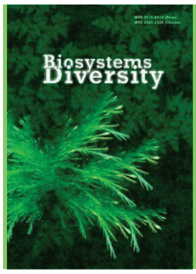

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Impact of climate change on potential distribution of *Quercus suber* in the conditions of North Africa

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Climate change, which is expected to continue in the future, is increasingly becoming a major concern affecting many components of the biodiversity and human society. Understanding its impacts on forest ecosystems is essential for undertaking long-term management and conservation strategies. This study was focused on modeling the potential distribution of *Quercus suber* in the Maamora Forest, the world's largest lowland cork oak forest, under actual and future climate conditions and identifying the environmental factors associated with this distribution. Maximum Entropy approach was used to train a Species Distribution Model and future predictions were based on different greenhouse gas emission scenarios (Representative Concentration Pathway RCPs). The results showed that the trained model was highly reliable and reflected the actual and future distributions of Maamora's cork oak. It showed that the precipitation of the coldest and wettest quarter and the annual temperature range are the environmental factors that provide the most useful information for *Q. suber* distribution in the study area. The computed results of cork oak's habitat suitability showed that predicted suitable areas are site-specific and seem to be highly dependent on climate change. The predicted changes are significant and expected to vary (decline of habitat suitability) in the future under the different emissions pathways. It indicates that climate change may reduce the suitable area for *Q. suber* under all the climate scenarios and the severity of projected impacts is closely linked to the magnitude of the climate change. The percent variation in habitat suitability indicates negative values for all the scenarios, ranging –23% to –100%. These regressions are projected to be more important under pessimist scenario RCP8.5. Given these results, we recommend including the future climate scenarios in the existing management strategies and highlight the usefulness of the produced predictive suitability maps under actual and future climate for the protection of this sensitive forest and its key species – cork oak, as well as for other forest species.

Keywords: Cork oak; habitat suitability; MaxEnt; modelling species distribution; Morocco.

Introduction

Human activity reflected in the emission of greenhouse gas will have a significant impact on the future climate (Stocker et al., 2013). Climate change is expected to continue in the future(Pielke Jr et al., 2022) and is increasingly becoming a major concern affecting many components of the biodiversity on a global scale (Hughes, 2000; McCarty, 2001; Nolan et al., 2018) and the aspects of human society. Climate change is even involved in the most of shocks that keep or push households into poverty (Hallegatte et al., 2015) and is increasingly and disproportionately affecting all species and the integrity of the world's ecosystems (Allan et al., 2021). Evidence shows that in various regions, climate change is contributing to increased water erosion, storm damage, frequency of forest fires, inundation and flood damage, pests, disease outbreaks, dieback of trees, landslides and avalanches. Those effects are already visible in the physiology, phenology and ecological organization of species, are leading to changes in their composition and distribution (Avtaeva et al., 2021a, 2021b; Di Nuzzo et al., 2021; Li et al., 2020) and can jeopardize the contribution of forests to the provision of ecosystem services (Allan et al., 2021).

For Morocco, which is a North-African country, the climate projections were reported to have trends towards rising temperature, more brutal extreme weather events, and reduction in the rainfall volume (Driouech et al., 2010). These variations are likely to lead to alterations (reductions or expansions) of the distribution areas of certain forest species (Moukrim et al., 2020; Moukrim et al., 2019a). Long-term conservation of valuable forest species and their habitat under climate change rely on developing consistent and reliable information about the spatial distribution and identifying locations in which suitable habitat conditions exist and would remain suitable in the future for those species (Franklin, 2009; Guisan et al., 2017). Such information remains scarce in the context of developing countries, which is a fundamental challenge that complicates the task of different stakeholders to better study and sustainably manage these forest ecosystems. The cork oak (*Quercus suber* L.), which is a remarkable forest ecosystem in the Mediterranean Basin (Fennane & Ibn Tattou, 2012), is a good example of those challenges and the impact of climate change on this species distribution should be assessed to better prioritize short and long-term management efforts.

To address this issue and to guide the development of relevant management strategies in the context of the climate change, the objectives of this research were modeling *Q. suber* distribution in the Maamora forest under actual and future climate conditions, identifying the environmental factors associated with this distribution to improve the knowledge about the ecology of this species and predict how cork oak distribution could shift in the future under climate change projections. For this purpose, we used the Maximum Entropy approach (Phillips et al., 2006; Merow et al., 2013), to train the Species Distribution Model, which represents a relevant approach in conservation ecology and is an effective tool for ecologists and biosystems managers (Franklin, 2009; Guisan et al., 2017).

Material and methods

Ecology of the cork oak and study area. The cork oak (*Q. suber*) is an endemic Western Mediterranean sclerophyllous oak, which belongs to the Fagaceae family (Fennane & Ibn Tattou, 2012). It is widely spread on the Atlantic coasts of Portugal, Spain and Morocco and is also present in North Africa, southern France, the Italian coast and some Mediterranean islands (Corsica, Sardinia and Sicily) (Vessella & Schirone, 2013). Late Quaternary pollen sequences suggest that cork oak in North Africa has survived the Last Glacial period and important developments of this species have been occurring from the Late Glacial to the Middle Holocene (Carrión et al., 2000). The species grows in warm-humid areas, from the sea-level to 2,000 m above sea level and prefer siliceous- or carbonate-free soils and can colonize extremely acid soils. The cork oak forests sustain a great variety of floral and faunal diversity and are of the highest social, economic, cultural and ecological value (Orgeas et al., 2003; Benabou et al., 2022).

This study was conducted in the territory of Morocco, which is located at the northwest corner of the African continent, between the Mediterranean Sea in the north, the Atlantic Ocean in the west and the Sahara Desert in the south. Special research was conducted in the Maamora Forest, which represents the largest lowland cork forest in the world (Natividade, 1956; Benabid, 2000; Aafi et al., 2005). It covers an area of 132,000 hectares, including 60,000 hectares of pure cork oak populations and approximately 10,000 ha mixed with other species (Benabou et al., 2022). The study area is dominated by the Mediterranean climate with dry season generally beginning in late April or early May and extending through October (Aafi et al., 2005). The localization of the study area and the current spatial distribution of *Q. suber* are presented in Figure 1. It shows that almost 46–53% of the study area is composed of natural stands of cork oak (*Q. suber*). The rest of the territory is occupied by some restricted urban areas and other stands based on exotic species belonging to the genus: *Eucalyptus*, *Acacia* and *Pinus* (Aafi et al., 2005; Benabou et al., 2022).

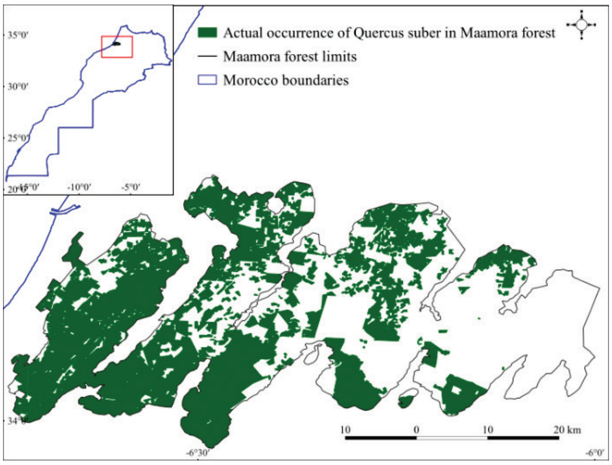

Fig. 1. Maamora Forest localization and current occurrence of *Q. suber* in the study area

The Maamora Forest represents valuable natural capital and constitutes a space of primary importance for the local population including urban citizens (Boudy, 1950; Benabou et al., 2022). In the recent decades, the Maamora Forest has faced severe anthropogenic pressures (overgrazing, excessive clearance of woodlands, overexploitation, fires and improper tapping) (Bugalho et al., 2011) provoking a large dedensification, as well as the reduction in its area (decreased by 45% compared with the beginning of the last century (Emberger, 1939)) which negatively affects the ecosystem's functions and services.

Modeling approach, datasets and processing. Species Distribution Modeling (SDM) represents one of the most important tools in ecological forecasting, biogeography, species management, risk assessment, and conservation planning (Guisan & Zimmermann, 2000; Elith et al., 2006; Austin, 2007). It provides modeled information when there are gaps in the data and an overall lack of species distribution data. The principle of SDM is to link species locations with the environmental characteristics those species require in order to predict likelihood of species occurrence and to assess the contribution of each environmental variable to that prediction. The diversity of modeling techniques, ranging from expert opinion to mechanistic or correlative models based on classical statistics or artificial intelligence, is available and has been proposed for modeling species distribution (Franklin, 2009; Guisan et al., 2017), depending on the availability of the type of response variables and predictors. In this study, the maximum entropy approach was adopted by using the MaxEnt 3.3.3k algorithm (Phillips et al., 2006), since it is qualified as one of the best performing model (Elith & Graham, 2009; Merow et al., 2013). It used presence data only (Phillips et al., 2006), is relatively insensitive to spatial errors associated with location data (Elith et al., 2006) and helps users by providing parameters to assess model performance and contribution of each predictors to the model (Merow et al., 2013). Also, Quantum-GIS and R software were used to prepare the data, handle the spatial data, analyze the results and summarize the zonal statistics.

The majority of the SDM including MaxEnt use biological and environmental data. As biological data, a global dataset of one thousand two hundred seventy occurrence points (with precise geographic coordinates of latitude and longitude) of *Q. suber* was assembled. It comes specifically from the national forest inventory database (National Forest Inventory, 2005). As environmental variables, we selected nineteen bioclimatic variables, downloaded from Worldclim dataset (Hijmans et al., 2005; Fick & Hijmans, 2017), which are biologically more meaningful to define ecophysiological tolerances of a vegetal species. The dataset provides interpolated current and future climate layers, for each bioclimatic variable based on historical data in a 30 arc-second spatial resolution (equivalent to 1 km).

For future (2070s) potential distribution, the four greenhouse gas emission scenarios (RCP2.6, RCP4.5, RCP6.0 and RCP8.5 known as optimistic to pessimistic scenarios) and the average of an ensemble of eighteen General Circulation Models approved by the IPCC were used (Kriegler et al., 2012; Stocker et al., 2013; Fick & Hijmans, 2017). The average maps of many GCMs for each scenarios are useful (Knutti et al., 2010; Weigel et al., 2010).

As recommended by Phillips & Dudik (2008), default settings for MaxEnt were used and a random subsample of 75% of the data were used to train the model and 25% were withheld for testing the predictive ability of the model by cross-validation. MaxEnt generates an estimate of habitat suitability (S) for the studied species, under current and future climate conditions, that generally varies 0 to 1 (lowest to highest suitability). To produce the suitability maps, under current and future climate predictions, we imported the MaxEnt output data after we have applied the 'Equate entropy of thresholded and original distributions' as threshold criteria (T) for binary classification (presence/absence) maps. A series of reclassified maps were produced under current and future climate conditions, which were used to calculate the predicted change (stable, loss and new areas) in habitat suitability for each climate projection independently and to evaluate the impact of climate change on cork oak ecosystem.

Furthermore, the results from the MaxEnt model include the two model evaluations (i.e., AUC and Jackknife test), and provides the percent contribution and the permutation importance of each independent variable used to develop the model and generates response curves for each predictor variable (Phillips et al., 2006). Relevance of the generated model was tested through Area Under receiver-operating characteristic Curve (AUC) (Hanley & McNeil, 1982; Fawcett, 2006). According to Araújo et al. (2005), the model is bad or invalid when $AUC < 0.70$, acceptable or good when $0.70 \leq AUC \leq 0.90$: excellent when $AUC > 0.90$. The Jackknife test (Miller, 1974) was used to determine the prediction power of each variable by assessing the relative importance of single explanatory variables included in model development.

Results

Calculation of the receiver-operating characteristic curve showed that the AUC, which was 0.990 and 0.991 respectively for the training and the test data, is consistently high (Fig. 2a). The calculated AUC showed a significantly non-random distribution, indicating that our prediction models can be considered highly accurate and may accurately reflect the actual and future cork oak tree distribution.

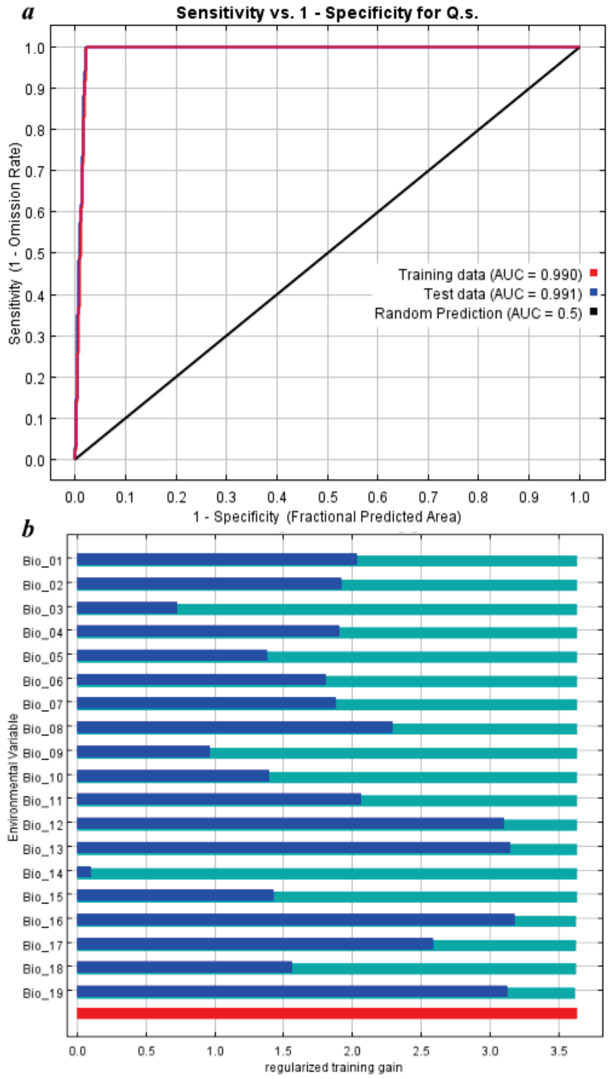

Fig. 2. Model quality and bioclimatic variables contributions: *a* – area under receiver-operating characteristic curve (AUC); *b* – Jackknife test of variable importance results; for each variable, red bar represents the gain obtained by introducing all the variables, blue bar shows the gain obtained if this variable was used alone and the remaining variables were excluded from the analysis, turquoise bar shows how much the total gain is reduced if that specific variable was excluded from the analysis; environmental variables used: Bio_1 – annual mean temperature; Bio_2 – mean diurnal range; Bio_3 – isothermality; Bio_4 – temperature seasonality; BIO_5 – max temperature of warmest month; Bio_6 – min temperature of coldest month; Bio_7 – temperature annual range; Bio_8 – mean temperature of wettest quarter; Bio_9 – mean temperature of driest quarter; Bio_10 – mean temperature of warmest quarter; Bio_11 – mean temperature of coldest quarter; Bio_12 – annual precipitation; Bio_13 – precipitation of wettest month; Bio_14 – precipitation of driest month; Bio_15 – precipitation seasonality (coefficient of variation); Bio_16 – precipitation of wettest quarter; Bio_17 – precipitation of driest quarter; Bio_18 – precipitation of warmest quarter; Bio_19 – precipitation of coldest quarter

Analysis of the relative contributions and the permutation importance of each independent variable to the MaxEnt model prediction suggests that the precipitation of coldest (Bio_19) and wettest (Bio_16) quarters and temperature annual range (Bio_07) are, in this order, the most important variables. In addition, the Jackknife test results confirm the importance of those variables in the cork oak distribution modeling (Fig. 2b). It shows that the environmental variable with the highest gain, when used in isolation, is the precipitation of wettest quarter, which therefore appears to have the most useful information by itself. The environmental variable that decreases the gain mostly when it is omitted is the precipitation of coldest quarter, which therefore appears to have the most information that is not present in the other variables.

Potential suitable areas of Q. suber. Results of the cork oak distribution model were continuous probability maps showing the current and future potential distribution areas of *Q. suber* in the Maamora Forest (Fig. 3). Under the current climatic conditions, the habitat suitability for *Q. suber* is primarily predicted to be highest and most concentrated in the central and western parts of the Maamora Forest (Fig. 3a). The trained model predicts a broad area as highly suitable (S ≥ T) for *Q. suber* occurrence under the current climate conditions (121,727 ha). This potential areas are mostly confined to the areas where the species is currently present but is significantly much larger than the actual occurrence of this species (~ 60,000 ha, Fig. 1). The overall effective occurrence of this species was predicted to be highly suitable and some new areas in the eastern part were predicted as suitable under the current climate conditions.

For 2070, MaxEnt model projections based on the average of different Global Circulation Models revealed that suitable areas for cork oak distribution are located in some specific sites in the Maamora forest and appear to be highly dependent on future climate conditions (Fig. 3b–e). The predicted future ranges of the habitat are likely to be negatively affected by future climate and under each of future scenarios (going from the optimistic to the pessimistic scenario) (Fig. 3b-e). Large parts of the currently highly suitable areas will be affected and only few or no initial areas (depending on climate scenario) will remain suitable in the future. Under RCP8.5 scenario (Fig. 4d), a total absence of suitable areas of cork oak was noted. Also, suitable areas under RCP6.0 (Fig. 3d) are projected less than those predicted in intermediate (Fig. 3c) and optimistic (Fig. 3b) scenarios. In addition, actual suitable areas located in the eastern part (Fig. 3a), where the species are actually present in some part (Fig. 1), will be unsuitable in the future.

Habitat suitability changes of Q. suber. Overlaying the potential distribution maps under the current (Fig. 3a) and future climate (Fig. 3b–e) conditions allowed us to estimate changes in the distribution of *Q. suber* for each future climate scenarios (Fig. 4). The predicted changes in the potential suitable areas of this species in the Maamora Forest are significant and expected to vary in the future under the different emission pathways (Fig. 4, Table1).

The percent variation in habitat suitability indicates negative values for all the scenarios, ranging –23% to –100%. These regressions are projected to be more important under pessimist scenario RCP8.5 and less important under optimistic scenario RCP2.6 (Fig. 4, Table 1).

Table 1
Predicted change in habitat suitability (ha)
for Maamora *Q. suber* distribution under future climate conditions

Characteristic	Current climate prediction, ha	Future climate prediction 2070			
		RCP2.6	RCP4.5	RCP6.0	RCP8.5
Stable suitable area	121 727	94 015 (77.2%)	33 794 (27.8%)	20 817 (17.1%)	0 (0.0%)
Lost of suitable area	–	27 712 (–22.8%)	87 933 (–72.2%)	100 910 (–82.9%)	121 727 (–100.0%)
New suitable area	–	0	0	0	0
Unsuitable area	10 273	37 985	98 206	111183	132 000

Note: % for future habitat suitability, the percent changes from current climate predictions are provided in parenthesis.

Discussion

This research represents the first attempt to understand impacts of the future climate change on the distribution of *Q. suber* and the developed model was highly reliable and reflected the actual and future Maamora Forest's cork oak distributions (Merow et al., 2013). The trained model showed that the precipitation of coldest and wettest quarters and the annual temperature range are the environmental factors that provide the most useful information for *Q. suber* distribution in the study area, which confirmed the affinity of this species to warm-humid Mediterranean bioclimatic environment (Achhal et al., 1979; Benabid, 1982; Aafi et al., 2005). The other environmental variables contributed very little to the prediction. These results highlight the importance of understanding seasonal weather patterns and considering extreme values of variables. Annual mean values of temperature and precipitation have little significance and limited periods (monthly) are too short as bioclimatic indicators. Such kind of results contributes to a better understanding of the range of environmental conditions that suit *Q. suber* in the Maamora forest and improves our knowledge about the ecology of this species.

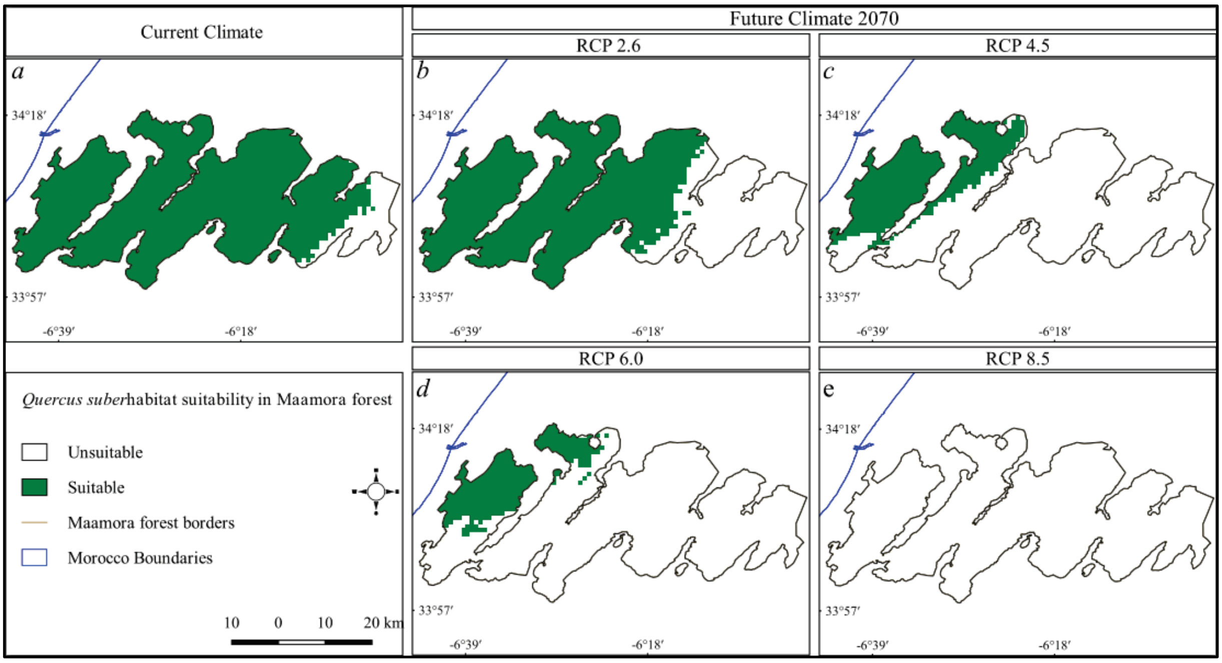

Fig. 3. *Q. suber* habitat suitability (predicted habitat suitability of this species in the Maamora Forest using): *a* – actual and future climate scenarios for 2070: *b*– RCP2.6, *c* – RCP4.5, *d* – RCP6.0, *e* – RCP8.5

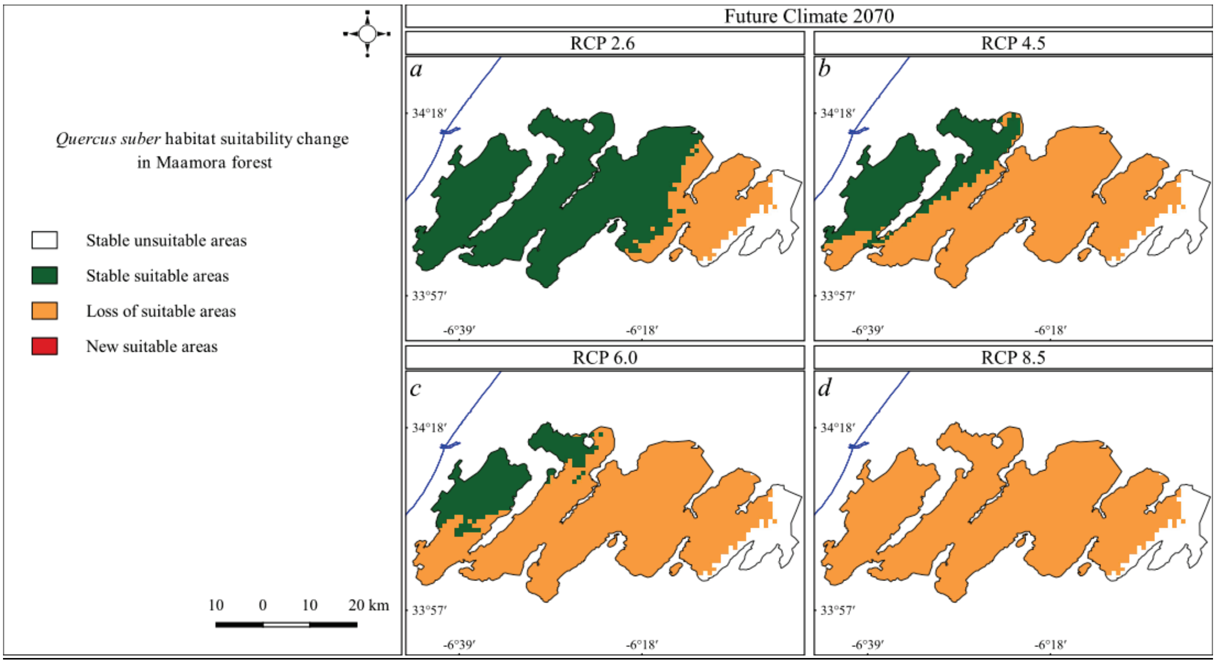

Fig. 4. *Q. suber* habitat suitability changes by 2070 for future climate scenarios: *a* – RCP2.6, *b* – RCP4.5, *c* – RCP6.0, *d* – RCP8.5

The current potential suitable areas confirmed the affinity of this species to large areas in the Maamora Forest, especially for the western region of the Maamora, which spreads significantly from the Atlantic Ocean. It correlated strongly with the actual occurrences of this species (Fig. 1) and with the existing literature (Achhal et al., 1979; Benabid, 1982, 2000). Current potential suitable areas (Fig. 3a) suggested that other parts of the Maamora Forest are bioclimatically suitable for this species. This is coherent with the results related to the potential distribution of other species in Morocco (Moukrim et al., 2018, 2020; Rifai et al., 2020). However, despite favourable bioclimatic conditions, this species has not colonized all potential areas and is still absent in some parts, mainly from the eastern parts of the current distribution areas. This absence can be probably due to: excessive pressure and silvicultural choices made in the past for the establishment of exotic forest species (*Pinus* and *Eucalyptus*) in order to meet the needs of industry (pulpwood production) and needs of local populations in terms of firewood (Benabou et al., 2022); and difficulties of regeneration of this species (Lahssini et al., 2015). Those difficulties will be greater in the context of the future climate.

For the future conditions, changes in potential suitable areas for cork oak in the Maamora Forest have been recorded for different climate scenarios (Fig. 4). The analysis of changes in the suitability indicates that climate change may reduce the suitable area for *Q. suber* and the severity of projected impacts is closely linked to the magnitude of the climate change. The computed results showed a gradual regression under all the climate scenarios (Table 1). This evidence is coherent with the results of other work related to other species, which globally confirm that negative impacts are found more commonly than positive ones (Hughes, 2000; McCarty, 2001; Moukrim et al., 2019a; Moukrim et al., 2020; Di Nuzzo et al., 2021). Those results present a clear picture of the potential impacts of the climate change on forest resources. The severity of this impact, in turn, depends crucially on human-caused emissions of greenhouse gases over the next few decades and the involvement of the parties in the implementation of international commitments in relation to the climate change. Therefore, in order to protect this ecosystem, we recommend including the future climate scenarios in the existing management strategies (Millar et al., 2007).

Faced with the impacts of climate change and the uncertainties generated by this phenomenon, the classic tools for the choice of conservation and development of actions for the Maamora Forest appear ill-suited to guide managers and scientists in terms of choice of sites and also in terms of techniques, intensity and time frame of action. Such inadequacy was noticed in the current management plan of this forest, which does not consider that the natural spatial distribution of cork oak may vary in the context of the climate change. Maps produced under the current and future climatic conditions (Fig. 3) improve our knowledge of the ecology of the studied species and provide additional information compared to the occurrence data only. They constitute a reflection tool available to the scientist and manager to clarify decision-making and apprehension of the behaviour of this species in the context of the climate change. Those maps will make it possible to identify and clarify the choice of priority action sites for the conservation and development of the *Q. suber* in the Maamora Forest. They will also make it possible to better reason the intensity of the interventions and to remodel the efforts according to the suitability and the probability of the presence recorded in different environments. Highly suitable areas under the current climatic conditions (Fig. 3a), mainly those currently characterized by the occurrence of cork oak (Fig. 1), and which will remain favorable for this species in the future (Fig. 3b-e), must be managed by urgent conservation actions (Moukrim et al., 2019b).

Conclusion

The computed results of cork oak's habitat suitability showed that predicted suitable areas are site-specific and seem to be highly dependent on climate change. The comparison of potential distribution maps under the current and future climate conditions reveals that the habitat suitability may decline with the global warming. Based on those results, we recommend including the climate change scenarios in the existing restoration and conservation strategies for the protection of this sensitive forest and its key species – cork oak. In this context, predictive suitability maps will be valuable tools for developing adaptive strategies to deal with the future climate change in the largest lowland cork forest in the world and in all forest ecosystems.

Author contributions: conceptualization, S.M., A.B. and S.L.; methodology, S.M., A.B. and S.L.; software, S.M., A.B. and S.L.;validation, S.M., A.B. and S.L.; formal analysis, S.M., A.B., S.L. and L. R.; investigation, S.M., A.E. K.M., M.E. and M.E.M.; resources, B.A., A.E., K.M., M.E. and M.E.M.; data curation, S.M., A.B. and L.R.; writing – original draft preparation, S.M., A.B. and S.L.; writing – review and editing, S.M., A.B., S.L., L.R., A.E., K.M., M.E. and M.E.M.; visualization, S.M. and A.B.; supervision, S.M.; project administration, S.M. and A.B.

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