# Stacked machine learning models for predicting species richness and endemism for Mediterranean endemic plants in the Mareotis subsector in Egypt

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## Abstract

An effective method for identifying species and evaluating the effects of changes caused by humans on specific species is the application of species distribution modelling (SDM) in desert environments. The fact that many dry lands and deserts throughout the world are situated in inhospitable regions may be the reason why such applications are still infrequently used on plant species in Egypt's Mediterranean region. Henceforth, the current study aims to map species richness and weighted endemism of Mediterranean endemics in the Mareotis subsector in Egypt and determine the environmental variables influencing distribution of these taxa. We produced a map of species distribution range using Ensemble SDMs. Further, stacked machine learning ensemble models derived from Random Forest (RF) and MaxEnt models were applied on 382 Mediterranean endemics distribution data to estimate and map diversity and endemism using two indices: species richness (SR) and weighted endemism index (WEI). The best models for ensemble modelling were chosen based on Kappa values and the Area Under the Receiver Operator Curve (AUC). The results showed that the models had a good predictive ability (Area Under the Curve (AUC) for all SDMs was > 0.75), indicating high accuracy in forecasting the potential geographic distribution of Mediterranean endemics. The main bioclimatic variables that impacted potential distributions of most species were wind speed, elevation and minimum temperature of coldest month. According to our models, six hotspots were determined for Mediterranean endemics in the present study. The highest species richness was recorded in Sallum, Matrouh wadis and Omayed, followed by Burg El-Arab, Ras El-Hekma and Lake Mariut. Indeed, species richness and endemism hotspots are promising areas for conservation planning. This study can help shape policy and mitigation efforts to protect and preserve Mediterranean endemics in the coastal desert of Egypt. These hotspots should be focused on by policy makers and stakeholders and declared as protectorates in the region. The largest number of species per area would be protected by focusing primarily on the hotspots with high species richness.

**Keywords** Ensemble modelling · Machine learning · Potential suitable distribution · Stacked SDMs · Endemism · Mediterranean

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## Background

According to Myers et al. (2000), the Mediterranean basin is one of the world's top 25 biodiversity hotspots. It is regarded as the second-largest biodiversity hotspot in the world, according to Lopez-Alvarado and Farris (2022). It comprises important terrestrial habitats such rainforests, maquis, garrigues, pastures, marshes, coastal regions and transitional to desert zones and spans more than 30 states. Also, it contains more than 25,000 species of flowering plants worldwide (Zahran 2010; Bedair et al. 2023a, b). In contrast to the more homogeneous regions to the north and south, the Mediterranean basin is bordered by the temperate,

desert and tropical biogeographical regions since it is the meeting place for Europe, Asia and Africa (Zahran 2010). As a result, the Mediterranean basin has an extraordinarily high level of biodiversity due to its complex topography, climate and edaphic features (Thompson 2020). Moreover, roughly 63.5% of species, according to the Med-Checklist, are endemic to the area (Heywood 2002). Due to the fact that many Mediterranean species are confined to a single or small number of locations, such as rocky or unusually fertile islands, isolated mountain ranges, or sandy plains, this region is distinguished by a higher degree of endemism than other regions (Zahran 2010).

The Mediterranean region's plant diversity depends heavily on endemism (Fois et al. 2022; Bedair et al. 2023c). This endemism is characterised by the fact that 60% of all species native to the Mediterranean region are narrow endemic species, meaning that their range is constrained to a single well-defined location within a relatively small portion of the Mediterranean region (Thompson 2020). Hence, the flora of the Mediterranean is abundant in small, indigenous taxa. This area's geographic isolation is characterised by a number of islands, peninsulas and tall mountains (Vargas 2020). There are more than 10,000 islands and islets scattered throughout the Mediterranean Basin. The two largest islands in the area, Sicily and Sardinia, are good instances of this (Médail 2022). They are followed by Cyprus, Crete, the Aegean Islands, Corsica and the Balearic Islands. Species isolation at high altitudes is also impressive. Because of the gradual changes in many parameters, such as temperature, precipitation and soil properties with the changes in altitude, mountain environments in particular provide good opportunities to study how plant species richness fluctuates in response to environmental conditions within geographically confined areas (Di Biase et al. 2021; Bedair et al. 2023c).

An SDM is a method for predicting a species' geographic spread using mathematical model that links its occurrence to the environmental variables in its habitat. It is also known as a "habitat suitability model," "ecological niche model," and "predictive habitat distribution model" (Schmitt et al. 2017). SDM is still one of the ecological methods most suited for figuring out how species distribution and environmental variables relate to one another (Guisan and Thuiller 2005). Indeed, multiple separate SDMs may be combined using stacked species distribution models (SSDMs) to create a community-level model (Ferrier and Guisan 2006). Rough probabilities (pSSDMs) have been shown by Calabrese et al. (2014) to function similarly, when estimating species richness, overestimate for low species richness sites and underestimate at high species richness sites.

Any species distribution model's accuracy and predictive capability depend on the reliability of the field data utilised and the selection of the environmental variables to be incorporated into the model (Peterson and Nakazawa

2008). For modelling the distribution of species at landscape dimensions, the availability of high spatial resolution environmental predictors is crucial (Austin and Van Niel 2011). It is challenging to find such high spatial resolution environmental data in the areas that have not been well explored. One of the biggest issues facing researchers is the lack of geographic resources (such as topographic and climatic databases) that represent regions in emerging countries and impoverished areas. However, it should be highlighted that even high-resolution maps may have errors of commission since the availability and resolutions of the predictor variables utilised restrict SDMs' accuracies and precision (McKerrow et al. 2018). The efforts to minimise omission errors from prior coarse resolution maps also lowered the underestimation in species richness maps and highlighted diversity hotspots in areas that the earlier maps had missed (Dlamini and Loffler 2023).

Regarding the evaluation of their biodiversity and comprehending the distribution of species nearby, arid lands generally and deserts especially are understudied regions (Brito et al. 2009). This is probably due to the harsh environment in these locations and the difficulty accessing some desert areas. In the few studies that did so, methods for modelling species distribution in desert ecosystems were successful in supplying tools for modelling species distribution patterns. However, the impact of environmental changes (climate, land-use change or any other disturbances) on the distribution of species in arid environments has not often been addressed using SDM techniques (Halmy 2012). This might be due to the fact that arid lands are some of the least researched regions in the world. Indeed, although some studies applied SDMs in Egypt (e.g. Halmy 2012; Khafagia et al. 2012; Kaky and Gilbert 2016, 2019; El-Barougy et al. 2021; Abdelaal et al. 2019; Kaky et al. 2020; Omar and Elgamal 2021a, b), few studies applied SDMs on the western Mediterranean region (Halmy 2012; Halmy et al. 2015a, 2019). The current study will estimate the effects of environmental changes on the distribution of Mediterranean endemics in the northwest coastal desert of Egypt using species distribution modelling methodologies. Recent coastal development projects have caused a dramatic change in the land use and cover of this region. The region includes El-Omayed biosphere reserve, a protected area that is also recognised by the UNESCO MAB program as a biosphere reserve. Species-distribution modelling techniques and available environmental predictors (bioclimatic and soil parameters) will be used here to: (1) Produce a map of species distribution range using ensemble SDMs; (2) Map species richness and weighted endemism of Mediterranean endemics; and (3) determine the environmental variables influencing distribution of these taxa.

## Materials and methods

### Geographic scope (study area)

The study covers the Mediterranean endemics whose distribution is restricted to the Mediterranean floristic region established by Good (1974), and spread along Egypt's Mediterranean coast as described by Zahran et al. (1985). In the present study, we depended on the checklist previously published by Bedair et al. (2022, 2023c).

The western Mediterranean territory in Egypt (the Mareotis subsector) extends for a distance of about 550 km between Alexandria and Sallum, with a rainfall of 220–150 mm annually). The area is bounded on the north by the Mediterranean Sea and extends south for an average distance of 30–50 km, crossing the Northern Limestone Plateau. The north-western coastal region stretches between 31° 38′ N and about 30° 40′ N (south of Hammam), and between 25° 11′ E (Sallum) and 29° 57′ E (Alexandria). It covers an area of 2.4 million ha (Bedair et al. 2022). In the present study, we focused on the Mediterranean endemic species in only the Mareotis subsector (Fig. 1).

### Environmental predictors and multicollinearity

Thirty-six environmental predictors were utilised. As model predictors, we used 8 precipitation measurements and 11 temperature metrics from the WorldClim database (1950–2000; version 2.1; Fick and Hijmans 2017) at a 30 arc-second resolution (about 1 km). These bioclimatic variables, which include regional variations of annual means, extreme or limiting climatic conditions, and seasonality (e.g. Buermann et al. 2008; Saatchi et al. 2008), have previously been used to estimate the distribution of plant species. Mean, minimum, maximum temperatures, solar radiation, precipitation and wind speed for each month were also used. Elevation data were gathered from the USGS National Elevation Dataset version 3.0, dated January 2022, the United States Geological Survey's digital elevation model. The data were used to model terrain features in the study area (https://www.usgs.gov).

Soil data including organic carbon content, pH, bulk density of the fine earth fraction, volumetric fraction of coarse fragments ($>2$ mm), cation exchange capacity, proportion of clay particles ($<0.002$ mm) in the fine earth fraction, proportion of sand particles ($>0.05$ mm) in the fine earth fraction, total nitrogen, Proportion of silt particles ($\geq 0.002$ mm and $\leq 0.05$ mm) in the fine earth fraction were obtained from Soil Grids version 2.0, dated October 2021, a global soil
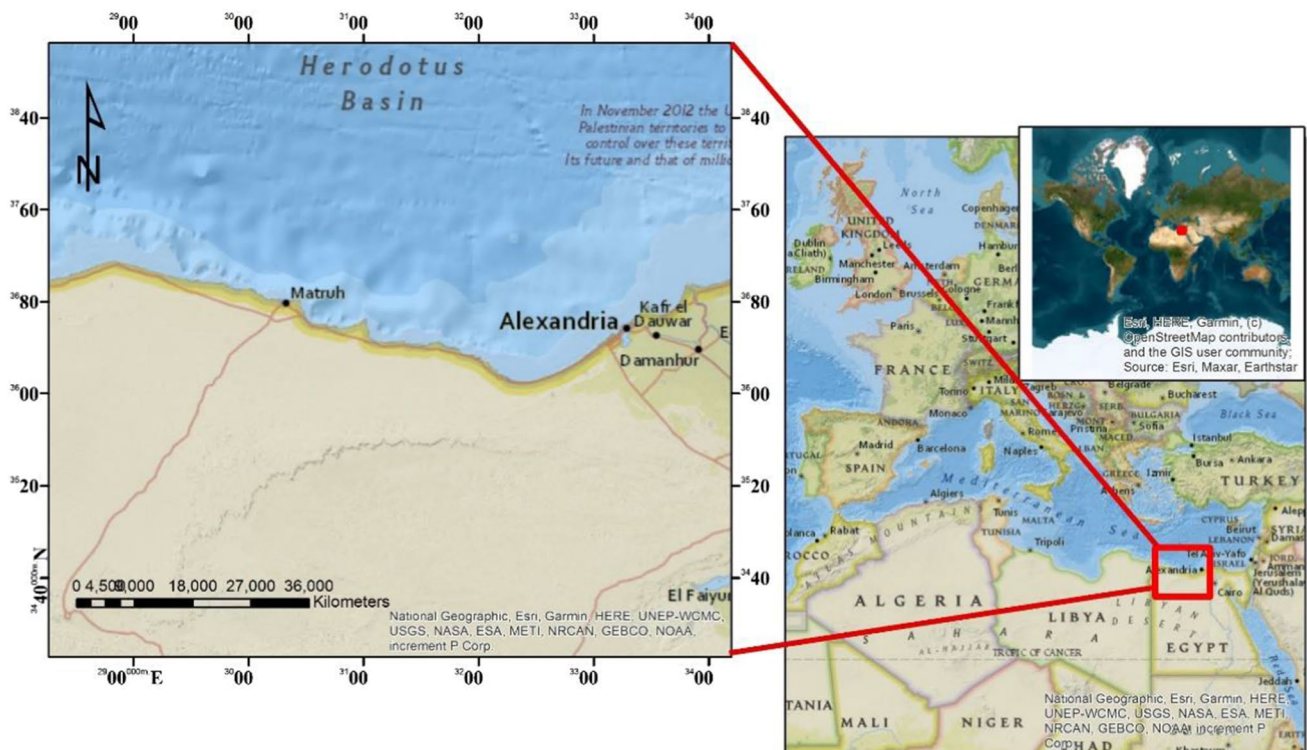


**Fig. 1** Map of the study area demonstrates the Mareotis subsector of Egypt's Mediterranean region

information system constructed by the International Soil Reference and Information Centre (ISRIC) in collaboration with a range of partners (Batjes et al. 2020), available at: https://soilgrids.org. Prior to analysis, to ensure spatial consistency between the 36 predictors, the Soil Grids data and the USGS elevation data were resampled to a projection of the cell size (1 km 1 km), pixel location, spatial resolution of 30 arc seconds and extent of the bioclimatic variables using the ArcGIS 10.2 software (ESRI 2013). Moreover, we used the ArcGIS tools were used to clip the bioclimatic, soil and elevation layers according to the study area shapefile.

The variance inflation factor (VIF), which evaluates how strongly each predictor may be explained by the other predictors, was used to identify highly correlated variables and eliminate them from SDM models in order to reduce overfitting (Naimi and Arajo 2016). We implemented the recommendations of Guisan et al. (2017) and performed VIF analysis using the vifcor and vifstep functions of the package "usdm" in R 4.2.3 (Niami 2017). These functions allow us to filter out variables with VIF values greater than five and a correlation threshold of 0.75. The "SDM" package's function getVarImp in R 4.2.3 was utilised to calculate the relative importance of the predictor variables (Naimi and Araújo 2016).

## Ensemble species distribution models (ESDMs) and stacked species distribution models (SSDMs) of Mediterranean endemic species

The distribution range of the Mediterranean endemics was predicted using ESDM. The prediction was done by combining 382 occurrence point data (collected from field visits, herbaria and data bank of Tanta Ecology group) of the endemic species of the Mediterranean with pseudo-absence data that the model generated at random (Barbet-Massin et al. 2012). Figure 2 represents some habitats of the Mediterranean endemics in the Mareotis subsector (taken by the authors). Spatial occurrence data filtering was implemented to consolidate all occurrence records into one point within a given distance in order to prevent the impact of spatial autocorrelations and clusters of occurrence records on the outcomes of the species models (i.e. under-prediction or over-prediction in specific areas). When creating species distribution models, this method has been advocated for taking into account spatial autocorrelation in occurrence data and minimising the impact of uneven sampling (Kramer-Schadt et al. 2013).

We implemented two machine learning algorithms: random forest (RF) and Maxent. RF works by growing a suite of regression trees that bootstrap the original data. The outcome of each bootstrap iteration informs the algorithm on how to fit the model (Fletcher and Fortin 2018). RFs have proven to be a powerful and versatile tool for predicting plant endemics and understanding the factors influencing their distribution because of their ability to handle high-dimensional and noisy datasets, nonparametric nature, feature importance assessment, handling missing data, model interpretability and the ability for identification of outliers in the training data (Gaier and Resasco 2023).

Further, Maxent is one of the most widespread and routine algorithms for SDMs in scientific studies and applied modelling approach (Lissovsky and Dudov 2021). It is based



**Fig. 2** Some habitats of Mediterranean endemics in the Mareotis subsector (taken by the authors)

on the principle of maximum entropy, which states that the most uniform distribution is the best approximation of an unknown distribution (Phillips et al. 2006). The advantages of this technique include that it (1) employs presence-only data, avoiding the need for confirmation of absences from specific places, (2) enables the use of environmental variables of different data type (categorical and continuous), although it does tend to favour categorical variables with more levels and (3) gives a technique for creating probability of occurrence estimates for the entire study area using sparse data (Wang et al. 2019). Moreover, RF and Maxent have proved their compatibility with small-area modelling.

To choose the best models for the ESDM, all the models were processed using special SDM algorithms (Ranjitkar et al. 2014). Following that, the best models for ensemble modelling were chosen based on Kappa values and the Area

Under the Receiver Operator Curve (AUC). The accuracy of the models was evaluated using the area under the receiver operating characteristic (AUC; Area under the ROC Curve) which is a nonparametric rating tool for the model's ability to predict both presence and absence (sensitivity and specificity; Ngarega et al. 2022). AUC values range from 0 to 1, and the closer an AUC value is to 1, the more effective the model is (Swets 1988: Table 1). The following analyses were carried out using two models: With appropriateness ranging from 0 (not suitable) to 1 (highly suitable), RF stands for Random Forest and Maxent for Maximum Entropy. AUC, Cohen's kappa coefficient, sensitivity (true positive rate), omission rate and specificity (true negative rate) were used to assess the effectiveness of our model (Fielding and Bell 1997) (Fig. 3).

We set the threshold to 0.75, indicating that any species with an AUC below 0.75 will not be included in the modelling. Finally, the final maps of the Species Richness (SR) were computed by summing continuous habitat suitability maps (pSSDM) with the "ssdm" package in R 4.2.3 (Schmitt et al. 2017). This was calculated through investigating the weighted means in the ESDM of our aggregated multiple species for each model that was selected. The species richness map, however, was scaled from 0 to 20 in order to allow for more accurate comparisons across the area. The produced computed maps were imported into ArcGIS as GeoTIFF files for further visualisation. Using Pearson's

**Table 1** The five categories used to rate the model's accuracy (Swets 1988)

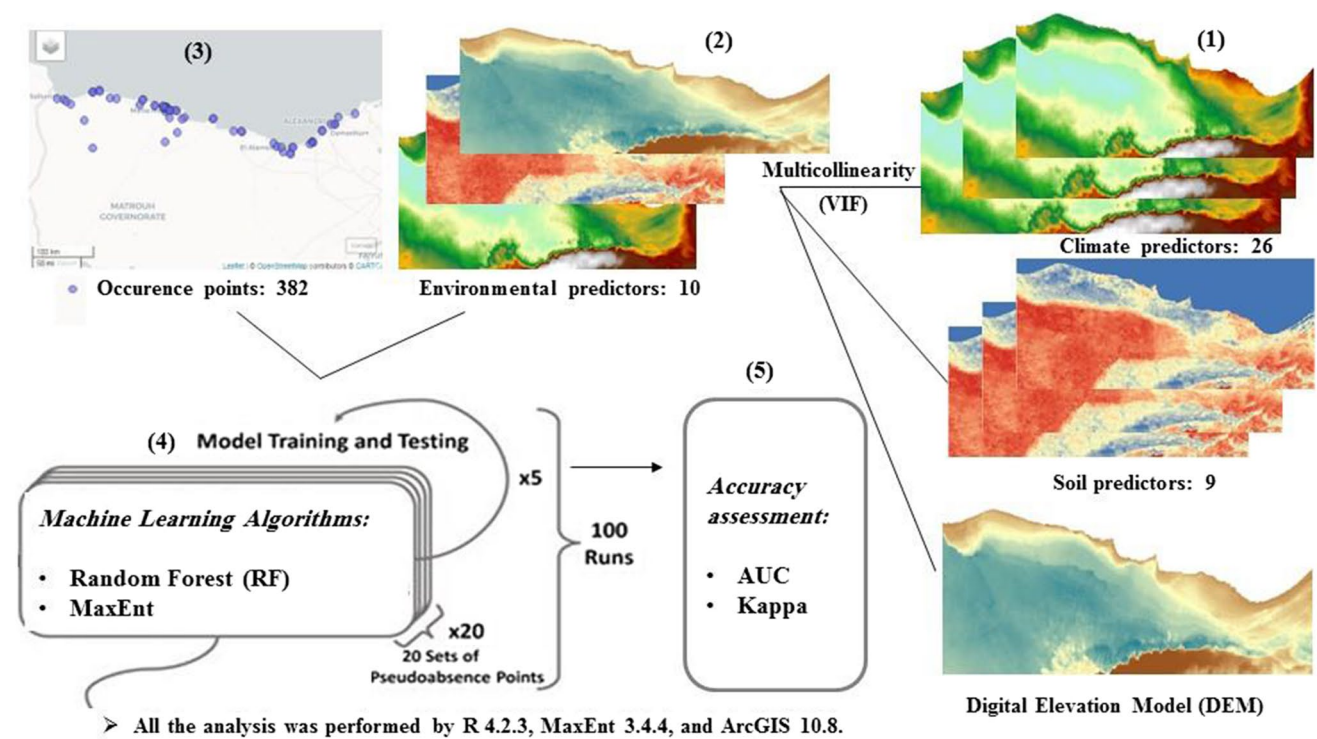| AUC | Category |
| --- | --- |
| 0.50–0.60 | Failure |
| 0.60–0.70 | Poor classification |
| 0.70–0.80 | Fair classification |
| 0.80–0.90 | Good classification |
| 0.90–1.00 | Excellent classification |



**Fig. 3** Species distribution modelling (SDMs) process

correlation coefficients, we assessed the variable importance/contribution scores for each individual variable in the study area (Nneji et al. 2020). In addition to species richness, we utilised the "ssdm" package for mapping local species endemism using the weighted endemism index (WEI) metric (Schmitt et al. 2017) that is calculated as follows:

$$WEI_c = \sum_{i=1}^{n_c} \frac{1}{r_{i,c}}$$

By adding the inverse of the geographic range size $r_{i,c}$ for each of the $n_c$ species, WEI for cell c is computed. The issue of defining what constitutes an endemic species using an arbitrary geographic or range-size criteria is something that WEI wants to avoid. Applying a straightforward continuous weighting function, WEI gives high weights to species with short ranges and progressively lower weights to species with broader ranges in order to avoid establishing a threshold for endemism.

## Results

Multicollinearity analysis of the total 36 environmental variables resulted in ten uncorrelated variables with VIF > 5 and a correlation threshold of 0.75 (Table 2), which had been used in the stacked species distribution modelling.

The Area Under Curve (AUC) and Kappa values show that the models created for the training data set are trustworthy (AUC = 0.892 and 0.784, respectively). Our ensemble SDM presents high species richness in coastline extending from Burg El-Arab to Alamein in the east and from Matrouh to Sallum in the west. Further, *Lotus polyphyllos*, *Posidonia oceanica* and *Thymbra capitata* were the most dominant Mediterranean endemics in the Mareotis subsector. According to Pearson's correlation coefficient analysis, the wind speed had the highest environmental importance as it contributed about 30% of the total variance. In comparison, the total Nitrogen, Bio 5 and Bio 13 had the least < 5% (Fig. 4). We found that our RF model had a better fit than the MaxEnt model with AUC more than 0.75. This was surprising because Maxent is a more widely used modelling algorithm for SDMs and has often been treated as the default method for its high predictive performance.

The separate SDMs of the Mediterranean endemics were stacked to produce models of current distribution of each species (Fig. 5). The spatial distribution pattern of Mediterranean endemics in the ESDM map is highly correlated with the species richness (SR) map (Fig. 5a). Indeed, six hotspots were determined for Mediterranean endemics in the present study (Lake Mariut, Burg El-Arab, Omayed, Matrouh wadis, Ras El-Hekma and Sallum). The highest species richness was recorded in Sallum, Matrouh wadis and Omayed, followed by Burg El-Arab, Ras El-Hekma and Lake Mariut, respectively. The Weighted Endemism Index (WEI) map constructed provides a picture of how the level of endemism of Mediterranean endemics is spatially organised in the Mareotis subsector. Indeed, the degree of endemism increases closer to the coastline of the Mediterranean Sea. The highest WEI hotspot was recorded in Omayed in the east and the coastline extending from Matrouh wadis to Sidi Barrani in the west (Fig. 5b).

According to Pearson's correlation coefficient analysis, elevation and wind speed had the highest environmental importance as they contributed about 20% and 17%, respectively (Fig. 6). The AUC values of the SSDMs ranged from a minimum of 0.5 to a maximum value of 1 (mean = 0.921), suggesting strong prediction performance for all the species included and studied (Table 3). According to all of the utilised measures of accuracy assessment, the models of sixteen of the nineteen species fared fairly well (they attained an AUC value over 0.7). Based on kappa values, *Thesium humile* var. *maritima* and *Ebenus armitagei* models are regarded as performing poorly as they had kappa values < 0.4, AUC 0.5 and omission rate 0.5 (Table 4).

## Discussion

While the scales and predictors required for robust and accurate predictions will vary depending on the target species' ecology, biology and life history, accurate predicting habitat suitability for species with specialised habitat requirements and specific biological dependencies using SDMs will frequently require local-scale predictors. Special consideration should be given to the variables crucial to the distribution of those organisms on which the focal species depends in the choice of suitable habitat for these sorts of species (Wang et al. 2019). In such cases, data quality filtering has the potential to improve species distribution forecasts, particularly for species where SDMs are less sensitive to sample size reductions (Van Eupen et al. 2021). Modelling small-size areas has been applied in ecological research and conservation such as Halmy (2012), Halmy et al. (2015a, 2019), Wang et al. (2019), Abdelaal et al. (2019) and Ahmadi et al. (2023).

In fact, modelling small-size areas plays a crucial role in conservation planning, especially for the identification of important habitats and the design of protected areas. Especially for the distribution of endemic plant species in a small region to prioritize conservation efforts and allocate resources effectively (Huang et al. 2020; Bedair 2023). Further, it is preferable in cases of island endemics and riparian zones that are typically narrow and exhibit distinct ecological conditions. Modelling these small zones can help understand the distribution of vegetation, habitat quality

**Table 2** Summary of the 36 total and 10 selected predictor variables explaining the potential distribution of Mediterranean endemics

| Correlated variables code | Variable | Correlated variables code | Variable |
|---|---|---|---|
| Bio 1 | Annual mean temperature | Tav | Average temperature (°C) |
| Bio 2 | Mean diurnal range (mean of monthly (max temp—min temp)) | Tmax | Maximum temperature (°C) |
| Bio 3 | Isothermality (Bio2/Bio7) ($\times 100$) | Tmin | Minimum temperature (°C) |
| Bio 4 | Temperature Seasonality (standard deviation $\times 100$) | Vapr | Water vapour pressure (kPa) |
| Bio 7 | Temperature annual range (Bio5-Bio6) | Srad | Solar radiation (kJ m$^{-2}$ day$^{-1}$) |
| Bio 8 | Mean temperature of wettest quarter | Prec | Precipitation (mm) |
| Bio 10 | Mean temperature of warmest quarter | pH | pH |
| Bio 11 | Mean temperature of coldest quarter | Bulk density | Bulk density of the fine earth fraction (cg cm$^{-3}$) |
| Bio 12 | Annual precipitation | Carbon | Soil organic carbon content in the fine earth fraction (dg kg$^{-1}$) |
| Bio 14 | Precipitation of driest month | Cation | Cation Exchange Capacity of the soil (mmol© kg$^{-1}$) |
| Bio 15 | Precipitation seasonality (coefficient of variation) | Sand | Proportion of sand particles ($> 0.05$ mm) in the fine earth fraction (g kg$^{-1}$) |
| Bio 16 | Precipitation of wettest quarter | Silt | Proportion of silt particles ($\geq 0.002$ mm and $\leq 0.05$ mm) in the fine earth fraction (g kg$^{-1}$) |
| Bio 17 | Precipitation of driest quarter | Bio 18 | Precipitation of warmest quarter |
| Selected variables code | Variable | VIF | |
| Bio 5 | Maximum temperature of warmest month | 1.75 | |
| Bio 6 | Minimum temperature of coldest Month | 1.60 | |
| Bio 9 | Mean temperature of driest quarter | 1.63 | |
| Bio 13 | Precipitation of wettest month | 1.95 | |
| Bio 19 | Precipitation of coldest quarter | 1.34 | |
| Clay content | Proportion of clay particles ($< 0.002$ mm) in the fine earth fraction | 3.62 | |
| Corase fragment | Volumetric fraction of coarse fragments ($> 2$ mm) | 2.38 | |
| Elevation | Digital elevation model | 2.74 | |
| Nitrogen | Total Nitrogen | 3.15 | |
| Wind | wind speed (m s$^{-1}$) | 2.66 | |

Correlated variables with variance inflation factor (VIF) values $> 5$ and a correlation threshold of 0.75 were removed to avoid multicollinearity problems

The linear correlation coefficients range between minimum correlation (nitrogen ~ bio 5: $-0.008$) and maximum correlation (nitrogen ~ clay content: 0.645)

for endemic species, or the impact of land-use changes on their ecosystems (Van Eupen et al. 2021). Nevertheless, the specific approaches and methods used will depend on the research question, available data and the characteristics of the small area under investigation.

Numerous environmental factors are frequently linked to the pattern of species distribution (Abdelsalam et al. 2023). Austin & Van Niel (2011) reviewed the conceptual framework of Franklin (1995) proposed for modelling plant species. Environmental predictors, which are thought of as direct factors impacting plant growth and spread, were highlighted. This comprised biotic interaction, temperature, light, water, nutrients and carbon dioxide. The findings of this study show that species distribution is influenced by topographic factors, where the elevation was found to be important in predicting most of the modelled species. In a study focusing on the Omayed region (one of the transects of the study area), Hammouda (1988) discovered that topography, type and origin of the parent material, level of human interventionand the land use, affect species distribution and the make-up of plant communities. The factor affecting how much moisture is available on the land surface is significant for species distribution, according to other studies that investigated environmental elements'
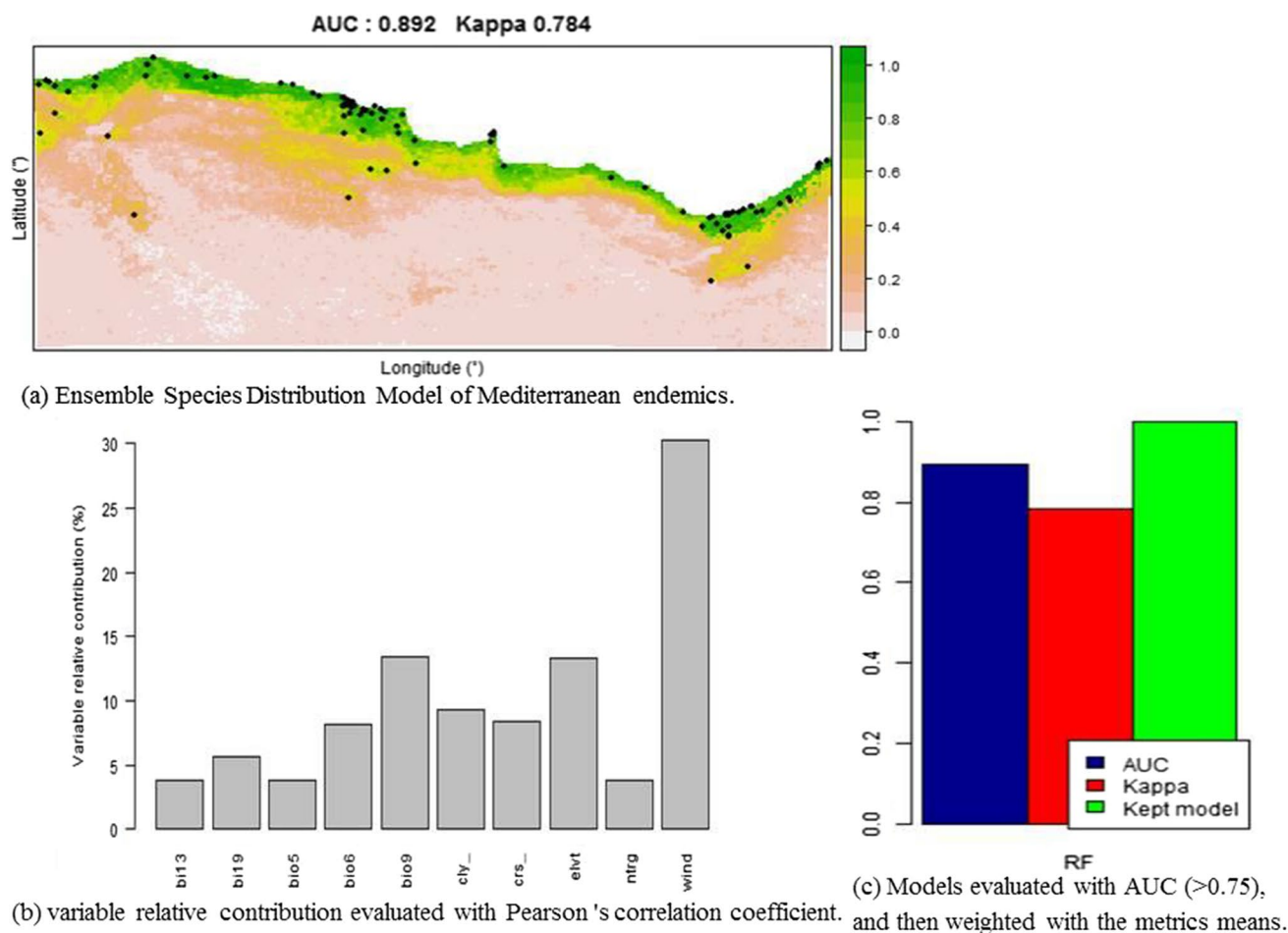
AUC : 0.892  Kappa 0.784

(a) Ensemble Species Distribution Model of Mediterranean endemics.

(b) variable relative contribution evaluated with Pearson's correlation coefficient.

(c) Models evaluated with AUC (>0.75), and then weighted with the metrics means.

**Fig. 4** Ensemble species distribution model (ESDM) of Mediterranean endemics in the Mareotis subsector

quantitative interactions with one another and vegetation in the northwest desert of Egypt (e.g. Ayyad 1973; Ayyad and Ammar 1973; Ayyad and El-Ghareeb 1972, 1982; Bedair 2020; Bedair et al. 2020). The natural vegetation is mostly governed by the microclimatic fluctuations caused by the topographic and physiographic variability (Shaltout et al. 2021). According to Ayyad and Ammar (1973), slope and curvature, which govern moisture availability through run-off, have a greater impact on the distribution of perennials than other parameters. Ayyad and Ammar (1974) also discovered that the main determinants of the region's vegetation composition were elements affecting moisture availability, such as topographic position, slope inclination, surface type, soil texture and depth. According to Ayyad and El-Ghareeb (1982), the soil's micro-variations were caused by changes in topography and the influence of the parent materials on the local species' distribution. Similar results were reported by Fois et al. (2017) who attained that the distribution of unique vascular plants on Sardinia, the second-largest island in the Mediterranean Basin, was discovered to be significantly influenced by elevation. Other Mediterranean contexts

have similarly observed an increase in the richness of plant endemics as elevation rises (Kallimanis et al. 2011; Steinbauer et al. 2013; Bonanno and Veneziano 2016; Steinbauer et al. 2016).

Relationships between environmental variables and richness of Mediterranean endemics may be affected by other significant factors, mainly wind speed. The ability of a plant to grow, reproduce, spread, die and ultimately evolve is influenced by wind. The air boundary layers near to a plant's aerial components, over which gas and heat exchanges with the environment take place, are responsible for some of the impacts. Wind also carries a variety of other particles like pollen, plant seeds and disease-causing organisms (Nobel 1981). A study conducted on Holocene coastal dunes in the Sardinia and Latium regions (Italy) of the western Mediterranean basin elucidated that wind-related factors are main variables regulating the richness of plant communities along coastal dunes (Fenu et al. 2013). It controls a significant difference in sand and salt spray conveyance, evaporation and transpiration in these significant habitats along the coastline (Maun 2004). A recent study by Halmy et al. (2015a)
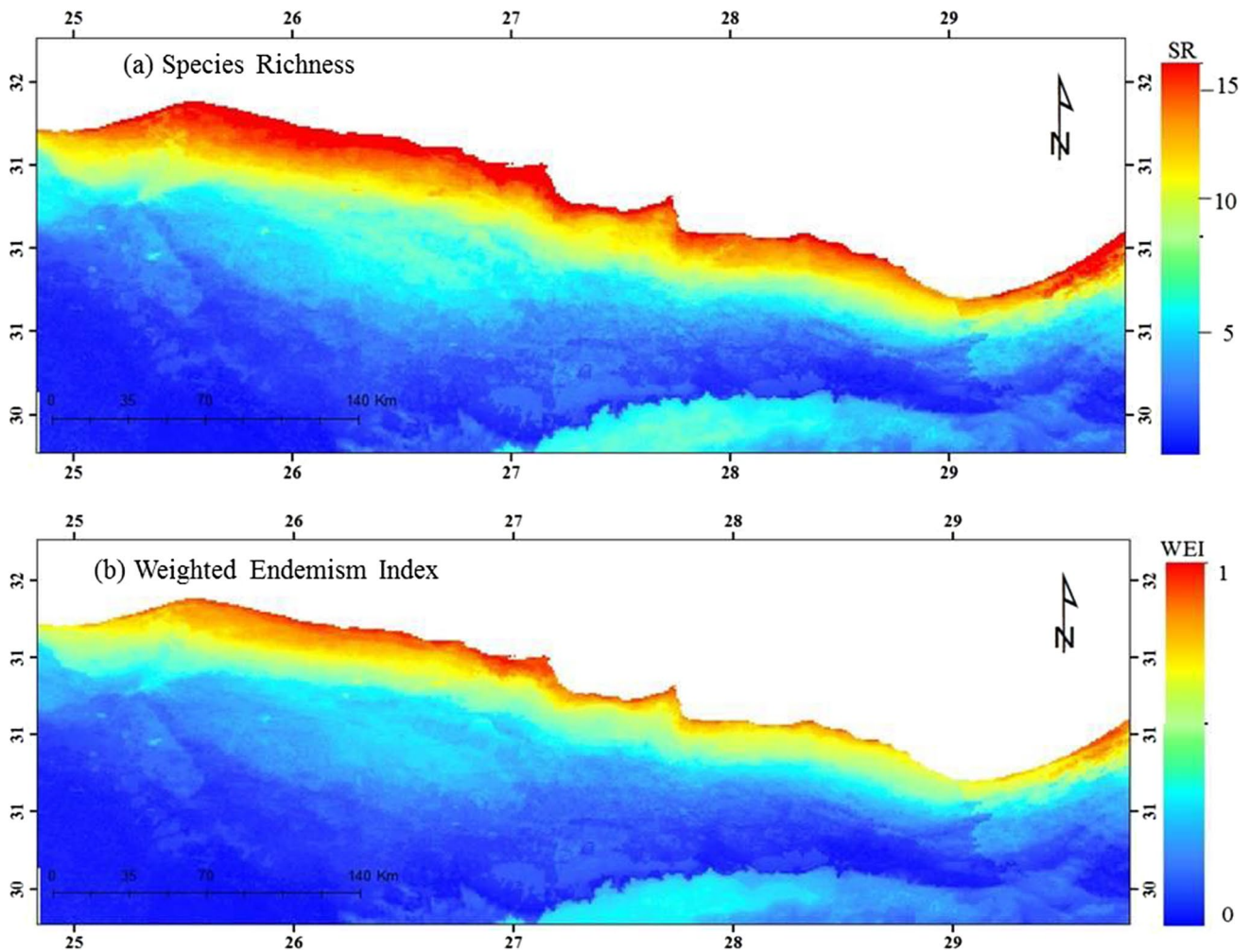
**Fig. 5** Maps of the predicted species richness (**a**) and weighted endemism index (**b**) of the Mediterranean endemics in the Mareotis subsector based on the stacked species distribution models (SSDM) produced by the "ssdm" package
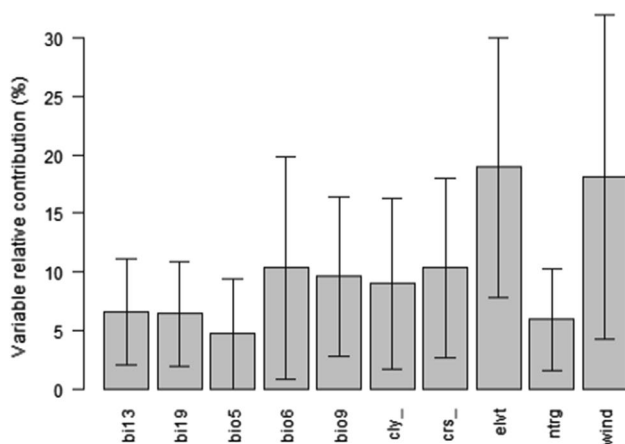


**Fig. 6** Mean variable relative contribution evaluated with Pearson's correlation coefficient

emphasised that elevation, climatic variables and proximity to the sea are significant factors controlling the locations of significant plant species in Egypt's northern coastal desert. Further, pioneer research on Spain's eastern and southern coastal regions (Guara-Raquena 1989, 1992) revealed that three primary factors (topography, distance from the sea and habitat modification) were primarily associated to the distribution of psammophilous plants and coastal dune communities.

The overall vegetation cover seems to be affected by climatic variables that represent the annual cycle, such as annual temperature and precipitation. Due to their proximity to the Mediterranean Sea and the Atlantic Ocean, these characteristics set apart wet regions from desert areas (Walas and Taib 2022). In the present study, minimum temperature of coldest month (Bio 6) and mean temperature of driest quarter (Bio 9) were the common climate variables that influenced the distribution of the majority of the species in

**Table 3** Accuracy measures of the SSDM of Mediterranean endemics in the Mareotis subsector

| Accuracy assessment | Species richness | Prediction success | AUC | Kappa | Specificity | Sensitivity | Jaccard |
|---|---|---|---|---|---|---|---|
| Mean | 13.92 | 1.27 | 0.92 | 1.00 | 0.21 | 1 | 0.11 |
| Standard deviation | 4.35 | 1.09 | 0.16 | 0.01 | 0.25 | 0 | 0.09 |

the models. According to the findings of the present study, Halmy (2012), Halmy et al. (2015a) and Abdelaal et al. (2020), climatic variables that reflect seasonality are more significant for the distribution of the species at local scales. According to Abdelaal et al. (2020), mean temperature of wettest quarter (Bio 8) and precipitation seasonality (Bio 15) are the key drivers for species richness at the Mareotis subsector of Egypt. The comparatively heavy rains and low temperatures are the main distinguishing characteristics, which in turn sustain a broad variety of endemic species and the diversity of plants (Abdelaal et al. 2020). These findings agree to some extent with those of Zahran et al. (1990), Zahran and Willis (2009) and Frihy and El-Sayed (2013).

The distribution patterns of Mediterranean endemic species richness and endemism demonstrate considerable

**Table 4** The modelled selected important plant species recorded in the study area

| Species | Threshold | AUC | Omission rate | Kappa |
|---|---|---|---|---|
| *Lotus polyphyllos* | 0.32 | 0.82 | 0.18 | 0.64 |
| *Thymbra capitata* | 0.50 | 1.00 | 0 | 1.00 |
| *Posidonia oceanica* | 0.33 | 0.75 | 0.25 | 0.50 |
| *Hyoseris scabra* | 0.46 | 1.00 | 0.00 | 1.00 |
| *Hyoseris radiata* subsp. *graeca* | 0.55 | 1.00 | 0.00 | 1.00 |
| *Cynara cornigera* | 0.43 | 1.00 | 0.00 | 1.00 |
| *Ebenus armitagei* | 0.42 | 0.50 | 0.50 | 0.00 |
| *Thesium humile* var. *maritima* | 0.49 | 0.50 | 0.50 | 0.00 |
| *Allium barthianum* | 0.46 | 1.00 | 0.00 | 1.00 |
| *Allium blomfieldianum* | 0.66 | 1.00 | 0.00 | 1.00 |
| *Anthemis microsperma* | 0.49 | 1.00 | 0.00 | 1.00 |
| *Bupleurum nanum* | 0.63 | 1.00 | 0.00 | 1.00 |
| *Centaurea pumilio* | 0.53 | 1.00 | 0.00 | 1.00 |
| *Helianthemum crassifolium* subsp. *sphaerocalyx* | 0.67 | 1.00 | 0.00 | 1.00 |
| *Lathyrus marmoratus* | 0.61 | 1.00 | 0.00 | 1.00 |
| *Limonium echoides* | 0.55 | 1.00 | 0.00 | 1.00 |
| *Lotus cytisoides* | 0.32 | 1.00 | 0.00 | 1.00 |
| *Pancratium arabicum* | 0.61 | 1.00 | 0.00 | 1.00 |
| *Verbascum letourneuxii* | 0.19 | 1.00 | 0.00 | 1.00 |

Accuracy assessment measures presented are: Cohen's Kappa statistic; omission rate and the area under the curve (AUC) statistic of the receiver operating characteristic (ROC)

regional overlaps despite various degrees of correlations. Overall, patterns of endemism and species diversity are very similar, largely because fragile ecosystems characterise areas with high endemism. Additionally, the majority of endemic species have a small range, are vulnerable to outside intervention and are at risk of going extinct (Myers et al. 2000; Zhao et al. 2016). As a result, there is geographic overlap between the hotspots identified by the SR and WEI indices. The WEI, however, exhibits more restricted and smaller hotspots. This may be the result of the distribution patterns of endemic species being strongly connected with human disturbance or threat circumstances, in addition to the relationship to actual species distribution (Zhao et al. 2016). The findings not only underscore current hotspots for Mediterranean endemics, but also shed light on the distribution biogeographically and evolutionary history of the Mediterranean flora, as was also shown for southern Africa by Daru et al. (2015) and Dlamini and Loffler (2023).

Spectacularly, endemism and species richness hotspots are promising areas for conservation planning (Shaltout et al. 2023). The largest number of species per area would be protected by focusing primarily on the hotspots with high species richness (Dlamini and Loffler 2023). The protection of species with limited ranges is emphasised by concentrating conservation efforts in regions with high levels of endemism, where there may be low levels of species composition similarity (Xu et al. 2017). Although, the staff of the Nature Conservation Sector has established and are managing thirty protected areas, which represent Egypt's most ecologically significant regions, only two of these reserves (Omayed Biosphere Reserve and Sallum) are located in the Mareotis subsector (Shaltout and Eid 2017). Nevertheless, due to unabated human activity, these protectorates are susceptible to several hazards. Habitat loss due land-use change in a large portions of the coastal strip between Alexandria and Matruh that have been consumed by urban growth and tourism development (Halmy 2012; Halmy et al. 2015b). Unfortunately, this area is considered an endemism hotspot for 54 Mediterranean endemics of the present study such as *Anthemis microsperma*, *Bupleurum nanum*, *Cynara cornigera*, *Filago mareotica*, *Fumaria gaillardotii*, *Fumaria judaica*, *Hyoseris radiata*. Subsp. *Graeca* and *Hyoseris scabra*.

Furthermore, using criteria that consider species vulnerability (i.e. threatened species at the global, regional and national scales), irreplaceability (i.e. near-endemics, steno- and national endemics and Mediterranean endemics) and

species richness, ten out of twenty Important Plant Areas (IPAs) were chosen in Egypt (Shaltout and Eid 2017, Shaltout and Bedair 2022, 2023). These criteria also take into account threatened habitats (at the Mediterranean and national scales), which are only found in the Mediterranean region. Five of which (Omayed Biosphere Reserve, Lake Mariut, Moghra Oasis, Sallum Area and Western Mediterranean Coastal Dunes) are located in the Mareotis subsector (Shaltout and Eid 2017). Although Ras El-Hekma holds a fauna and flora characteristic of the western Mediterranean coast of Egypt, perhaps the floral components are what matter the most as it supports 7 Mediterranean endemics such as *Ebenus armitagei*, *Centaurea pumilio*, *Helichrysum orientale*, *Pancratium arabicum*, *Lycium schweinfurthii* var. *aschersonii*, *Thesium humile* var. *maritima* and *Verbascum letourneuxii*. It is quite simple to determine the boundaries of priority conservation areas in the Mareotis subsector since there is significant spatial overlap among the hotspots identified using the SR and WEI. However, compared to employing SR, the size of hotspots is decreased when using the WEI index. Therefore, merging the hotspots will probably produce a larger conservation effect with limited resources, even if it is important to develop a clear and agreed-upon index when prioritising places for conservation. Therefore, in order to ensure the greatest scope of protection, creative community-public–private conservation partnerships must be adopted as part of conservation plans. Particularly, where there is a significant environmental fragmentation, the identified hotspots could be conserved individually or as a continuum connected to the current protected area network.

## Conclusions

The application of RF and Maxent to the employed climatic and soil variables proved to be successful in predicting the distribution of Mediterranean endemics in the western Mediterranean coast of the desert of Egypt. Although Maxent is a more popular modelling algorithm for SDMs and is frequently regarded as the standard approach by modellers, with an AUC greater than 0.75, it was revealed that our RF model fits the data better than the Maxent model. This caught people off guard because. The minimum temperature of the coldest month, wind speed and elevation were the main environmental parameters impacting the potential distribution of most species. High species richness is shown by our ensemble SDM along the coast, which stretches from Burg El-Arab to Alamein in the east and from Matrouh to Sallum in the west. To create models of each species' present range, the independent SDMs of the Mediterranean endemics were stacked. In fact, six hotspots for Mediterranean endemics (Lake Mariut, Burg El-Arab, Omayed, Matrouh wadis, Ras El-Hekma and Sallum) were identified in the

current study. Sallum, Matrouh wadis and Omayed have the most species, followed by Burg El-Arab, Ras El-Hekma and Lake Mariut, in that order. The SSDMs' AUC values ranged from 0.5 to 1 (mean = 0.921), indicating high prediction performance for all the included and investigated species, which in turn proves the efficiency of SSDMs for predicting species richness and endemism for confined species. Indeed, hotspots for endemism and species diversity offer potential locations for conservation planning in the future.

## Declarations

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