls etc. or steep topography (Mitra et al., 2013; Duncan et al., 2018). In the case of Le Morne, mangroves are bordered by terrestrial trees and infrastructure such as roads and amenities which restrict the natural migration and expansion of mangroves as reflected in the models. Temperature seasonality is another climatic factor that affects mangrove growth and distribution (Quisthoudt et al., 2012; Gilman et al., 2008). According to Inoue et al. (Inoue et al., 2022), mangroves need a particular temperature range to ensure that respiration rates are sufficient for maintenance and growth, especially in their roots. Increasing temperature at Le Morne under different climate change scenarios for the coming century could result in changes in mangrove physiology and hence distribution patterns (McIvor et al., 2013). DEM also played a significant role, but less important while height and slope were less influential but still contributed to the model. DEM typically determines the suitability of habitats for mangroves by influencing factors like salinity and water levels (Storlazzi et al., 2020). While less influential in model performance, height and slope still contributed to the overall model by affecting factors such as water drainage and sediment deposition (Krauss et al., 2014).

It is worth to note that the use of these four predictors (temperature seasonality, DEM, slope and LULC) only does not imply that mangroves at Le Morne are only influenced by these factors (Phillips et al., 2006); instead, it indicates that the values of these conditions significantly affect model performance. As a case in point, when Li et al. (Li et al., 2023) screened 29 variables to identify key environmental factors affecting mangrove suitability in the Beibu Gulf, China (coastline length of approximately 1628 km), 16 variables were selected for the analysis. In the context of this study (noting that Le Morne has a coastline of approximately 3.5 km), using the four predictors provided a balanced approach as these variables captured the key environmental gradients affecting mangrove distribution while minimizing collinearity thereby enhancing model performance. This is because the high collinear variables led to redundancy causing the model to overfit the training data but when the collinear variables were removed, the remaining predictors provided clearer insights into the factors that affect mangrove species distribution. As pointed out by Merow et al. (Merow et al., 2013), by reducing the number of collinear predictors, the model became more computationally efficient resulting in faster and more accurate predictions.

4.2. Spatio-temporal changes at Le Morne for the century

Key observations that can be made from Fig. 4 on the predicted future distribution of mangroves at Le Morne under SSP126 and SSP245 across the four selected time periods (2021–2040; 2041–2060; 2061–2080; 2081–2100) is that the overall low habitat suitability (blue) region is more extensive than the moderate (yellow) to high (red) suitability regions. The geographical region used in the baseline map to depict mangrove distribution was extended to cover a large part of non-mangrove area as the mangrove forest at Le Morne is very small (Fig. 3). This nonetheless showed how accurate the models were in identifying mangrove-only regions which is basically the moderate to high regions in the distribution maps while the blue regions are other land uses such as terrestrial trees and agriculture (Fig. 1). What can be noted is that mangrove suitability is restricted to the sandy regions (Figs. 1 and 3) and under changing climate scenarios cannot expand anymore due to the

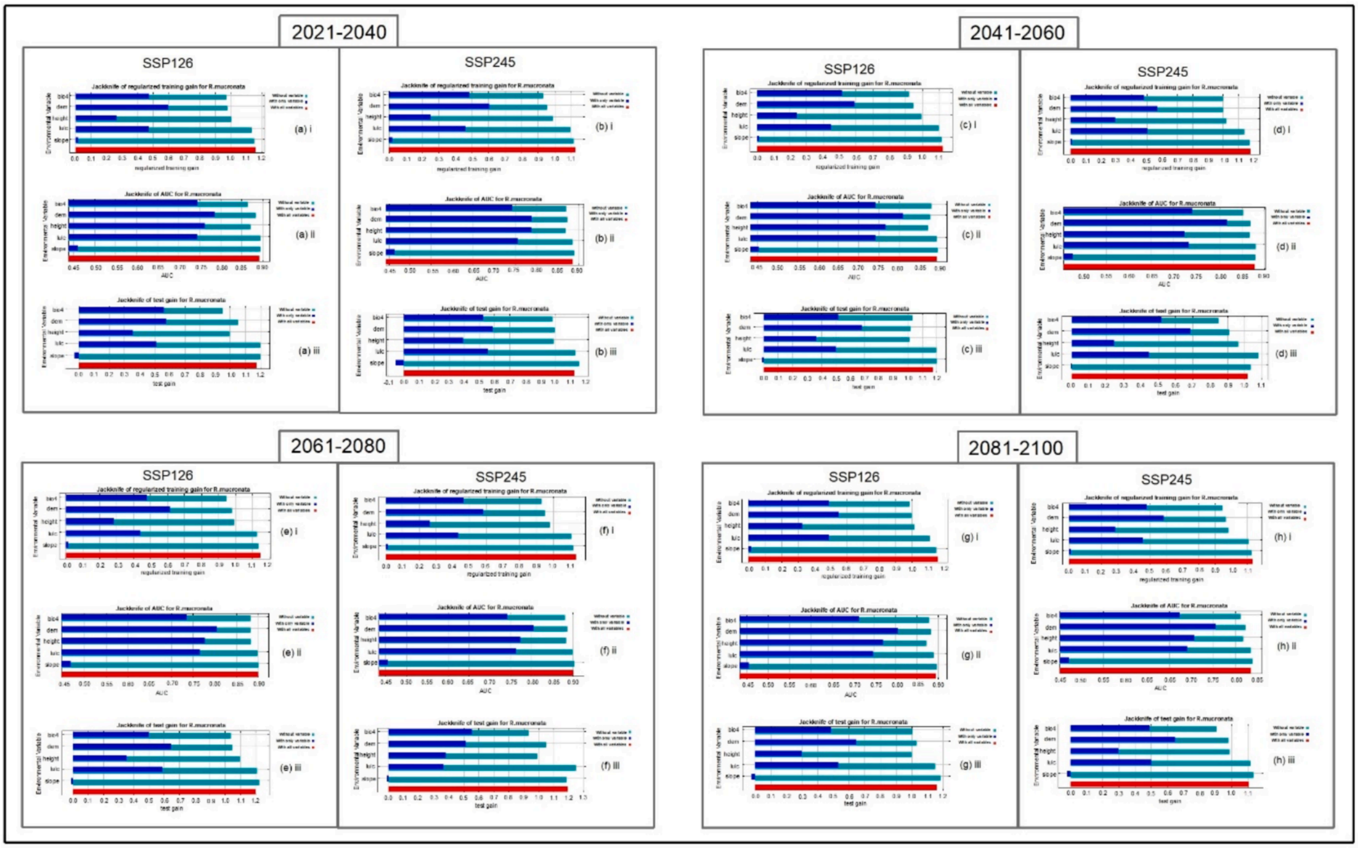

Fig. 6. Jackknife results of simulated models.

different land uses in the region which prevent mangroves from expanding inland. Other studies such as Li et al. (Li et al., 2023), Wang et al. (Wang et al., 2022) and Ellison (Ellison, 2000) have noticed similar trends of habitat restriction and mangrove expansion limitations during to surrounding land uses.

In terms of temporal changes, the time period 2021–2040 show a mix of moderate and high suitability areas. This can be attributed to a balance of conditions that favour mangrove growth at Le Morne with environmental factors, mainly temperature seasonality here, supporting both moderate and high suitability areas. Moderate suitability areas start to expand during the 2041–2060 period suggesting that as the climate continues to change, some regions previously identified as highly suitable may experience stress due to altered temperature increases. This results in an expansion of areas that are only moderately suitable as the environmental conditions become less optimal for high suitability. A noticeable increase in moderate suitability areas with high suitability regions slightly decreasing is observed for 2061–2080. It can be inferred that continued climate change exacerbates environmental stress thereby reducing the area that can sustain optimal conditions for mangrove growth. Moderate suitability areas increase as they can still support mangroves, albeit not in optimal conditions, while high suitability regions shrink due to unfavourable changes. Moderate suitability areas further expand for 2081–2100 with high suitability regions remaining limited. This suggests that more regions become moderately suitable for mangroves due to persistent climate change while high suitability regions remain limited as existing land use (e.g. forests, agriculture) and geomorphological constraints prevent further inward expansion of optimal mangrove habitats. These changes reflect the interplay between climate dynamics, environmental stress and physical land constraints at Le Morne.

4.3. Analysis of the SSPs at Le Morne, Mauritius

The MaxEnt models suggest that under both SSP126 and SSP245 scenarios, the overall habitat suitability of *R.mucronata* in Le Morne will shift, with moderate suitability areas expanding at the expense of high suitability areas over the next century. The differences observed in mangrove suitability between SSP126 and SSP245 scenarios can be attributed to varying levels of greenhouse gas emissions and their associated impacts on climate factors. Under SSP 126 (low emissions scenario), a gradual increase in moderate suitability occurs due to lower emissions that lead to more gradual and less severe changes in temperature. Lower emissions basically result in smaller increases in temperature thus favouring mangrove distribution. These conditions allow for a moderate expansion of suitability areas for mangroves while the retention of high suitability areas is facilitated by the relatively stable environmental conditions, which are less extreme compared to higher emission scenarios. Studies in fact show that under lower emission scenarios, ecosystems have more time to adapt to gradual changes, retaining more high suitability areas (Alongi, 2022). Under SSP245 (medium emissions scenario), moderate emissions result in more pronounced climate impacts particularly higher temperatures. This increase in temperature creates heat stress conditions in mangroves that reduce the extent of high suitability areas while expanding moderate suitability areas (Alongi, 2022; Cobacho et al., 2024). Wang et al. (Wang et al., 2022) also used MaxEnt to model mangrove distribution in China under similar climate scenarios (SSP126 and SSP245); their study showed a similar trend where lower emissions result in gradual shifts in habitat suitability and higher emissions result in more pronounced changes and stress on the ecosystems. Similar observations have been made by Zeng et al. (Zeng et al., 2024) and Hu et al. (Hu et al., 2020). The findings of the current study concur with other studies on the inward migration of mangroves in response to climate change such as Samal et al. (Samal et al., 2023) along coastal India, Ellison (Ellison, 2000) in the South Pacific, Di Nitto et al. (Di Nitto et al., 2014) in Gazi Bay, Kenya, Galeano et al. (Galeano et al., 2017) in the Colombian Caribbean and Cinco-Castro et al. (Cinco-Castro and Herrera-Silveira, 2020) in the Yucatan Peninsula.

4.4. Influence of local climate factors on mangroves in Mauritius

The present study demonstrates that when modelling mangrove distribution under different climate change scenarios, significant shifts driven by temperature and land use, can be observed. However, under real life conditions, several climatic factors in fact would work together to influence mangrove shifts in Mauritius. The ability of mangroves to adapt to rising sea levels would be one such critical factor for their survival (Gilman et al., 2008). As seen in regions such as the Pacific coast of Mexico and Micronesia, sea level rise can induce inward migration of mangroves but local geomorphology and human development can obstruct this shift leading to potential habitat loss in some regions and expansion in others (Ward et al., 2016). Additionally, variations in rainfall, influenced by shifts in the ITCZ and monsoon systems in the region, could affect mangrove health and growth. Altered precipitation patterns could change freshwater input into mangrove systems, affecting local salinity regimes, sediment supply and competitive interactions of mangroves with other ecosystems such as coral refs (Cobacho et al., 2024; McKee, 2004) thereby stressing mangroves leading to shifts in suitable habitat areas. Enhanced frequency and intensity of cyclones, driven particularly by the Indian Ocean Dipole and extratropical cyclones, could also physically damage mangrove forests and alter sediment deposition patterns (McKee, 2004; Goldberg et al., 2020). While mangroves play a crucial role in buffering against storm surges, repeated exposure to severe weather conditions could hinder their recovery and result in long term shifts in their distribution. This could lead to both immediate damage and long term changes in habitat suitability. Changes in wave patterns as a result in shifts in wind systems and ocean currents, together with alterations in salinity due to varying rainfall and sea levels, could significantly affect mangrove stability as well (McKee, 2004). The combination of these factors could influence the overall suitability of habitats for mangroves, leading to dynamic changes over time. All these highlight the complex interplay of climatic factors that could affect mangrove ecosystems in Mauritius.

4.5. Mitigating climate change impacts on mangroves at Le Morne

Le Morne, Mauritius, is a well-known tourist site where several activities take place such as beach activities, water sports like kite surfing and snorkelling, boat tours and dolphin watching, hiking and mountain climbing at the UNESCO World Heritage Site Le Morne Mountain and artisanal fishing and crab catching. The different activities that occur at Le Morne, potential impacts of mangrove migration on these activities and mitigation measures are listed in Table 4.

Mangrove propagation and plantation have been ongoing at Le Morne since 1995 under the Ministry of Fisheries as a means to restore denuded areas. Since 2008, the NGO ADD (Association Pour Le Développement Durable) has been actively involved in mangrove afforestation there as part of broader initiatives funded by the European Union, and the Mauritius Commercial Bank Forward Foundation. Following the MV Wakashio Oil Spill off the south-east coast of Mauritius in 2020, the SOS Mangrove Project under the MOL (Mitsui O.S.K Lines) adopted a community approach to restore mangroves at Le Morne. Undoubtedly, all the projects have led to increased mangrove cover at Le Morne helping to mitigate coastal erosion and provide habitat for marine life (McLeod and Salm, 2006; The Nature Conservancy, 2014; Mangrove Alliance, 2023).

The findings in the present study indicate varying degrees of resilience among mangroves to climate change. The ongoing restoration works at Le Morne have the potential to significantly enhance this resilience by increasing mangrove coverage (Sunkur et al., 2024), improving root networks and enhancing the overall health of mangrove ecosystems, thereby boosting their capacity to withstand environmental stressors such as rising sea levels, storm surges and temperature fluctuations. At the same time, the inward migration of mangroves highlights the need for preserving migration pathways, which is now constrained by physical barriers, to ensure continued natural regeneration. Thus it is critical to include adaptive management techniques which consider climate change impacts to ensure the long term success of restoration projects (Sunkur et al., 2023). Similarly, educating communities on climate change impacts on the mangroves can foster greater involvement in conservation efforts. These strategies can therefore facilitate the resilience of mangroves at Le Morne in the face of climate change. Effective conservation strategies will not only protect mangroves but also sustain the myriad of ecological, social and economic benefits they provide to the coastal community and country at large.

On a broader scale, by integrating climate change strategies into

Table 4
Activities that take place at Le Morne, Mauritius, potential impacts of mangrove migration on these activities, proposed mitigation measures and references.

Activities	Potential impacts of mangrove migration	Mitigation measures	References
Beach activities – popular spot for swimming and sunbathing by both locals and tourists	Beach erosion and alteration as mangroves move inward thereby affecting beach-based recreational activities	Implement beach nourishment and restoration projects; create buffer zones for mangrove migration	81,82,83
Water sports – renowned for its excellent kite surfing conditions due to large lagoon and strong winds	Changes in the dynamics of coastal waters through altered wave patterns and underwater ecosystems thus affecting water sports	Monitor and adapt water sports activities to changing conditions; maintain clear zones for recreation	84
Boat tours – offer opportunities to explore the area including the world famous underwater waterfall illusion and dolphins in their natural habitat	Altered navigational routes and potential changes in marine biodiversity due to mangrove expansion	Adjust boat tours to ensure safe navigation	84
Le Morne Brabant Cultural Heritage Site – hiking and mountain climbing opportunities related to maroon slavery with informational plaques at the base of the mountain	Access to routes may become restricted and aesthetic value of the site may be affected	Develop alternative access routes; integrate mangrove conservation into cultural heritage management	83
Development infrastructure – roads and beach amenities surround the mangrove forest	Potential conflict with existing infrastructure restricting mangrove migration	Change land use planning and development strategies to accommodate migrating mangroves	18,81
Fishing and crab catching – traditional activities that support the livelihoods of local communities	Habitat shifts affecting both terrestrial and marine ecosystems which could affect local biodiversity including fish species	Support community based conservation and alternative livelihoods	81,82

mangrove restoration in Mauritius, it will not only increase coastal resilience and socio-economic wellbeing, but also support the island's adaptation and mitigation goals including the Paris Agreement on Climate Change (Government of Mauritius, 2022). These integrated approaches will ensure that Mauritius is better equipped to handle the adverse impacts of climate change while contributing to the global Sustainable Development Goals (SDGs) including SDG 13 (Climate Action) which underscores the importance of integrating climate change measures into adaptive management strategies, SDG 14 (Life Below Water) and SDG 8 (Decent Work and Economic Growth) which promote the sustainable management and protection of marine and coastal ecosystems which is critical for sustaining fisheries and improving the livelihoods of local communities and SDG 6 (Clean Water and Sanitation) given that mangroves are important pollutant filters.

5. Limitations

A key limitation of the present study was the high collinearity among selected predictors limiting the model to only four variables. While the VIF analysis retained only variables with low collinearity to ensure the robustness of the model, this constraint could have oversimplified the analysis by excluding other important factors that influence mangrove distribution at Le Morne. Moreover, the model is based only on abiotic stressors and does not account for long-term ecological interactions such as those with terrestrial trees which could also influence mangroves' resilience to climate change. Nonetheless, this choice aligns with the study's emphasis on abiotic stressors as primary drivers under changing climate scenarios. The use of global datasets could have introduced the risk of inaccuracies in the models especially since mangrove patches in Mauritius are small and fragmented which also makes effective modeling challenging due to minimal environmental variation. This could result in persistent high collinearity and limited predictive reliability in Mauritius and in other regions with similar mangrove distributions. However, to address these challenges, all datasets were resampled to a standard resolution and validated against field observations to ensure accuracy and relevance to the study site.

6. Recommendations

Based on the current findings, future studies could consider the following recommendations to enhance their results. Local environmental data such as temperature, rainfall, salinity etc. could be used to improve prediction accuracy. The Mauritius Meteorological Services provide historical, current and future climate data for the whole of Mauritius and site specific but for a fee. Similarly, other global climate models can be used for prediction such as the Max Planck Institute Earth System Model (MPI-ESM), the Community Climate System Model (CCSM) or even the updated Coupled Model Intercomparison Project (CMIP6) models which have been widely used and shown promising performance for studying climate change impacts in the region. In this study, MaxEnt as the standalone java software was used for modelling together with ArcGIS, but future studies could use the MaxEnt package in R software which also allows for more statistical analyses of predictors before selecting the relevant predictors for modelling. Also, ensemble modelling approaches based on multiple modelling techniques such as MaxEnt, GLM and ANN can be used to build more robust models which can provide a more comprehensive understanding of mangrove response to climate change effects. While MaxEnt is an excellent presence-only model, by supplementing the model with absence data also, model accuracy can improve thus reducing prediction bias. Finally, since the size of mangroves is very small in Mauritius, the geographical baseline shapefile used to develop the models were based on the first author's expert judgement of probable distribution; for future studies, it is strongly recommended to thoroughly research past and present distribution of mangroves and adding a coastline data layer to accurately model mangrove distribution within its natural habitat.

7. Conclusion

The current study assessed the potential impacts of climate change on the mangroves at Le Morne, Mauritius using a presence-only species distribution model, MaxEnt under two climate change scenarios, SSP126 and SSP245 for the period 2021–2040, 2041–2060, 2061–2080 and 2081–2100. All models produced had high accuracy levels indicating reliable predictions regarding mangrove distribution under changing climate conditions. The study also demonstrated that MaxEnt modelling can be used for small areas. Out of 29 variables, only 4 predictors were used to create the models due to high collinearity among the variables; this streamlined approach however helped in accurately predicting mangrove distribution. LULC and temperature seasonality emerged as the key drivers in predicting mangrove distribution followed by DEM, height and slope. Under both SSP126 and SSP245 scenarios, the overall suitability of habitats of mangroves at Le Morne shifted over time, with moderate suitability areas expanding and high suitability areas shrinking. This trend was more pronounced under SSP245 scenario which represents greater environmental stress. Future mangrove distribution depends on several stressors influenced by local conditions. The potential future migration of mangroves at Le Morne could potentially affect the various local and tourist activities that occur there thereby necessitating adaptive management strategies to support their resilience and conservation.

The results underscore the urgency of integrating mangrove conservation into broader coastal management strategies, especially for island states that are highly vulnerable to climate-related impacts. The methodology and results have broader applicability and can be scaled to other island ecosystems globally, particularly those facing similar challenges from climate change. Mangroves are critical ecosystems that not only protect coastal populations against storm surges but also provide critical ecosystem services such as carbon sequestration and nursery habitats for biodiversity. Because of their critical ecological and socio-economic importance, mangrove conservation efforts should be focused on safeguarding existing habitats, promoting restoration initiatives as well as including mangrove ecosystems into broader climate adaptation frameworks. This includes addressing drivers of habitat loss, enhancing community engagement and adopting nature-based solutions to strengthen coastal resilience. Island nations like Mauritius can leverage mangroves as key assets in mitigating climate risks while supporting livelihoods and biodiversity by aligning conservation policies with the sustainable development goals.

CRediT authorship contribution statement

Reshma Sunkur: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Komali Kantamaneni:** Writing – review & editing, Supervision. **Chandradeo Bokhoree:** Writing – review & editing, Supervision. **Upaka Rathnayake:** Writing – review & editing, Visualization, Validation. **Michael Fernando:** Writing – review & editing, Validation.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

GPS coordinates of mangrove location points used in the present study can be made available upon request from the first author. All the software utilized in the assessment are detailed in the manuscript.

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