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Ekológia (Bratislava) - Journal of the Institute of Landscape Ecology, Slovak Academy of Sciences Vol. 41, No. 4, p. 329–339, 2022

DOI:10.2478/eko-2022-0034

CLIMATE CHANGE IMPACT ON POTENTIAL DISTRIBUTION OF AN ENDEMIC SPECIES *Abies marocana* TRABUT

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Received: 16 June 2022 / **Accepted:** 24 October 2022

Abstract

Moukrim S., Lahssini S., Rhazi M., Menzou K., El Madihi M., Rifai N., Bouziani Y., Azedou A., Boukhris I., Rhazi L.: Climate change impact on potential distribution of an endemic species *Abies marocana* Trabut. Ekológia (Bratislava), Vol. 41, No. 4, p. 329–339, 2022.

Global warming is becoming a major concern affecting many components of the biodiversity at a global scale and disproportionately affecting the integrity of ecosystems, particularly the habitat of endemic species. Understanding its impacts on most vulnerable species is essential to improve knowledge on the ecology of these species and for their long-term management and conservation. *Abies marocana* Trabut (Moroccan fir), a remarkable forest tree of the Mediterranean basin, is an endangered species that is present in discreet small areas of the Rif Mountains, which is highly vulnerable to the ongoing climate warming and facing severe anthropogenic pressures. For conservation and management purposes, our work focused on improving understanding of the impacts of future climate change on the distribution of this species through its habitat suitability modeling. The maximum entropy approach was used, which achieved good predictive abilities. Habitat suitability was identified and then predicted under current and future climate conditions. A significant change and a gradual regression of the habitat suitability to *A. marocana* was shown under different future climate scenarios. The magnitude of the simulated changes is important and tends to have negative consequences for Moroccan fir conservation. For this purpose, outputs from models are useful to improve our knowledge about the ecology of *A. marocana,* and predictive maps produced under current and future climate conditions constitute reflection tools available to scientists and managers to better integrate actual and future climate impacts into existing and upcoming management strategies to prevent any future locale extinction.

Key words: Moroccan fir, modeling species distribution, MaxEnt, ecology, management, Morocco.

Introduction

Global climate change is confirmed and largely resulting from anthropogenic activities (IPCC, 2021). It is expected to continue in the current century (Alimonti et al., 2022; Pielke et al., 2022) and become a major concern affecting many aspects of human society and components of the biodiversity at a global scale (Hughes, 2000; McCarty, 2001). The Intergovernmental Panel on Climate Change (IPCC, 2021) highlights how climate change is increasingly and disproportionately affecting all species, their habitats, and the integrity of world's ecosystems. Such impacts are already visible, affecting the physiology, phenology, and ecological organization of species, and are leading to changes in their composition and distribution (Di Nuzzo et al., 2021; Hughes, 2000; Iler et al., 2019; McCarty, 2001; Moukrim et al., 2020; Savage, Vellend, 2015).

The ability of forests to provide functions necessary for the well-being of humans depends on the integrity of these ecosystems. Such an integrity seems to become altered within the climate change context. Long-term conservation of ecosystems, prevailing valuable species, and their habitats under climate change relies on developing consistent and reliable information about the spatial distribution and identifying the locations on which suitable habitat conditions exist and remain suitable in the future for those species (Franklin, 2009; Guisan et al., 2017)resource management and conservation planning. These include biodiversity assessment, reserve design, habitat management and restoration, species and habitat conservation plans and predicting the effects of environmental change on species and ecosystems. The proliferation of methods and uncertainty regarding their effectiveness can be daunting to researchers, resource managers and conservation planners alike.

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Franklin summarises the methods used in species distribution modeling (also called niche modeling. Given the scale and urgency required, sustainable management of vulnerable forest species and ecosystems in the context of climate change requires knowledge of potential current and future distribution areas, knowledge of expected changes, and identification of factors that affect these distributions and changes (Thuiller et al., 2008). This information remains scarce and disparate in the context of developing countries, which is a fundamental challenge that complicates the task of scientists, conservators, and managers of forest ecosystems. These actors often have to work with limited data to study, preserve, restore, and sustainably manage these resources.

For Morocco, climate projections are announcing rising temperature trends, frequent brutal extreme weather events, in addition to reduced rainfall volume and rainy days (Driouech et al., 2010). These variations are likely to lead to alteration (reductions or expansions) of the distribution areas of some tree species (Benabou et al., 2022; Gbetoho et al., 2017; Moukrim et al., 2019, 2020). Endemic species seems to be particularly most vulnerable to climate change (Malcolm et al., 2006). As an example, Moroccan fir (*Abies marocana* Trabut), a remarkable forest species of the Mediterranean Basin (Fennane, Ibn Tattou, 2012; Myers et al., 2000), illustrates these challenges. Indeed, the current distribution of the *Abies* genus in the Western Mediterranean is the result of climatic oscillations and geodynamic processes that occurred in the past (Sánchez-Robles et al., 2014). *Abies* species, which had a wide distribution in the past (Linares, 2011) and spread to the south from Europe during glaciation periods (Terhürne-Berson et al., 2004), remains nowadays as a relic species occupying very small and discreet areas in the Rif Mountains.

In a region expected to be severely impacted by climate change according to different climate models' projections and for species conservation and management purposes, there is a need to assess climate change impact on the Moroccan fir distribution in order to prioritize short- and long-term management and restorative activities to preserve this vulnerable species.

To address this objective, our approach involved the following:

- modeling *A. marocana* Trabut habitat distribution and predicting its potential suitability maps under actual and future climate conditions and
- identifying how Moroccan fir distribution may shift under future climate scenarios to guide and develop relevant management strategies in the context of climate change.

The maximum entropy approach (Merow et al., 2013; Phillips et al., 2006) was used for training Species Distribution Model, which represents a relevant approach in conservation ecology (Franklin, 2009; Guisan et al., 2017)resource management and conservation planning. These include biodiversity assessment, reserve design, habitat management and restoration, species and habitat conservation plans and predicting the effects of environmental change on species and ecosystems. The proliferation of methods and uncertainty regarding their effectiveness can be daunting to researchers, resource managers and conservation planners alike. Franklin summarises the methods used in species distribution modeling (also called niche modeling and has become an effective tool for ecologists and land managers.

Material and methods

Study area and ecology of the model species

The study was conducted in the territory of the Kingdom of Morocco. This country is located at the northwestern corner of the African continent within 21° and 36° North and 1° and 17° West, between the Atlantic Ocean in the west, the Sahara Desert in the south, and the Mediterranean Sea in the north. The Morocco's relief is diverse and characterized by the presence of rugged mountains (Fig. 1a). The Atlas Mountains are subdivided into three ranges: Anti, Middle, and the High Atlas. The Rif Mountains complete the Arch of Gibraltar, which connects Spain and North Africa on the northern border of Morocco. The country is characterized by its wide diversity of ecological conditions and includes four of 14 terrestrial biomes, with some critical and endangered ecoregions in the WWF Global 200 list (Dinerstein et al., 2017). It is one of the most diverse countries of the Mediterranean region in terms of vegetal species (Medail, Quezel, 1997) and is home to 4,200 floral taxa with a high level (19.2%) of plant endemism (Fennane, Ibn Tattou, 2012).

Moroccan fir species *A. marocana*, which is studied in this work, is a North Moroccan endemic species belonging to the Pinaceae family (Fennane, Ibn Tattou, 2012; Trabut, 1928) and is considered as a Tertiary relict species (Linares, 2011). It is a majestic narrow coniferous tree that occupies a discreet small area (about 4,770 ha) in the Rif Mountains (Fig. 1b) and organizes limited but interesting forests and landscape. The remaining stands were declared as part of protected area Talassemtane National Park (Benabid, 2000) and also as United Nations Educational, Scientific and Cultural Organization (UNESCO)'s Mediterranean Intercontinental Biosphere Reserve of Morocco and Spain (2006). A number of its ecological characteristics have been clarified (Achhal et al., 1979; Barbero, Quezel, 1975; Benabid, 1982; Quezel, 1998). Like all Mediterranean firs, optimal growth of this tree occurs in dolomitic limestone soils on north-facing slopes in a humid and extremely cold Mediterranean bioclimatic environment. Moroccan fir stands occurred at an altitude ranging between 1,400 and 2,100 (m a.s.l.) (sometimes less in some areas), in areas characterized by a mean monthly temperature ranging from −1.3 to 26.5 °C and rainfall that can reach 1,900 mm/year.

The floristic richness of the Rif fir forest is significant. Their stands are characterized by the presence of other remarkable tree species such as *Cedrus atlantica* Manetti, *Quercus ilex*, *Q. faginea*, *Q. rotundifolia, Acer opalus* subsp. granatense, *Pinus pinaster* var. *maghrebiana*, and *Juniperus oxycedrus;* other species reflecting the local particularities of the Rif, such as *Origanum elongatum, O. grosii, Ionopsidium prolongoi, Arabis josiae, Paeonia corallina* subsp. *atlantica*, and *Saponaria glutinosa* are also present (Benabid, 2000).

Moroccan fir forest represents valuable natural capital for the region as it plays a crucial role in rural area development through its usage in ecosystem services (local biodiversity, cultural identity, esthetic benefits, and recreation/tourism; enhanced by the creation of the Talassemtane National Park which included all fir stands). During the last century, natural and anthropogenic pressures (fires, excessive clearance of woodlands, overexploitation, and unsustainable harvesting) caused a large reduction (70%

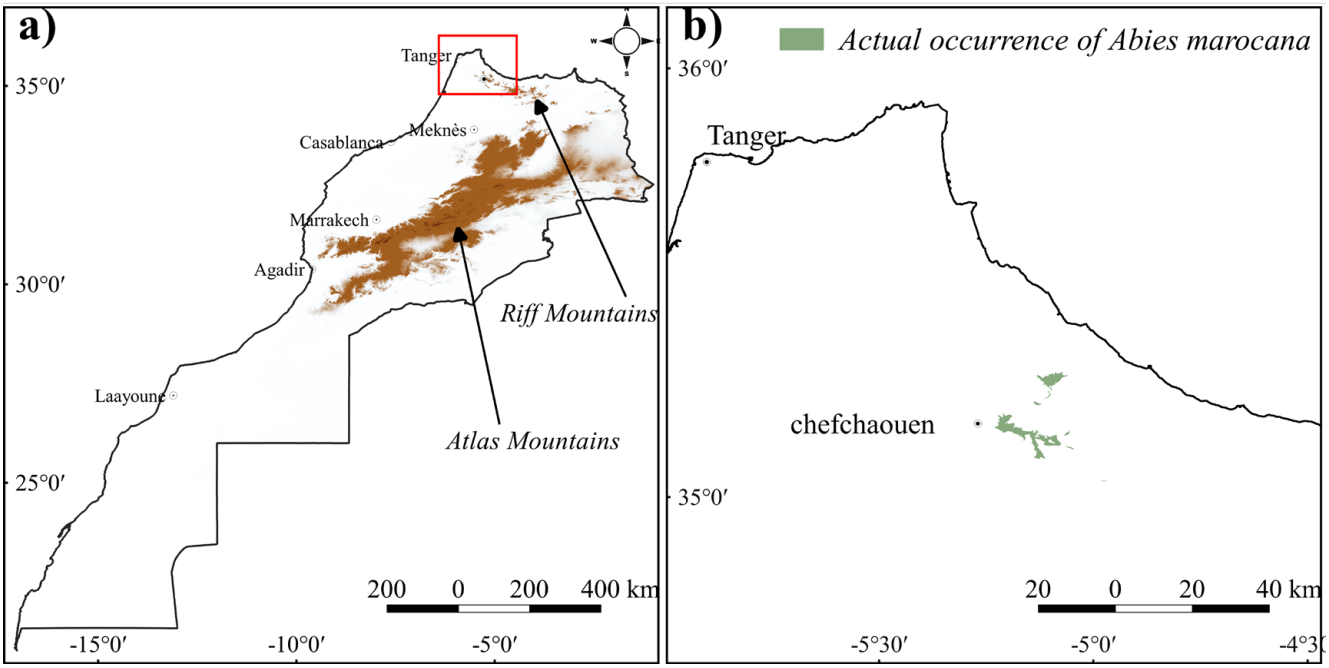


Fig. 1. Study area and current occurrence of Moroccan fir. (a) Geographic location of Morocco at the northwestern angle of the African continent, including the location of cities and main mountains. (b) Current occurrence of *Abies marocana* Trabut.

drop) in its distribution (Barbero, Quezel, 1975; Benabid, 2000; Ben-Said et al., 2020; Castro et al., 2022; Quezel, 1998). Actually, the Moroccan fir is on the IUCN Red List as a globally threatened species in the category "Endangered" (Alaoui et al., 2011).

Modeling approach and tools used

Species distribution modeling (SDM) represents a predictive approach in conservation ecology and is one of the most important tools in ecological forecasting, conservation planning, biogeography, risk assessment, and species management (Austin, 2007; Guisan et al., 2017; Guisan, Zimmermann, 2000; Phillips et al., 2006). It attempts to link environmental conditions in known localities of species occurrence with the surrounding environment and then probabilistically estimate potential distribution (Franklin, 2009). Based on the training dataset, which consists of location of the site where the studied species occur and the prevailing environmental factors at these sites, a model is then fitted in order to predict species occurrence likelihood (response function) as a function of the prevailing environmental parameters (predictors) (Guisan et al., 2017). This approach provides information in a situation when there is a gap or lack of species distribution data. SDM has been used, among other applications, to describe, understand, and predict the distribution of species, respond to major issues, and estimate the future range of a species under climate change (Franklin, 2009; Guisan et al., 2017; Moukrim et al., 2019, 2020).

Today, impressive diverse modeling techniques, ranging from expert opinion to mechanistic or correlative models based on classical statistics and/or artificial intelligence and depending on the availability of the type of response variables and predictors, are available and have been proposed for modeling species distribution (Franklin, 2009; Guisan et al., 2017).

In this study, the maximum entropy approach, which finds its origins in information theory and is related to machine learning, was adopted by using the "MaxEnt 3.3. 3k" algorithm (Phillips et al., 2006). MaxEnt was chosen since it is qualified as one of the best performing models (Elith, Graham, 2009; Merow et al., 2013; Phillips et al., 2006). It is specifically developed for use with presence-only data (Phillips et al., 2006), requires few occurrence data to build useful models (Elith, Graham, 2009), and is able to use both continuous and categorical variables (Elith et al., 2006; Phillips et al., 2006). Also, it is relatively insensitive to spatial errors associated with location data (Elith et al., 2006; Elith, Graham, 2009) and helps users by providing the relative contribution of each predictor and some parameters to assess model performance (Merow et al., 2013).

Datasets used

The majority of SDM uses biological data (precise geographic coordinates of species occurrences) and data related to environmental variables. A global dataset of 137 occurrence points of Abies marocana was assembled using a random sampling strategy across the species' range reported in the national forest inventory database (NFI, 2005). This dataset covers the entire range of occurrence of the species to have a more elongated data configuration, allowing to improve the performance of the model and reduction of the variance. A single point of occurrence per element of the environmental variable format was retained in order to limit the sampling bias and the autocorrelation effect in this type of sampling (Guisan, Zimmermann, 2000). For verification purposes, data were examined and verified during field mission to avoid any error or confusion with other species.

Nineteen bioclimatic variables considered as biologically meaningful to define the eco-physiological needs of a plant species and may limit their distributions were selected. These variables indicate average, seasonal, and extreme monthly conditions of climatic parameters and are downloaded from WorldClim v2.1 dataset (Fick, Hijmans, 2017). This dataset provides interpolated current and future climate layers for each bioclimatic variable based on historical data in 30″ spatial resolution (approximately 1 km2 cell size).

For the prediction of potential future areas for near term (2050s) and long term (2070s), three greenhouse gas emission scenarios (RCP2.6, RCP4.5, and RCP8.5 known as optimistic, intermediate, and pessimistic scenarios, respectively) and an ensemble of 18 general circulation models (GCMs), approved and used by the IPCC, were retained (Fick, Hijmans, 2017; IPCC, 2013; Kriegler et al., 2012). The average maps of many GCMs for each period and each scenario are useful (Knutti et al., 2010; Weigel et al., 2010) and often outperform any individual model to limit uncertainties and to draw inferences in a more relevant way (Gleckler et al., 2008; Pierce et al., 2009).

Model training, validation, and data analysis

During the simulation of Moroccan fir distribution, the default settings of the MaxEnt algorithm, relating to background data, the maximum number of iterations, and to the adjustment and model training, were used as recommended by Phillips and Dudík (2008). The "equal training sensitivity and specificity" was used as the threshold criteria (*T*) for binary classification (presence–absence) maps. The raw output from MaxEnt was an exponential function that assigned a probability of occurrence to each site under current and future climate conditions (Phillips et al., 2006), also called the index of relative habitat suitability "R" (Fitzpatrick et al., 2013).

MaxEnt model prediction accuracy was tested through cross-validation, which consists of dividing occurrence point data into "training data 80%" and "testing data 20%" (Guisan, Zimmermann, 2000). This pertinence of model is also tested through the area under receiver-operating characteristic curve (AUC) (Hanley, McNeil, 1982) and the true skill statistics (TSS) (Allouche et al., 2006). The AUC statistic measures model performance by plotting the sensitivity values (the true-positive fraction of test points) against 1 - specificity (the false-positive fraction of test points) for all available probability thresholds. The model is excellent where AUC >0.90, acceptable where $0.70 \leq AUC \leq 0.90$, or bad/invalid where AUC <0.70 (Swets, 1988). The TSS is calculated as "sensitivity + specificity + 1" and can range from −1 to 1. Model is good where TSS >0.60, fair where $0.40 \leq TSS \leq 0.60$, or poor where AUC <0.40 (Franklin, 2009). 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.

The MaxEnt output includes results of model evaluations and the contribution, importance, and the predictive power of each independent variable used to develop the model. Also, it provides response curves for each predictor variable (Phillips et al., 2006).

To produce the suitability maps, under current and future climate predictions, we took the MaxEnt output data and other analyses were implemented. Habitats' suitability was reclassified using the predefined threshold "T" and the relative habitat suitability "R" into three arbitrary classes of suitability. The habitat suitability was high where ($R \geq T$), low where ($\frac{1}{2}T \leq R < T$), and unsuitable for ($R < \frac{1}{2}T$) (Moukrim et al., 2020).

To demonstrate how each climate projection performed in our analysis, a series of reclassified maps were produced under current and future climate conditions "under three Representative Concentration Pathway (RCPs)" for the 2050s and the 2070s. Then, we calculated the predicted change in habitat suitability (stable, loss, and new areas) for each climate projection independently. For geographic and visual representations, we produce change maps that differentiate areas of increasing, decreasing, and stable suitability from current to future climate scenarios. These results can help us to appreciate the impact of climate change on fir ecosystem by showing how *A. marocana* may shift under multiple climate change scenarios and time periods. To prepare and process spatial data, analyze results, and summarize zonal statistics, R software and Quantum GIS (QGIS) were used.

Results

Model quality and environmental variables' contributions

Analysis of the predictive model for *A. marocana* created using the MaxEnt algorithm showed a high success rate (the AUC scores were 0.989 and 0.987 for the training and test data, respectively: Fig. 2a, and the TSS score was 0.927), indicating that the model performed with high accuracy.

The initial examination of environmental variables that determine the distribution of this species was based on the relative contribution and the permutation importance of each independent variable to the mode and response curves. This analysis showed that precipitation of the wettest quarter (Bio_16) was the most relevant variable for the distribution of *A. marocana* according to the model.

Analysis of the Jackknife test results (Fig. 2b) likewise confirmed the importance of precipitation of the wettest quarter as the environmental variable that has the highest gain and the most useful information by itself when used in isolation. It also suggested that the environmental variable that decreases the gain mostly when it is omitted is precipitation of the coldest quarter (Bio_19), which, therefore, appears to have the most information that is not present in the other variables.

Predicting current and future potential suitability of Abies marocana

Results of the Moroccan fir distribution model were continuous probability maps showing current and future potential suitable areas of this species in Morocco (Fig. 3). Under current climate conditions, the potential suitable areas of *A. marocana* are mostly confined to the northern part of Morocco (Fig. 3a), where the species is currently present, and this confirms the affinity of this species to a restricted geographic range "the Rif Mountains" (Fig. 1a). Map generated from the model showed that suitable areas were distributed between the parallels 34°43'–35°31' N and the

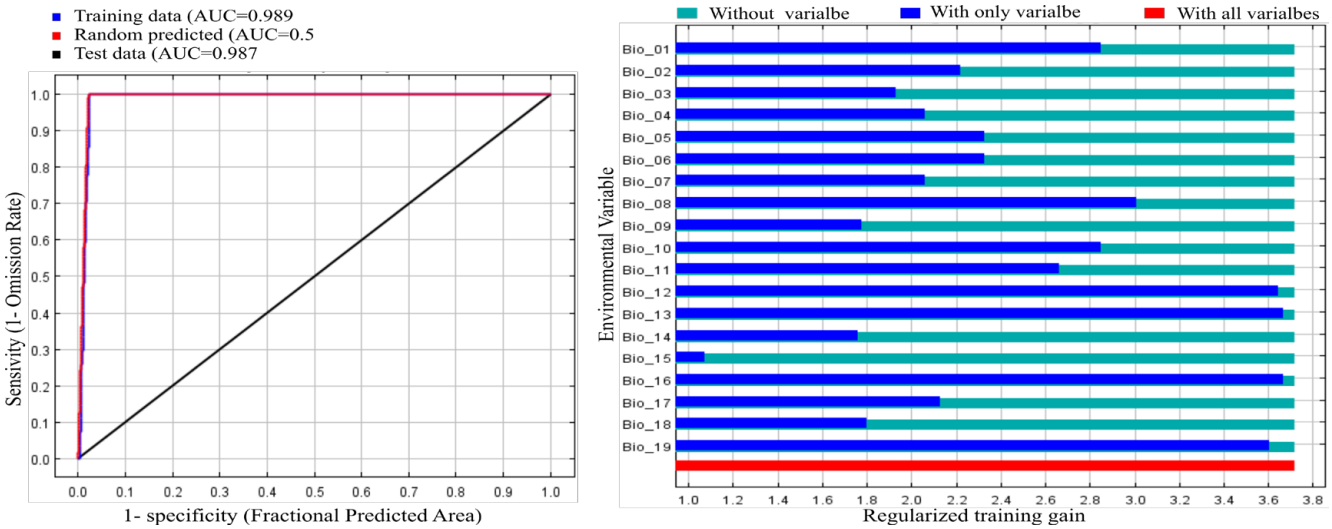


Fig. 2. Model performance and variables' contribution. (a) AUC which represents sensitivity versus 1 - specificity and (b) results of the Jackknife test of variable importance: for each variable (Bio_1: annual mean temperature; Bio_2: mean diurnal range; Bio_3: isothermality; Bio_4: temperature seasonality; BIO_5: max. temperature of the warmest month; Bio_6: min. temperature of the coldest month; Bio_7: temperature annual range; Bio_8: mean temperature of the wettest quarter; Bio_9: mean temperature of the driest quarter; Bio_10: mean temperature of the warmest quarter; Bio_11: mean temperature of the coldest quarter; Bio_12: annual precipitation; Bio_13: precipitation of the wettest month; Bio_14: precipitation of the driest month; Bio_15: precipitation seasonality (coefficient of variation); Bio_16: precipitation of the wettest quarter; Bio_17: precipitation of the driest quarter; Bio_18: precipitation of the warmest quarter; Bio_19: precipitation of the coldest quarter), the turquoise bar shows how much the total gain is reduced if that specific variable is excluded from the analysis, the blue bar shows the gain obtained if this variable is used in isolation and the remaining variables are excluded from the analysis, and the red bar represents the gain obtained by introducing all the variables. AUC – area under the ROC, ROC – receiver-operating characteristic.

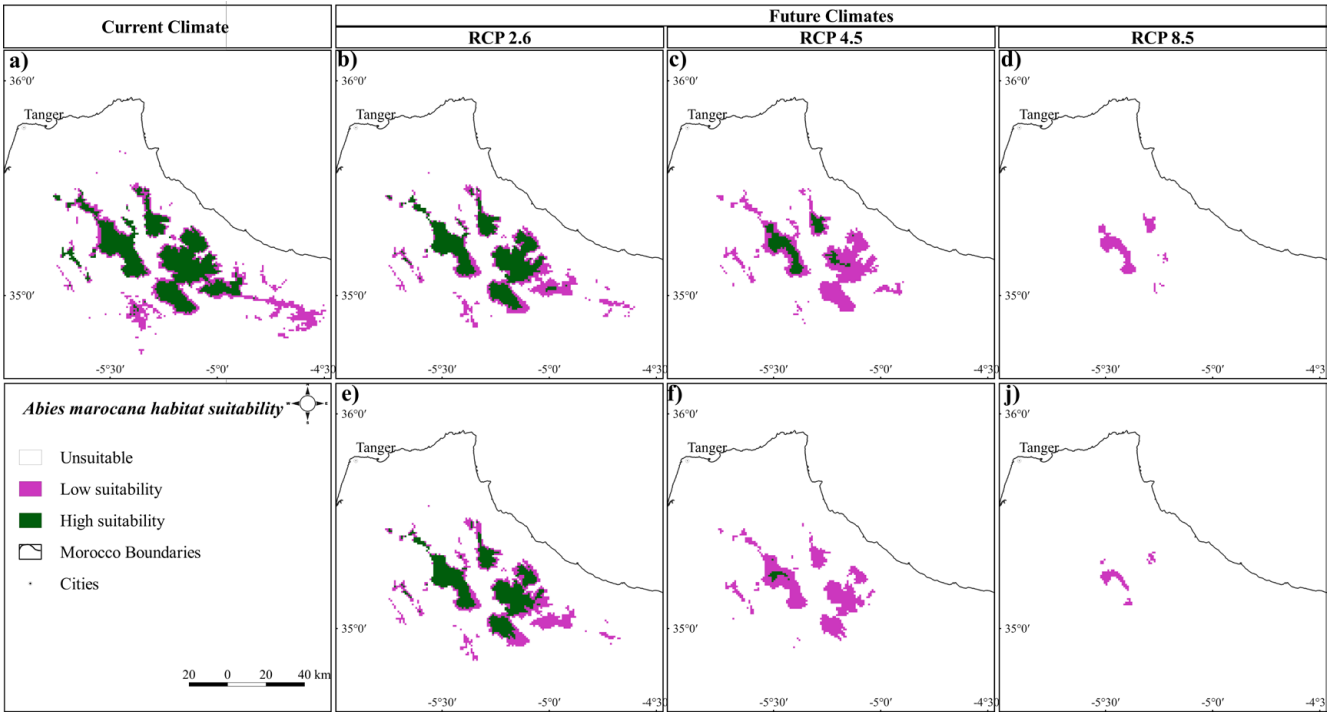


Fig. 3. *Abies marocana* habitat suitability under actual (a) and future climate scenarios for 2050: RCP2.6 (b), RCP4.5 (c), RCP8.5 (d) and 2070: RCP2.6 (e), RCP4.5 (f), RCP8.5 (j).

Table 1. Potential suitable area (in km²) of *Abies marocana* under current and future climate conditions.

	Actual occurrence of *A. marocana*	Current climate prediction	Future climate prediction					
			2050			2070		
			RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Low-suitability	-	1,051.6	708.9	927.5	210	755.7	787.7	81.2
High-suitability	-	1,304.5	875.2	213.9	0	767.4	23.4	0
Total	**47.7**	**2,356.1**	**1,583.2**	**1,141.4**	**210**	**1,523.1**	**811**	**81.2**

Table 2. Predicted changes in habitat suitability (in km²) for Moroccan fir distribution under future climate conditions.

	Current climate prediction	Future climate prediction (averaged GCMs)					
		2050			2070		
		RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Total high-suitable area (R ≥ T)	**1,304.5**	**875.2** (−32.9)	**213.9** (-83.6)	**0** (−100)	**767.4** (-41.2)	**23.4** (-98.2)	**0** (−100)
Loss of high-suitable area	-	0	186.6 (−14.3)	1,094.5 (-83.9)	0.8 (−0.1)	499.6 (−38.3)	1,223.3 (-93.8)
Stable high-suitable area	-	875.2 (67.1)	213.9 (16.4)	0	767.4 (58.8)	23.4 (1.8)	0
New high-suitable area	-	0	0	0	0	0	0
Total low-suitable area (½T ≤ R <T)	**1,051.6**	**708.1** (−32.7)	**927.5** (−11.8)	**210** (-80)	**755.7** (−28.1)	**787.7** (−25.1)	**81.2** (-92.3)
New low-suitable area	-	429.4 (+32.9)	904.0 (+69.3)	210.0 (+16.1)	536.3 (+41.1)	781.5 (+59.9)	81.2 (+6.2)
Loss of low-suitable area	-	772.9 (-73.5)	1,028.2 (-97.8)	1,051.6 (−100)	832.2 (-79.1)	1,045.3 (-99.4)	1,051.6 (−100)
Stable low-suitable area	-	278.7 (26.5)	23.4 (2.2)	0	219.4 (20.9)	6.2 (0.6)	0
Total suitable area (low and high: R ≥ ½T)	**2,356.1**	**1,583.2** (−32.8)	**1,141.4** (-51.6)	**210** (-91.1)	**1,523.1** (−35.4)	**811.1** (-65.6)	**81.2** (-96.6)

Notes: R – relative habitat suitability; T – predefined threshold; GCMs – general circulation models. For future habitat suitability, the percent changes from current climate predictions are provided in parenthesis.

meridians 04°29'–05°40' W, and that there were areas outside the sampling sites with high or low suitability (Fig. 3a).

Model predictions showed that the current potential distribution with high *(*R ≥ T*)* and low (½T ≤ R < T) relative habitat suitability was 1,304.5 and 1,051.6 km², respectively (Fig. 3a, Table 1). The total potential suitable area covered 2,356.1 km² and was much larger than the actual occurrence of this species (47.7 km²; Table 1). The comparison of the current potential distribution (Fig. 3a) and the actual occurrence (Fig. 1b) of *A. marocana* showed that the totality of effective occurrence of this species was predicted to be highly suitable and new areas in the northwestern part of the actual occurrence of this species were predicted as suitable under current climate conditions.

The trained model was used with the climatic projections for 2050 (Fig. 3b–d) and 2070 (Fig. 3e–j) based on the use of the average of the predicted future conditions using different global circulation models. The predicted distribution maps revealed that suitable areas for Moroccan fir distribution are located in some specific sites, confirming the affinity of this species to the north of Morocco. These suitable areas will be altered in the future horizons (from the near, i.e., 2050, to the long term, i.e., 2070), and under each of the future climate scenarios, from optimistic to pessimistic scenario (Fig. 3b–j, Table 1). Large parts of currently high- and low-suitable habitat classes will be affected and only few initial areas (ranging from 4% to 67% depending on the climate scenario) will remain suitable in the future (Table 1).

Suitable areas for *A. marocana* under RCP8.5 (Fig. 3d, j) are projected less than those predicted by optimistic (Fig. 3b, e) and intermediate (Fig. 3c, f) scenarios. Under the RCP8.5 scenario, a total absence of high-suitable areas was noted in the near and long term.

An absence of new high-suitable areas was noted in the future. Under all scenarios, no new high-suitable areas and no transition from low-suitable to high-suitable areas were noted. Also, the actual suitable areas located in the eastern part (Fig. 3a), where the species are actually present (Fig. 1b), will be unsuitable in the future.

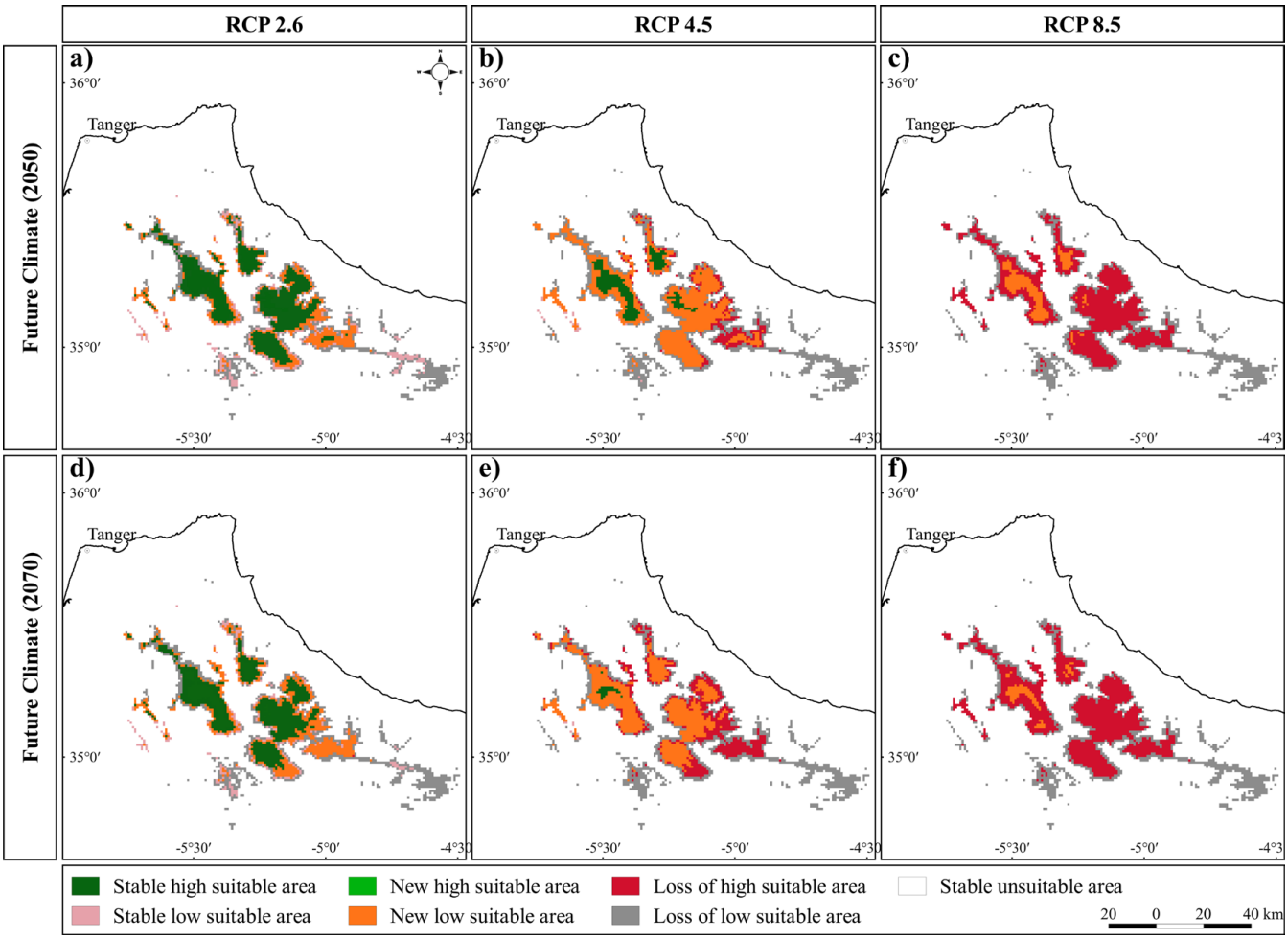


Fig. 4. Suitability changes of *Abies marocana* for the three climate scenarios: 2050: RCP2.6 (a), RCP4.5 (b), RCP8.5 (c) and 2070: RCP2.6 (d), RCP4.5 (e), RCP8.5 (f).

Habitat suitability changes of Abies marocana

The comparison of potential distribution maps under current and future climate conditions made it possible to estimate changes of Moroccan fir distribution under each of the future climate scenarios. A brief summary of the changes occurring due to potential future climate scenario over two time periods is given in Table 2. As shown in Fig. 4 and Table 2, the simulated changes in the potential distribution of this species are significant and projected to vary in the future under the different emissions pathways.

For the two time horizons and under the three climate change scenarios retained, the model predicted significant changes of suitable areas to this species (Fig. 4). The percentage variation in habitat suitability indicates negative values for all scenarios, ranging from −32.8 to -96.6%. The largest regressions in the suitable areas are forecasted under the RCP8.5 scenario and the smallest changes are forecasted under the optimistic scenario RCP2.6 (Fig. 4, Table 2). These regressions are projected to be more important in the long term (2070) than in near term (2050).

The analysis of results showed that no gains in terms of high-suitable areas (Table 2, light green color in Fig. 4) were recorded in the different time horizons and climate scenarios. Only limited new low-suitable areas (orange color in Fig. 4) have been identified, which mainly represent transitions from high-suitability areas to this low-suitability class.

For the two time horizons and passing from the optimistic to the pessimistic scenario, current potential suitable areas located in the eastern part will be unsuitable in the future. The direction and amplitude of the regressions of high-suitable areas are projected from the eastern part to the northwest part.

Discussion

SDM to improve knowledge of Abies marocana ecology

This research represents the first attempt to model actual and future distribution of *A. marocana* and to understand the impacts of future climate change on the spatial distribution of this endemic species. Despite previous research on forest and climate change in the Mediterranean region, there is still scientific gap related to the knowledge of spatial distribution of this species under current or future climatic conditions and also to the climate change uncertainties that have not been addressed.

The trained model showed that precipitation of the wettest quarter and precipitation of the coldest quarter are the environmental factors that provide the most useful information for *A. marocana* distribution, which confirmed the affinity of this species to cold and humid Mediterranean bioclimatic environment (Achhal et al., 1979; Barbero, Quezel, 1975; Benabid, 1982). This concords with López-Tirado and Hidalgo's (2014) results, which highlight seasonal precipitation as the main predictor of relict tree distribution in Mediterranean mountain forests. The other environmental variables contributed very little to the prediction. Results of this kind, as mentioned in the literature (Guisan, Zimmermann, 2000), contribute to the improvement of knowledge around the ecology of different species and create a better understanding about the range of environmental conditions that suit *A. marocana*.

The current potential (low and high) suitable areas of Moroccan fir confirmed its affinity to the northern part of Morocco, which is coherent with the species status as endemic to this specific location on the Rif Mountains having special bioclimatic conditions. This finding strongly agrees with the existing literature (Barbero, Quezel, 1975; Benabid, 2000; Quezel, 1998) and with the actual occurrences of this species (Fig. 1b). The current potential map presents a more extended distribution than the current occurrences, which is consistent with other findings for the genus *Abies* (Alaoui et al., 2021; Gazol et al., 2015; Navarro-Cerrillo et al., 2020)this modification may vary in strength and intensity across a species' biogeographical range. Here, we study European populations of silver fir (Abies alba. The large current potential suitable areas suggest that other parts of the Rif Mountains are bioclimatically suitable and present favorable environmental conditions for this species. However, despite favorable bioclimatic conditions, this species has not colonized all potential areas and is still absent in majority of the parts of the northern Morocco, mainly around the current distribution areas (northwestern parts), where the ecological conditions are highly suitable. This absence can be probably due to some factors, which are as follows: i) the nature of the forest land tenure in North Morocco, where the presence of forest species like *A. marocana* could consider land parcels as part of public forest domain, such presumption limits species extension (in private land) outside the forest-recognized areas (Moore et al., 1998); ii) the dissemination capacity of this species (Ben-Said et al., 2020; Navarro-Cerrillo et al., 2020) difficulties encountered in its regeneration (removal of juvenile plants and the horticultural commerce of individual living plants of *A. marocana* (Khabbach et al., 2022)); iv) silvicultural choices made in the past, advocating the expansion of certain species (pines, cypresses, sometimes holm oak) to meet the needs of local populations in terms of firewood (Moore et al., 1998); and v) past excessive pressure (fir clearance for wood used in building purposes) and illegal cutting and clearance by the local population of appropriate highly fertile land for the establishment of cannabis cultivation (Moore et al., 1998).

Climate change impact on potential Abies marocana distribution

Climate represents a critical ecological factor, and species distribution changes are the clearest responses to this factor. Future climate may disproportionately affect all biota at all ecological levels, leading to changes in species distribution (Di Nuzzo et al., 2021; Hughes, 2000; McCarty, 2001; Moukrim et al., 2019) bryophytes, and vascular plants. One of the objectives of this work was to examine the climate change impact on Moroccan fir distribution. Changes in potential suitable (high and low) areas to this species have been recorded for future time periods and for different climate scenarios. The results showed an important change and a gradual regression in *A. marocana* suitability by 2050 and 2070 under all three climate scenarios (optimist, intermediate, and pessimist) (Table 2, Fig. 4). These results agreed with other reports related to the genus *Abies* in the Mediterranean region (Gazol et al., 2015; Navarro-Cerrillo et al., 2020)this modification may vary in strength and intensity across a species' biogeographical range. Here, we study European populations of silver fir (Abies alba. However, under the optimistic scenario, relatively large areas of the current potential distribution (Fig. 4a, d) remain suitable unlike the other scenarios, which challenges us to limit global warming to 1.5 °C or well below 2 °C (IPCC, 2021).

The analysis of suitability changes showed that future climate was projected to have negative impacts on the potential suitable areas of *A. marocana* in different parts of the Rif Mountains where this species is predicted by the model to be suitable under current climate conditions. This result is also confirmed by the evidence from other studies and historical investigations, which documented that Moroccan fir forest was wider in the western part of the Rif Mountains during the last century (Barbero, Quezel, 1975; Benabid, 2000; Castro et al., 2022; Quezel, 1998), as a number of previously existing habitats had been narrowed around the world (Di Nuzzo et al., 2021; Hughes, 2000; McCarty, 2001; Moukrim et al., 2020).

The net negative impacts of climate change on the potential suitable areas could lead to a net decline in *A. marocana* distribution in the future, increase the risk of local extinction of this species in the future, and considerably affect the functions and services provided by this ecosystem. This is in agreement with results from other studies related to local extinction, specific to the genus *Abies* in the Mediterranean region (Gazol et al., 2015; Navarro-Cerrillo et al., 2020) this modification may vary in strength and intensity across a species' biogeographical range. Here, we study European populations of silver fir (Abies alba or to other plant species around the world (Brooks et al., 2002; Fordham et al., 2012; Hooper et al., 2012; Sánchez-Velásquez et al., 2021; Thomas et al., 2004).

On the other hand, it should be noted that the trained model ignores several factors, which may bias the projected impacts of climate change by making a number of simplifying assumptions. These include the specific capacity of a species to locally adapt to climate change, phenotypic plasticity, dispersal capacities, migration, and competition abilities (Phillips et al., 2006). Furthermore, the model ignores uncertainties related to future natural and human disturbances.

Exploring these uncertainties represents important opportunities for future research, especially since the colonization of new areas by fir trees is highly dependent on their migration and competitive abilities, phenotypic plasticity, specific ability to adapt locally to climate, and on human land use, management, and disturbance in the future.

The magnitude of the simulated shift in the potential distribution of this species is important. Alteration of this magnitude

would tend to have negative consequences for Moroccan fir conservation. Therefore, we recommend including future climate scenarios in existing management strategies for the protection of the entire ecosystem that is supported by this endemic flagship species and prevent its future locale extinction (Hooper et al., 2012).

Considerations for management

Due to the status of *A. marocana* as a relic species and the need to maintain this emblematic species for future generation, conservation strategies have been adopted. Climate change brings new challenges that managers and conservators must take into account in order to ensure sustainability of this natural capital. Indeed, with the severity of expected impacts, classic management and conservation actions toward Moroccan fir forest management appear less appropriate to guide managers and scientists. Such inadequacy is well observed in current management plans of various Moroccan forests and protected areas, which rarely consider that the spatial distribution of species may vary in the context of climate change. According to the conservation needs, orientation toward adoption of the precautionary principle must be followed during conduction of silvicultural activities. It must focus on the choice of sites and the intensity and appropriate period of required activities.

Potential maps produced under current and future climate conditions (Fig. 3a–j) improve our knowledge of the biogeography and ecology of *A. marocana* and provide additional information compared to the occurrence maps (Fig. 1b). They constitute a tool to enhance understanding of the impact of climate changes on the species distribution, which will make it possible to clarify the choice of action sites for the conservation and development of the Moroccan fir and will help to better prioritize the intensity of interventions. Indeed, comparison of current and future suitability sites can guide identification of sites that must be managed according to the precaution principles (sites on which the species is undergoing severe future reduction of its potential distribution) and those that can be planned as development sites (which will remain suitable or may be potential suitable areas) that will harbor *A. marocana* in the future.

In this context, *in situ* and *ex situ* conservation strategies should, therefore, be explored. Highly suitable areas under current climate conditions, characterized by the occurrence of this species, and which will remain favorable in the future must be managed by urgent participative conservation actions. The areas predicted as highly suitable under current climatic conditions and which will remain favorable in the future, but currently not occupied by fir forest, will have to be supervised by programs of artificial regeneration and assistance to the migration of the species (Vitt et al., 2010). These future micro-refugia present valuable opportunities as management targets to maintain this endemic species in the face of climate change (Moritz, Agudo, 2013).

In a different register, the maps produced could be important tools, available to managers, for achieving the expected objectives of the Talassemtane National Park and the Intercontinental Biosphere Reserve of the Mediterranean by integrating future potential suitable areas in the management plans of these protected areas and could be useful to form a new design of their limits in the future.

Conclusion

This work successfully modeled the habitat suitability of a North Moroccan endemic species *A. marocana* Trabut under the current climate scenario and predicted its future distribution under projected climate scenarios. It contributed to deepen the ecological knowledge about this species by identifying bioclimatic variables underlying its distribution. This study concludes that the current potential map of suitable habitat for fir tree presents a more extended distribution than current occurrences and the predicted future distribution seems to be highly dependent on climate change. Results showed an important change and a gradual regression of the habitat suitability of this species under different climate scenarios. These projected negative impacts could have significant implications for the conservation of this species in the future. Given this, the use of produced suitability maps of this relic species will be valuable tools to inform and guide managers and decision-makers to deal with climate change and develop adaptive strategies.

Acknowledgements

The authors would like to acknowledge anonymous reviewers and editor for providing helpful comments and suggestions. This work was supported by BiodivRestore Program (RESPOND Project) funded by the Ministry of Higher Education, Scientific Research and Innovation of Morocco (MESRSI).

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