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Original Article

Changes in the Potential Distribution of Atlas Cedar in Morocco in the Twenty-First Century According to the Emission Scenarios of RCP 4,5 and RCP 8,5

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ABSTRACT

The increasing temperatures and decreasing rainfall are expected to have negative effects on ecosystem services causing significant shrinkage or shift in forest distributions particularly in the Mediterranean basin. In this study, we aimed to determine the distribution of Atlas cedar (*Cedrus atlantica* Manetti), modeling the current and potential future distributions in Morocco with Maximum Entropy (MaxEnt) approach. Modeling was performed using all bioclimatic variables that show a significant relationship to the current distribution of Atlas cedar and that were specifically preferred in the literature by several similar studies. Prediction of warmer future scenarios showed that populations in the potential area would decrease by 21% for RCP 4.5 (2050), by 23% for RCP 4.5 (2070), by 35% for RCP 8.5 (2050), and 41% for RCP 8.5 (2070) and that there would be an impact in all ranges including the Cedar Biosphere Reserve in Morocco. Similarly, the Atlas cedar would lose its isolated-marginal populations in its southern and western extents. The results underline the importance of a genetic conservation program for cedar populations in Morocco. Otherwise, gene pools seem to turn extinct due to climate change. Furthermore, this study is intended to provide a starting point for continuous monitoring of Atlas cedars distributions while observing its climatic migration. Species distribution modeling generates valuable information for conservation management strategies for this endemic, rare, and threatened relict tree species. The results can be used to identify high-priority areas for Atlas cedar restoration and conservation against the expected impact of climate change.

Keywords: *Cedrus atlantica*, climate change, maximum entropy, RCP, spatial modeling

Introduction

The climate plays a decisive role in the large-scale distribution of forest tree species (Guisan and Thuiller, 2005). Particularly in the upcoming near future, climate change may dictate major roles in species adaptation and distribution (Almeida et al., 2022; Thurm et al., 2018). The effects of this unfortunate phenomenon are ever more visible in Morocco, which has been identified as a very vulnerable country by the 4th Assessment Report of the United Nations Intergovernmental Panel on Climate Change (IPCC, 2007). Morocco is highly vulnerable to climate variability and change (World Bank Group, 2021). It is a major risk to sustainable development and has negative effects on all ecosystem services seriously hampering forest ecosystems.

The entire Mediterranean basin is considered as one of the most vulnerable regions to climate change in the world (Ayan et al., 2022; Barbati et al., 2018; IPCC 2007). Regato and Salman (2008) stated that the Mediterranean highlands are among the areas that will be most affected by the phenomenon (rising temperatures and increasing drought). It is estimated that increasing frequency of extreme climatic events, e.g., dry years, heat waves, and irregular but heavy rains will increase forest mortality (Bussotti et al., 2021). In order to mitigate the effects of climate change on forest ecosystems, distribution modeling of rare forest species will help us draw new strategies to preserve what is left. Conservation of biodiversity is a key target that requires both the quantification of biodiversity and the monitoring of its gains/losses in order to reduce the impacts of climate change on ecosystems (Balmford, 1996). Thus, we can effectively target conservation strategies. However, occurrence data tend to be very sparse for the vast majority of species, especially the rare ones (Alaoui et al., 2021a,b; Marcer et al., 2013). Model simulations could help depict potentially suitable areas and evaluate the risk of extinction possibilities based on a variety of climate scenarios (Thuiller et al., 2005). Conservation policies for an organism would benefit from a temporal perspective based upon the relationship between the species' present extents and its past environments (Willis & Birks, 2006; Willis & Bhagwat, 2010).

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There are four species of cedar in the world (*Cedrus libani* A. Rich (Anatolia, Taurus Mountain, Erbaa, Niksar, Lebanon, Palestine, and Syria), *Cedrus deodara* (Roxb.) G. Don (Himalaya, Afghanistan, and Balochistan), *Cedrus brevifolia* (Hook. f.) Henry (Cyprus), and *Cedrus Atlantica* Manetti (Rif and Atlas Moroccan Mountain, Algeria) (López-Tirado et al., 2021).

Atlas cedar is an endemic species and emblematic species, appreciated for its technological, ecological, and biogeographical values (Laaribya et al., 2016; Terrab et al. 2006). Despite its inclusion in the World Network of Biosphere Reserves in 2016 (UNESCO, 2016), the Moroccan Atlas cedar forests show a regressive trend both in time and space. The International Union for Conservation of Nature (IUCN) has included it in its red list of endangered species (IUCN, 2017). The Atlas cedar Biosphere Reserve, located in the central Atlas Mountains of Morocco (1,375,000 ha), is home to 75% of the world's majestic Atlas cedar tree population (UNESCO, 2018). This region, characterized by a wealth of ecosystems and the mountain peaks, reaches up to 3700 m, provides critically important water resources (Laaribya & Belghazi, 2016). However, climate change is expected to alter the natural distribution of the Atlas cedar and lead to a loss of biodiversity in this ecosystem. Both paleo-ecological data and model simulations showed that Atlas cedar populations are declining in Northern Morocco due to a combined effect of climate and human-induced changes (Cheddadi et al., 2017). Çalıkoğlu et al. (2021) conducted a research on the adaptation of species and origin in cedar in southwestern Turkey. In this research, 20 provenances of Atlas cedar, 3 provenances of Lebanon cedar, and 2 provenances of Cyprus cedar had been subjected to 20-year adaptation trials in Soutwestern Mediterranean Elmalı-Antalya and Keçiborlu-Isparta locations in Turkey where Supra-Mediterranean (cool, semi-arid) bioclimatic conditions prevail. According to 20 years' results, it was determined that Algerian Atlas cedar, Lebanon cedar, and Cyprus cedar provenances had adaptation capability to mentioned conditions. Nevertheless, Morocco's provenances of Atlas cedar had lower adaptation capability compared to the other two. Therefore, vulnerability to the expected climate change and the resulting global warming was found high.

Maximum Entropy (MaxEnt) model algorithm methods (Phillips, 2006) has proved powerful when modeling rare species and various earthly phenomenon with narrow ranges and available scarce presence-only occurrence data (Abdelaal et al., 2019; Aili et al. 2017; Alaoui et al., 2021a; Al-Qaddi et al., 2016; Ayan et al., 2022; Elith et al., 2006; Elith et al., 2011; Laaribya et al, 2021; Phillips et al., 2006; Stephan et al., 2020; Torun & Altunel, 2020). Indeed, species distribution models (SDMs) are frequently used to predict the potential and future geographic range of a species based on observations of species occurence or abundance with environmental estimates. (Peterson et al., 2011; Wilson et al., 2011). Accurate modeling of geographic distributions of species is crucial to various applications in ecology and conservation (Phillips & Dudik, 2008).

Sustainable management and conservation of Morocco's Atlas cedar ecosystems in the context of current climate change requires focused scientific insights and spatial analysis to formulate and implement a well-functioning strategy. The knowledge of the potential distribution of the Atlas cedar under climate change, as well as the identification of the environmental factors that condition it, is an inevitable step that can provide crucial information. This study was carried out to investigate some soil groups and spatial distribution scenarios for orientation, conservation , and cultivation of the endemic species *Cedrus atlantica Manetti* (Pinaceae) in order to examine the effects of climate change on the potential habitat.

Methods

Study Area

The spatial data of the Atlas cedar used in the study comprise the entire current distribution area of the Atlas cedar in Morocco (Figure 1). Atlas cedar occurrence data were obtained from the national water and forestry agency. In Morocco, Atlas cedar forests are located in the central Middle Atlas (120,000 ha), in the eastern Middle Atlas (23,000 ha), in the eastern High Atlas (26,000 ha), in the Rif (15,000 ha), and in the Tazekka region (850 ha) (Laaribya et al., 2016; Mhirit, 1993).

Modeling Approach, Processing, and Data Used

To determine the predicted current and future potential distribution range of the Moroccan Atlas cedar, the maximum entropy algorithm "MaxEnt" was used. This model makes it possible to establish a relationship between the ecological niche of the species and the environmental variables (Elith et al., 2011). It represents an important prediction tool in conservation ecology (Phillips et al., 2006). In this study, we selected 1251 points of occurrence of the Moroccan Atlas cedar from the National Forest Inventory database (IFN, 2005). Subsequently, we carried out verification trips on 125 presence points (i.e., 10% of our initial sample) to avoid any omission or confusion with other species.

The basic climatic data concerned the period 1970–2000. They were extracted in Raster form from version 2.1 of the "WorldClim" database (http://www.worldclim.org), a worldwide catalog of temperature and rainfall data, collected at a ground resolution of 30 arc-seconds "≈1 km^2/pixel" (Fick & Hijmans, 2017). Indeed, 24 environmental variables were used to model the probability of occurrence of Moroccan Atlas cedar: 19 bioclimatic variables most related to physiological aspects of plant growth, 3 topographical variables, altitude, exposure, and slope which, according to the literature, have an effect on the distribution of Moroccan Atlas cedar (Laaribya & Alaoui, 2021). Two other indices that affect the distribution of species in the context of the Mediterranean climate: The Emberger bioclimatic index (Emberger, 1939; Sauvage, 1963) and relative humidity (RH) (Monteith & Unsworth, 2008). It must be emphasized that this work is addressing the potential distribution of Atlas cedar. Therefore, habitat suitability according to the explanatory variables is detected; no biotic interactions are considered because of their difficulty to be incorporated into the model.

The data on annual mean temperature "T," water vapor partial pressure "Pvap," altitude and bioclimatic variables used were also extracted from the WORLDCLIM database (http://www.worldclim.org), at a resolution of 30 arc-seconds (Fick & Hijmans, 2017; Hijmans et al., 2005). The bioclimatic variables and altitude, which are widely used in species distribution modeling studies and also directly affect the natural distribution of Atlas cedar, were used in this study to optimize the future distribution.

For the simulation of potential future areas, two greenhouse gas emission scenarios (Representative Concentration Pathway) were used in our study. These are the intermediate (RCP 4.5) and the most extreme scenario (RCP 8.5) adopted by the Fifth Assessment Report (IPCC, 2014). Indeed, two time slots were studied for each RCP: 2050 (average for 2041–2060) and 2070 (average for 2061–2080).

Model Performance and Cartography

The receiving operator characteristic (ROC) curve (Hanley & McNeil, 1982) and the AUC (area under the ROC curve), which is a threshold that

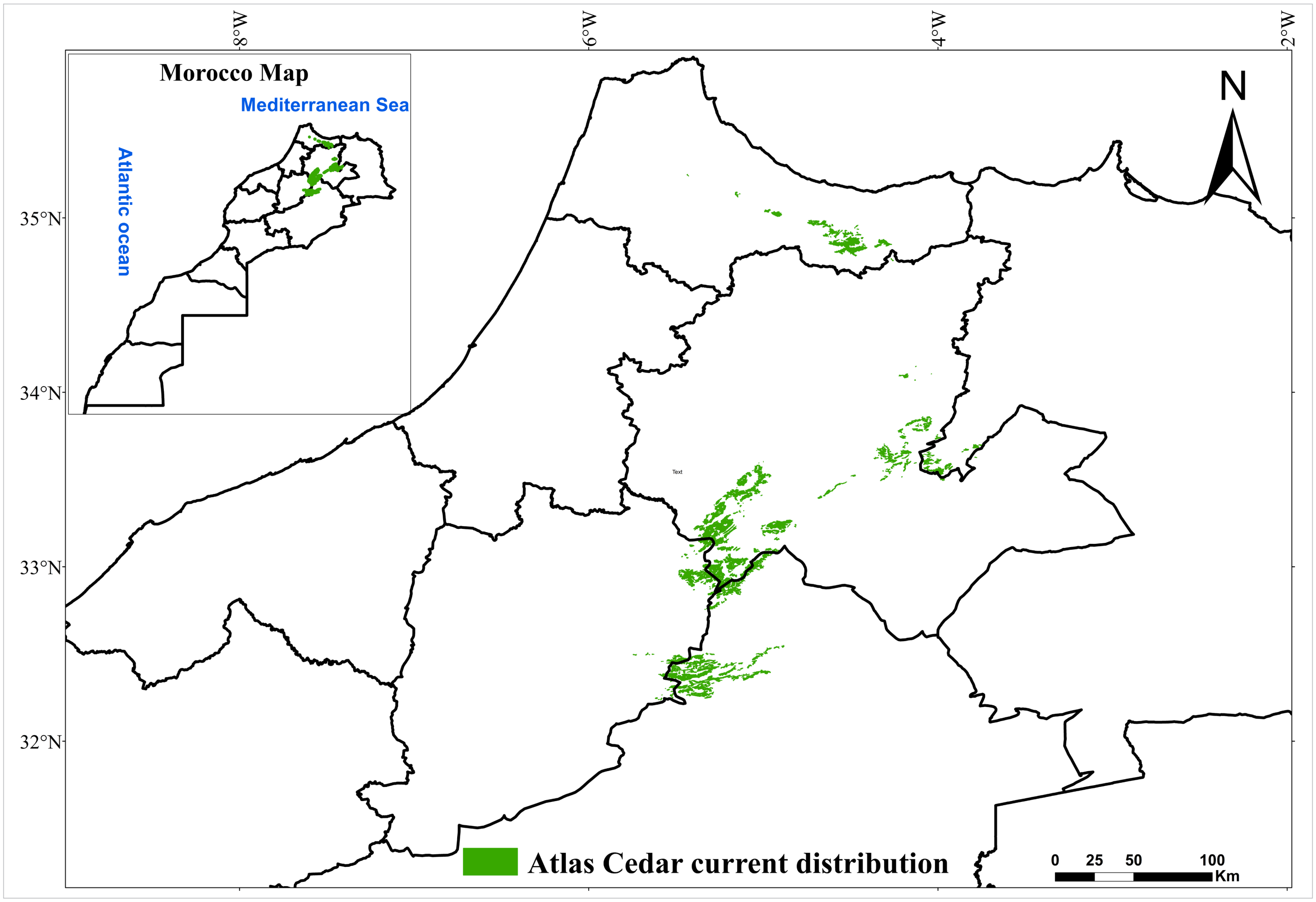

Figure 1.
Study Area (Atlas Cedar Current Distribution).

evaluates the predictive capacity of the model; the higher the value of AUC is close to one, the further it deviates from a random pattern. (Phillips et al., 2006). According to the proposal of Araújo et al. (2005), the AUC values are interpreted as follows: the model is "excellent" if AUC > .90; "good" if .80 < AUC ≤ .90; "acceptable" if .70 < AUC ≤ .80; "bad" if .60 < AUC ≤ .70; and "invalid" if AUC ≤ .60.

The jackknife test (Miller, 1974) allows the determination of the predictive power of each variable and the identification of those that contribute most to the generation of the distribution model produced by MaxEnt.

The MaxEnt model for Atlas cedar is a representation of the probability of occurrence of the species at each pixel in the study area. This model produces the distribution map of Atlas cedar based on a classification of the results into two probability of presence intervals "P," defined mainly by a threshold "S" retained. This threshold "S" is relative to a training presence at the 10th percentile (10 percentile training presence), representing the probability that 90% of the presence points fall within this potential area (Phillips & Dudik, 2008).

To carry out the necessary mapping, we used two softwares "ArcGIS 10.4.1" and Diva GIS. The principle of maximum entropy (MaxEnt) was used to model the Atlas cedar potential distribution area under current and future climates.

Results and Discussion

Model Performance

The area under the ROC curve, which measures the prediction accuracy of the model, is 96.7% which confirms the excellence of the modeling that was carried out and indicates the performance and robustness of the model chosen for the prediction of the potential area of Atlas cedar in Morocco (Figure 2). The Jackknife test shows that the environmental variable that leads to a strong reduction (i.e., 18.1%) in the predictive power of the model when RH is omitted. The environmental variable that leads to the best gain (35.7%) when used in isolation in the model is the mean annual temperature (Bio1). These two variables thus seem to have more explanatory information on the distribution of Atlas cedar and the results of the Jackknife test (Figure 2) (Laaribya & Alaoui, 2021).

The results of the Jackknife test (Figure 2) reveal that the main variables that have the most influence on the presence of Atlas cedar in Morocco are Bio17 (precipitation of the driest quarter), Bio14 (precipitation of the driest month), Bio9 (average temperature of the driest quarter), and Alt (altitude) with 71.3%, 9.9%, 4.3%, and 3.3% contribution, respectively (Laaribya & Alaoui, 2021).

Spatial distribution modeling reveals that precipitation in the driest quarter (Bio17), precipitation in the driest month (Bio14), mean annual temperature (Bio1), and mean annual RH are the most influential

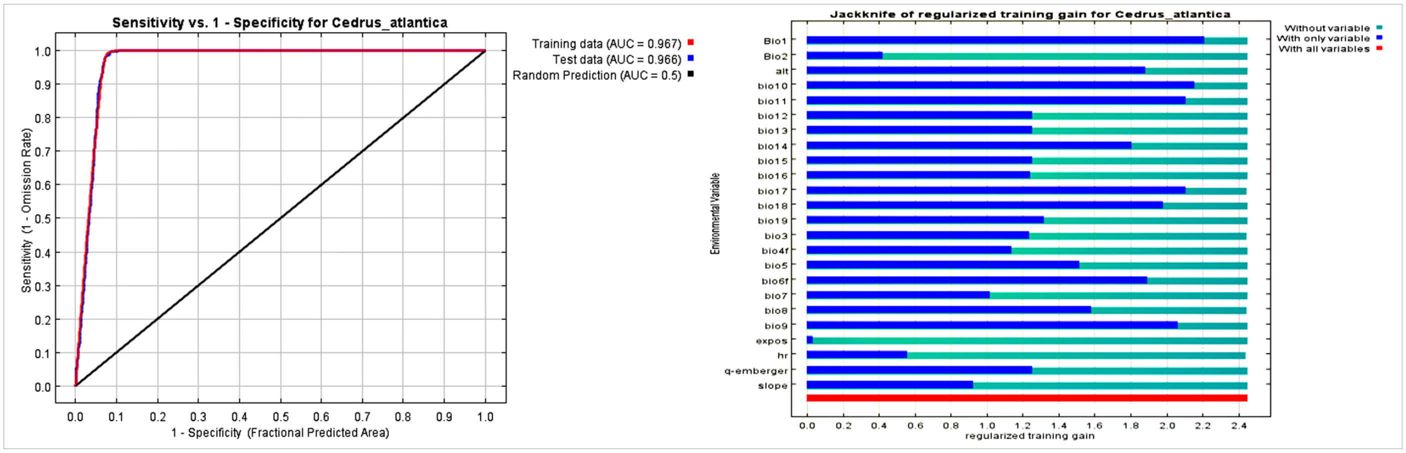

Figure 2.
Receiver Operating Characteristic Curves for the Occurrence of Cedrus atlantica *in Morocco and Results of the Jackknife Test of Variable Importance. AUC = area under the curve.*

variables in the current distribution of Atlas cedar in Morocco (Figure 2). The other environmental variables have smaller contributions to the prediction of the model in question. The species is absent in arid and semi-arid areas with low precipitation and high temperatures, which are limiting factors for it in Morocco. These results have been confirmed by several studies which stated that climatic variables played a role of primary importance in the distribution of Atlas cedar in Morocco (Achhal et al., 1980; Cheddadi et al., 2017; Laaribya et al., 2016; Mhirit, 1982).

Predicted Current and Future Potential Area of Atlas Cedar

The soil map of the current distribution area of the cedar in Morocco is given in Figure 3. In addition, the distribution of soil groups in the possible distribution areas of Atlas cedar under different emission scenarios is given in Table 1. It has been determined that the main soil group is Regosol/Renosol, where Atlas cedar grows in both current and potential distributions under climate change conditions.

The modeling method used and completed by the cartographic work allowed us to produce the first map of the potential distribution area of the Atlas cedar in Morocco, taking into account the threshold for the presence of training at the 10th percentile.

The current mapped area of Atlas cedar in Morocco is about 138,691 ha. The predicted suitable distribution of Atlas cedar covers 770,605 ha including areas where the species is currently present (Figure 4).

Also, by superimposing the current range of Atlas cedar on its predicted potential range (Figure 5), we detected a surplus of 631,914 ha (a predicted increase of +455%). A surplus is marked in the southern part of the Cedar Biosphere Reserve, also in the Rif Mountains (northern Morocco) and in the eastern Middle Atlas.

The model results obtained based on the current and future (2050 and 2070) projections carried out in this study were mapped and displayed in Figure 6(A)–(D).

The ecological response curves of the most important variables showed that the presence of Atlas cedar was optimal in areas with more precipitation in the driest quarter (Bio17) and precipitation in the driest month (Bio14), while the annual mean temperature (Bio1) showed low values. Indeed, under the current climatic conditions, precipitation and its variability are the most important factor in the distribution of Atlas cedar and its growth (Figure 7). It is believed that the factor that interrupts the migration of cedars from the south in the Tertiary to the east (Algeria, Tunisia, the Taurus Mountains, Syria, and Lebanon) is drought (Qiao et al. 2007). According to Ladjal et al. (2005), they stated that the Atlas Mountains being more humid than the Eastern Mediterranean (ocean effect) may be the reason for the sensitivity of the Atlas cedar origin to drought. Ulbrich et al. (2006) have expressed that the results of various scenarios have shown that the net water decency in the Mediterranean basin will increase between 1.3% and 14% by the end of the century, and the net heat flow per unit area (m^2) will increase between 3.6 and 11.9 W. In general, it is expected that annual precipitation will decelerate by 10–30%, although it varies by region.

The cedar individualizes stands in cold mountainous areas, mainly in sub-humid, humid, and per-humid bioclimatic environments, under cold and very cold stages. Atlas cedar stands at altitudes between 2200 and 2500 m and stands out in the extremely cold variance in the Middle and High Atlas. This result confirms the fact that climatic parameters, such as temperature and precipitation, have the greatest effect on species distribution (Guisan & Zimmermann, 2000). Quezel (2004) also emphasized that annual precipitation (P) and the average temperature (°C) of the coldest month are the main determining parameters in the Mediterranean bioclimate.

Apart from altitude, the geo-topographical variables (exposure and slope), in the light of the other climatic variables, contributed very little to the prediction of the model and were therefore very insignificant. However, taking into account the close relationship of the spatial variability of the climatic factors with the geo-topographical factors, the influence of the latter on the distribution of Atlas cedar is considered indirect.

The current mapped area of Atlas cedar in Morocco is 138 691 ha, while the modeled potential distribution area is 770 605 ha, i.e., a surplus of 631 914 ha (+455%) compared to its current habitat. This result shows, on the one hand, the regression of the surface area occupied by the Atlas cedar and reveals the possibility of reconstituting its habitat under the current climatic conditions by reconstituting it at the scale of its predicted potential area. Cheddadi et al. (2017) by its simulation showed that the range of Atlas cedar decreased by about 75% over the last 50 years and that the eastern populations of the range in the

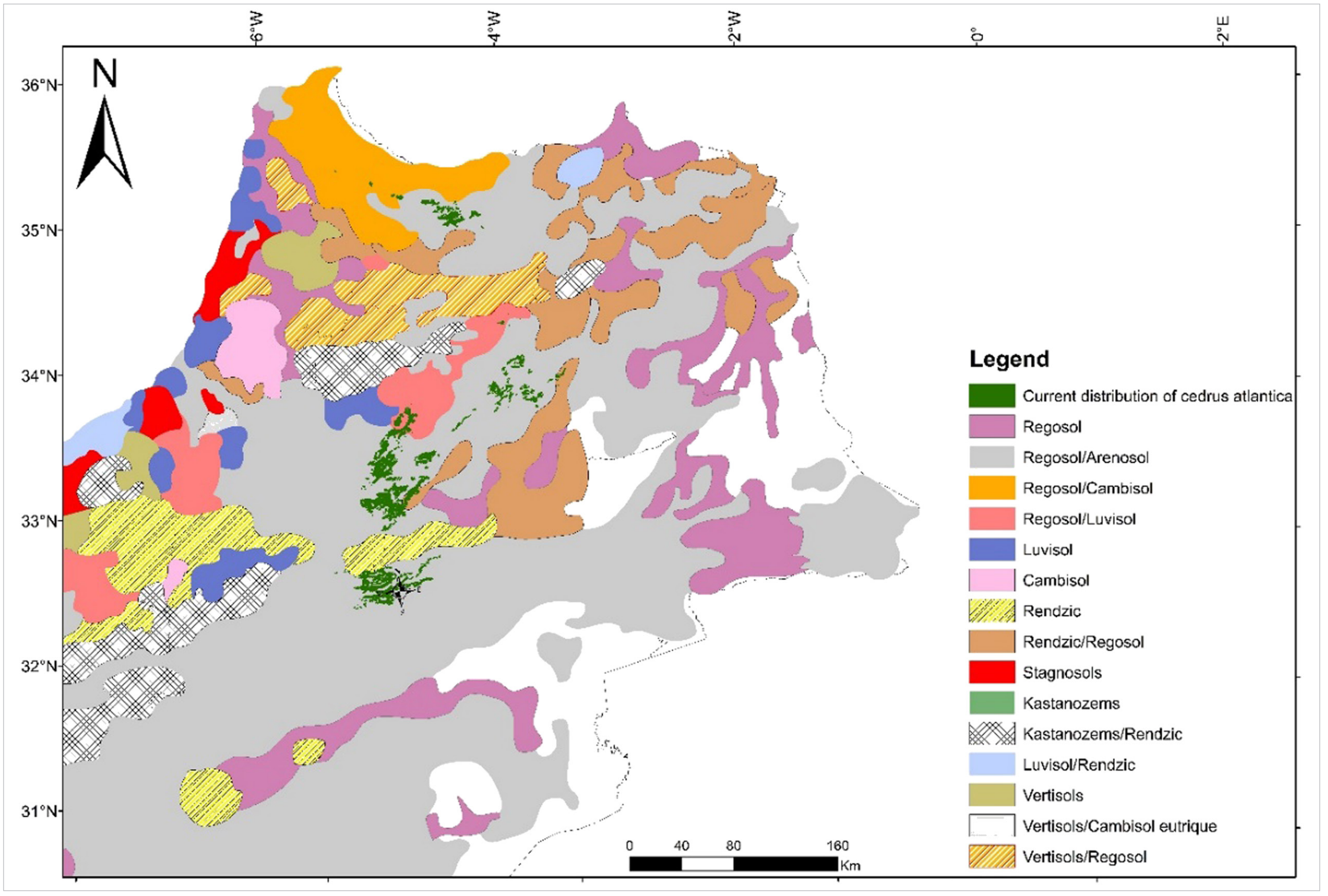

Figure 3.
The Soil Map with Current Distribution of Cedrus atlantica *in Morocco (WRB, 2014).*

Rif Mountains were even more threatened by the overall lack of water availability than the western ones. In addition, Linares et al. (2013) stated that increasing drought effects are harmful to sensitive species like mountain conifers and *Cedrus* in particular.

The comparison of potential distribution maps under current and future climate conditions made it possible to estimate the impact of climate change on the distribution of cedar. Although the location of the future potential distribution of Atlas cedar is lower than the current potential distribution, our model results show that the geographic distribution would expand under predicted levels of climate change.

Compared with the result of the most optimal habitat under current climate prediction, the predictions for the intermediate scenario (RCP 4.5) showed almost the same for 2050 and slightly lower for 2070. The results of this scenario show that new potential areas, even if limited, will emerge in the future. This is consistent with some studies, which have recognized that global warming could also have a positive effect on ecosystems and species in some parts of the world, through the expansion of their habitats (IPCC, 2018; López-Tirado et al., 2021). However, for the RCP 8.5 scenario, the model predicts moderate and high climate change impact of optimal habitat in 2050 and 2070. The most affected areas by future climate change are located in the southern part of the

Table 1.
Distribution of the Soils Group under Climate Change Scenarios of Cedrus atlantica

	Current Distribution	Potential Distr. Present	RCP 4.5		RCP 8.5	
			2050	2070	2050	2070
Habitat suitability area (hectare)	138,691	770,605	644,996	593,366	503,205	460,051
Regosol/Arenosol (%)	84	84	84	85	87	87
Regosol/Luvisol (%)	2	2	2	2	1	1
Regosol/Cambisol (%)	2	2	2	2	1	1
Rendzic/Regosol (%)	1.5	1	1	0.5	1	1
Other soils (%)	0.5	1	1	0.5	—	—

Table 2.
Predicted Current and Future Potential Natural Distributions of Cedrus atlantica

		Current Distribution	Potential Distr. Present	RCP 4.5		RCP 8.5	
				2050	2070	2050	2070
Habitat suitability area (hectare)		138,691	770,605 (+455%)	644,996	593,366	503,205	460,051
Habitat suitability area (km^2)		1386.91	7706.05	6449.96	5933.66	5032.05	4600.51
Percentage of *Cedrus atlantica* in the forested areas in Morocco (%)		1.54	8.56	7.17	6.59	5.59	5.11
Percentage of *Cedrus atlantica* in Morocco (%)		0.20	1.08	0.91	0.83	0.71	0.65
Area loss (%)/compared to the predicted potential distr. present				21	23	35	41
Unchanged (%)/compared to the predicted potential distr. present				81	79	43	41
Gain (%)/compared to the predicted potential distr. present				33	29	20	10
Elevation (m)	Min.	1200	1000	1300	1300	1350	1350
	Max.	2600	3000	3100	3200	3200	3200
	Mean	1900	2250	2200	2250	2275	2300

Cedar Biosphere Reserve, the central and eastern Middle Atlas and the eastern High Atlas Mountains. It can be noted that the Atlas cedar forests in Morocco will tend to be more negatively affected by the temperature increase and low rainfall, expected to occur in the future within the framework of global warming in the Mediterranean mountainous region (Çalıkoğlu et al., 2021).

Dagher-Kharrat et al. (2007) stated that both Atlas cedar Morocco origins and Himalayan cedar origins have been identified as the cedar origins with the lowest genetic diversity. The low adaptation capacity and rapid degradation of Atlas cedar may be attributed to its low genetic diversity. Unfortunately, Atlas cedar forests' degradation will continue to take place at alarming rates, which contributes implicitly to the ongoing loss of biodiversity especially in the Cedar Biosphere Reserve. Recent studies have demonstrated that mountain species such as *C. atlantica* are persisting in restricted and isolated areas considered as microrefugia (Cheddadi et al. 2017). Nevertheless, today, the forests of all three cedar species (Atlas cedar, Lebanon cedar, and Cyprus cedar) in the Mediterranean are protected on different scales. For example, the presence of the Cyprus cedar in the Paphos region is fully protected, the productive stands of the Taurus cedar in Turkey are not subject to interventions aimed at natural regeneration, the degraded stands are rehabilitated, the residual cedar trees in the Basherra region of Lebanon are being protected, and the Atlas cedar forests in the Atlas Mountains also deserve protection (Çalıkoğlu et al., 2021). Beyond that, populations in Morocco to adapt to predicted climatic change may be necessary to migrate to regions more suited to their ecological aspirations for Atlas cedar. A similar trend has been detected in Atlas cedar populations in Algeria, where the southern limit of distribution has shown high tree mortality in recent decades (Slimani et al. 2014).

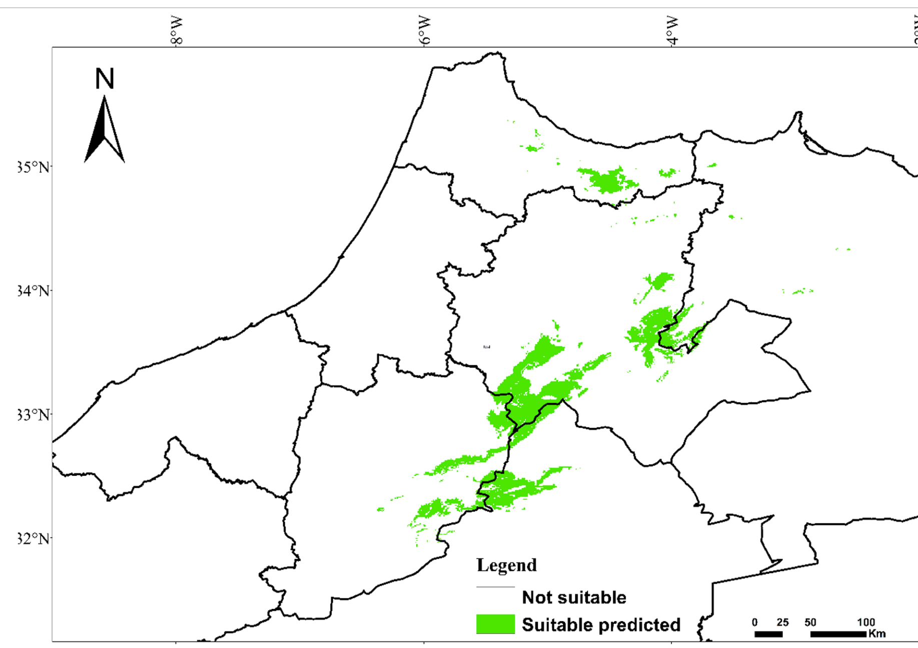

Figure 4.
Suitable Predicted Areas for Cedrus atlantica *in Morocco.*

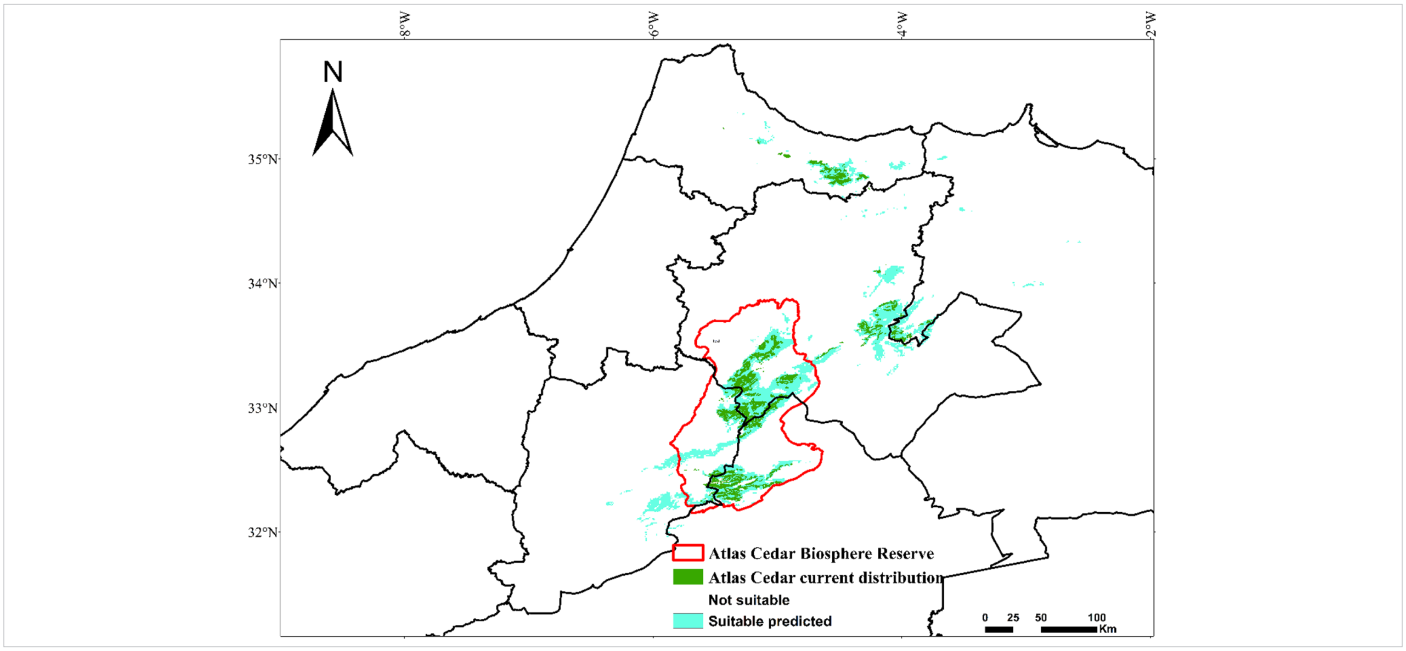

Figure 5.
Map Linking Current and Potential Distribution of Cedrus atlantica *in Biosphere Reserve and in All Morocco.*

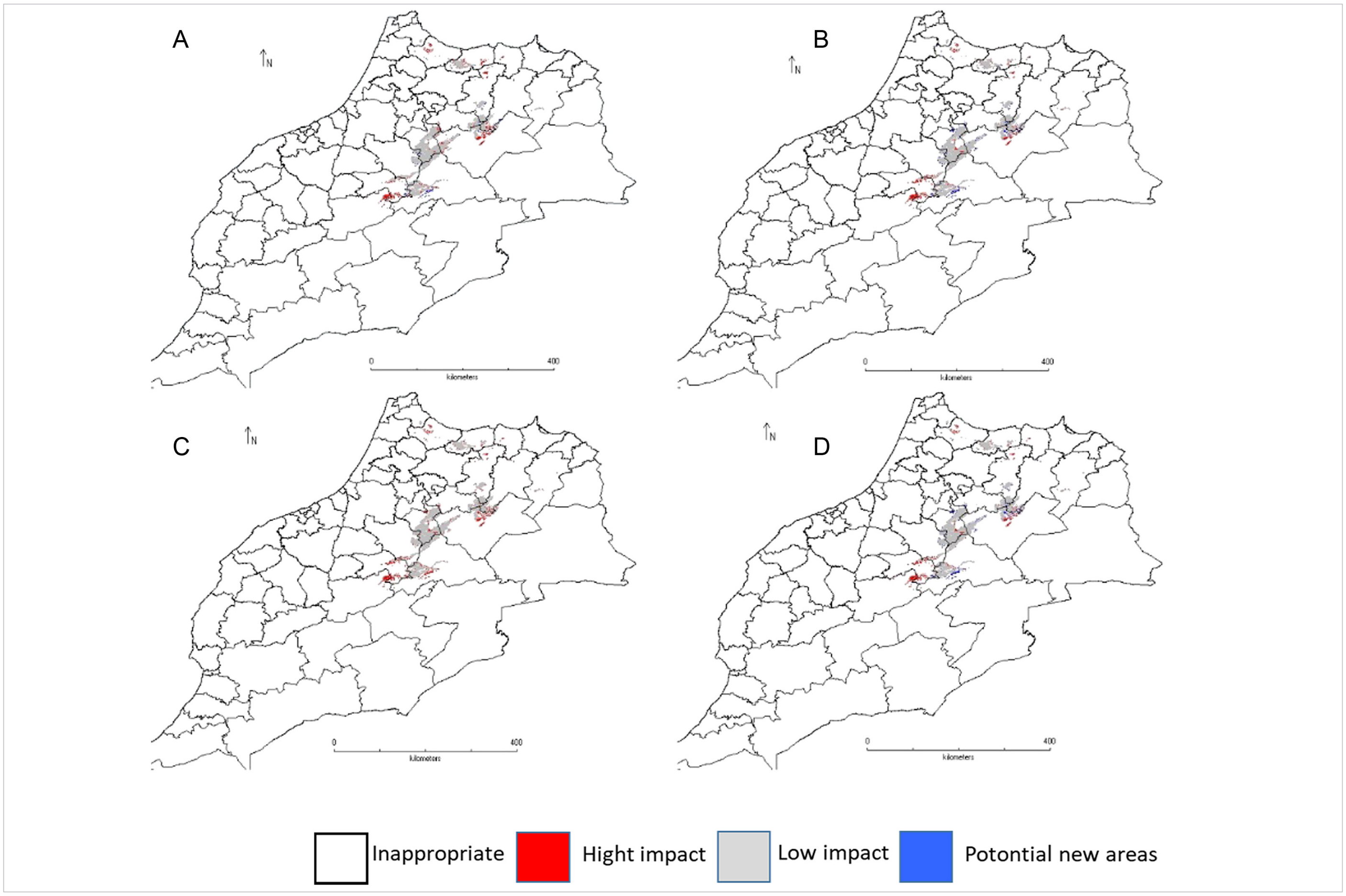

Figure 6.
Impacts of Climate Change on Potential Distribution of Cedrus atlantica *According to (A) RCP 4.5 (2050), (B) RCP 4.5 (2070), (C) RCP 8.5 (2050), and (D) RCP 8.5 (2070).*

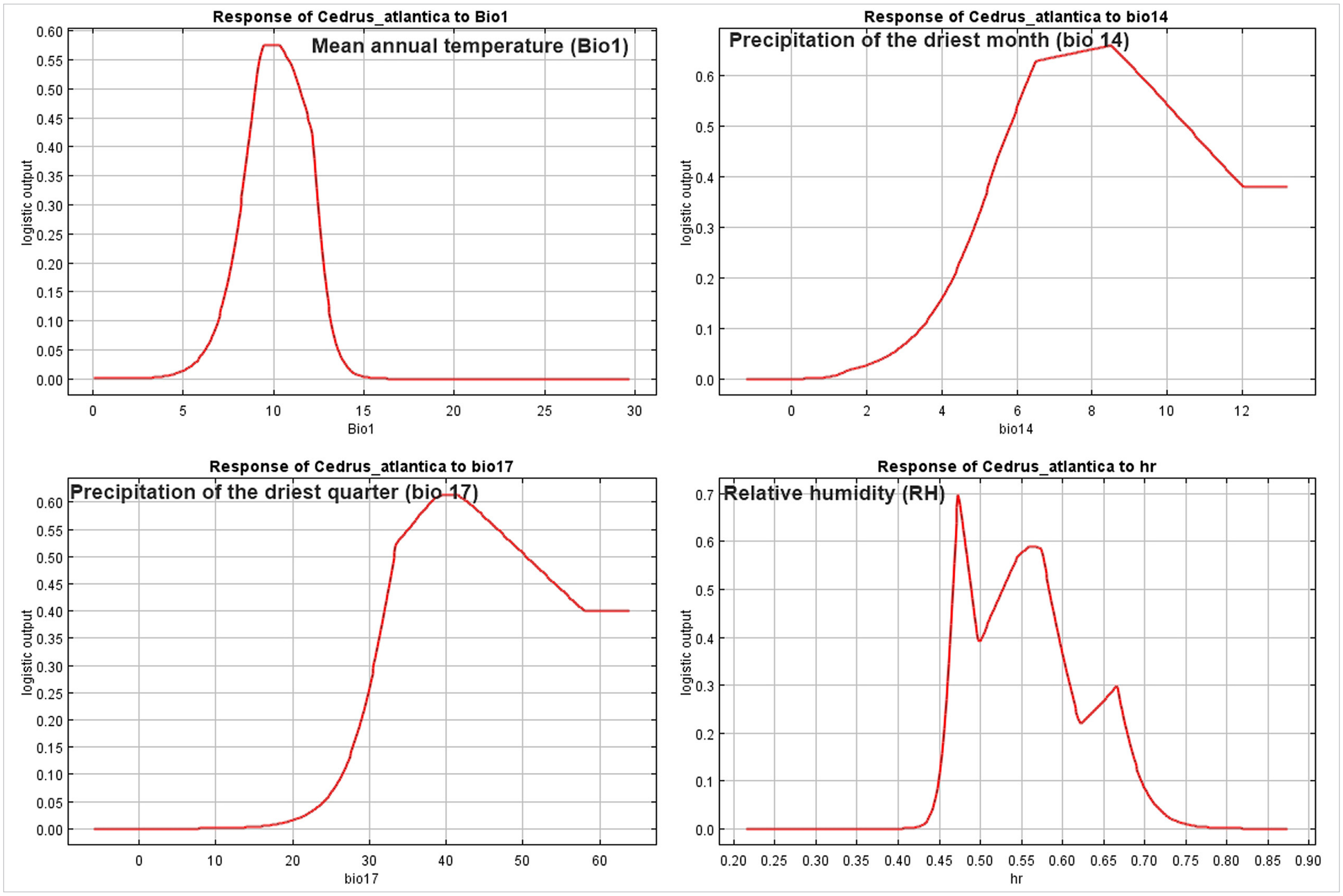

Figure 7.
Responses of Cedrus atlantica *to the Most Important Variables.*

Conclusion

Atlas cedar is an emblematic species that has undergone severe degradation and a reduction in its distribution over time. It is now classified by the IUCN in the list of endangered species.

Our results suggest that a larger area climatically suitable for *C. atlantica* to naturalize and potentially spread in Morocco exists than its current distribution including the area of the Cedar Biosphere Reserve. The MaxEnt model developed (AUC = .967) allowed the delimitation of the potential area which represents a gain of more than 425% compared to the current situation of the Moroccan Atlas cedar. Indeed, the present work provides the first map of the potential range of Atlas cedar in Morocco in the context of current climatic data.

Under current climatic conditions, the precipitation of the driest quarter, the precipitation of the driest month, the mean annual temperature, and the mean annual RH are the descriptors that most influence the range of the Atlas cedar in Morocco.

The comparison of potential distribution maps under current and future climate conditions made it possible to estimate the impact of climate change on the distribution of cedar, although the location of the future potential distribution of Atlas cedar is low than the current potential distribution.

The results of various future climate emission scenarios should be included in existing conservation strategies for the protection of forest species and the ecosystem services they provide, in order to avoid future local extinctions, given that Moroccan forest ecosystems are home to an important part of international biodiversity.

Species distribution modeling generates valuable information for conservation management of this rare and endangered endemic species in Morocco. Indeed, this study will serve as a basis for any strategic planning for conservation and sustainable management of the Atlas cedar in North Africa.

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