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Dynamics of mangrove forest distribution changes in Iran

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ABSTRACT

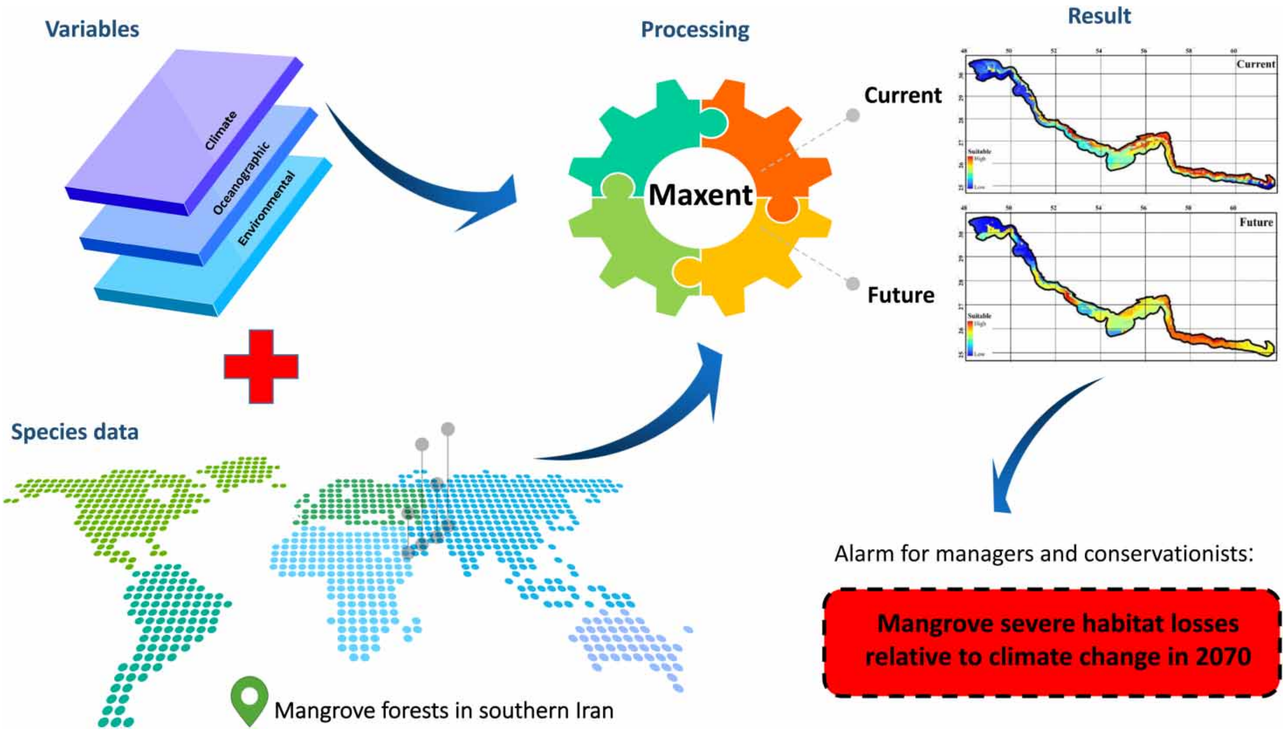
Mangroves are known for providing multiple ecosystem services and critical habitats for diverse species and are one of the most threatened ecosystems by human activities and climate change. However, little is known about their distributional patterns. In this study, the distribution of the dominant species, *Avicennia marina* was examined in the context of climate change to identify conservation priority objectives at the spatial and temporal scales on the southern coast of Iran. A maximum entropy model was used to predict the potential distribution of the mangrove forest in the current situation and forecast its future (2070: RCP 8.5, CCSM4). The result revealed that the potential distribution for the mangroves will decrease in the future and probably two habitat patches remain, one patch in the middle of the coasts of the Persian Gulf and another patch in the middle of the coasts of the Oman Sea. Annual mean temperature, temperature annual range, and annual precipitation were the most important determinants of the mangrove distribution. The findings can be used as a theoretical basis to manage and protect the habitat of mangroves in Iran.

Key words: *Avicennia marina*, MaxEnt, Oman Sea, Persian Gulf, species distribution model

HIGHLIGHTS

- Mangrove forests in Iran are found on the sheltered coasts, estuaries, and some near-shore islands of the Persian Gulf and the Oman Sea and *Avicennia marina* is the dominant species.
- Mangrove habitat distribution in the southern coasts of Iran under climate, biochemical, and environmental conditions were predicted.
- The potential distribution for A. marina will decrease under RCP 8.5 by 2070.
- Eastern parts of the coasts of the Persian Gulf and the Oman Sea are the most suitable areas for mangrove distribution.

GRAPHICAL ABSTRACT



INTRODUCTION

Natural resources and ecosystems provide various functions and services for human society in different regions (Falahatkar *et al.* 2017; Buonocore *et al.* 2020). Human activities, climate change, and the reduction of a large number of natural resources are the most important causes of the destruction and degradation of these resources (Taleshi *et al.* 2019; Mousavi & Falahatkar 2020; Mousavi *et al.* 2022). Marine and coastal ecosystems include a wide range of goods and services that provide vital food supplies for millions of people in the world (Haines-Young & Potschin 2018). Mangrove forests, as one of the highly productive coastal ecosystems and an important tropical environment, provide a large variety of goods and services, including being the source of wood products for many coastal communities, essential habitats for marine fishes, high rates of carbon sequestration in soil, high intrinsic natural productivity, valuable natural resource with distinctive diversity, and coastal defense service (Harris *et al.* 2017; Nazarnia *et al.* 2020; Kamil *et al.* 2021). Unfortunately, these forests have been threatened due to the development of aquaculture, agriculture, urban development, oil exploration activities, and industry worldwide and have lost significant amounts of their areas in recent decades. (Abbaspour *et al.* 2011; Haddad *et al.* 2015; Mokhtari *et al.* 2015; Kourosh Niya *et al.* 2019a). In addition to human activities, climate change is one of the most important causes of the change and destruction of mangroves (Mousavi *et al.* 2017; Cinco-Castro & Herrera-Silveira 2020; Banerjee *et al.* 2021).

Under long-term impacts of climate change, marine ecosystems are becoming environments with new conditions that may affect current conservation mechanisms (Johnson & Watson 2021). In the future, mangrove forests are also expected to be significantly affected by climate change (Ward *et al.* 2016). Due to the rising sea level as the most critical factor in climate change, the distribution and diversity of mangrove communities could change and consequently lead to fewer mangrove carbon stocks (Adame *et al.* 2021; Davar *et al.* 2021). Climate change is also predicted to have diverse effects on different mangrove communities and some regions are likely to experience more adverse effects (Ward *et al.* 2016). Changes in the distribution, health and productivity of mangrove forests can largely affect the presence and abundance of other species, as well as the ecosystem services of the forests (Brandt *et al.* 2019; Garcia *et al.* 2020; Wang & Gu 2021). Nowadays, a significant amount of research uses the species distribution modelling method to identify the effects of climate change on species distribution and to identify conservation priorities (e.g., Amiri *et al.* 2021; Ebrahimi *et al.* 2021; Ghane-Ameleh *et al.* 2021;

Sales *et al.* 2021; Tehrani *et al.* 2021) and it is even used in other fields of science as well (Allahbakhshi *et al.* 2020; Firozjaei *et al.* 2021). In this regard, species distribution models (SDMs) have been ranked as one of five research methods in biological sciences (Warton *et al.* 2013) that utilize the presence/absence of data to predict species distribution and thus cover an important part of ecological studies (Warton *et al.* 2013; Mohammadi *et al.* 2019; Ilanloo *et al.* 2020). Therefore, to recognize priority areas for mangrove conservation actions, SDM results can be used under current and future climate conditions (Rodríguez-Medina *et al.* 2020; Lemes *et al.* 2022).

In this study, the SDM tool was used to assess the potential impacts of climate change on the distribution of mangrove forests along the southern coasts of Iran. Although studies have been conducted on mangroves in a range of subjects in the past, a complete picture of the entire region of mangrove distribution is not available. (Ghayoumi *et al.* 2019; Forouzannia & Chamani 2022). This study aims to investigate the current distribution of the *Avicennia marina* (dominant species in mangroves across habitats in Iran) and evaluate the consistency and variations in the forecast potential distributions of this species in Iran under the IPCC's future climate scenario (2070: Representative Concentration Pathway (RCP) 8.5, CCSM4). The results will help us understand how mangrove forests will experience the effects of climate change in concerning distributional shifts.

MATERIALS AND METHODS

Study area

The habitat of *A. marina* is located on the shores of the Persian Gulf and Oman Sea. The natural mangrove habitats in Iran range from areas spanning the latitudes of 24° to 35 °N in latitude and 51° to 58 °E in longitude (Figure 1). These forests in

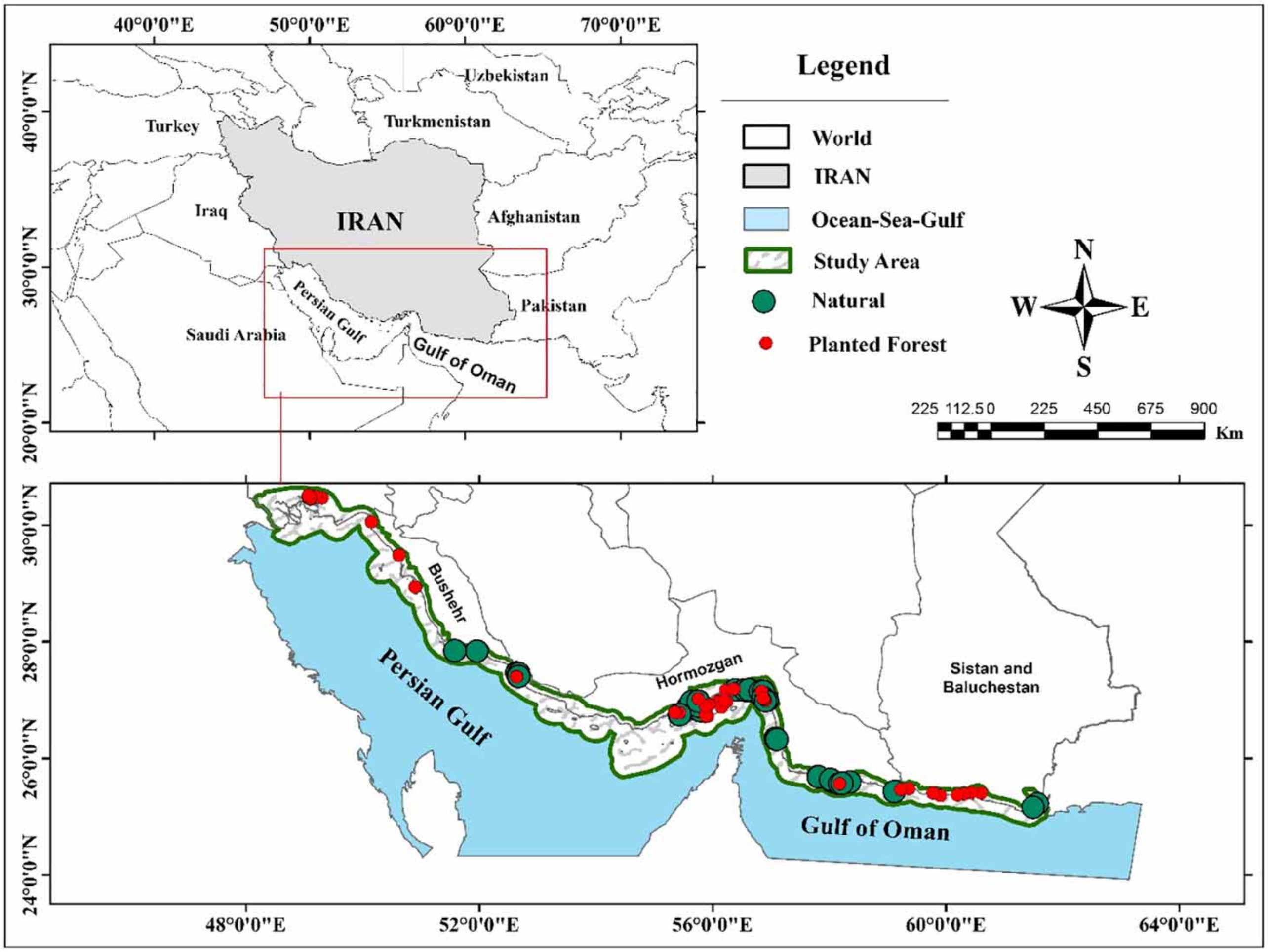


Figure 1 | Mangrove forests in the study area (south of Iran).

Iran are categorized into the 'non-industrial' and 'conservation tree' communities (Safa Eisini 2006; Tiab *et al.* 2014). The distribution of natural mangrove forests in Iran starts in the eastern part of the Oman Sea at the Iranian border (Guater/Gwadar Bay) and ends in the west of the Persian Gulf and the Bushehr Province. Generally, mangrove forests are distributed in southern Iran on the coasts of the Persian Gulf and Oman Sea and in three provinces (from east to west): Sistan and Balouchestan, Hormozgan and Bushehr with 1,380, 19,381, and 325 hectare areas, respectively (Safa Eisini 2006). Khuzestan is the western-most province to the coast that does not have natural mangroves (Ghayoumi *et al.* 2019). *A. marina* forests in Iran are categorized as non-industrial and conservation tree communities; their exploitation only happens in the forms of harvesting of branches, beekeeping, aquaculture, recreational, and medicinal use. Parameters affecting the distribution of mangrove species include soil salinity, water penetration, physical and chemical properties of soil, water cycle, biological interactions, nutrients, and climate effects (Danehkar 1998; Safa Eisini 2006).

Data collection

To construct the SDMs, we applied climatic, oceanographic, and environmental variables relevant to the species ecology (Supplementary material, Appendix 1). Climatic variables were downloaded from WorldClim (Fick & Hijmans 2017; https://www.worldclim.org/data/worldclim21.html). Environmental variables were acquired from the Iranian Ports and Maritime Organization and Oceanographic variables were downloaded from Auckland data (https://gmed.auckland.ac.nz/). To equalize the layers, ArcGIS 10.8 (30 arcsec resolution, ~1 km^2) was used to calculate the Euclidean distances of all pixels. During a year of field investigation, the intertidal zone in the Persian Gulf and the Sea of Oman was also studied, and each natural and planted polygon was recorded as a point. Finally, only natural points (32 points) were used as model inputs (Figure 1). The variance inflation factors (VIFs) in the niche-based model were calculated using the R programme (Naimi *et al.* 2014). This method allows us to avoid collinearity that could bias forecasts made by the niche-based model. A VIF larger than 10 indicates a collinearity problem in the model and by taking VIF>10 into account, the species' linear variables were removed (Naimi *et al.* 2014). Thus, we retained eight variables that were applied throughout this study (see Supplementary material, Appendix 1).

The CCSM4 was used for future (2070) climatic conditions (Gent *et al.* 2011) since the CCSM4 climate model is widely used in Southwest Asia (e.g., Mohammadi *et al.* 2019; Ebrahimi *et al.* 2022; Ebrahimi & Ahmadzadeh 2022), and is one of the most efficient global climate projections to forecast the impact of future climatic changes on the distribution pattern of animal and plant species (e.g., Mohammadi *et al.* 2019). For the future climatic conditions, RCPs 8.5 climate scenarios based on Intergovernmental Panel on Climate Change (IPCC) reports were used from the WorldClim database (1.4; Fick & Hijmans 2017). The RCP 8.5 predicts the effects of climate change on pessimistic conditions, indeed RCP 8.5 depicts a rising radiative forcing pathway leading to 8.5 W m^{-2} by 2070 (Shekede *et al.* 2018).

Species distribution modelling

Species distributions were modelled using the Maximum Entropy (MaxEnt) approach, with presence-only species occurrence records and randomly generated background points (Phillips *et al.* 2006). Various SDMs have been used to evaluate the ecological requirements, ecological responses, and distribution areas (Sheykhi Ilanloo *et al.* 2021). Among these different modelling approaches, Maxent is widely used since it performs better (Pearson *et al.* 2007). Not requiring the points of absence is one of the main advantages of this approach (Felicísimo *et al.* 2013). This method estimates the most uniform distribution of sample points for the limitations of the data (Phillips *et al.* 2006). Also, some studies have shown that Maxent performs equally to an ensemble approach, but with less computational time, so an ensemble approach is not superior to this model (Hao *et al.* 2020; Kaky *et al.* 2020).

In this study, data were randomly divided into 70% records for model calibration and 30% for model evaluation (Naimi & Araújo 2016). To investigate the importance of variables, the Jackknife test was used. Furthermore, receiver operating characteristics (ROC) and the area under the curve (AUC) were used for the performance evaluation of the model (Elith *et al.* 2011; Naimi *et al.* 2014; Zhao *et al.* 2021). It is necessary to mention that the range of the AUC is 0.5–1.0 and the closer it is to 1 indicates the better performance of the model (Phillips *et al.* 2006).

RESULTS

The results of assessing MaxEnt model performance showed that AUC was equal to 0.907 for the training and 0.894 for the test data, which shows a pretty good prediction of the habitat distribution of *A. marina* in this study area. This model shows that suitable habitats for the *A. marina* in Iran are located on parts of the eastern coast of the Persian Gulf and the middle parts between the Persian Gulf and the Sea of Oman. Other habitats in the Persian Gulf are either completely unsuitable or have very low suitability for this species (Figure 2). We found that temperature annual range with a contribution of 21.4%, sea surface temperature range with a 16.4% contribution, and slope with a 15.71% contribution were the most important variables in determining the distribution of *A. marina* in our study area (Figure 5). According to the results, the highest probabilities of species occurring are in: slope <10%, sea surface temperature range <5.78, chlorophyll A (min)=1, BIO 19=6.5, BIO 12=9, BIO 07=18.5 and tidal range=0 (Figure 4).

Climate change

This study of the effects of climate change on suitable habitats for *A. marina* in Iran using CCSM4 general circulation models showed that this species will lose a significant portion of its suitable habitats in the period of 2060–2080 under RCP 8.5 (Figure 3). The current potential suitable habitat of the species is 12.5% of the study area but will decrease to 2.1% of the study area. The highest loss of suitable habitats would be in the eastern parts of the Persian Gulf and Oman Sea (Figure 3).

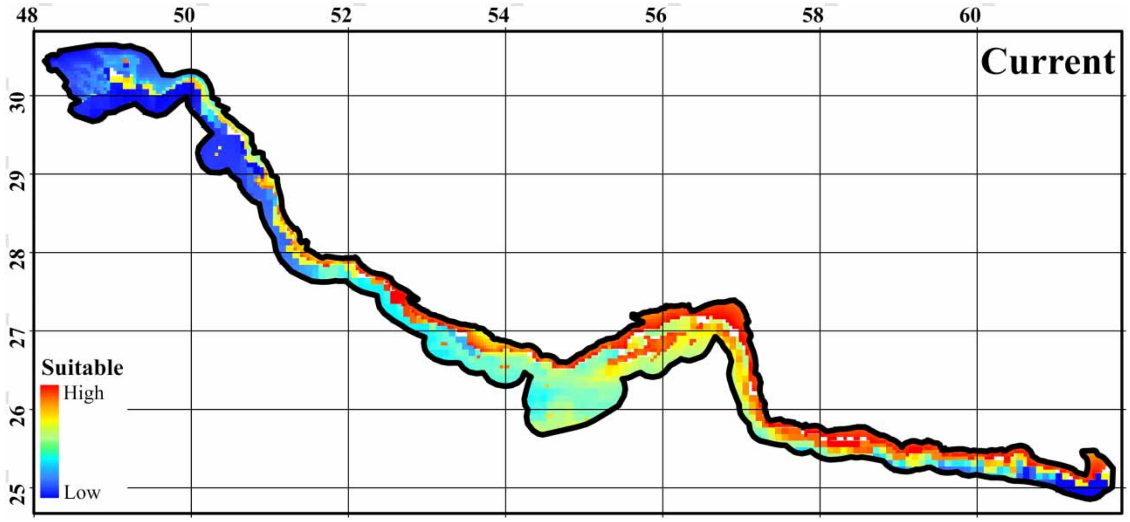


Figure 2 | Distribution map of the *A. marina* in Iran under current climate conditions.

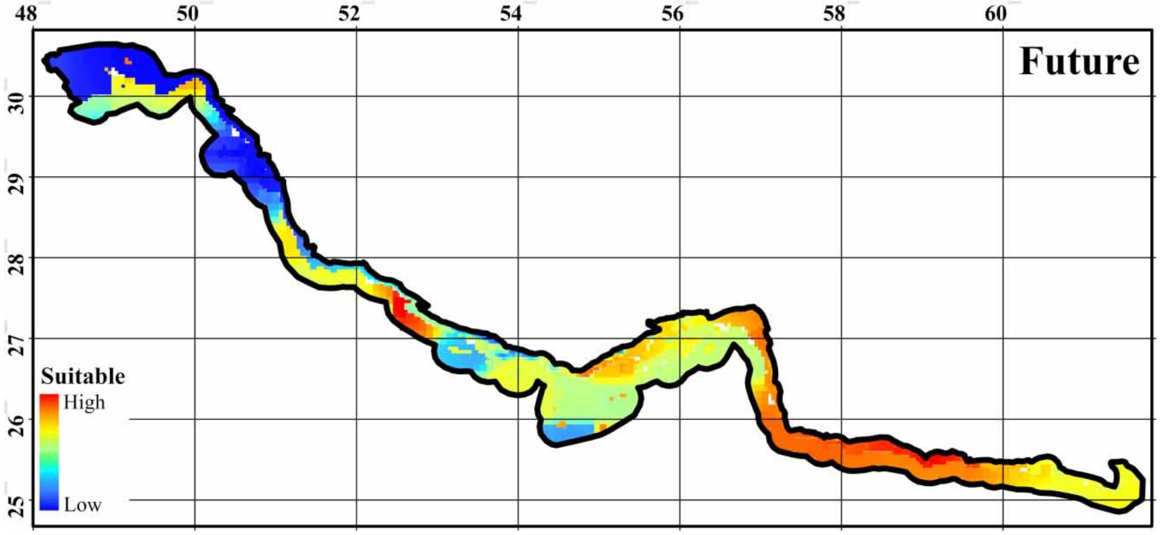


Figure 3 | Distribution map of the *A. marina* in Iran under future climate conditions.

DISCUSSION

The global mangrove area is declining due to increased human activities, climate change, and adverse environmental conditions (Kourosh Niya *et al.* 2019b; Goldberg *et al.* 2020). The mangrove ecosystem on the southern coasts of Iran is the last distribution edge range of these forests and has harsh and dry environmental conditions close to the species' climatic tolerance limits (Schile *et al.* 2016; Mafi-Gholami *et al.* 2020). Therefore, they demonstrate lower productivity and biomass than mangrove communities in humid areas and are more sensitive to any additional pressure (Etemadi *et al.* 2018; Adame *et al.* 2021). Hence, climate change as extra stress can have irreversible impacts on these communities (Etemadi *et al.* 2021).

This study discusses the distribution of *A. marina* under climatic factors and oceanographic conditions. However, it should be considered that various factors are involved in mangrove distribution on a national and local scale (Jayanthi *et al.* 2018). The results showed that the most important variables in the distribution of *A. marina* are the temperature annual range, sea surface temperature range, and slope, which are consistent with previous studies (Servino *et al.* 2018). Mangrove forests are located in estuaries and the coasts where the environment is harsh and are highly resilient to changing conditions (Alongi 2015). However, one of the most important possible drivers of their extinction which has been identified in the distribution of *A. marina* is the increased thermal stress that causes an increase in evaporation and leads to more salinity and ultimately reduces tree growth and leaf gas exchange as well as seedling survival (Servino *et al.* 2018).

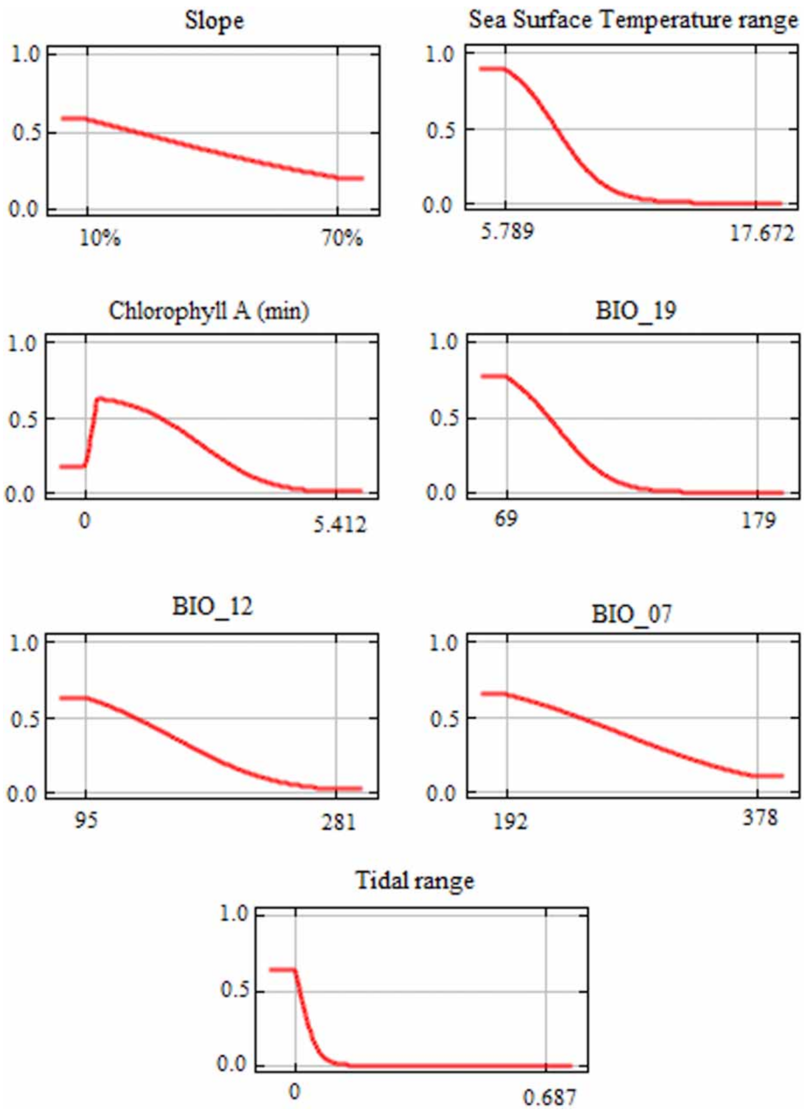


Figure 4 | Response curves of species to different variables.

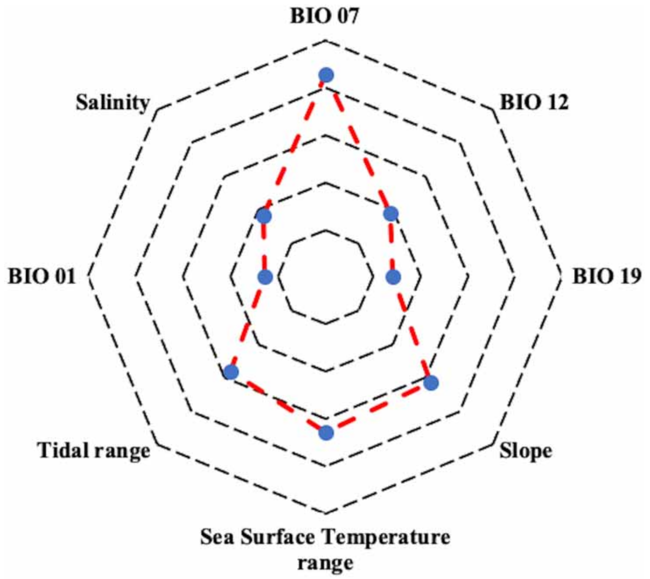


Figure 5 | Important variables in predicting the distribution of the *A.marina.*

The slope is also identified as one of the effective natural factors influencing mangrove development. Light slope and tidal flat habitats are more suitable conditions for the distribution of the species (Figure 4) (Chen *et al.* 2017; Duncan *et al.* 2018).

The previous study has shown that the eastern part of the Persian Gulf, the western part of the Oman Sea, and a few spots in the easternmost part of the coastal areas in Hormozgan province are the most suitable areas in terms of ocean characteristics for mangrove development (Khayrandish *et al.* 2015) which is consistent to our findings in this study.

Geological evidence shows that mangroves have adapted to previous climate changes (Alongi 2015; Woodroffe *et al.* 2016; De Palma *et al.* 2017). However, some species are susceptible to changes in hydrological or tidal levels that can lead to damage or destruction (Blasco *et al.* 1996; Martínez-López *et al.* 2015; Cui *et al.* 2021).

In general, the results of this study depicted the losses of suitable habitat area for *A. marina* in Iran based on 2061–2080 future climate scenario (RCP 8.5) compared to the current condition and climate and oceanographic changes emerging as critical drivers of the future distribution causing biological range shifts toward the Oman Sea.

Alongi (2015) showed that mangrove forests in humid climate conditions experience less stress, less salinity, and more freshwater and therefore, their biomass and productivity are greater than the communities residing in more arid areas like the southern coasts of Iran.

Predictions for the Persian Gulf, which is considered a dry region, show that the area of mangrove forests will be declining due to the synergistic impacts of salinity and aridity, shortage of freshwater and frequent exposure to the critical temperature threshold (Alongi 2015; Ward *et al.* 2016).

According to the results, *A. marina* conservation is likely to be a difficulty in the future, and future temperature increase could be the most important factor in the species' distribution (Figure 5). Temperature increase could limit the width of mangrove forests by salt marsh changes in a spatial context and, as a result, changes the species composition (Saintilan *et al.* 2014; Alongi 2015; Godoy & Lacerda 2015).

The future suitable habitat projections can help various aspects of decision-making in action management, resource management, conservation, restoration, and sustainable use. Since there is little information on the effects of climate change on mangrove forests in this area (Ward *et al.* 2016), this research provides valuable information for climate change mitigation initiatives and future adaptation of habitats, as well as the determination of protected areas and management areas to protect mangroves on the coasts of the Oman Sea and the Persian Gulf. In this study, only climatic data were used to determine future species distribution. Therefore, it is suggested that small-scale research be performed based on the appropriate combination of variables to provide more realistic outputs. On the other hand, it is suggested that in addition to ecological aspects, social and behavioural aspects should be considered in the management and protection of these forests (Garcia *et al.* 2020).

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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