

Effects of climate change on the distribution of the native Carob tree (*Ceratonia siliqua* L.) in Morocco

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Research Article

Keywords: *Ceratonia siliqua* L., Morocco, MaxEnt, Species distribution modelling, Climate change scenarios

Posted Date: February 1st, 2024

DOI: <https://doi.org/10.21203/rs.3.rs-3910804/v1>

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Additional Declarations: No competing interests reported.

Abstract

Climate change is expected to alter many natural ecosystems around the world, by affecting plants growth and distribution. This is particularly emphasized for several Mediterranean plant species and communities. In this study, we investigate the suitable habitat and geographical distribution of a remarkable Mediterranean tree, *Ceratonia siliqua* L. (Leguminosae), in Morocco. We hypothesized a reduction in the carob tree suitable habitats under climate change scenarios. To this end, we applied the maximum entropy algorithm (Maxent) to generate current and future models using 303 occurrence points coupled with 19 bioclimatic variables. Two representative concentration pathways (RCP4.5 and RCP8.5) by 2050 and 2070 were considered as future input scenarios. The maximum entropy model provides satisfactory results, with a high value of the Area Under Curve equal to 0.987 (± 0.001). Jackknife tests indicate that precipitation followed by temperature play a significant role in the biogeographical dynamics of the Moroccan carob tree. Thus, the obtained results confirm our hypothesis of a reduction of the suitable area under the projected climate change scenarios by 2050 and 2070. The approaches developed in this study is promising to predict the potential distribution of native Mediterranean species and can be an effective tool to support conservation and restoration programs.

1. Introduction

The ongoing global warming is already altering plant species growth and geographical distribution (Doblas-Miranda et al. 2017; Vellend et al. 2017; Kassout et al. 2022a). In fact, with the current rapid rate of warming, global temperature is expected to reach $+1.5^{\circ}\text{C}$ between 2030 and 2050 (IPCC 2018). The complexity of climate change impacts on naturel ecosystems could lead to expansions, reductions or range shifts in the patterns of plant species geographical distribution (Lenoir et al. 2008), leading to significant effects on terrestrial energy, water fluxes and therefore CO_2 emissions (Forzieri et al. 2020). Furthermore, this warming is affecting biodiversity at multiple levels; from individuals and communities to the entire ecosystems (Franklin et al. 2017). As noticed in the Mediterranean region, natural ecosystems are most affected by global warming and extreme climatic events (Doblas-Miranda et al. 2017; Lionello and Scarascia 2018). Therefore, there is a tremendous interest in understanding geographical distribution of plant species under predicted climate change scenarios (Franklin et al. 2017), particularly to set well-adapted conservation and management programs (Kozak et al. 2008).

To assess plant species vulnerability to climate change, the approach of species distribution models (SDM) is commonly and increasingly used to predict species geographical range through interpolating and extrapolating their distributions according to environmental factors (Guisan et al. 2017; Pecchi et al. 2019). Moreover, species distribution models provide a comprehensive basis for species conservation and naturel resources management (Sinclair et al. 2010; Qin et al. 2017). Currently, a considerable number of SDMs method were available and widely used such as, BIOCLIM (bioclimatic modeling), Domain (domain environmental envelope), GAM (generalized additive models), MARS (multivariate adaptive regression splines) and MaxEnt (Maximum entropy) (Pecchi et al. 2019). Among theme, MaxEnt algorithm (Phillips et al. 2006) provides reliable results of suitability when presence-only data are

available and high flexibility to deal with both widely distributed and rare species occurrences (Elith et al. 2006; Moukrim et al. 2019; Kassout et al. 2022a). For instance, the maximum entropy model has been used to predict macroecological patterns (Harte 2011), species abundance distributions (White et al. 2012), trait-based community assembly (Shipley et al. 2011) and species ecological niche models at multiple scales (Elith et al. 2010; Guisan et al. 2017).

Ceratonia siliqua L. (Leguminosae) is an evergreen, thermophilous and dioecious Mediterranean fruit tree (Batlle and Tous 1997; Baumel et al. 2018), with some rare hermaphrodite and monoecious cases (Batlle and Tous 1997). The carob (*C. siliqua*) is slow-growing and long-lived tree dotted with high resistance to drought with limited resistance to extreme cold (Batlle and Tous, 1997), thus it shows important genetic diversity (Viruel et al. 2019) and phenotypic variability (Kassout et al. 2022b, 2023). The carob tree has been exploited around the Mediterranean region since antiquity as food and forage source (Zohary 2002), thus, it represents an important component of its semi-natural and traditional agroecosystems (Ramón-Laca and Mabberley 2004; Viruel et al. 2019). Nowadays, carob pods are highly used in the agri-food industry to produce syrups and powder (Papaefstathiou et al. 2018) and the gum extracted from the seed is extremely sought for pharmaceuticals and cosmetics products (Batlle and Tous 1997; Stavrou et al. 2018). Furthermore, the carob tree has shown great potential in reforestation programs and for soil restoration and rehabilitation purposes (Batlle and Tous 1997). Even though its relevant economic and ecological importance, the native status of *C. siliqua* still source of debate (Ramón-Laca and Mabberley 2004; Baumel et al. 2018). Previous archaeological and historical studies (Hillcoat et al. 1980; Zohary 2002) suggested an Eastern domestication center of the carob tree followed by human-driven dissemination to the West parts of the Mediterranean region. However, recent phylogeographic evidences suggest a strong west-east genetic structuring and the presence of multiple domestication centers from native populations throughout the Mediterranean basin (Viruel et al. 2019). Moreover, distribution models for past periods during the Last Glacial Maximum (c. 22 ka) suggests probable presence of the carob tree in the Western Mediterranean before its domestication (Viruel et al. 2019). Though, floristic data shows a higher species richness of the Western Mediterranean plant communities associated with carob tree compared to the Eastern parts (Baumel et al. 2018).

In Morocco, carob communities show significant differentiation between the North, characterized by a thermo-Mediterranean vegetation under sub-humid and semi-arid climate, and the South region communities characterized by a quasi-steppic vegetation under semi-arid climate (Baumel et al. 2018; Taleb and Fennane 2019; Kassout et al. 2022b, 2023). Despite their interest, the carob tree populations show a declining trend (Rankou et al. 2017), mainly due to the multiple threats from the rapid global warming and anthropogenic pressures. Therefore, it is crucial to understand possible responses of *Ceratonia siliqua* to climate change and predict the area of its potential distribution under different climate change scenarios.

In this study, we used the MaxEnt SDM model to predict the potential distribution of *Ceratonia siliqua* in Morocco under climate change scenarios. Specifically, we used species distribution models (SDMs) to answer two main questions: (1) what are the key climatic factors that affect current *C. siliqua* distribution

and suitable area in Morocco? and (2) how the future climate scenarios would affect their habitat suitability? Finally, our study will provide a theoretical basis for management and conservation decisions and possible plantation and reforestation efforts.

2. Materials and Methods

2.1 Study region

The study region covers the whole Moroccan territory, situated in the western part of the Mediterranean Basin and the extreme north-west of Africa (Fig. 1). As a biodiversity hotspot (Médail and Diadema 2009), the study region presents a wide range of phytogeographic and phytoecological units including forests, matorrals and shrub-lands (Taleb and Fennane 2019), with an important variation in climatic conditions (Kassout et al. 2019, 2022b, 2023).

2.2 Occurrence data

Occurrence data of *Ceratonia siliqua* were collected through field surveys recording each presence points with GPS coordinates. In addition, we extracted additional occurrence data from the Global Biodiversity Information Facility-GBIF (2020) and from previous published studies dealing with carob presence in Morocco (e.g., Baumel et al. 2018; Viruel et al. 2019; Kassout et al. 2022b, 2023). In this study, we considered only occurrence data within natural conditions. All occurrence data were merged into one single presence-only dataset. Finally, we got 303 occurrence points, a sufficient dataset to construct MaxEnt models of current and future potential distribution of *C. siliqua* suitable habitats. The spatial distribution of this occurrence data is shown in Fig. 1.

2.3 Bioclimatic variables and future scenarios

We used 19 bioclimatic variables (Table 1) extracted from the Worldclim database version 2.0 (Fick and Hijmans 2017) with a spatial resolution of approximately 1 km² (30 arc seconds). These variables consisted of monthly averages of temperature and precipitation covering the period between 1970 and 2000. Considering their relevant influence on plant growth, productivity, and physiological processes (Moles et al. 2014; Li et al. 2016; Kassout et al. 2021, 2022b, 2023), the extracted bioclimatic variables are largely used in species distribution models (Elith et al. 2010; Guisan et al. 2017; Du et al. 2021; Kassout et al. 2022a). The future projections by 2050 (average for 2041 - 2060) and 2070 (average for 2061 - 2080) were used to predict future distribution of *Ceratonia siliqua* L. in Morocco.

Two representative concentration pathways (RCPs) trajectories were considered RCP 4.5 and RCP 8.5 corresponding to an increase by 4.5- and 8.5-watts m⁻² of radiative forcing and an increase of CO₂ levels by 650 ppm and 1350 ppm, respectively, by 2100 (IPPC 2018). We supposed a moderate and an extreme

scenario to build the future projections (van Vuuren et al. 2011). From the Global Circulation Models (CGMs), and for all projections, we adopted the Community Climate System Model 4.0 (CCSM4) from the CMIP5 (Coupled Model Inter-comparison Project phase 5) model developed by the Intergovernmental Panel on Climate Change (IPCC). The CCSM4 has been reported to better predict precipitation and temperature variables (Gent et al. 2011), thus, gives efficient predictions of future plant species distribution (Al-Qaddi et al. 2017).

To avoid collinearity issues, the bioclimatic variables were tested for multicollinearity using Pearson's correlation test. The highly correlated variables ($|r| > 0.9$) were removed from predictor variables dataset before species distribution modeling (Dormann et al. 2013). Multicollinearity of variables can result in over-fitting of species distribution models and lead to miss interpretation of variables contribution (Elith et al. 2010). Pearson's correlation coefficient was calculated with the open R software v 3.5.1 (R Core Team 2018). As a result, we used a subset of 12 bioclimatic variables to construct current and future models of *C. siliqua* in Morocco (see Table 1).

Table 1 Bioclimatic variables used as environmental input in the modelling of *Ceratonia siliqua* potential distribution in Morocco and their percentage contribution. The highlighted variables were selected after multicollinearity test

Bioclimatic Variable	Description	Units	% contribution	Permutation importance
Bio1	Annual mean temperature	°C	12.1	2
Bio2	Mean diurnal range (mean of monthly max. and min. temp.)	°C	3.4	3.5
Bio3	Isothermality $((\text{Bio2}/\text{Bio7}) \times 100)$	Index	3.9	1.9
Bio4	Temperature seasonality (standard deviation $\times 100$)	Index	14.7	36.5
Bio5	Maximum temperature of warmest month	°C	3	1.5
Bio6	Minimum temperature of coldest month	°C	2.9	15.4
Bio7	Temperature annual range (Bio5–Bio6)	°C	-	-
Bio8	Mean temperature of wettest quarter	°C	3.8	3.2
Bio9	Mean temperature of driest quarter	°C	-	-
Bio10	Mean temperature of warmest quarter	°C	-	-
Bio11	Mean temperature of coldest quarter	°C	-	-
Bio12	Annual precipitation	mm	-	-
Bio13	Precipitation of wettest period	mm	-	-
Bio14	Precipitation of driest period	mm	0.2	0.4
Bio15	Precipitation seasonality (Coefficient of variation)	Index	5.3	6.3
Bio16	Precipitation of wettest quarter	mm	-	-
Bio17	Precipitation of driest quarter	mm	2.4	2.6
Bio18	Precipitation of warmest quarter	mm	2.7	1.6
Bio19	Precipitation of coldest quarter	mm	45.7	25.2

2.4 Model structure and data processing

MaxEnt 3.4.1 (Phillips et al. 2017) software was used to predict the potential geographical distribution of *C. siliqua* under current and four future scenarios (RCP4.5-2050s, RCP4.5-2070s, RCP8.5-2050s, RCP8.5-2070s). This modelling approach is based on the Maximum entropy algorithm allowing to estimate habitat suitability and ecological niche (Phillips et al., 2006) using bioclimatic variables. All models were executed using 10 bootstrap runs with a 25 percent random test percentage, which allows to use 75% of presence data to construct and calibrate the models and 25% to test and evaluate the accuracy and the predictive ability of the models. This procedure is appropriate for estimating occurrence probability (Phillips et al. 2017). The average of all runs was used as final models. As settings, and for all models, we used an auto-feature option (linear, quadratic, product, threshold and hinge methods) and the loglog output format (ranging from 0 to 1), a maximum number of 5000 iterations with a convergence threshold of 10^{-5} , a maximum number of background points as 10000, and a regularization parameter value of 1. The use of a loglog transform provides a stronger theoretical justification than the logistic transform, which replaces it by default (Phillips et al. 2017). The jackknife test was used to determine the climatic variables that influence significantly the potential distribution of *C. siliqua* (Li et al. 2016). To determine the accuracy of the models, we used the Area Under the Curve (AUC) of the Receiver Operating characteristics Curve (ROC) (Phillips et al. 2017). High AUC values indicates that the model can distinguish between presence and background points, and therefore indicates a better performance of the model (Elith et al. 2006). AUC values less than 0.5 indicates a model with random prediction, values between 0.5 and 0.7 are considered low accuracy, values between 0.7 and 0.9 are adequate and values higher than 0.9 indicates excellent accuracy of the predicted model (Elith et al. 2006; Yang et al. 2013; Kurpis et al. 2019).

For display and further analysis, we first used binary maps for current and future distribution to calculate the suitability and unsuitability habitat using the maximum training sensitivity plus specificity threshold, which is more suitable for large distributed species (Liu et al. 2013). Secondly, and to highlight area of optimal occurrence of *C. siliqua* we divided the potential suitability probability to four classes (Yang et al. 2013; Qin et al. 2017) as follow: unsuitable habitat (0-0.2), barley suitable habitat (0.2-0.4), suitable habitat (0.4-0.6), optimal habitat (0.6-0.7) and highly optimal habitat (0.7-1). Finally, spatial analysis and cartographic processing of the final results were performed using QGIS, version 2.18.20, open sources GIS software (QGIS Development Team 2015).

3. Results

3.1. Model performance

Table 2 resumes the area under the curve (AUC) average values of MaxEnt models performance for *Ceratonia siliqua* and suitable area under current and future RCPs scenarios by 2050 and 2070. These results showed that the average AUC values for training and testing was higher than 0.9 for both the current and the future scenarios, which indicates an excellent model performance (Phillips et al. 2006). The average AUC training values of the 10 bootstrap runs of current climatic conditions was 0.987 ($\pm$

0.001) with a maximum training sensitivity plus specificity threshold of 1.952. The future suitability distribution of *C. siliqua* predicted by the models showed high AUC values for both RCPs scenarios by 2050 and 2070 representing a good success of the models. These results showed that the bioclimatic variables included in this study could led to an excellent prediction of *C. siliqua* distribution in Morocco.

Table 2 The area under the curve (AUC) average values of Maxent models performance for *Ceratonia siliqua* and suitable area under current and future RCPs scenarios by 2050 and 2070. AUC mean values of training and test data are given after partitioning subspecies presence-only data into training (70%) and test (30%) with standard deviation. Suitable area was determined using the maximum training sensitivity plus specificity threshold

Period/Climate scenario		1. AUC		1. Suitable Area	
		AUC _{mean} † Training	AUC _{mean} †	Area (Km ²)	Percentage (%)
			Test		
Current (1970 – 2000)		0.987 ± 0.001	0.978 ± 0.004	78 233	11.46
Projected	2050 - RCP4.5	0.969 ± 0.003	0.961 ± 0.007	70 185	10.28
	2050 - RCP8.5	0.971 ± 0.003	0.957 ± 0.009	70 579	10.35
	2070 - RCP4.5	0.970 ± 0.005	0.955 ± 0.008	68 746	10.07
	2070 - RCP8.5	0.967 ± 0.004	0.962 ± 0.006	71 457	10.47

† Mean values of 10 bootstrap runs.

3.2. Contributions of bioclimatic variables

Fig. 2 shows the Jackknife test results for the regularized training gain (Fig. 2a) and the AUC of *C. siliqua* potential suitable habitat (Fig. 2b). These results indicated that the precipitation of the coldest quarter (Bio19) has the most influential impact on the current distribution of *C. siliqua* and contributes with 45.7% to the final model. The temperature seasonality (Bio4) and the annual mean temperature (Bio1) were the second highest contributor to the model with, respectively, 14.7% and 12.1%. The precipitation seasonality (Bio15), the isothermality (Bio3), the mean temperature of the wettest quarter (Bio8), and the mean diurnal range (Bio2) contributed respectively with 5.3%, 3.9%, 3.8%, and 3.4%. The lowest contributors were the maximum temperature of warmest month (Bio5, 3%), the minimum temperature of coldest month (Bio6, 2.9%), the precipitation of the warmest quarter (Bio18, 2.7%), the precipitation of the driest quarter (Bio17, 2.4%) and the precipitation of the driest period (Bio14, 0.2%).

The cumulative contributions of the precipitation-related variables were 56.5% and the temperature-related variables was 43.8% (Table 1).

3.3. Predicted habitat suitability for the *Ceratonia siliqua* in Morocco

Fig. 3 represents the habitat suitability maps of *C. siliqua* in Morocco under current and future climate scenarios by 2050 and 2070. After these maps, the potential current suitable area of *C. siliqua* in Morocco is 78,233 km², which represents 11.46% of the total studied area. Thus, the optimal (0.6-0.7) and the highly optimal (0.7-1) distribution area were 4765 km² and 15,054 km², respectively (Table 3; Fig. 4). The majority of the optimal habitats (≥ 0.6) was located in the north-west and the south-west parts of the country (Fig. 4).

Habitat suitability distribution for *C. siliqua* showed significant changes under global climate models (GCMs) of CCSM4 for both RCPs pathways (RCP4.5 and RCP8.5) by 2050 and 2070 (Table 2; Fig. 5). Overall, suitable area variation between current and future conditions showed progressive reduction along with increasing climate warming. Under RCP4.5 scenario, the potential distribution of *C. siliqua* would decrease by 1.18% and 1.39% respectively for 2050 and 2070. A similar pattern was observed under RCP8.5 with decreasing suitability by 1.11% and 0.99%, respectively for 2050 and 2070 (Table 2; Fig. 3).

Regarding variable contributions, the precipitation of the coldest quarter (Bio19) represented the most bioclimatic variable contributing to the prediction models of *C. siliqua* habitat suitability distribution by 2050 and 2070 (Fig. 6). By focusing on optimal area (0.6-0.7), we observed a slight gain in area suitability by 2050 from 4765 km² to 5060 km² and 4781 km², respectively, under RCP4.5 and RCP8.5 (Table 3; Fig. 4). However, by 2070, only under RCP4.5, we observed a gain in suitability area from 4765 km² to 5090 km², while we observed a decrease in suitability under RCP8.5 from 4765 km² to 4571 km² (Table 3; Fig. 4). Compared to the current potential distribution, the future scenarios show a progressive reduction in optimal habitats (≥ 0.6) of *C. siliqua* in the north-west and the south-west parts, replaced by suitable (0.4-0.6) habitats, while a gaining of suitable area (≥ 0.6) in the middle-center region of the country was observed by 2050 under RCP8.5.

Table 3 Habitat suitability area (Km²) of *Ceratonia siliqua* under different suitability classes. Percentage of suitable area are shown between brackets

Period/Climate scenario		Suitability classes area (km ²)				
		Unsuitable (0-0.2)	Barley suitable (0.2-0.4)	Suitable (0.4-0.6)	Optimal (0.6-0.7)	Highly optimal (0.7-1)
Current (1970 – 2000)		60 4796 (88.63)	41 287 (6.05)	15 361 (2.25)	4 765 (0.70)	15 054 (2.21)
Future	2050 - RCP 4.5	61 2778 (89.80)	32 414 (4.75)	18 154 (2.66)	5 060 (0.74)	12 852 (1.88)
	2050 - RCP 8.5	61 2202 (89.71)	34 955 (5.12)	16 803 (2.46)	4 781 (0.70)	12 514 (1.83)
	2070 - RCP 4.5	61 4103 (89.99)	31 847 (4.67)	17 445 (2.56)	4 571 (0.67)	13 291 (1.95)
	2070 - RCP 8.5	61 1289 (89.58)	33 864 (4.96)	17 219 (2.52)	5 090 (0.75)	13 796 (2.02)

4. Discussion

Modelling the impacts of climate change on potential habitat suitability of plant species at global and local scales is critical to understand their ecological and evolutionary future pathways (Kozak et al. 2008; Dawson et al. 2011). In this context, species distribution models (SDMs) are relevant tools to forecast natural habitat expansions or contractions (Guissan and Thuiller 2005; Guissan et al. 2017). They are required for setting adequate monitoring and restoration programs of natural ecosystems (Pecchi et al. 2019), particularly in the light of the rapid rate of biodiversity loss (Dawson et al. 2011). Looking at the vulnerability of Mediterranean natural ecosystems under the current global changes (Blondel et al. 2010), it is crucial to understand the future dynamics of native plant species and its genetic resources. Here, we highlighted the potential distribution of the multipurpose species *Ceratonia siliqua* in Morocco under four different climate change scenarios by 2050 and 2070, which presents a contribution to set both conservation and reforestation programs of this remarkable Mediterranean plant species.

Our results show that the potential geographical suitable habitat of the carob tree in Morocco can be accurately predicted by bioclimatic factors. The average AUC values of 10 bootstrap runs were greater than 0.9, for both current and future scenarios, indicating the high accuracy and reliability of the final models (Elith et al. 2006; Merow et al. 2013). Thus, our results agree with other studies showing that the maximum entropy algorithm can provide high accurate prediction of plant species potential habitat (Yang et al. 2013; Qin et al. 2017; Moukrim et al. 2019; Kurpis et al. 2019; Du et al. 2021; Kassout et al. 2022a).

Moreover, our findings highlight the importance of climatic factors in controlling the carob tree suitable habitats in Morocco, as previously demonstrated for the establishment of several Mediterranean plant species (Médail and Diadema 2009). The potential distribution model of *C. siliqua* show that the precipitation of the coldest quarter (Bio9) has the largest impact on defining its current suitable habitat. Thus, temperature seasonality (Bio3) and the annual mean temperature (Bio1) has substantial contribution on carob tree potential distribution. These results consolidate the findings suggesting that precipitations and temperature are the most common factors shaping the distribution of plant communities and diversity (Moles et al. 2014) with direct implication in the ecological and evolutionary trajectory of plant species (Donoghue 2008; Frank 2011). However, our results show that the precipitation-related variables have greater influence on the geographical distribution of *C. siliqua* compared to temperature-related variables. The low contribution of temperature variables might be explained by the thermophilous nature of *C. siliqua* and its distribution under various climatic conditions from sub-humid to semi-arid climates (Baumel et al. 2018; Kassout et al. 2022b). Hence, the weak sensitivity of suitable habitat models to temperatures could be interpreted as an adaptation form of the carob tree. The high contribution of precipitation-related variables can be viewed as the effect of aridity and its direct relationship with water availability, which is the limiting factor for physiological responses and adaptation process for most plant species (Doblas-Miranda et al. 2017; Kassout et al. 2019, 2021, 2023). Thus, these variables largely design the structure of Mediterranean plant communities (Doblas-Miranda et al. 2017). In addition, seasonal variation of precipitation regime within the Mediterranean region induced stressful conditions, which limiting the plant growth, development and survival (Vellend et al. 2017). The correlations between precipitations-related variables and plant physiological responses were also reported for the thermophilous and Mediterranean wild native olive tree (*Olea europaea* subsp *europaea* var. *sylvestris*) in Morocco (Kassout et al., 2019, 2021). This observed pattern might be regarded as the results of the biogeographic history of Mediterranean flora (Blondel et al. 2010).

Predicted climate change scenarios (RCP4.5 and RCP8.5) by 2050 and 2070 show a declining rate of carob suitable habitat in Morocco. For instance, suitable area will decrease from 78,233 km² (11.46%) to 70,185 km² (10.28%) and 68,746 km² (10.07%), respectively, under RCP4.5 by 2050 and 2070 (Fig. 5). In fact, precipitation-related variables largely defined the future potential habitat of *C. siliqua* in Morocco (Fig. 6). These results are consistent with some findings stated that suitable habitat of plant species might decrease under climate change scenarios (Moukrim et al. 2019; Kassout et al. 2022a). Hence, the loss of carob tree suitable habitat might be greatly influenced by the projected increasing temperature and decreasing precipitations in the Mediterranean region (Driouech et al. 2010; Lionello and Scarascia 2018). It is indisputable that climate change is expected to reduce plant species capacity to withstand new challenging conditions, such as extreme aridity (Dawson et al. 2011; Doblas-Miranda et al. 2017). However, when taking in consideration highly suitable habitat (Fig. 4), we observed a slight increasing in suitable conditions of carob tree. In fact, the future suitable climatic envelope of the species ranges from Northern to Southern regions of the country can explain this tendency. Meanwhile, the response of *C. siliqua* to climate change will depend on several factors such as anthropogenic activities, phenotypic plasticity, genetic diversity and competing ability (Phillips et al. 2006; Parmesan and Hanley 2015).

In the case of *C. siliqua*, a species with long-term longevity and limited dispersal ability, gain of suitable habitat under climate change is significantly limited. Using MaxEnt algorithm, we show that climate change might impose challenging conditions for this multipurpose plant species. However, looking into biological and ecological process underlying spatial distribution of plant species (Shipley et al. 2011), such as genetic diversity, dissemination rate, and inter-specific interactions, SDMs has its limitation to predict the exact relationship between species occurrence and environmental factors without considering biological and ecological variables when constructing the models (Bedia et al. 2013). These limitations can be explained by the lack of comprehensive database, integrating accurate climatic data at local scales with reasonable resolution, coupled with data on plants functional and ecological characteristics.

5. Conclusion

In this study we used MaxEnt approach to provide a comprehensive basis for current and future potential habitat suitability of the carob tree in Morocco using two IPCC climatic scenarios (RCP4.5 and RCP8.5) by the years 2050 and 2070. Our results conclude that the geographic distribution of the carob might experience a considerable decline regarding climate change scenarios with noticeable risk of disappearance in some areas, in particular those projected to be drier as the case of the south-eastern parts of Morocco. Therefore, the loss of natural vegetation of *C. siliqua* communities will greatly affect the ecological functions and services of natural ecosystems and, therefore, affecting valuable genetic resources.

Our results contribute to understand the biogeography and the history of Mediterranean native tree species, and the potential dynamics of natural vegetation communities facing the global change. The prediction method used in this study can be applied into several tree species distribution to predict future trends at the ecosystem and population levels under climate change scenarios. Furthermore, it is wise, in light of the above, to encourage and promote *C. siliqua* for reforestation programs.

Declarations

Author contributions

Jalal kassout Conceptualization, Methodology, Data curation, Formal analysis, Software, Investigation, Writing - original draft, Writing - review & editing, Visualization. **Soufian Chakkour** Investigation, Writing - original draft. **Abdeltif El Ouahrani** Investigation, Writing - original draft. **Younes Hmimsa** Investigation, Writing - original draft. **Salama El Fatehi**: Investigation, Writing - original draft. **Yanzheng Yang** Writing - original draft, Writing - review & editing. **Rachid Hadria**: Visualization. **David Ariza-Mateos** Project administration; Resources. **Guillermo Palacios-Rodríguez**: Project administration; Resources. **Rafael Navarro-Cerrillo** Funding acquisition, Resources, Writing - review & editing. **Mohammed Ater** Conceptualization, Funding acquisition, Resources, Writing - original draft, Writing - review & editing, Supervision.

Acknowledgment

The authors thank the members of the BioAgrodiversity Team for helpful discussions and comments. Likewise, the authors thank agents of the Water and Forests Department of Morocco for helpful information during fieldwork. This study was supported by the Agencia Andaluza de Cooperación Internacional para el Desarrollo (AACID) and the project « Amélioration de la productivité des cultures forestières d'intérêt socio-économique élevé dans les zones rurales du nord du Maroc, n° 2018004 ».

Data Availability Statement

The occurrence records used to calibrate and evaluate SDMs are available on request from the corresponding authors.

Ethic approval

No approval of research ethics committees was required to accomplish the goals of this study.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Informed consent

Informed consent was obtained from all individual participants included in the study.

Financial or non-financial interests

None.

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Figures

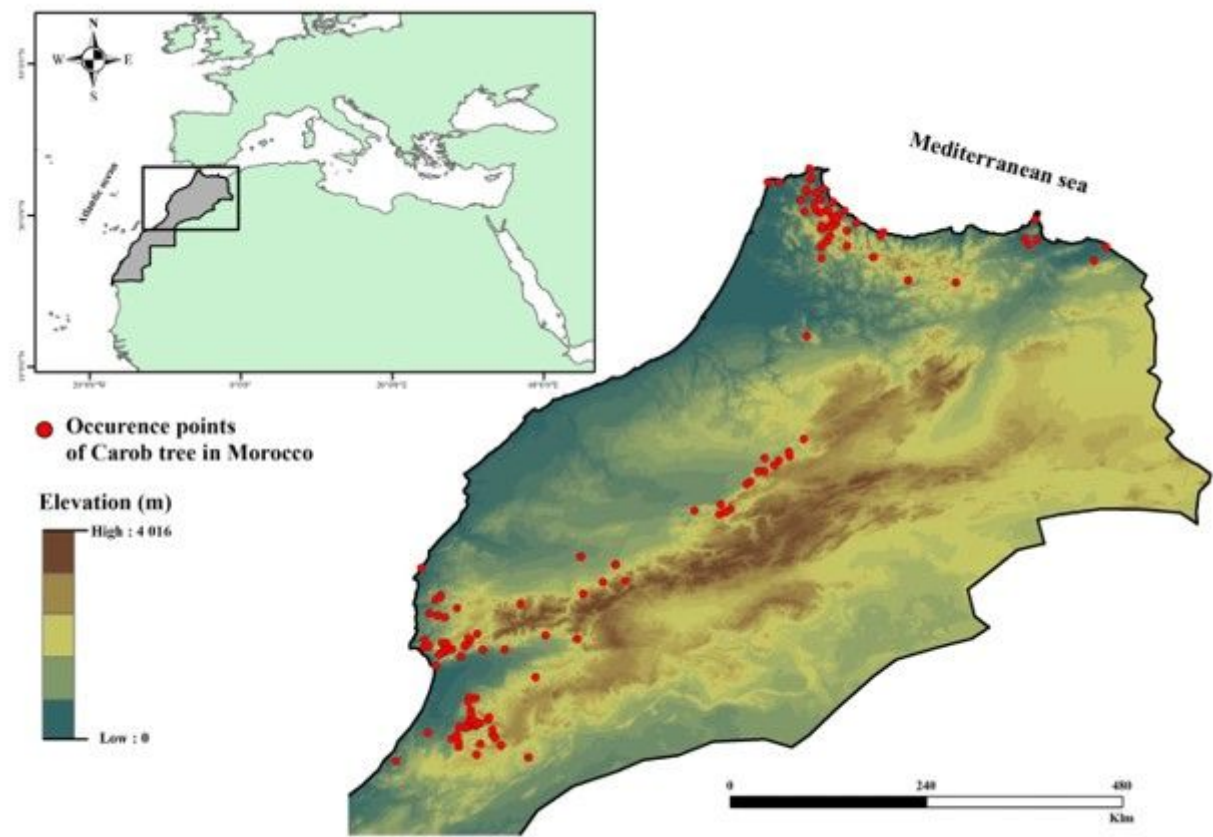


Figure 1

Study area and occurrence records (red points) of *Ceratonia siliqua* L. in Morocco

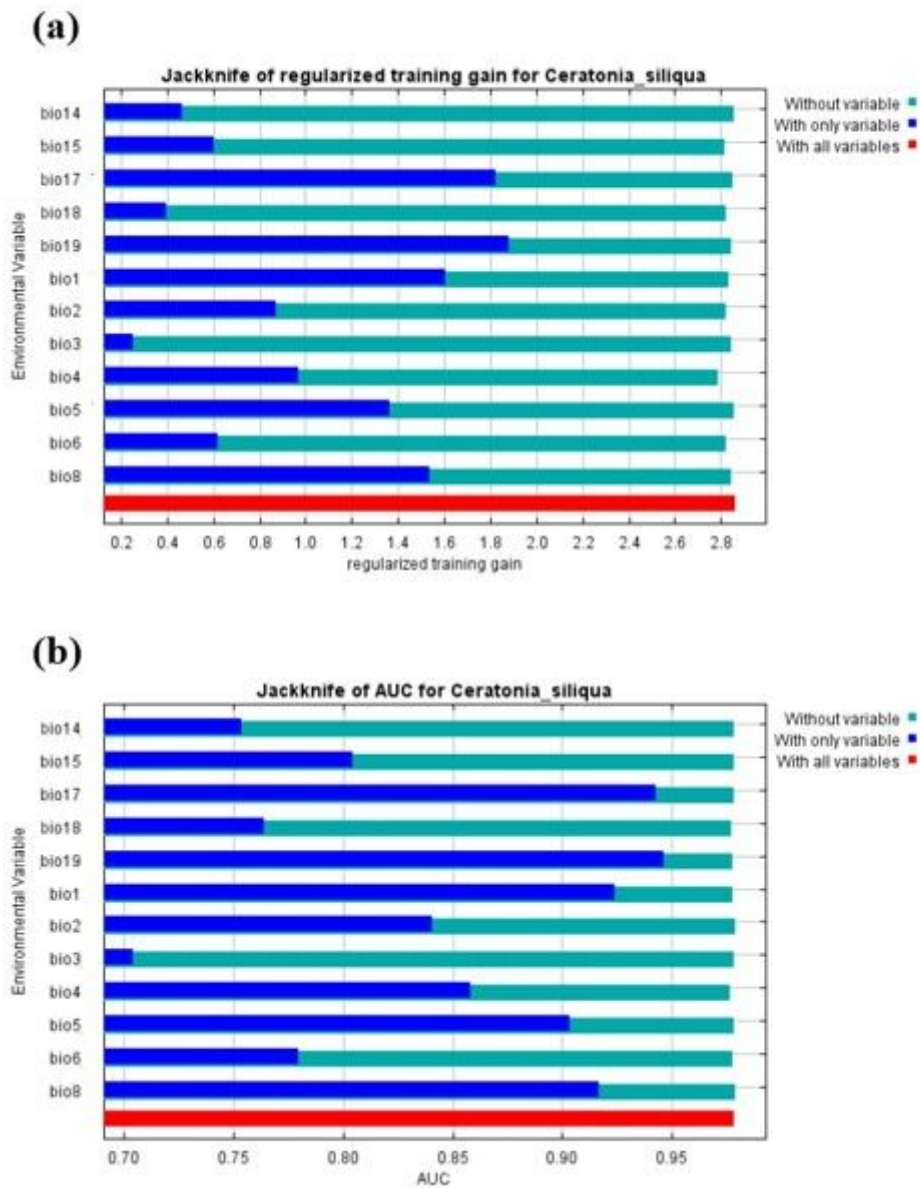


Figure 2

The Jackknife test plot for the regularized training gain (a) and the AUC of *C. siliqua* (b)

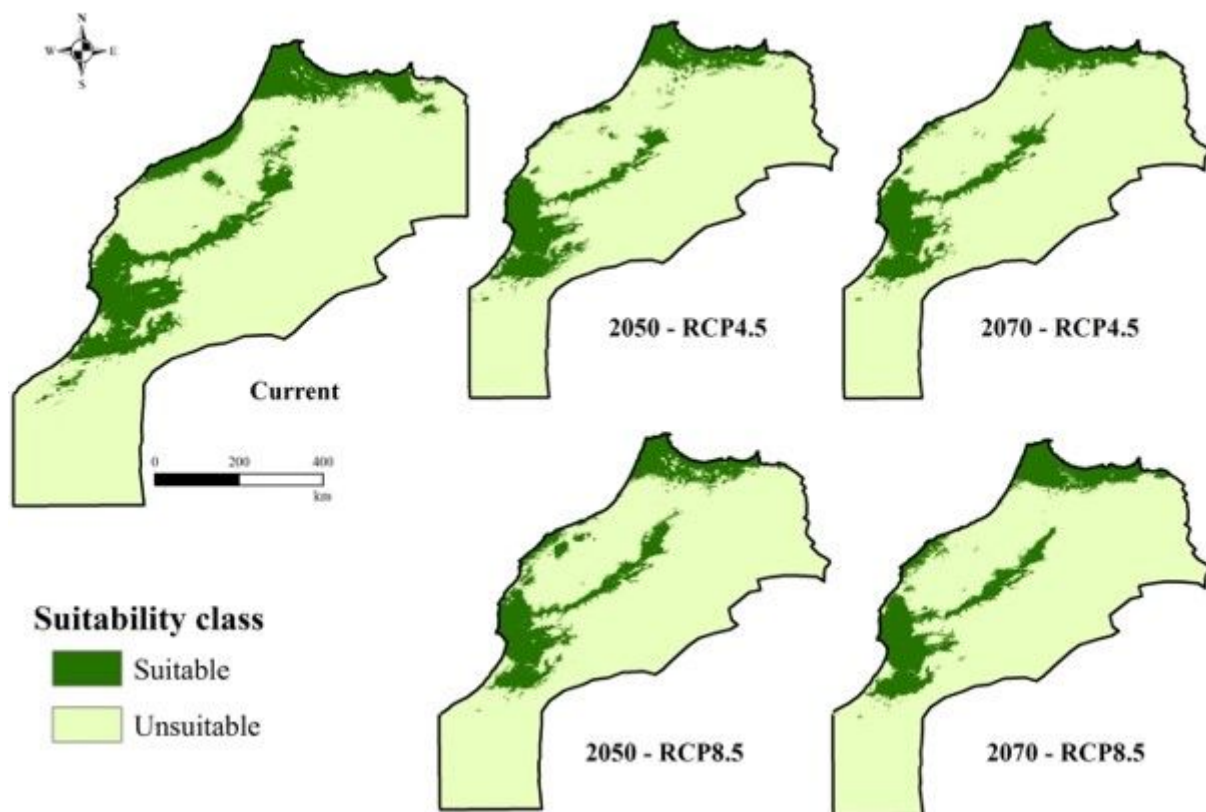


Figure 3

Habitat suitability of *C. siliqua* in Morocco under current and future climate scenarios by 2050 and 2070

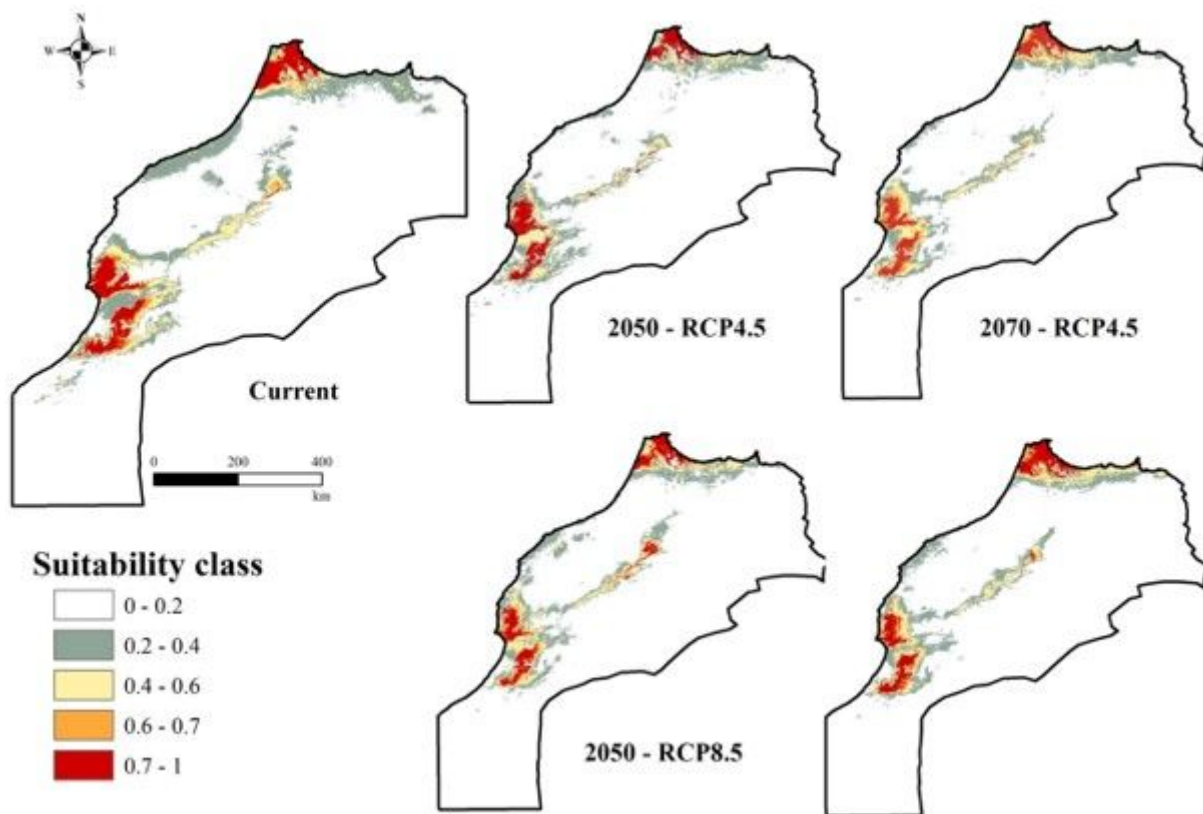


Figure 4

Classes of habitat suitability of *C. siliqua* in Morocco under current and future climate scenarios by 2050 and 2070

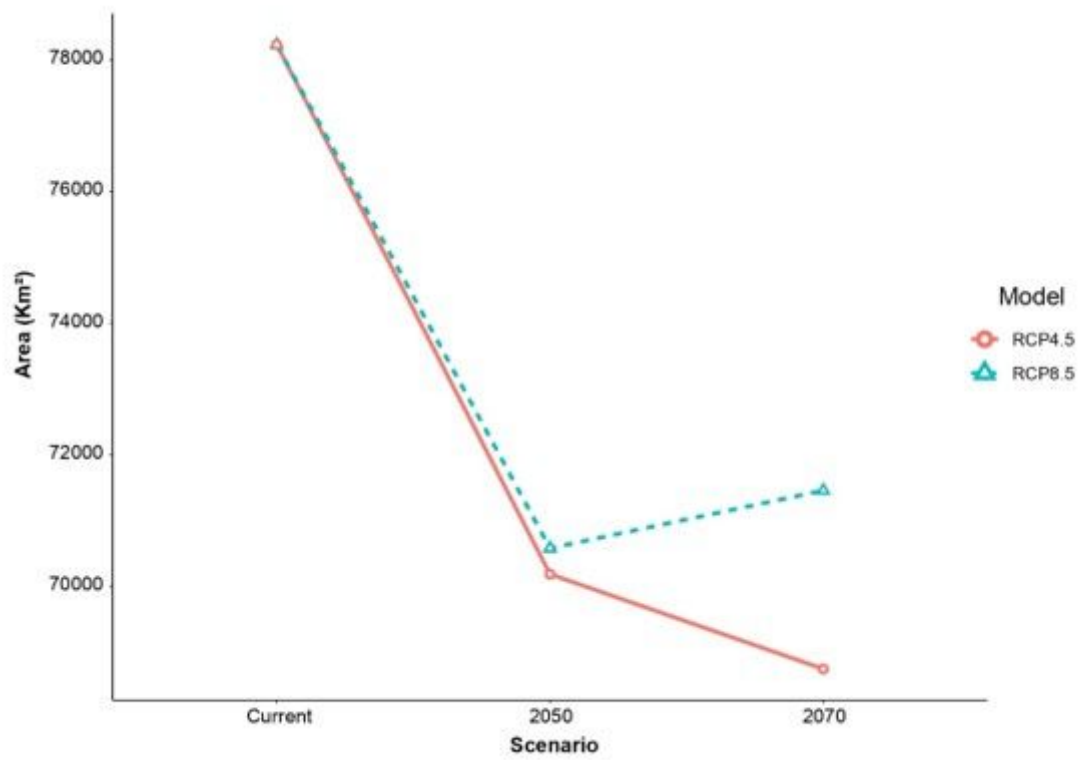


Figure 5

Suitable area in Km^2 of *C. siliqua* for both RCP scenarios by 2050 and 2070

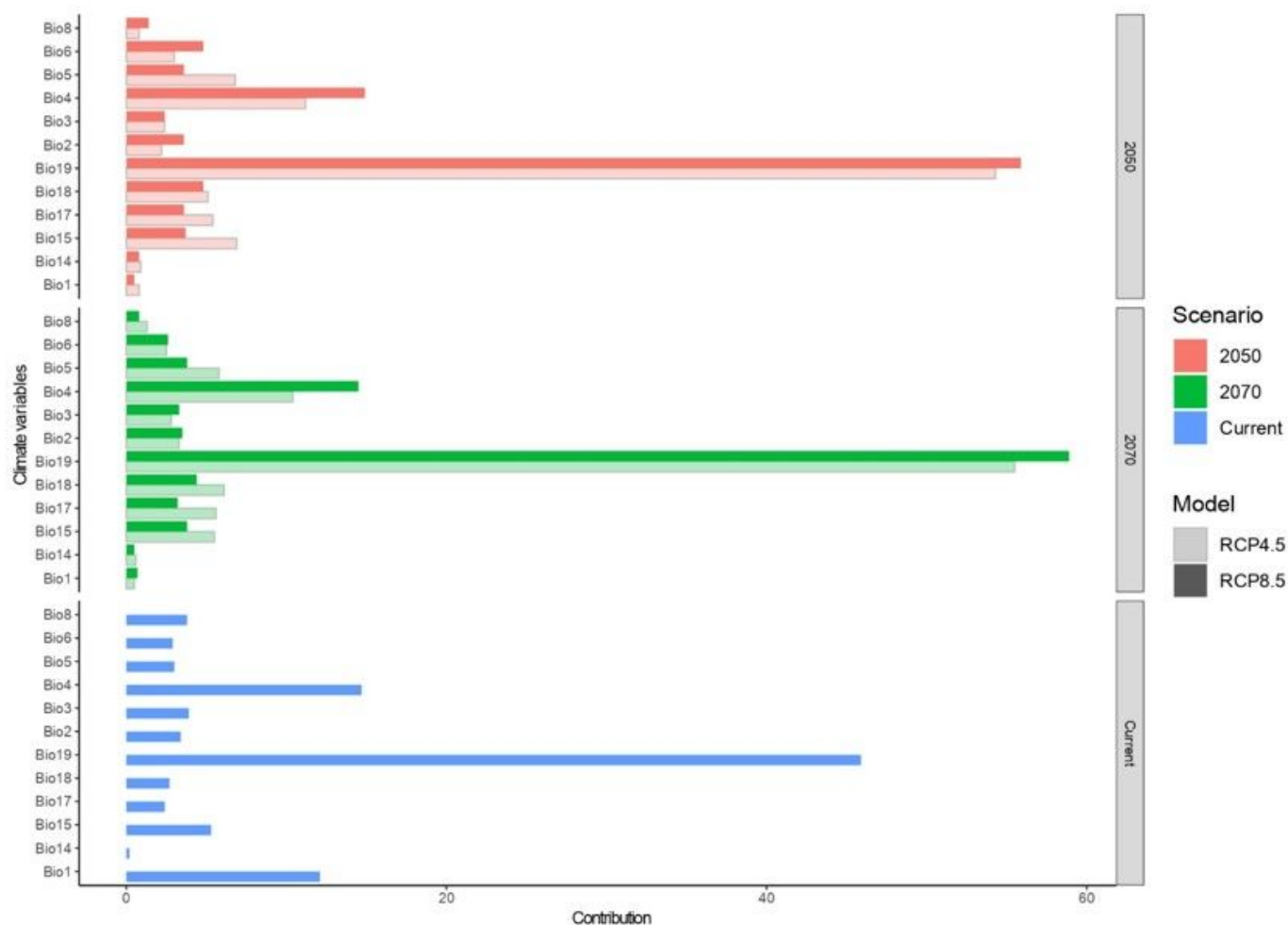


Figure 6

Bioclimatic variables contributions for the current and future climate scenarios by 2050 and 2070. Abbreviation of climate variables are given in Table 1