Assessment of the vulnerability of coastal mangrove ecosystems in Mozambique

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Assessment of the vulnerability of coastal mangrove ecosystems in Mozambique

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Abstract

Mangrove forests are among the most productive ecosystems on Earth. However, there is still insufficient information available for strategic prediction of conservation and management intervention, particularly in the case of Mozambique. This country has the longest coastline and mangrove forests of Eastern Africa, but is prone to global climate hazards. Using recent field data and environmental parameters subjected to the Variance Inflation Factor (VIF) collinearity test (bioclimatic variables, slop, salinity, land cover, and elevation), we ran MaxEnt to model the distribution of mangrove forests based on occurrence data of the most emblematic and representative mangrove species in Mozambique (*Avicennia marina* and *Rhizophora mucronata*). Moreover, in order to understand which areas should be prioritized for management interventions on mangroves and costal dunes, an Exposure Index (EI) to climate hazards and erosion was compared with the potential distribution of these species. Our results showed that average wind speed of summer season, land surface elevation, Mean Diurnal Range, and saltwater exposure (salinity) were determinant on the distribution models of both species. The central coastal region of Mozambique (so-called swamp coast) presents the largest potentially suitable areas for mangroves species occurrence, having the highest levels of exposure. We also found that *A. marina* presents a higher EI than *R. mucronata*. The scarcity of studies concerning the central region of Mozambique; which was recently devastated by cyclone Idai (category four, 2019), which hit Mozambique and the neighboring countries, reinforce the urgency for management intervention. The findings of this study should be used by managers and decision makers to promote best practices to safeguard lives and people's livelihoods and assets threatened by coastal climate hazards and anthropogenic impacts.

Keywords: Eastern Africa; mangrove trees; MaxEnt; Coastal habitats; Exposure Index

1. Introduction

Mangroves are highly productive carbon rich ecosystems as they receive nutrients from both sea and land, and local populations rely on them for fuelwood, construction material, medicine, food from mangrove fisheries, timber, and tannins (Aheto et al., 2016; Stephanie et al., 2018). They also play an important role in coastal protection against extreme tides, cyclones and storm water (Blankespoor et al., 2017). However, the global area of mangrove forests has declined by 30–50% over the past half century as a result of coastal development, aquaculture expansion and over-harvesting (Donato et al., 2011).

The Eastern African Region contains a remarkable diversity of coastal habitats, including sandy beaches, coastal dunes, coral reefs, estuaries, bays, seagrass meadows, and a huge mangrove-rich area (Hoguane, 2007). Within this region, Mozambique has one of the largest mangrove areas in Africa (with 3054 km^2), only second to that of Nigeria (8573 km^2) (Fatoyinbo and Simard, 2013; Simard et al., 2019a).

Mangrove forests exhibit pronounced zonation, which has been attributed to the species responses to factors such as hydrology (e.g. river discharge/flow accumulation), bioclimatic (e.g. temperature and precipitation), land surface elevation (inundation vulnerability), and soil geochemistry (e.g. salinity) of these ecosystems (Blankespoor et al., 2017). In Mozambique, the most frequently dominant mangrove tree species are *Avicennia marina* (Forssk.) Vierh. and *Rhizophora mucronata* Lam., but there are other common trees such as *Ceriops tagal* (Perr.) C.B.Rob., *Bruguiera gymnorhiza* (L.) Lam., *Lumnitzera racemosa* Willd., *Xylocarpus granatum* J.Koenig, *Heritiera littoralis* Aiton, and *Sonneratia alba* Sm. (Bandeira and Paula, 2014; Sitoe et al., 2014).

Mozambique coastal regions are particularly affected by natural phenomena such as cyclones and floods (Mavume et al., 2014; Macamo et al., 2016). In March 2019, the central region of Mozambique (Sofala province and surrounding areas), characterized by the most representative mangrove forests, was hit by a devastating tropical cyclone, the category four "Idai" (Devi, 2019), and few days later the northern provinces of Nampula and Cabo Delgado were also hit, by cyclone "Kenneth". These cyclones brought torrential rains, floods and high wind speeds, resulting in massive destruction of coastal regions, with very negative impacts on vegetation. The vulnerability of the central region of Mozambique was previously highlighted by Cabral et al. (2017) who estimated that Sofala and Zambézia provinces have a high exposure to coastal climate hazards and erosion through the calculation of an Exposure Index (EI). Exposure is defined by the United Nations International Strategy for Disaster Reduction (UNISDR, 2009) as "the situation of people, property, systems, or other elements present in hazard zones that are thereby subject to potential losses", whereas vulnerability can be described as the susceptibility of elements exposed to damaging effects when impacted by a hazard event or disaster (Cardona et al., 2012). However, the word vulnerability is used, in a broad sense, including the element's exposure (UNISDR, 2009).

Although with several limitations due to inaccuracy of sources and biases, species distribution models (SDMs) are widely used to estimate the geographical distribution of species, being key modeling tools in ecology (Guisan and Thuiller, 2005) and conservation (Kaky and Gilbert, 2016; Root and Schneider, 2006). SDMs have been used to predict species spatial distributions in Africa under current and future climatic conditions (e.g. Zimbabwe: Masocha et al., 2018; Burkina Faso: Schumann et al., 2016; and Cape Floristic Region in South Africa: Adu-acheampong et al., 2017). Although, several studies using distribution models were published about Mozambique fauna (e.g. Monadjem et al., 2010) very few studies used models to predict flora distributions in this country, which lacks well sampled local inventories for some areas and taxa. Moreover, the availability and quality of existing data, such as those found in public repositories (e.g. https://www.gbif.org/) are still insufficient to adequately feed such models.

The present study has two main goals. First, to update the inventory concerning *A. marina* and *R. mucronata*, the most emblematic and representative mangrove species in Mozambique, based on recent field surveys. Second, through MaxEnt (Phillips et al., 2017) to model the potential distribution of *A. marina* and *R. mucronata* as a *proxy* (indicators) of mangroves occurrence area, and an Exposure Index (EI) to climate hazards and erosion was combined with the output of the species distribution models, to better understand which areas should be prioritized for management interventions. Specifically, our goals were: (i) to identify the most important environmental variables affecting the mangroves distribution patterns; (ii) to predict the spatial distribution pattern and suitable areas for their development; (iii) to quantify *A. marina* and *R. mucronata* exposure to climate hazards and erosion (EI); and (iv) to provide new insights for the future management and conservation of coastal habitats, which are seriously threatened by a number of hazards, of both natural and anthropogenic origin.

2. Materials and Methods

2.1. Study area

Mozambique is located in the south-eastern coast of Africa between latitudes 10° 20'S to 26° 50'S and has an area of 800,000 km^2, with 11 provinces. It shares land borders with six countries: Tanzania, Malawi, Zambia, Zimbabwe, South Africa, and Swaziland (now called Kingdom of Eswatini). To the east, the country is bordered by the Indian Ocean, and the main coastal cities include Maputo (the capital and the largest city), Maxixe (Inhambane province), Beira (Sofala province), Quelimane (Zambezia province), Angoche and Nacala (both in Nampula province), and Pemba (Cabo Delgado province) (Cabral et al., 2017) (Fig. 1). The country is characterized by a tropical climate, with a wet summer season from November to March, and a cooler dry winter season from April to October (Barbosa et al., 2001; Hoguane, 2007). Mozambique comprises 11 main international rivers (the Zambezi and Limpopo being the largest) and about 104 river basins (Cabral et al., 2017) that are vital to valuable ecosystems, including mangroves. The Mozambique coastline extends for about 2770 km and hosts a variety of biodiversity-rich ecosystems. According to Macamo et al. (2016) the coastline is divided into three regions with different geomorphological characteristics: (i) coral coast, located in northern Mozambique (from Angoche northwards) and mostly dominated by shallow reefs forming hermatypic corals but with mangrove forests confined to sheltered bays and river estuaries; (ii) swampy coast or "so-called swampy coast", stretching from Bazaruto archipelago (southern province of Inhambane) to Angoche in the northern province of Nampula, and dominated by mud rich in organic matter. The swamp coast includes the Sofala Bank (the largest fishing ground in Eastern Africa), with the highest number of rivers (ca. 24) discharging into the Indian Ocean, and encompasses almost continuous mangroves from the Zambezi River to near Beira and then southwards to the estuary of the Save River (Inhambane); and (iii) cooler sand dune coast in the south, between Ponta do Ouro to Bazaruto archipelago, characterized by predominant sandy beaches and taller sand dunes, with mangroves in sheltered bays and estuaries such as Maputo Bay.

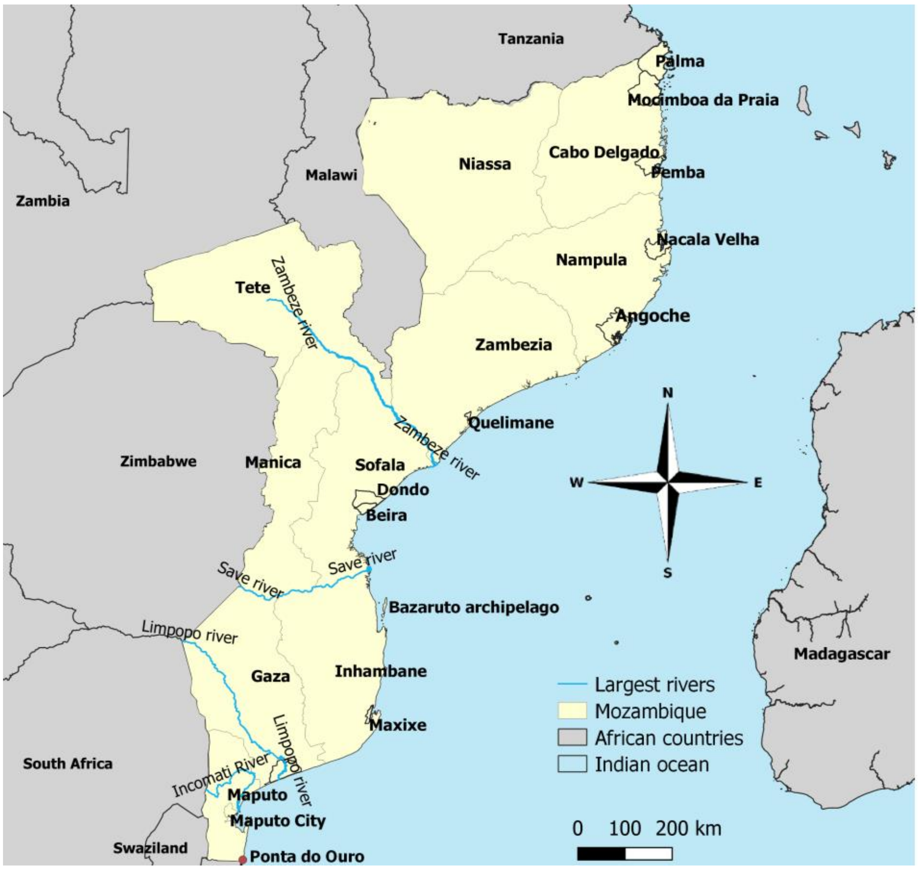

Figure 1. Map of Mozambique, showing the main rivers and coastal cities.

2.2. Species occurrence data

Our field data was collected in mangrove areas of the Sofala Province, from November 2018 to February 2019. This fieldwork was conducted in Nhangau, Casa Partida and Chiveve (Beira district) and in Mvisa and Fernando Óleo (Dondo district). We collected 58 occurrence records, including 24 of *A. marina* and 34 of *R. mucronata*. The geographical coordinates of the occurrence points were obtained using a high-sensitivity handheld Global Positioning System (GPS) receiver (GPS 72H, Garmin, Taiwan) with positional accuracy around 5 m. Field surveys led by the second author (S. Bandeira) in March 2016 in Nacala Velha (province of Nampula, north Mozambique) (29 occurrence records) and across all eight coastal provinces of the country (51 occurrence records) were also included in our database.

The field data was complemented with available information: (i) in GBIF (2018) (https://www.gbif.org/) (65 occurrence records); (ii) herbarium specimens housed by the Herbarium of the Instituto de Investigação Científica Tropical, University of Lisbon (LISC) (11 records); and (iii) literature search (e.g. Barbosa et al., 2001; Massuanganhe et al., 2015; Sitoe et al., 2014; Trettin et al., 2016).

The occurrence records without geographical coordinates were georeferenced using Google Earth Pro, version 7.3.2.5491 (Serea, 2018). Duplicated records and records without data on the environmental layers were discarded to avoid inaccurate predictions, and a total of 65 and 54 presence records for *A. marina* and *R. mucronata*, respectively, were obtained and used for the distribution models. We previously ran two individual species distribution models (one for *A. marina* and another for *R. mucronata*) and no significant differences were found. So, the occurrence data of both species were pooled and thus used to produce a model to identify potential mangrove areas in Mozambique.

2.3. Environmental variables

The species distribution model is determined by biophysical and bioclimatic variables (Kaeslin et al., 2012). Hence, selected environmental variables were considered as the main predictors for this study. Initially we had 29 bioclimatic, hydrological, and geomorphological variables (Table 1), including 19 bioclimatic variables (summary statistics of precipitation and temperature: bio1 to bio19) (Record et al., 2013) and wind speed data downloaded from WordClim dataset for 1970-2000 with 30 seconds (~1 km^2) resolution (Fick and Hijmans, 2017). The wind speed is a crucial parameter influencing ocean circulation (tidal) as well as an important variable in a cyclone prone areas like Mozambique. As the wind speed varies seasonally (Chevane et al., 2016), we calculated average wind speed in the winter season (WW) and the average wind speed in the summer season (SW). According to Taillie et al. (2019), we used soil sodium concentration as a proxy for saltwater exposure (salinity), which is an important predictor of vegetation shifts. Soil sodium concentration was retrieved from the International Soil Reference and Information Centre

(ISRIC) dataset with 250 m resolution (Hengl et al., 2015). A land cover map of year 2016 with a spatial resolution of 20 m was downloaded from the European Space Agency, Climate Change Initiative (ESA CCI) database (European Space Agency, 2019); land surface elevation and a digital elevation model (DEM), both with 90 m resolution, were downloaded from CGIAR-CSI Consortium for Spatial Information (CGIAR-CSI, 2018). Land surface elevation has been used as a proxy for inundation vulnerability (Taillie et al., 2019) and it is an important variable influencing mangroves exposure. River discharge was calculated based on catchment size and represented by flow accumulation derived from DEM (Record et al., 2013, Jenson and Domingue, 1988). The slope was calculated using the terrain analysis tool available in QGIS 3.4.4 with GRASS 7.4.4 (QGIS Team, 2019). The maps of mangrove aboveground biomass, maximum canopy height, and basal-area weighted height with 30 m resolution were downloaded from the Oak Ridge National Data Archive (ORNL DAAC) (Simard et al, 2019b). Using QGIS 3.4.4., all environmental variables were resampled to the same pixel size (30 seconds, ~1 km^2) and projected into the same Geographic Coordinate System (WGS 1984). To avoid model over-fitting (Graham, 2003), the collinearity test was conducted by applying the Variance Inflation Factor (VIF) in R v3.6.0 (´car` package) (Hijmans and Van Etten, 2012) and 18 variables were removed; only 11 variables remained for use as model predictors (Table 1). These 11 variables were converted into Raster ASCII grids (.asc) format, to run the model as required by Maxent.

2.4. Maximum Entropy modeling (MaxEnt)

Maxent is a Java-based software package which uses known data (species presence/occurrence data together with predictor variables which can be continuous and/or categorical) to establish a model of habitat suitability with a maximum entropy (Phillips et al., 2006; Phillips and Dudík, 2008; Elith et al., 2011). We used a recent version of the Maximum Entropy model v3.4.1 (Phillips et al., 2017) to predict the distribution of *A. marina* and *R. mucronata*. For relatively few records and presence-only data, this software has been reported to perform better than other algorithms (Elith et al., 2006; Franklin and Miller, 2009). After exhaustive runs with different combinations of settings, the following options were used to obtain the best models: feature classes QPT, 10000 background points, cross-validation with 10 repetitions, 1000 maximum iterations, 10% training presence thresholding, logistic output format and Jackknife to measure variables importance (Kaky and Gilbert, 2017). We previously ran different training data percentages to select the "best model". The percentage of occurrence records used for the training model was 70, and the remaining 30% were used for model validation (Yi et al., 2016; Abolmaali et al., 2018).

According to Yi et al. (2016), four results are possible when we use Maxent for prediction results of SDMs: (1) the studied species exist where the model predicted to exist (true positive, TP), (2) the studied species does not exist where the model predicted to exist (false positive, FP), (3) the studied species exist where the model not predicted to exist (false negative, FN), and (4) the target species does not exist where the model not predicted to exist (true negative, TN). Therefore, both FN and FP are the most common errors found. To evaluate the accuracy of each model, we used AUC, which is the area under the Receiver Operating Characteristic (ROC) curve (Phillips and Dudík, 2008); it has been used as an excellent index of model's goodness-of-fit as is not affected by choice of threshold (Vanagas, 2004). AUC generally ranges from 0.5 to 1, and a higher AUC indicates a better model. According to Araujo et al. (2005), the AUC can be categorized as: "excellent" (>0.9), "good" (0.80 < AUC < 0.90), "fair" (0.70 < AUC < 0.80), "poor" (0.60 < AUC < 0.70), and "fail" (0.50 < AUC < 0.60).

The importance of the environmental predictors was analyzed using three different approaches in MaxEnt: the percent contribution, the permutation importance and the Jacknife test (Phillips et al., 2006). The percent contribution of environmental variables is heuristically defined and depends on the path used by MaxEnt model to obtain the optimal solution. The permutation importance indicates the percentages of contribution of each variable, determined by permuting the values of the variable among the training points and measuring the resulting decrease in AUC. The Jacknife test excludes each variable in turn and creates a model with the remaining variables. The application of Maxent theory for prediction results of species habitat suitability express that the most reasonable prediction for an area be considered suitable or not suitable for the species are both 0.5 (Yi et al., 2016). Therefore, the probability bands ranged from 0 to 0.9892 and was divided into four classes: "Low potential" (<0.3); "Moderate potential" (0.3-0.6); "Good potential (0.6-0.9); and "High potential" (>0.9) **(**Abolmaali et al., 2018**)**.

2.5. The Exposure Index

The obtained species occurrence points and the map of Mozambique's exposure to climate coastal hazards and erosion (Cabral et al., 2017) were overlaid. The term "exposure" and "vulnerability" are used in many different ways by various scholarly communities, and even within the same knowledge domain (Fussel, 2007). In this work, exposure is considered as biophysical (or natural) vulnerability (Cutter et al., 2003; Martins et al., 2012) which has been reported as one of the determinants of social (or socioeconomic) vulnerability (Klein and Nicholls, 1999). The Exposure Index (EI) measures the relative exposure of the Mozambican coastline to climate coastal hazards and erosion and was estimated using the Coastal Vulnerability model in InVEST (for more details about this model, see Tallis et al., 2015). InVEST is an open-source tool developed by the Natural Capital Project, available at www.naturalcapitalproject.org, and it includes a set of different ecosystem service models. For Mozambique, the EI ranged from 1.39 to 4.26 and was categorized into five quantiles: "Very low" (< 2.54); "Low" (2.54–2.90); "Moderate" (2.90–3.22); "High" (3.22–3.53); and "Very high" (> 3.53). Further information about the EI calculations can be found in Cabral et al. (2017). We also calculated the average value of the EI for each species because coastal climate hazards and erosion are factors with a great potential to threaten mangrove along the coastline (Langa, 2007; Massuanganhe et al., 2015).

3. Results

3.1. Models accuracy and variables contribution

All the models showed a good performance in terms of AUC values, ranging from 0.891 to 0.994 (mangroves; mean: 0.975, standard deviation: 0.032). Among the eleven environmental predictors used for the model, average wind speed of summer season (SW), land surface elevation (Elev), Mean Diurnal Range (BIO2), and saltwater exposure (salinity, Na) were found to be the most important variables affecting mangrove species distribution model and the importance of each predictors in the model varies with Maxent evaluation ways (percent contribution, permutation importance, and Jacknife) (Phillips et al., 2006). The percentage of contribution of these top four variables decreased in the order SW > Elev > BIO2 > Na and together they had more than 90 % of contribution while the permutation importance decreased as follow BIO2 > Elev > Na > SW (Table 1). These findings are in agreement with the Jackknife test results (SW > Elev > Na > BIO2), reinforcing that these are the environmental variables with higher gain when used in isolation (Fig. 2).

Figure 2. The Jackknife test to evaluate the relative importance of environmental variables for mangrove species in Mozambique coastal area. Variables: Bio02 - Mean Diurnal Range (Mean of monthly (max temp - min temp)); Bio04 - Temperature Seasonality (standard deviation *100); Bio05 - Max Temperature of Warmest Month; Bio14 - Precipitation of Driest Month; Bio18 - Precipitation of Warmest Quarter; Bio19 - Precipitation of Coldest Quarter; Elev – Land surface elevation; LULC – Land use/ Land cover; Saltwater exposure (salinity, Na); SLO – slope; and SW – average wind speed of summer (SW).

3.2. Mangrove species distribution in Mozambique

The predicted distribution of mangrove species in Mozambique is shown in Fig. 3. The maximum probability of occurrence for both species along the coastline was approximately equal to 1 (Table 2). According to the model (Fig. 3), the most suitable areas for mangroves species occurrence are in Maputo Bay (south) and swampy coast (central region) including the stretch from the northern bank of the Save River (near the border between Inhambane and Sofala provinces) up to Angoche, in Nampula province (further north). The areas of highly suitable habitat (>0.6) for mangrove species were about 890 km^2 in Sofala, 645 km^2 in Maputo, 412 km^2 in Inhambane, and 413 km^2 in Zambézia. The less suitable areas are in the provinces of Cabo Delgado and Gaza (Table 3).

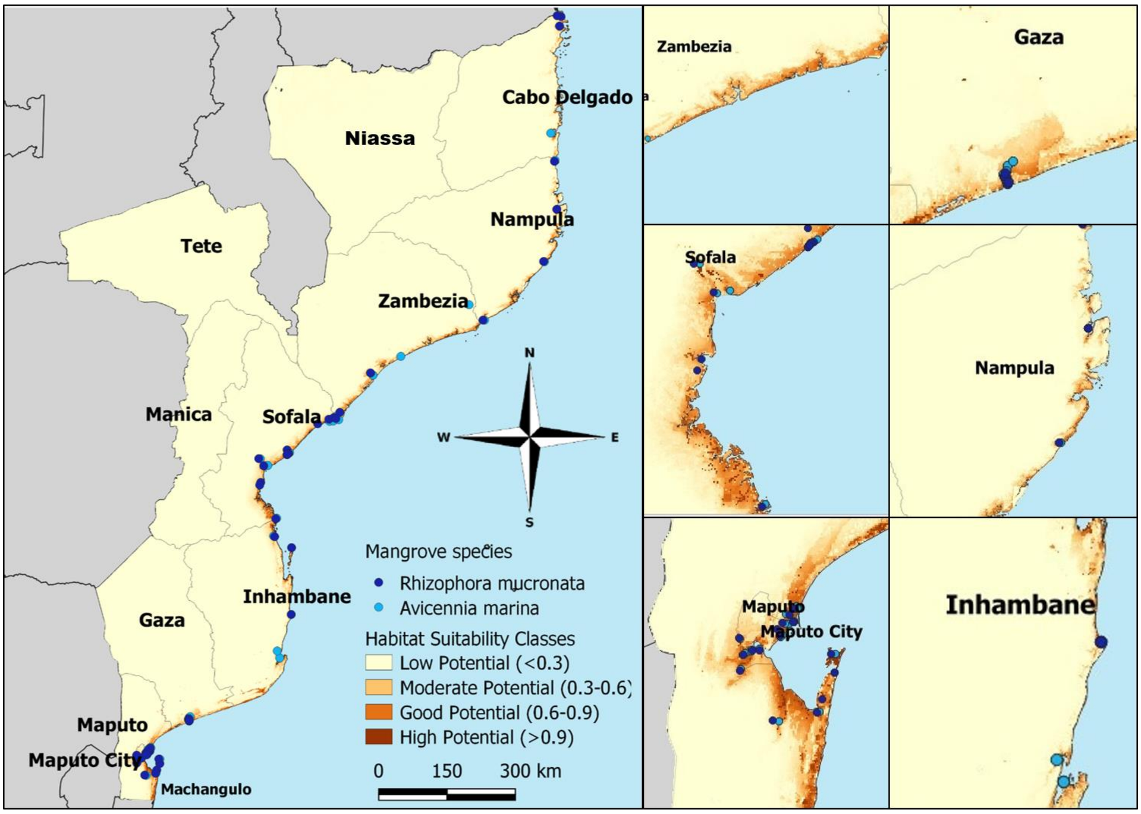

Figure 3. Predicted potential distribution of mangrove species (*A. marina* and *R. mucronata*) in the coastal area of Mozambique.

3.3. Exposure Index for *A. marina* and *R. mucronata*

The erosion and flooding EI of the coastal area of Mozambique ranges from 1.39 to 4.26 (Fig. 4). The exposure indices in Sofala and Zambézia were classified as “High” and “Very high”, and had ranges of 1.94 – 4.26 and 2– 4.26, respectively (Fig. 4; Table 2). The high risk found in the central region is related to large estuaries and deltas forming low-lying lands (land surface elevation below 5 m) vulnerable to floods, some originated by tropical cyclones, and to the transnational and torrential nature of the big rivers associated with them. Moreover, it has been reported that Sofala Bank (so-called swamp coast) exhibits the largest tides in the western Indian Ocean (WIO)

(Hoguane 2007; da Silva et al, 2009). However, our models showed that the provinces of Sofala and Zambezia provide an important habitat for the studied mangrove species. The average EI for *A. marina* distribution was 2.94 (classified as Moderate) whereas EI was 2.75 for *R. mucronata* (classified as Low) (Table 4). It is worth mentioning that results shown in Fig. 4 revealed the need for effective management practices in order to protect the coastal areas with high EI, as well as throughout the whole country coastline.

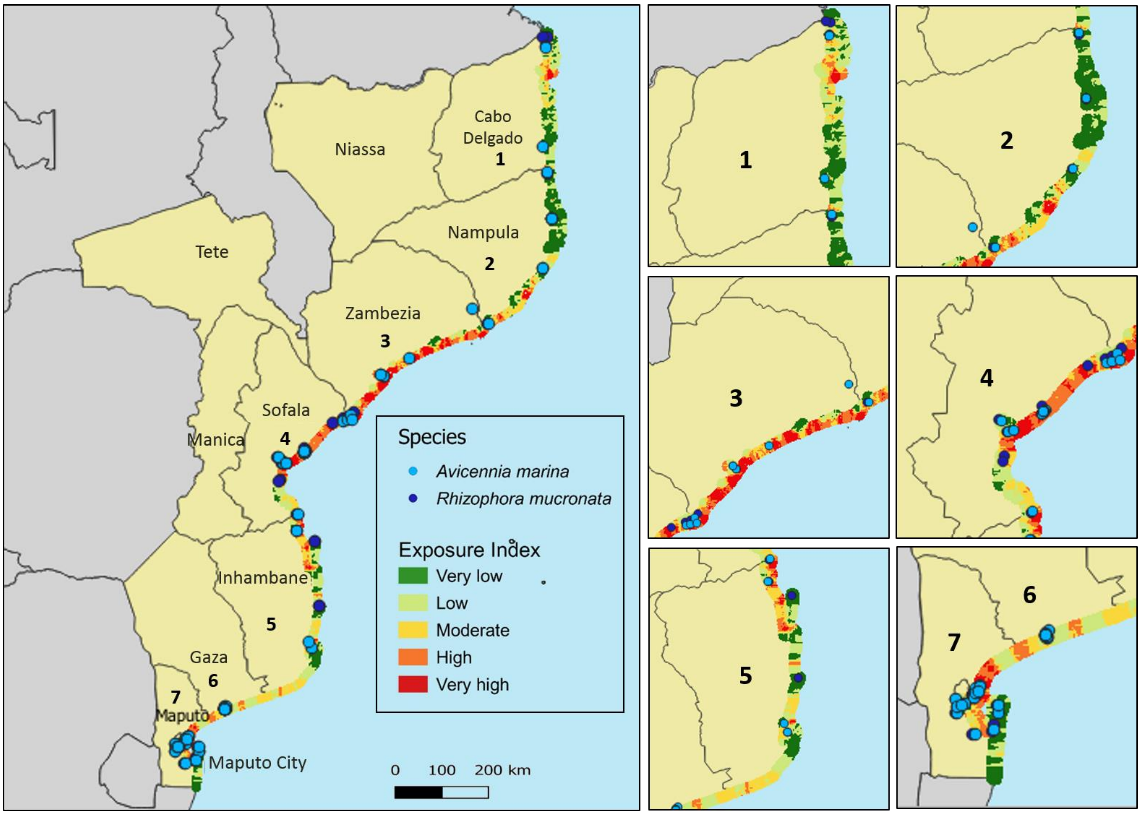

Figure 4. The sample points of *A. marina* and *R. mucronata* and the exposure index (EI) to coastal climate hazards and erosion of Mozambique (left). Details for each of the seven coastal Mozambique provinces are provided (right). Adapted from Cabral et al. (2017).

4. Discussion

4.1. Suitable areas for the occurrence of mangrove species

Based on recent field surveys across all seven coastal provinces of the country, this work presents a comprehensive study of the most emblematic mangrove species in Mozambique, providing an important step towards the protection and management of this coastal ecosystem at both national and global level. The new potential areas of occurrence for *A. marina* and *R. mucronata* revealed by our models pointed out that Southeastern region (e.g. Machangulo Peninsula, Maputo province) as having a high potential for mangrove forests occurrence. Although, this region is currently dominated by sand dunes (Bandeira and Paula, 2014) and coastal lakes and lagoons (da Costa and Ribeiro, 2017), other studies performed in the Amazon Coast of Brazil (see Costa et al., 2016) revealed a high rate of survival and growth of mangrove seedling survival on sandy soils. Excluding estuaries, coastal Mozambique has rather sandy sediments; the sand dunes dominating the long stretch of southern Mozambique, and also South Africa (Kwazulu/Natal) (Tinley, 1985) are potentially favourable for mangrove recolonization provided that a conducive condition exists, such as regular tidal flooding (Spier et al. 2016). For wise management, emerging mangrove areas such as those reported in our study for Maputo Bay are paramount for the protection of local communities and their assets, specially in these tropical cyclone-prone areas, given their high vulnerability to climate hazards (Macamo et al., 2016; Devi, 2019).

Although the Maputo Bay area was revealed as a new potential area of occurrence for *A. marina* and *R. mucronata*, the central coastal region of Mozambique - Sofala Province (so-called swamp coast) presents the largest potentially suitable areas for mangroves species occurrence (890 km^2) (see Fig. 3). It must be noted that all Mozambique Rivers drain into the Indian Ocean, and around 80% of this flow feeds the Sofala Bank, which is the largest fishing bank in Eastern Africa (Hoguane, 2007). *Avicennia marina* is the dominant plant species of the estuary of the Chiveve Creek (locally called "Chiveve River"), which is a mangrove natural river-creek system with about 3 km long, runs across Beira City (the capital of Sofala Province and the second largest city in the country after Maputo City), and has rather high regeneration rate (Antonio et al., 2018). The high dominance of this species was also reported for other Mozambique coastal areas, such as Quelimane, in northern Zambezi delta (e.g. Paula et al., 2014, Macamo et al., 2015).

The mangrove habitat of the Zambezi River Delta (a part of Zambezi Province) has been mentioned as the second largest continuous one in Africa (305 km^2), extending for 150 km along the coastline and around 50 km inland (Barbosa et al., 2001). This agrees with our results, as the entire Zambezia province showed a predicted suitable mangrove area (suitability >0.6) of 413 km^2 (see Table 3). Inhambane also presented a considerable suitable mangrove area (412 km^2), probably related with the Save River estuary (Macamo et al., 2016). These results are in line with a previous study indicating areas of 932 km^2 for Sofala (Marzoli, 2007). Moreover, our model estimated a suitable area of 645 km^2 for the entire Maputo province (suitability >0.6), which matches the findings of previous works reporting a 175.96 km^2 mangrove area in Maputo Bay with an expected increasing trend (Bandeira and Paula, 2014; Bosire et al., 2016). On the other hand, an area of 369 km^2 of mangrove in the northern province of Cabo Delgado has been reported (Ferreira et al., 2009), while in our study we found a suitable area around 308 km^2 with a probability higher than 0.6. Fatoyinbo and Simard (2013) estimated a total area of 3054 km^2 for all mangrove species in Mozambique and our model estimated (prob.>0.6) a total of 2904 km^2 (north: 368 km^2, central region: 1303 km^2 and south: 1237 km^2). Therefore, the estimated mangroves area (see Table 3) strongly depended on the given range of suitability.

This study could not model individual species distribution occurrence in the context of climate change and its consequences which greatly affect mangrove species occurrence and dynamics (e.g. seawater level rise, extreme climate events, and species shifting as well). However, *A. marina* has been found to occupy both inner (at the seaward edge) and outer areas of mangroves (dwarf mangroves) (Bandeira and Paula, 2014, Neukermans and Koedam**,** 2014) and a similar pattern was observed in neighbouring South Africa (Rajkaram and Adams, 2015). In the regions of southern Mozambique, we expect *A. marina* to occupy more areas wherever mangrove colonization opportunities exist. Over 90% of mangrove trees by the Chiveve Creek (central Mozambique), and the Incomati estuary (southern Mozambique), correspond to *A. marina* (Macamo et al., 2015; António, 2018). Therefore, more attention should be given to *R. mucronata*, as few individuals occur or are expected to expand easily. *R. mucronata* is frequently found inland and on creek banks, which is probably related to its lower tolerance to salinity variation (Bandeira and Paula, 2014; Hoppe-Speer et al., 2011). We hypothesize that, in general, creeks near the coastline have a stable salinity (Lutjeharms, 2006; Neukrmans and Koedan, 2014) and are suitable for the continuous presence and colonization by *R. mucronata*.

4.2. Important environmental variables influencing mangroves distribution

The selection of adequate environmental variables is crucial for the construction of robust models (Elith and Leathwick, 2009). Our results revealed that the most important environmental variables responsible for mangroves distribution patterns were land surface elevation (elevation), average wind speed in the summer season, thermal amplitude (i.e. mean diurnal range) and salinity (saltwater exposure). The real influence of these factors on African mangroves' distribution patterns and their optimum range for each species is still largely unknown. Wind direction and velocity particularly influence the spatial diversity and dispersion of mangrove species, and are even responsible for mechanical damage (high speed winds) (Krauss and Osland, 2019). If we take this into account, *A. marina* seems less resistant to wind damage than *R. mucronata*, supporting previous findings of Wadsworth and Englerth (1956). Moreover, sand-carrying winds can change the original soil structure by gradually burying and reshaping the mangrove species composition (Blasco, 1984). The southern and central Mozambique areas are predominantly subject to southeast trade winds, whereas a monsoon regime with northeast winds during the summer and southwest winds during the winter affects the northern areas (Hoguane, 2007). During summer the average wind speed is weak but shelf waters are sensitive to tropical cyclones which generally move poleward through the Mozambique Channel (Van Heerden and Taljaard, 1998). Data from the National Institute of Meteorology of Mozambique show wind speeds ranging from 0.28 to 8.31 m/s during the wet season, and from 7 to 9 m/s, with gusts up to 27 m/s, in the dry season (INAM, 2019). Therefore, average summer wind speed (2.48 m/s) can be associated with rain and mild water levels rises, and with salinity drops due to fluvial discharges and runoff from upland areas (Lutjeharms, 2006). These factors, adding to the increase in rainfall and river flow from January to March in the South, and from January to May in the North of

Mozambique (Asante et al., 2009), greatly contribute to geomorphic processes (Thom et al., 1975) and to mangrove distribution along the coastal line as predicted by MaxEnt.

Water and air temperatures and their amplitudes (daily, monthly and annually) are essential bioclimatic factors contributing to mangrove geographical distribution. According to Blasco (1984), mangrove species are extremely sensitive to cold, with the exception of some *Avicennia* species. A study of mangroves communities in Australasia reported mangrove disappearance when the average temperature in the coldest months reached ≤ 16 °C (Saenger et al., 1977) while other studies found a decline of mangrove species with a temperature below 19 °C (Alongi, 2008; 2002). The southernmost limit of mangroves in Eastern Africa is the Gqunube estuary (near the city of East-London, South Africa), having only *A. marina*; these are areas where mangrove management must be continuously reinforced. The southernmost limit of mangroves in Africa are limited by currents - warm Agulhas Current in east Africa (Rajkaram and Adams, 2015) and cold Benguela current in its southern limit in Angola here with *Avicennia germinans (*Beentje and Bandeira, 2007). Southern Mozambique tip and Maputo Bay are the southernmost limits of the mangrove species *Xylocarpus granatus, Lumnitzera racemosa* and *Rhizophora mucronata* (Paula et al., 2014; Benntje and Bandeira, 2007). Known primary causes of destruction of mangroves in Maputo Bay include deforestation and urban expansion (Macamo et al., 2015, Paula et al., 2014); this should be reduced. Whenever mangrove extraction is intense and difficult to halt, a system of rotating blocks might favour easy regrowth in previously deforested areas (Murdiyarso et al., 2015). The strategic Mangrove Management Plan of Action as, for example, those developed for Kenya (GoK, 2017) should be concluded with wider stakeholder engagement, and later implemented locally. The photosynthesis of some mangrove species sharply drops when air temperature reaches 35 °C (Moore et al., 1972) and the mangrove community is also extremely sensitive to thermal amplitude. It has been reported that the typical response of mangroves to drops in temperature and thermal amplitude is the reduction of species richness, as well as of species' height and diameter (Lugo and Zucca, 1977). As we move northwards along the coastal area, the temperature tends to increase (INAM, 2019). In Maputo Bay, mangroves develop with a water surface temperature averaging 23 °C and a between-seasons thermal amplitude of 8 °C, suggesting that a small increase in temperature could promote the development of mangrove forests (Boer, 2002). While Maputo is sub-tropical, located some 450 km south of the Tropic of Capricorn, the swamp coast in central Mozambique is within the tropics, with temperatures between 27 and 30 ºC (maximum) and 18 and 21 ºC (minimum), where our model indicates the highest suitability for mangrove forests. In the coral coast (north), where the model predicts less suitable areas, the temperatures are much higher (average of monthly max > 30 ºC) (INAM, 2019).

In Mozambique, elevation decreases from inland to the sea. A study carried out in Mobbs Bay-Australia found *A. marina* and *R. mucronata* occurring at elevations ranging from 0.01 to 0.79 m (Youssef and Saenger, 1999). The coastal morphology of Mozambique is characterized by low areas (44% of the coastal region) (Kokusai 2000) with favorable characteristics for mangrove stabilization and development. However, the Sofala Bank (swamp coast) is a flat coastal plain with many large rivers and an elevation rarely exceeding 5 m. This elevation range is also found in some specific sites of Maputo Bay, and in a few regions of the low-lying offshore islands in the northern province of Cabo Delgado (Asante et al., 2009). Accordingly, our model indicates a significant probability of mangrove occurrence in those regions.

The salinity increases from inland to the sea (Hoguane and Armando, 2015) and the salinity of shelf waters in Mozambique presents seasonal variations with the river outflow, with the lowest salinity value in summer (February) (Lutjeharms, 2006). Sofala Bank (swamp coast), where our model found the most suitable area for mangroves, is one of the most important ecological areas of Mozambique coastline (Hoguane, 2007) and presents the lowest salinity average ranging from 32 to 35 psu, and further drops (down to around 20 psu) during summer (rainy season) (Gammelsrød, 1992) due to freshwater discharge from numerous rivers draining into the Indian Ocean. This also contributes to the high productivity of the swamp coast, mainly through the input of terrigenous nutrients (Nehama et al., 2015). High defenition mapping of mangroves of expanding urban mangroves (Ghosh et al., 2020) would be an added management toll to better forecast and plan intervention.

4.3. Coastal vulnerability of Mangroves

The Exposure Index (EI) was calculated for individual mangrove species to provide new insights on their exposure and help decision-makers to define priorities for management and conservation of mangrove ecosystems in Mozambique. The "Moderate" and "Low" EI found for *A. marina* (2.94) and *R. mucronata* (2.75) may be explained by the fact that they easily occupy tidal areas that may be also prone to land-based erosion, namely the seaward edge in the case of *A. marina* and the creeks in the case of *R. mucronata*.

The overall EI calculated for Mozambique also shows the severity of the impact of climate events and erosion (see Cabral et al., 2017). The sites with a high EI (Fig. 4), a high potential distribution of mangrove (Fig. 3) and, simultaneously, are important population centers where urbanization and mangrove cutting for building material and firewood tend to be more pronounced (Macamo et al., 2016) were considered prioritary for mangrove management actions. Examples of such sites are Palma and Mocímboa da Praia (both in Cabo Delgado province), Angoche (Nampula), Quelimane (Zambezia), Beira (Sofala), Maxixe (Inhambane) and Maputo, where issues of erosion, sedimentation, deforestation, as well as mangrove encroachment due to infrastructure development, have already been identified. Nonetheless, inundation by sea level rising has also been found to cause retreat (negative rates of change) and advance (positive rates of change) of sea edge mangroves in Cameroon Estuary between 1975 and 2007 (Ellison and Zouh, 2012). Moreover, floods and cyclones may have contrasting results. It was already mentioned that central

Mozambique (including Sofala and Zambézia) presents lower elevation, higher tides and is more exposed to tropical cyclones, with 6 cyclones in 16 years (Asante et al., 2009). Globally, tropical cyclones were responsible for about 45% of global mangrove mortality over the past six decades (Sippo et al., 2018). The intensity of the damage to people and environment, caused by a tropical cyclone, depends on its category. For instance, the central region of Mozambique was recently hit by the strongest tropical cyclone ever recorded in the Southern Hemisphere ("Idai", category four, 14th March 2019) which brought high-speed winds, torrential rains and floods (Devi, 2019). It caused human deaths and severe mangrove damage (due to wind speed and to mangrove drowning by still water for several days) yet to be quantified. Recommendation is to use mangrove forests as smart solutions, a forefront protection line for community houses and other infrastructures. Frontal mangroves should be spared at any cost as they guarantee an important degree of protection of people and their assets in a country that is highly vulnerable to climate hazards.

4.4. New insights for management of coastal regions of Mozambique

The potential areas of mangroves occurrence in Mozambique revealed in our study (e.g. Maputo Bay, Sofala and Zambézia provinces) highlight the need to reinforce appropriate best practices issued from international and national bodies (e.g. Owuor et al., 2019). For instance emanated by Sustainable Development Goals (SDGs), including Nature Based Solutions (NbS) (Islam and Shamsuddoha, 2018); regional seas programmes such as UNEP-Nairobi Convention from Western Indian Ocean (WIO) (Bosire et al., 2015; Barwell et al., 2018; Owuor et al., 2019); and national Mozambican initiatives and related instruments to safeguard mangroves goods and services (Bandeira and Paula, 2014). Recently, Mozambique hosted the first conference focused on the country and the western region of the Indian Ocean (see http://growingblueconference.gov.mz/index.php/en/). During this conference it was recognized the need to increase the scientific knowledge on critical habitats like mangroves, and to target investment resources, both in training and building technical and institutional capacity, which will enable the development of a sustainable Blue Economy.

The NbS are highlighted in international agreements such as the Sendai Framework for Disaster Risk Reduction 2015–2030, as promising strategies to reduce disaster risk, adapt to climatic change, and strengthen community resilience (Arce-Mojica et al., 2019). NbS is rather smart, rather cheap green solution and can be recommended for similar circumstance for such as control of storm water and extreme tides in regions that presents both the largest potentially suitable areas for mangroves species occurrence, and have the highest levels of EI, as it was revealed for the central coastal region of Mozambique. However, the high population density found along this coastal area, is another factor in mangrove forest degradation, as the population (urban poor and rural communities) still depend on the mangrove for their economic activities. For instance, several mangrove potential areas do not have sufficient electricity, so the local people still depend on fuelwood, and particularly, *Rhizophora* and *Avicennia* are being threatened due to overexploitation (Macamo et al., 2016). Unless electric power can be utilized in these areas, the protection of mangrove forests will be seriously destroyed in the near future. Thus, relevant gaps should be identified in order to promote the sustainable use of these species and contribute to mangrove conservation. A successfully use and management of mangrove in Mozambique, specifically in high EI areas, require carefully thought and rules application, thereby contributing to achieve the benefits such as community development, stakeholders commitment, biodiversity conservation, and social equity (Van Lavieren et al., 2012; Feka, 2015).

5. Final Remarks

This study used the Maximum Entropy method (MaxEnt) to predict the potential distribution of *A. marina* and *R. mucronata*, as a proxy to identify potential mangrove areas in Mozambique. Our results showed the probability of their occurrence or their suitable areas, determined species EI to coastal climate hazards and erosion, and quantified the importance of the environmental variables contributing to species occurrence. They also revealed that average wind speed of the summer season, Mean Diurnal Range, elevation, and salinity (saltwater exposure) played a determinant role on the *A. marina* and *R. mucronata* distribution model. The most suitable areas for these two emblematic mangrove species are Maputo Bay, already with most of its perimeter covered with mangrove forests, and the stretch from the northern bank of the Save River up to Angoche, in Nampula province.

In Mozambique, mangroves can be wisely managed and protected based on directories of global platforms such as SDG 14, regional seas programs under UNEP-Nairobi Convention from Western Indian Ocean (Bosire et al., 2015; Barwell et al., 2018), main national governance instruments (e.g. Regulation on the Prevention of Pollution and the Protection of the Marine and Coastal Environment – Decree 45/2006 of 30th November) and associated international conventions (e.g. Ramsar - Resolution nr. 45/03, 5th November 2003). Sustainable management of mangrove forests is still a great concern across the country, particularly in areas with high EI. Highlights for mangrove management are the preservation of mangrove ecology integrity, sustainable harvesting and promotion of mangrove restoration; integration of local stakeholders and communities in overall design of management initiatives; investment of municipalities and corporates on climate adaptation of habitats and people; and community empowerment, among other initiatives.

The comparison of the three defined coastal regions indicated the so-called swamp coast (in central Mozambique) as the most important one for extensive mangrove occurrence. Moreover, the average inundation and erosion exposure indices of *A. marina* and *R. mucronata* were

"Moderate" and "Low", respectively. Nowadays, the effects of climate change are a great global concern to African countries including Mozambique which has a vulnerable coastline, demanding urgent and more effective management and conservation measures for mangroves.

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Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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List of Tables

Table 1. Environmental variables used in this study, percent contribution and permutation importance. Variables in bold were selected through the multi-collinearity test and then used for the model.

Code	**Environmental variables**	**Unit**	***Mangrove species*** % Contribution	Permutation importance	***Reason to be chosen***	***Reference***
BIO1	Annual Mean Temperature	◦C			Bioclimatic variables (precipitation and temperature) are commonly used to predict species distribution models including mangroves. Temperature has crucial effects on seedling establishment, survival and mangroves species distribution. Temperature varies significantly within mangrove forests as well as geographically across its distributional range. The effects of temperature (heat or cold tolerance in tropical and sub-regions) on early growth and physiology of mangrove species have been reported (Krauss et al., 2008). Moreover, higher temperature increases evaporation, resulting in higher salinity which in turn influences species distribution. The increasing of mean air and ocean temperatures favors the	Kaky and Gilbert (2016, 2017), Krauss et al. (2008) Record et al. (2013) Schumann et al. (1995)
BIO2	**Mean Diurnal Range (Mean of monthly (max temp - min temp))**	**◦C**	**13.1**	**44.1**		
BIO3	Isothermality (BIO2/BIO7) (* 100)					
BIO4	**Temperature Seasonality (standard deviation *100)**	**(coeff. of variation °C)**	**0.6**	**7.7**		
BIO5	**Max Temperature of Warmest Month**	**◦C**	**1.9**	**0.2**		
BIO6	Min Temperature of Coldest Month	◦C				
BIO7	Temperature Annual Range (BIO5-BIO6)	◦C				
BIO8	Mean Temperature of Wettest Quarter	◦C				

BIO9	Mean Temperature of Driest Quarter	◦C			expansion of mangrove forests (Schumann et al., 1995)	
BIO10	Mean Temperature of Warmest Quarter	◦C				
BIO11	Mean Temperature of Coldest Quarter	◦C				
BIO12	Annual Precipitation	mm				
BIO13	Precipitation of Wettest Month	mm			Precipitation is an important driver of mangrove productivity, nutrient up-take, propagules movements, and species survival. Higher precipitation may imply increase run-off, decreased salinity, moderate acid sulphide soils, and increased mangrove forest expansion, richness and productivity. Precipitation, temperature and cyclone frequency greatly explain the global trends in mangroves canopy height (Simard et al., 2019a). As salt secretion by some mangrove species is a means to cope with "salt root", so does rainfall help to wash the salt off the leaves and keep them healthier.	Snedaker (1995) Tomlinson (1998) Simard et al. (2019a)
BIO14	**Precipitation of Driest Month**	**mm**	**0.7**	**5.3**		
BIO15	Precipitation Seasonality (Coefficient of Variation)	(coeff. of variation; %)				
BIO16	Precipitation of Wettest Quarter	mm				
BIO17	Precipitation of Driest Quarter	mm				
BIO18	**Precipitation of Warmest Quarter**	**mm**	**1.3**	**2.5**		
BIO19	**Precipitation of Coldest Quarter**	**mm**	**0.5**	**0.6**		
hmax	Mangrove canopy maximum height (height of the tallest tree)	m			Since biomass can be used as indicator of productivity of mangrove stands, and of healthy and unhealthy forest, aboveground mangrove biomass, canopy maximum height, and basal-area weighted height can predict habitat suitability for mangrove species.	Numbere and Camilo (2018) Komiyama et al. (2005)
agb	Aboveground mangrove biomass	$Mg\ ha^{-1}$				
hba	Mangrove basal area-weighted height (individual tree heights weighted in proportion to their basal area)	m				
LULC	**land use/land cover**	**10 types**	**0.6**	**0.9**	Land cover is widely used to predict species distribution models. It is a crucial environmental variable to assess biodiversity patterns	Amatulli et al. (2018)
SLO	**Slope**	**Degree**	**1.4**	**3.2**	Elevation and slope affect hydrological processes by influencing flow direction and runoff velocity, erosion, inundation, soil moisture, local precipitation and temperature as well. Moreover, the survival of mangrove species depends on their ability to keep pace with the rise of sea level through the rates of slope and substratum elevation changes. Therefore, elevation can be used as a *proxy* of inundation vulnerability.	Simard et al. (2006) Day et al. (2008) McIvor et al. (2013) Kaky and Gilbert (2016, 2017), Amatulli et al. (2018)
Elev	**Land surface elevation**	**m**	**25.1**	**13.9**		
SW	**Average wind speed in summer**	**$m\ s^{-1}$**	**49.4**	**8.1**	Wind is an important driver of mangrove distribution patterns, especially in cyclone prone regions as Mozambique. Wind can influence water level fluctuations, propagules distribution, and mangrove plant structure. Furthermore, different wind intensities produce different effects on mangrove forest**.**	Yang et al. (2014)
WW	Average wind speed in winter	$m\ s^{-2}$				
Na	**Saltwater exposure/salinity (Soil sodium concentration)**	**$cmolc\ kg^{-1}$**	**5.4**	**13.6**	Soil sodium has been used as proxy for saltwater exposure which is a crucial factor for establishment and early development of different types of mangroves, as well as for species migration. Salinity limits water uptake and photosynthetic rates of mangrove species.	Taillie et al. (2019) Krauss et al. (2008) Sobrado (1999)
FlowAcc	Flow accumulation	m^2			Flow Accumulation is used to represent river discharge, an	Record et al. (2013)

important carrier of nutrients from high to lowlands, favoring mangrove establishment and development. River discharge plays an important role on salinity reduction of mangrove areas and it has been reported to influence mangrove distribution at relatively small scales.

Table 2. Descriptive statistics of the probability of occurrence of *A. marina* and *R. mucronata* in Mozambique and of the erosion and climate change exposure index in the coastal area.

Provinces	*Mangrove species*				Exposure Index			
	Min	Max	Mean	STD	Min	Max	Mean	STD
Maputo City	0.05	1	0.54	0.37	2.08	3.66	2.65	0.45
Maputo Province	0	1	0.08	0.21	2.08	3.98	2.77	0.50
Sofala	0	1	0.04	0.15	1.94	4.26	2.96	0.42
Inhambane	0	0.98	0.03	0.11	1.94	3.43	2.83	0.34
Cabo Delgado	0	0.90	0.01	0.06	1.75	3.87	2.62	0.39
Nampula	0	0.91	0.01	0.08	1.49	3.8	2.46	0.50
Zambezia	0	1	0.02	0.11	2.00	4.26	3.20	0.50
Gaza	0	0.95	0.01	0.07	2.68	3.22	3.02	0.21
Manica	0	0.01	2E-04	6E-04				
Tete	0	0.01	3E-04	1E-03				
Niassa	0	0.01	4E-05	2E-04				

Where: Min – Minimum, Max – Maximum and STD – Standard deviation

Table 3: Estimation of suitable areas for *A. marina* and *R. mucronata* according to different ranges of probability of occurrence in the coastal provinces.

Provinces	Regions	Estimated Occur. Area of Mangrove forest				Literature review of mangrove estimated areas (km^2)
		<0.3	0.3-0.6	0.6-0.9	>0.9	
Cabo Delgado (km^2)	North	75446	479	108	25	369*
Nampula (km^2)	North	75002	933	232	3	Not available
North region (km^2)		**150448**	**1412**	**340**	**28**	
Zambezia (km^2)	Central	98907	1447	408	5	Not available
Sofala (km^2)	Central	62872	1508	819	71	932**
Central region (km^2)		**161779**	**2955**	**1227**	**76**	
Inhambane (km^2)	South	65373	903	405	7	Not available
Gaza (km^2)	South	72629	570	162	18	Not available
Maputo (km^2)	South	20265	1009	628	17	Not available
South region (km^2)		**158267**	**2482**	**1195**	**42**	
Total (km^2)		**470494**	**6849**	**2762**	**146**	**3054*** **

* Ferreira et al. (2009)

**Marzoli (2007)

*** Fatoyinbo and Simard (2013)

Table 4: Coastal erosion and inundation exposure index of *A. marina* and *R. mucronata.*

Species	Exposure Index			
	Min	**Max**	**Mean**	**STD**
A. marina	2	3.66	2.94	0.67
R. mucronata	2	3.46	2.75	0.53