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Original Article

Prediction by maximum entropy of potential habitat of the cork oak (*Quercus suber* L.) in Maamora Forest, Morocco

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ABSTRACT

In this paper, the maximum entropy (MaxEnt) algorithm was applied to estimate the current and potential distributions of cork oak (*Quercus suber* L.) in the Maarmora forest of Morocco to provide a basis for its conservation under climate change conditions in the Mediterranean basin. A total of 1,428 field-based spatial records of cork oak locations were used (altitude and 19 bioclimatic environmental variables) to model the potential distribution of the cork oak. The adjusted model had a good predictive quality (area under the curve=0.81). Precipitation during the wettest quarter of the year, seasonality in precipitation, altitude, and seasonal variations in temperature were the key factors determining the distribution of the cork oak in the Maamora forest. Most areas with currently suitable conditions for cork oak were located in the western and central Maamora forest regions, which enjoy a humid bioclimate and receive significant sea spray from the Atlantic Ocean. Moving away from the ocean, the humidity decreases, and the temperature increases, such that the cork oak faces difficulties in adapting and regenerating. The results can be used to identify the high-priority areas for cork oak restoration and conservation of this species against the expected impact of climate change.

Keywords: Climate change, environmental variables, MaxEnt, spatial modeling, *Quercus suber*

Introduction

Cork oak (*Quercus suber* L.) is an endemic taxon in the oceanic Mediterranean climate, particularly on the Atlantic coasts in Morocco, Portugal, Spain, southwest of France, and the Bay of Biscay (Vessella & Schirone, 2013). The cork oak characterized by a mosaic of habitats ranked among the most valuable oaks in Europe and is listed in the European Commission Habitats Directive (Vessella & Schirone, 2013). The landscapes of *Q. suber* sustain biodiversity and conventional livelihoods, represent an important source of income, and play a major function in ecological processes, such as soil protection, water preservation, and carbon storage (Gil & Varela, 2008). Forest fires and diseases, overgrazing, and exploitation are causing a serious reduction of the species' area of occupancy all over the Mediterranean basin with subsequent biodiversity loss and degradation of ecosystem services (Bugalho et al., 2011; Sedda et al., 2011). Owing to the severe decrease in cork production, Vessella & Schirone (2013) proposed that deep investigations are required about the ecologically convenient areas in Italy for the species. Due to disturbance, habitat fragmentation, and climate change in cork oak areas, many researchers suggest that predictions of suitable expansion areas should be considered of high importance not only for reforestation but also for conservation and management purposes (Channell & Lomolino, 2000; Parmesan, 2007; Petit et al., 2005).

Maamora forest represents the largest lowland cork forest in the world; it covers an area of 133,000 hectares, including 60,000 hectares of pure cork oak. It constitutes a space of primary importance for the population of large urban agglomerations, such as Rabat, Salé, Khémisset, and Kénitra, with around 2 million inhabitants (Alaoui et al., 2020; Boudy, 1950; Laaribya, 2006). The cork oak forests of the coastal plains in the Maamora forest covered more than 130,000 hectares at the beginning of the 20th century (Emberger, 1939).

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The problem of regeneration of the cork oak in Maamora is posed since 1930 (Laaribya et al., 2013; Marion, 1951; Marion, 1953; Marion, 1955). Several studies have shown that the disturbance of this cork oak regeneration process is because of climatic and anthropogenic factors (overgrazing factors in particular) and a low germination capacity (Alaoui et al., 2020; Ezzahiri & Belghazi, 2000).

These factors urged to face the challenge of restoring this cork oak ecosystem and maintaining the current distribution of the cork oak (Alaoui et al., 2020; Laaribya et al., 2010; 2013; Oubrahim et al., 2015).

Given this situation, this study was necessary to highlight the spatial potential forest cover in connection with the ecological and bioclimatic requirements of the cork oak. This work aimed to identify the factors leading to the spatial distribution of cork oak and to map the potential habitat of this Mediterranean fragile species. Suitability has been assessed under the current climatic circumstances to ensure sustainable development. The maximum entropy (MaxEnt) algorithm was used to predict the potential habitat in order to link species locations with bioclimatic and environmental characteristics (Al-Qaddi et al., 2016; López-Tirado et al., 2020; Vessella & Schirone, 2013). Modeling potential distribution will help to develop forest policies and promote the conservation of the cork oak.

Method

Study Area

The Maamora forest is situated in the northwest of Morocco close to the Atlantic Ocean, between 6° and 6° 45′ West and 34° and 34° 20′ North. It is divided into 5 distinct cantons to facilitate forest management, denoted from west to east by the letters A, B, C, D, and E, respectively (Figure 1). The topography is flat. Its altitudes range from 6 to 8 m close to the coast, up to 300 m in the northeastern corner.

The Maamora cork oak forest occupies a subhumid bioclimatic zone in its western part (Cantons A, B, and C) and a semiarid zone in its central and eastern parts (Cantons D and E) (Emberger, 1939).

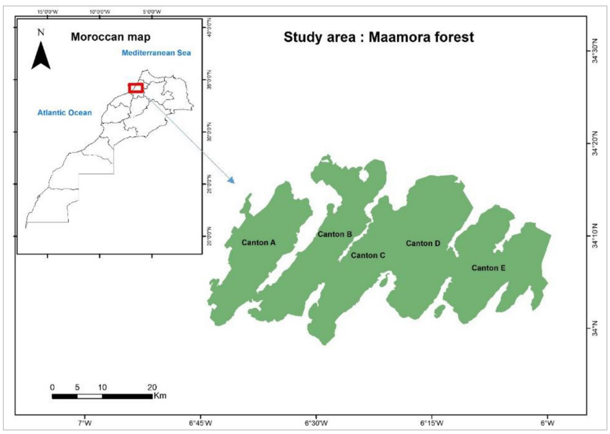

Figure 1
Study Area

Modeling Approach, Processing, and Data Used

On the basis of species presence data and environmental predictor maps, the spatial distribution modeling was used to predict the likely habitat for cork oak occurrence as a function of its environmental limitations. The algorithm was used as a modeling approach to link the species areas of occupancy with various environmental predictors.

MaxEnt software (Baldwin, 2009; Phillips et al., 2006; Phillips & Dudík, 2008), was used to predict the potential distribution on the basis of environmental factors and cork oak occurrence data. The MaxEnt algorithm method is justified by the performance of its modeling method, its robust handling of correlated variables, and its efficiency in handling complex interactions between response and predictor variables (Elith et al., 2011). We used all of the environmental variables described in this study in the final model.

We randomly sampled 1,428 spatial occurrence points of cork oak trees (Figure 2). Their coordinates (latitude and longitude) were mainly taken from the National Forest Inventory database (Anonymous, 2020). One tenth of the spatial records was ground surveyed to verify the database in the field.

In addition, 20 environmental predictors were used in the model—altitude and the 19 bioclimatic variables (Hijmans, 2004; Nix, 1986) most directly related to the physiological aspects of plant growth (Lehmann et al., 2011) (Table 1). The environmental variables were extracted from the WorldClim database (http://www.worldclim.org) in raster format at a resolution of 30 arcs per second (~1 km^2) (Fick & Hijmans, 2017).

Model Performance, Geographic Information Systems, and Cartography

The intrinsic validity of a model is characterized by its sensitivity and specificity. These two parameters allow the construction of a specific operating curve, the receiver operating characteristic (ROC) (Hanley & McNeil, 1982).

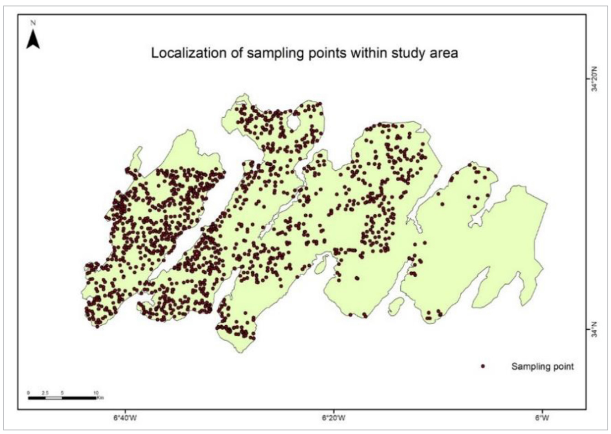

Figure 2
Sampling Locations for Cork Oak Within the Study Area

The calculated area under the curve (AUC) is a threshold that measures the accuracy of the model prediction (Fawcett, 2006) and provides information about the performance and quality of the model to correctly predict the occurrence of the species (Hanley & McNeil, 1982). The Jackknife test was used on our 20 predictors to rank those contributing the most to the model. The Jackknife test is a resampling technique especially useful for variance and bias estimation.

The probability map of the occurrence of cork oak corresponds to a logistical outing with values between 0 and 1. To better characterize the potential cork oak habitat, a threshold was used to delimit the predicted potential area. The threshold used was that relating to the 10th percentile training presence and represented the probability that 90% of the points of presence would fall in this potential area. This threshold improved the result and was ecologically significant when compared with the performance of other thresholds (Phillips & Dudík, 2008). Cartographic and geographic information systems processes were used (ArcGIS software) to design, prepare, and produce current and potential maps of cork spatial distribution.

Table 1
Predictors Used in the Modeling Process

Code	Variables	Unit
BIO1	Annual mean temperature	°C
BIO2	Mean diurnal range (mean of monthly [max temp-min temp])	°C
BIO3	Isothermality (BIO2/BIO7) (×100)	%
BIO4	Temperature seasonality (standard deviation ×100)	°C
BIO5	Max temperature of the warmest month	°C
BIO6	Min temperature of the coldest month	°C
BIO7	Temperature annual range (BIO5-BIO6)	°C
BIO8	Mean temperature of the wettest quarter	°C
BIO9	Mean temperature of the driest quarter	°C
BIO10	Mean temperature of the warmest quarter	°C
BIO11	Mean temperature of the coldest quarter	°C
BIO12	Annual precipitation	mm
BIO13	Precipitation of the wettest month	mm
BIO14	Precipitation of the driest month	mm
BIO15	Precipitation seasonality (coefficient of variation)	%
BIO16	Precipitation of the wettest quarter	mm
BIO17	Precipitation of the driest quarter	mm
BIO18	Precipitation of the warmest quarter	mm
BIO19	Precipitation of the coldest quarter	mm
BIO11	Mean temperature of the coldest quarter	mm
ALTI	Altitude	m

Max: maximum, Min: minimum.

Results

According to the ROC curve (Figure 3), the AUC value was 0.807. This value indicated a strong prediction of the distribution model for cork oak in the Maamora forest.

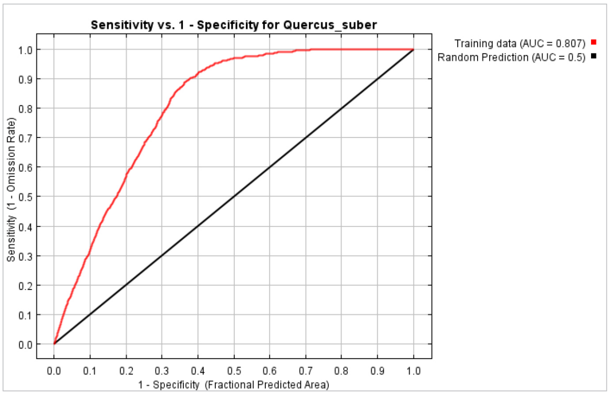

Figure 3
ROC Curves for the Occurrence of the Cork Oak
Note. ROC: receiver operating characteristic

Table 2
Relative Contributions of the Environmental Variables to the MaxEnt Model

Variable	Percentage contribution	Permutation importance
BIO16	57.6	28.4
ALTI	17.1	9.1
BIO15	8.4	12.4
BIO4	3.1	2.2
BIO3	2.4	2.9
BIO1	2.3	12.3
BIO8	1.4	2
BIO13	1.4	.9
BIO19	1.3	9
BIO17	1.3	3.3
BIO6	1	3.2
BIO5	.8	5.6
BIO12	.6	3.7
BIO14	.3	.1
BIO7	.3	3.2
BIO9	.3	0
BIO18	.2	1.6
BIO10	.2	.1
BIO11	.1	0
BIO2	.1	0

The adjusted MaxEnt model was clearly able to discriminate the most suitable cork oak habitat.

Table 2 gives the estimates of the relative contributions of the environmental variables to the MaxEnt model predictions. Analysis of the percentage contributions of different variables showed that precipitation during the wettest quarter (BIO16) was the most important variable and explained most of the variation (57.6%). Following this were the contributions of altitude (17.1%), seasonality of precipitation (BIO15) (8.4%), and seasonality of temperature (BIO04) (only 3.1%).

Figure 4 shows the results of the Jackknife test of variable importance. The environmental variable with the highest gain taken in isolation was the precipitation during the wettest quarter (BIO16), which therefore appeared to be the most useful single variable. The environmental variable that mostly decreased the gain upon omission was altitude (ALTI), which therefore appears to contain the most information not present in the other variables.

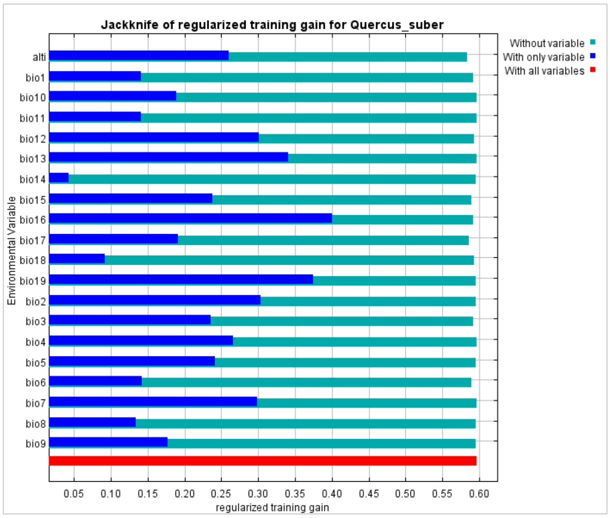

Figure 4
Results of the Jackknife Test of Variable Importance

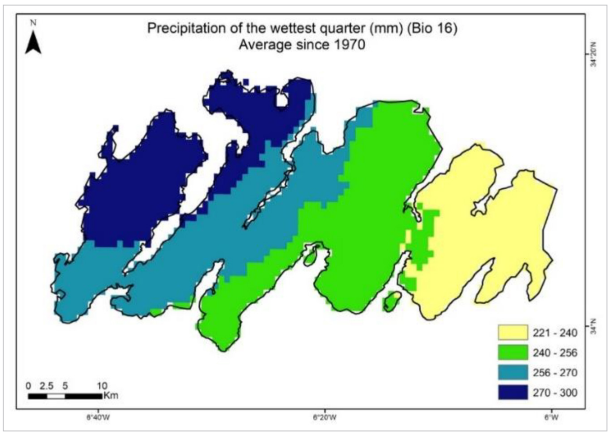

Figure 5
Precipitation of the Wettest Quarter (BIO16)

Figures 5-8 show environmental factors dictating the spatial distribution of cork oak in the Maamora forest: (1) precipitation during the wettest quarter, (2) precipitation seasonality (coefficient of variation), (3) altitude, and (4) temperature seasonality (standard deviation ×100).

The set of variables that contributed the most to the model predictions explaining the spatial distribution of cork oak were

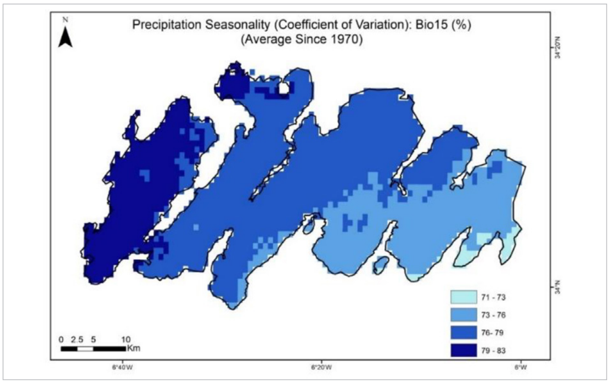

Figure 6
Seasonality of Precipitation (Coefficient of Variation) (BIO15)

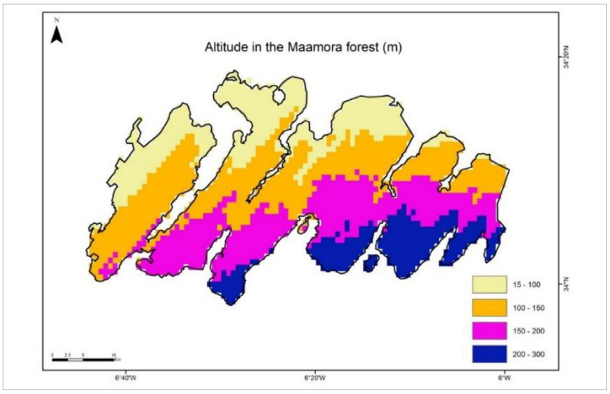

Figure 7
Altitude (ALTI)

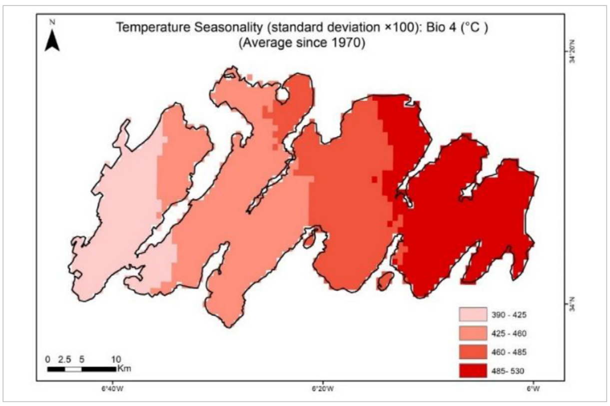

Figure 8
Temperature Seasonality (Standard Deviation × 100) (BIO04)

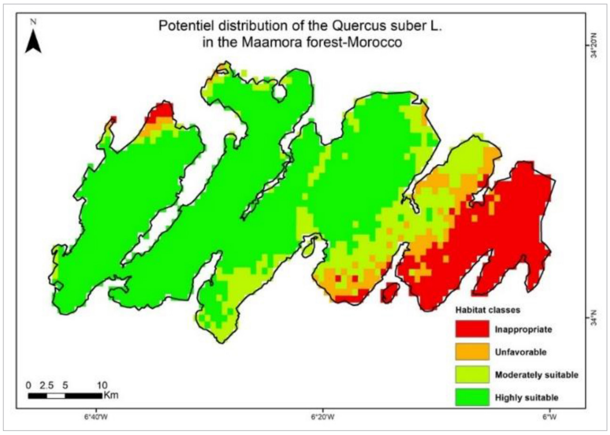

Figure 9
Map Showing the Suitable and Unsuitable Areas for Cork Oak

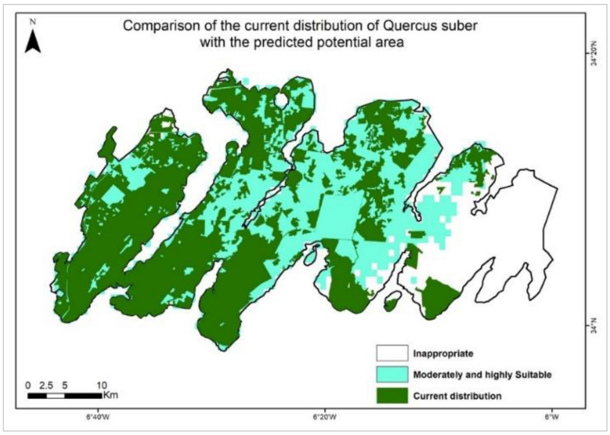

Figure 10
Map Linking Current and Potential Distribution of Cork Oak

those climatic descriptors linked to rainfall, which played a key role in preserving cork oak in the Maamora forest.

Figure 9 shows the MaxEnt model's representation of suitable/unsuitable potential areas for cork oak distribution. Green colors show the areas with predicted moderate and good conditions.

Regarding the current and potential distributions of cork oak, the map (Figure 10) confirms that the western and central areas of the Maamora forest region, which enjoy subhumid bioclimates, are ideal for cork oak. The semiarid bioclimate to the east seems inhospitable for this species expansion in the current Mediterranean climate.

Discussion, and Conclusion and Recommendations

In this study, the potential habitat (suitable and unsuitable) area of the cork oak in the Maamora forest in Morocco was investigated. The study area is interesting for two reasons: (1) this forest is the largest flatland cork oak forest in the world (133,000 hectares); and (2) it currently faces problems of natural regeneration and conservation, which are exacerbated by the Mediterranean climate change.

Thuiller et al. (2003) stated that heuristic (GARP) and MaxEnt approaches are useful tools in outlining improved and detailed prediction maps that play a major role in addressing focused strategies to achieve conservation and reforestation. Several similar recent studies have used MaxEnt for Modeling Spatial Distribution to predict the potential distribution of endemic species (Abdelaal et al., 2019; Al-Qaddi et al., 2016; Aghakhani et al., 2017; Lahssini et al., 2015; Stephan et al., 2020). The results of all these studies have highlighted the role of bioclimatic factors in providing suitable areas in which forest tree species can thrive and colonize.

Although the use of ROC analysis is lately being argued (Lobo et al., 2008; Peterson et al., 2008), numerous studies confirmed its wide application and efficacy to validate species distribution models (Allouche et al., 2006; Terribile et al., 2010). The AUC value was .807, indicating a strong predictive value (Araújo et al., 2005) of the distribution model for the cork oak in the Maamora forest. The high AUC value of the model for the cork oak reflects its strong predictive power. The area under the ROC curve values >.75 are indicative of powerful models (Phillips & Dudik, 2008), and the AUC value of .81 for our model indicates its high predictive value for the distribution of cork oak in the Maamora forest.

Analysis of the contribution of different variables to the model shows that precipitation during the wettest quarter contributes the most (57.6%). Next are the contributions of altitude (17.1 %), seasonality of precipitation (8.4%), and the seasonality of temperature (only 3.1%). The contribution of altitude could be explained by the interdependence between climatic parameters and geographic factors.

This analysis of the distribution of cork oak in the Maamora forest shows that the total precipitation during the wettest 3 months of the year has potential as an important bioclimatic index for suitable areas for cork oak growth and describes the areas with subhumid bioclimatic conditions in the oceanic western parts of this forest (Cantons A and B). On the other hand, the potential is less in the central part of the forest (Cantons C and D), and conditions are poor in the semiarid, eastern part (Canton E). This means that cork oak stands in Cantons C, D, and E are situated in much less favorable or even unfavorable locations for growth, regeneration, and sustainability. Other studies in the Maamora forest have confirmed these findings (Aafi, 2007; Benabid, 2000; Laaribya, 2006). The cork oak in Maamora has reached its ecological limit. Furthermore, climate change may exacerbate the area's decreasing rainfall gradient from west to east, putting the species under even more pressure.

GARP and MaxEnt identified draughtiness and cold stress as the main ecological factors for cork oak occurrence and growth performance in Italy and other Mediterranean countries (Hidalgo et al., 2008; Maltez-Mouro et al., 2009; Vessella et al., 2010). In this study, bioclimatic indicators showed that the Maamora forest is at the lower arid limit of the bioclimatic conditions suitable for cork oak. It largely explains the state of the cork oak forest stands and the difficulties encountered in regenerating them.

MaxEnt modeling provides an important tool to estimate the potential distribution of the cork oak trees. Basic bioclimatic and topographic factors (elevation) are good predictors of the actual and potential distribution of the cork oak in the Maamora forest in the context of Mediterranean climate change. Precipitation during the wettest quarter of the year is the key contributing factor in modeling the ecological habitat of the cork oak in the Maamora forest.

This study sheds light on the importance of understanding seasonal climate regimes. A period of 1 month is too short as a hydrological indicator. Likewise, average annual rainfall values have little meaning; it is more useful to study rainfall over periods corresponding to the seasons. In the western Maamora region, which receives significant sea spray from the Atlantic Ocean, the cork oak stands are thriving. However, moving away from the ocean, the humidity decreases, and the temperature increases, such that cork oak experiences difficulties regenerating in these increasingly unfavorable eastern parts.

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