Identifying Key Environmental Factors and Modelling of the Potential Distribution of Carob Tree (*Ceratonia siliqua* L.) in Morocco Using Maximum Entropy Principle

Amal LABAIOUI (✉)
Ahmed ELBAKKALI

Summary

The carob tree (*Ceratonia siliqua* L.) is a truly drought-resistant species. Because of its ecological and economic value to Morocco, it is one of the target species in the government's program to develop Moroccan agriculture. Carob planting programs are expected to reach 125,000 ha by 2030. In order to guide new plantations, this work aims to model the current distribution of the carob tree in Morocco and to identify the environmental factors that influence this distribution. The maximum entropy approach was used. The model generated is of excellent quality (AUC = 0.981). The most significant environmental parameters affecting the distribution of carob trees in Morocco are rainfall in the coldest quarter, mean temperature in the coldest quarter, mean diurnal variation and altitude. The model was used to map the potential area based on current climatic conditions. This shows that a large area is suitable for the expansion and development of this tree. The current range represents only 1.5% of the suitable habitat for this species. These findings could assist managers in more effectively identifying appropriate sites for planting this resilient alternative species in the face of climate change.

Key words

maximal entropy, *Ceratonia siliqua* L., Morocco, environmental variables

Regional center of agricultural research, Meknes, National Institute for Agricultural Research (INRA), Avenue Ennasr, P.O. Box 415 Rabat Principal, 10090 Rabat, Morocco

✉ Corresponding author: amal.labaioui@inra.ma

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Introduction

Carob tree (*C. siliqua*) is a species that combines agricultural, forestry and pastoral practices, typical of the Mediterranean flora. In Morocco, it typically coexists with olive, mastic, thuja, or argan (Sbay, 2008), in the plains and mid-mountains of the Rif, Middle Atlas, High Atlas and Anti-Atlas, across humid, sub-humid, semi-arid, and coastal arid bioclimates, with both warm and temperate variants (Khouas and Hamamou, 2020). The primary natural population of the carob tree is found at altitudes between 600 and 1000 m, in association with other forest species and sheltered from wind and cold (Ait chitt et al., 2007).

Studies confirm that the carob tree behaves like a truly drought-resistant species, adapting morphologically and physiologically to water shortage (Rejeb, 1995). Due to its ability to adapt to soil and climatic stresses, the carob tree could contribute to the development of disadvantaged areas. It is essential for preventing soil degradation and erosion, and for helping to combat desertification (Zouhair, 1996; Benmahioul et al., 2011; Boubkar et al., 2021). Its significance has notably increased in recent years due to the industrial development of carob, which has emerged as a crucial raw material in the agri-food sector (Sbay, 2008).

Climate change is affecting the availability of water resources. Water scarcity is increasing and droughts are becoming more frequent. For plants, the consequences are an increase in water deficit situations, a major factor limiting their growth and development (Sbay, 2022). In this context, carob tree, thanks to its hardiness, can be considered as a renewed alternative crop for certain dry areas and areas with low water resources.

Because of its ecological and economic interest for Morocco, this species is one of the target species of the governmental program for the development of Moroccan agriculture launched in 2008. According to the ANEF (National Water and Forestry Agency), the total area of carob trees in Morocco is 80,000 ha. 68,000 ha are in state forests and 12,000 ha are on private land, mainly in the Béni Mellal-Khénifra region. The "Morocco Forest 2020-2030" program aims to increase the area planted with carob by 5,100 ha·year^{-1} in forest estates by 2030 (AgriMaroc, 2023). Simultaneously, the Generation Green (GG) strategy calls for planting 125,000 hectares by 2030. Future plantations must consider the physiological and phytosociological aspects of the species as well as its requirements (xerophilous, thermophilous and heliophilous) (Eddabih, 2024). In order to direct new carob plantations towards areas favourable for its cultivation, it is necessary to study its potential geographical distribution on a national scale and to determine the environmental parameters governing this distribution.

One of the most widely used methods for identifying favourable areas for a species is the use of species distribution models, commonly known as "species distribution models" (SDM) or "ecological niche models" (ENM) (Delforge, 2020; Damaneh et al., 2022). Predictive modelling of the geographic distribution of species based on environmental conditions at the sites where the species occurs is an important technique in analytical biology with applications in conservation and reserve planning, ecology, evolution, epidemiology, invasive species management and other fields (Phillips et al., 2006). Predictive habitat models use a "correlative" approach to estimate the conditions conducive to the presence of one or more species by relating observed occurrences of the species under study to a set of eco-geographic variables likely to influence their distribution (Pearson et al., 2007). They also help evaluate the contribution of each environmental variable to this distribution (Austin et al., 2006). Examining the effect of various environmental factors on the potential spatial distribution of species will enhance the scientific understanding of species-environment spatial relationships (Ye et al., 2021). However, it is essential to use appropriate predictors based on local environmental conditions (Brambilla et al., 2017).

Alongside traditional statistical regression techniques, machine learning-based modelling is extensively applied, including methods such as artificial neural networks (Ripley, 1996), maximum entropy (Phillips et al., 2006), random forests (Evans et al., 2011), and classification and regression trees (Breiman et al., 1984). The maximum entropy algorithm (MaxEnt) is one of the most commonly used methods in the scientific community. It is considered to be one of the most effective algorithms for modelling species' ecological niches (Elith et al., 2006; Wisz et al., 2008; Merow et al., 2013).

MaxEnt demonstrates a clear superiority over other comparable models in predicting species distribution (Peterson et al., 2007). It performs well when modelling the geographical distribution of species using presence-only data (Xiaomin et al., 2018), and maintains strong predictive power regardless of sample size (Wisz et al., 2008). Numerous studies have highlighted the robustness and effectiveness of MaxEnt in ecological modelling. For instance, Elith et al. (2011) provided a comprehensive evaluation of species distribution models (SDMs), confirming MaxEnt's strong performance under a range of environmental conditions.

In recent years, MaxEnt has been widely applied to model plant species in Mediterranean environments. In Egypt, Mahmoud et al. (2025) reported high predictive performance (AUC > 0.90) for several Mediterranean species under different climate scenarios. Aouinti et al. (2022) used MaxEnt to project the current and future distribution of *Acer monspessulanum* L. in Tunisia under CMIP6 climate projections. Similarly, Mas et al. (2023) reconstructed the Holocene distribution of Mediterranean oaks (*Quercus pubescens* Willd. and *Quercus ilex* L.) in northeastern Iberia, while Bianchini (2025) applied MaxEnt to assess vegetation shifts across arid and temperate Mediterranean zones using remote sensing indices. In North Africa, Garah et al. (2019) used MaxEnt to model the distribution of *Pinus halepensis* in northeastern Algeria.

In Morocco, MaxEnt has been applied to several native species, including *C. siliqua* in the Azilal province (Lahssini et al., 2015), *Juniperus thurifera* L. in the Central High Atlas (Rupprecht et al., 2011), and *Argania spinosa* (L.) Skeels across the country (Moukrim et al., 2018). Unlike the more localized work by Lahssini et al. (2015), which focused on a single province, the present study aims to model the potential distribution of *C. siliqua* at a national scale. Additionally, it seeks to identify the key environmental factors influencing its distribution, thereby providing a broader ecological and spatial understanding of its suitable habitat under current climatic conditions.

Materials and Methods

Study Area and Species Ecology

The study area covers all of Morocco. This country is situated in the far northwest of Africa, between 21° and 36° north latitude and 1° and 17° west longitude, and is bordered to the north by the Strait of Gibraltar and the Mediterranean Sea, to the south by Mauritania, to the east by Algeria, and to the west by the Atlantic Ocean. Morocco has a total area of 710,850 km² (Fig. 1).

Morocco enjoys a warm, temperate Mediterranean climate, with oceanic nuances in the west (from 10° to 26 °C), continental in the center and east, and arid or desert in the south (contrasting temperatures, from 0° to 40 °C). Morocco's climate varies significantly from north to south, from temperate to semi-arid to desert, according to the Koppen-Geiger classification (DGM, 2023). Precipitation and temperature are heavily influenced by the Atlantic Ocean to the west, the Mediterranean Sea to the north, and the Sahara Desert to the south and southeast.

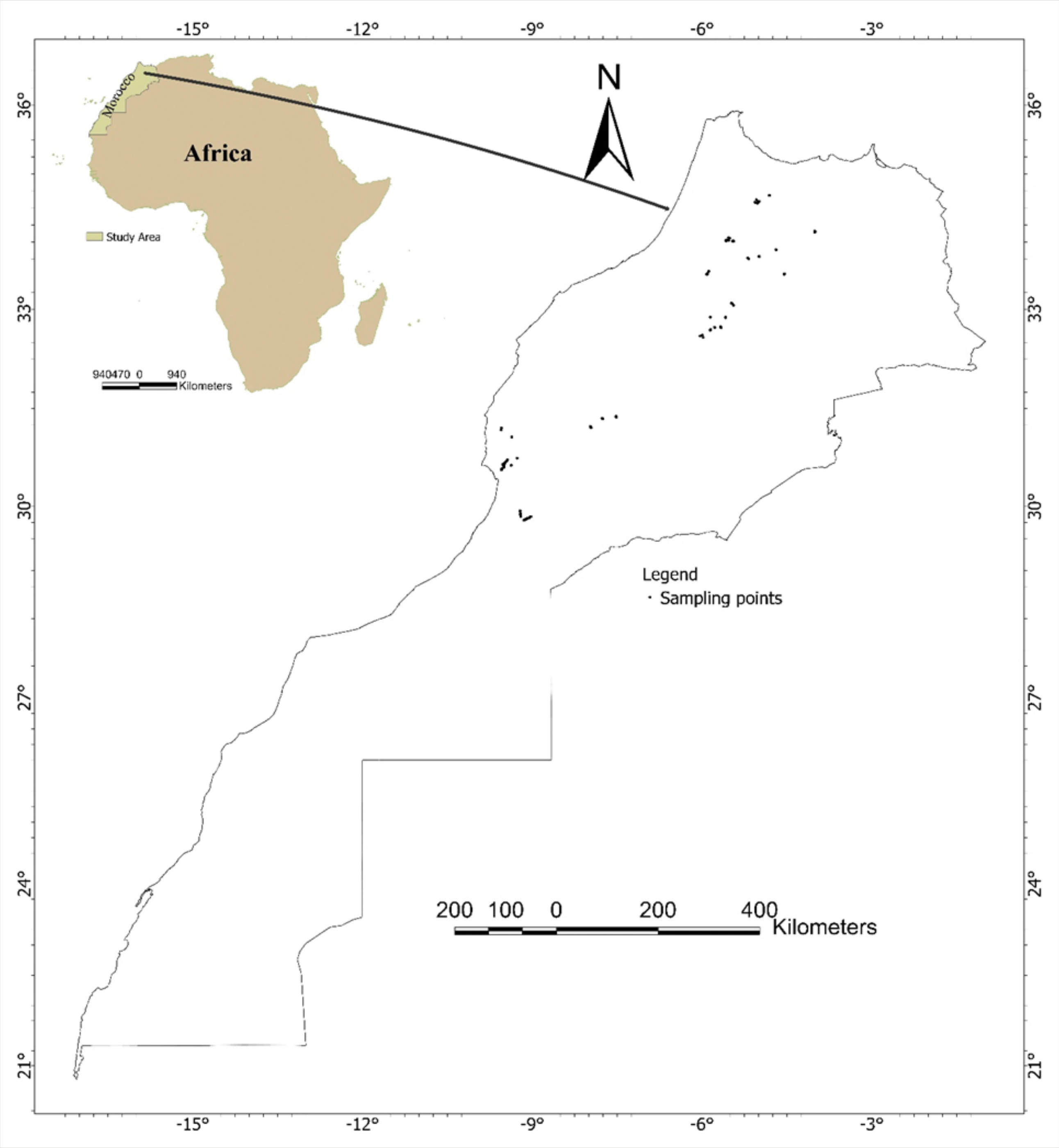

Figure 1. The geographic position of Morocco in the northwest of the African continent, along with the locations of the 229 carob occurrence points

Moroccan flora includes more than 4,000 species that are resistant to extreme climatic conditions. The forests and steppes at high altitudes with sufficient rainfall (Rif, Middle and High Atlas) are the most common. Atlas cedar, Moroccan fir and holm oak are very common, as well as low thorny vegetation (acacias). North of the Atlas massif, at medium altitude, holm oak and cork oak forests, olive trees, cedars and pines dominate.

The species studied in this study is the carob tree. The carob tree (*C. siliqua*) is a very plastic, heliophilous, thermophilous Mediterranean species, highly drought-resistant (200 mm of rainfall per year) but not cold-tolerant (minimum temperature of 0 °C). It can adapt to various soil types and is typically found in poor, sandy, heavy loamy, rocky, calcareous, schistose, and sandstone soils, with a pH ranging from 6.2 to 8.6. However, it is sensitive to acidic and hydromorphic soils (Baum, 1989; Sbay and Abourouh, 2006). The carob tree is a well-defined species in the humid, sub-humid and semi-arid zones.

Data Collection

To collect data on points of current presence of carob tree, several databases were consulted and other points were taken from the literature (articles, books and theses). The geographical coordinates were examined, validated and supplemented by other points of presence identified during field outings. A total of 229 georeferenced carob occurrence points were used in this study.

Twenty environmental variables listed in Table 1 were selected for this modelling, namely: 19 bioclimatic variables that are primarily connected to the physiological factors influencing plant growth, which can limit their distributions and indicate average, seasonal, and extreme conditions of climate parameters (Hijmans et al., 2005); and altitude, documented as having an influence on the distribution of the species studied. These predictors are biologically relevant variables for defining species distribution (Lehmann et al., 2011). Data on these variables for the current period (1960-2000) are extracted from the Worldclim version 1.4 database with a spatial resolution of 30 arc seconds, or about 1 km (Hijmans et al., 2005).

These variables were subjected to a correlation test (Pearson test), which highlights the relationships between variables. This test selects the least correlated variables with a correlation coefficient of less than 0.85 in absolute value (Asseh et al., 2019). The use of correlated variables in a statistical model tends to bias the results (Elith et al., 2011). This exploration also allows for the identification and selection of the variables that best explain the distribution of the species under consideration (Bargain and Fabri, 2016).

Modelling Approach

In our study, the maximum entropy approach was employed to model the geographic distribution of the carob tree in Morocco, utilizing the "MaxEnt" algorithm, version 3.3.3k (Phillips et al., 2006). This program estimates and predicts the spatial distribution of a species based on its presence in relation to the environmental conditions in the area of interest (Doffou et al., 2021)

This algorithm was chosen because it is one of the relevant methods for this type of modelling (known as empirical or correlative modelling) (Elith et al., 2006), making it possible to generate reliable species distribution models (Baldwin, 2009). It was developed specifically for use with presence data only and requires few species presence points to build efficient models (Hernandez et al., 2006; Phillips et al., 2006; Wisz et al., 2008; Feeley and Silman, 2011). It is also relatively insensitive to various spatial biases that are essentially related to the methods used to identify points of presence (Elith et al., 2006; Graham et al., 2007).

Table 1. The variables used in the distribution area modelling

Alt = Altitude

bio1	Average annual temperature
bio2	mean diurnal deviation (maximum temperature - minimum temperature; monthly average)
bio3	Isothermality (bio1/bio7) * 100
bio4	Temperature seasonality (Coefficient of variation)
bio5	Maximum temperature of the hottest period
bio6	Minimum temperature of the coldest period
bio7	Annual Temperature Difference (bio5-bio6)
bio8	Mean temperature for wettest quarter
bio9	Mean temperature for driest quarter
bio10	Mean temperature of the hottest quarter
bio11	Mean temperature of the coldest quarter
bio12	Annual precipitation
bio13	Precipitation during the wettest period
bio14	Precipitation during the driest period
bio15	Precipitation seasonality (Coefficient of variation)
bio16	Precipitation in the wettest quarter
bio17	Precipitation during the driest quarter
bio18	Precipitation during the hottest quarter
bio19	Precipitation of the coldest quarter

Training, Model Validation and Results Analysis

The model was implemented using species occurrence data and environmental variables. The raw output of MaxEnt is an exponential function that assigns a probability of occurrence to each site (Phillips et al., 2006). The raw values are converted to a cumulative probability to match the number 1 (Phillips et al., 2006). Cross-validation was carried out automatically 15 times in succession. 25 % of the total occurrence data was reserved to examine variability in model construction (Guisan and Zimmermann, 2000).

Model validity is characterized by the sensitivity and specificity parameters of the Receiving Operator Characteristic (ROC) curve (Hanley and McNeil, 1982). The calculation of the area under the curve (AUC), a metric that assesses the accuracy of the model's predictions, offers insights into the performance and reliability of the model in accurately predicting the species' occurrence (Hanley and McNeil, 1982). AUC values are interpreted as suggested by Swets (1988): the model is "poor" if AUC ≤ 0.70; "passable" if 0.70 < AUC ≤ 0.90; "excellent" if AUC > 0.90.

Modelling results also include assessments of the contribution of each variable to the model (Phillips et al., 2006). Response curves of the carob tree to the values of each environmental variable, expressed in terms of probability of occurrence, combined with the jackknife test, allow us to determine the predictive power of each variable and identify those that contribute most to the model.

To better characterize the potential distribution of the species of interest, an "S" threshold is required to convert continuous probabilities of occurrence into binary presence/absence values (Phillips and Dudík, 2008). MaxEnt provides thresholds based on a range of statistical indicators. The most commonly used thresholds are the logistic threshold of minimum training presence, the logistic threshold of 10th percentile training presence, the logistic threshold of equal training sensitivity and specificity (Young et al., 2011). The "10th percentile training presence" threshold (which corresponds to a maximum error rate of 10% on the presence points of the training data, i.e., no more than 90% of the presence points fall within the defined potential area) is frequently used in the literature (Barbain and Fabri, 2016).

The resulting map is provided by MaxEnt as a raster in ASCII grid format (*.asc) and reclassified in ArcGIS 10.3 for final editing. The extent of each habitat type under current climatic conditions was estimated from the number of pixels occupied by each habitat type.

Results

Model Performance and Contribution of Environmental Variables

The results relating to the accuracy of the model's prediction showed the reliability of the modelling performed, with an AUC value equal to 0.981 (Fig. 2).

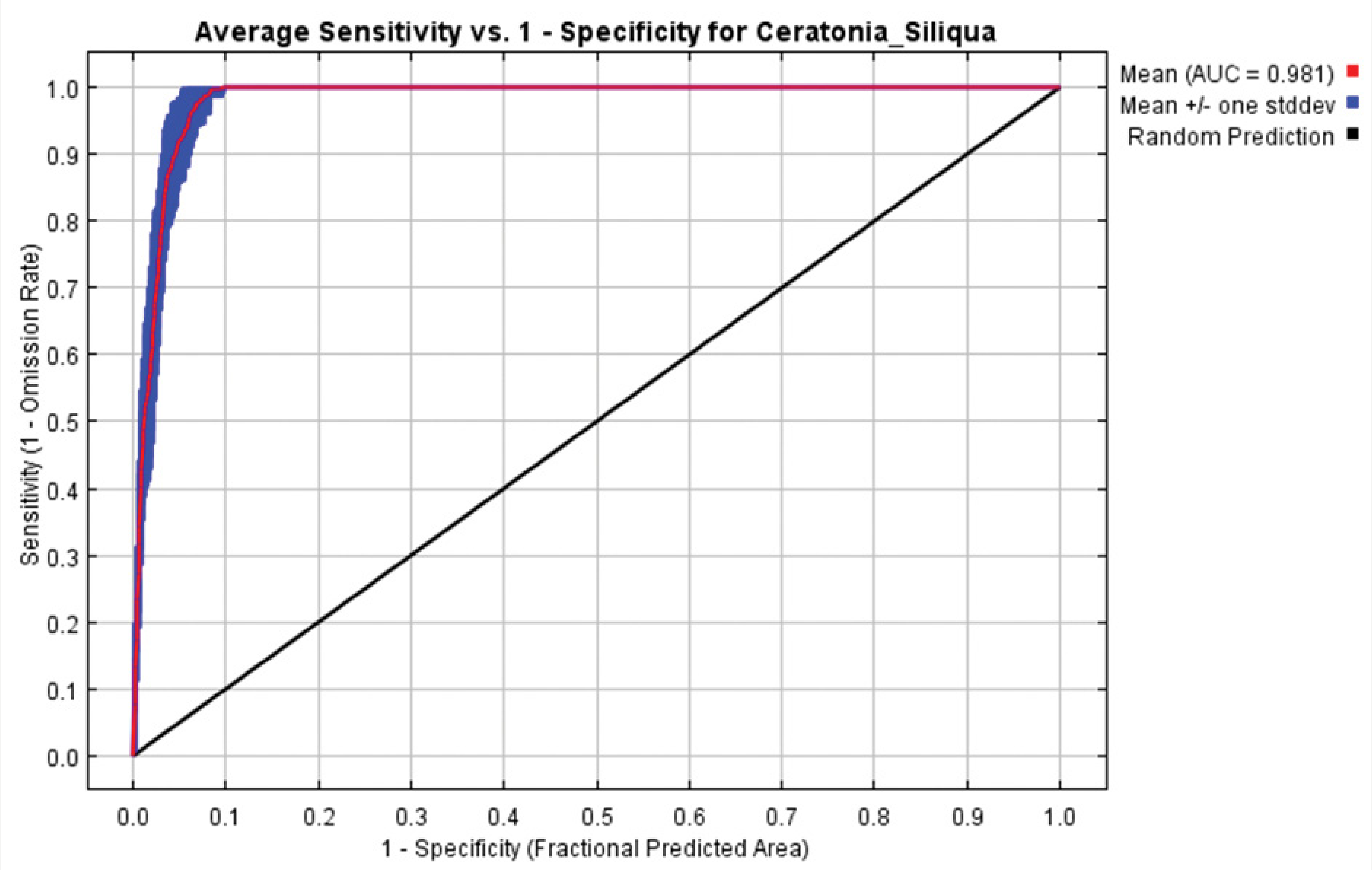

Figure 2. Receiver operating characteristic curve for the occurrence localities of carob trees

This attests to the excellent performance of the Maxent model in predicting the area favourable to the presence of carob (Swets, 1988).

Correlation analysis between the different variables using Pearson's test (Elith et al., 2010), allowed us to retain eleven variables least correlated with each other (r < 0.85) for the prediction of carob distribution area (Table 2).

Table 2. The relative impact of environmental variables on the distribution of the carob tree

Variabl	Percent contribution	Permutation importance
bio19	72	64.6
Alt	9.8	7.6
bio11	5.4	13
bio3	5	5
bio2	3.4	2.1
bio15	1.8	0.2
bio17	1.2	1.2
bio8	1	5.9
bio14	0.3	0.3

The analysis of the results in terms of the percentage contribution of each variable to the model's prediction suggests that precipitation in the coldest quarter (bio19) and altitude (Alt) are the most important variables, with contributions of 72% and 9.8% respectively. The importance of permutation (Table 2) also helps to assess the contribution of variables. A high permutation value indicates a high importance of that variable. The permutation values confirm the importance of the variable bio19 and highlight the importance of the average temperature of the coldest quarter (bio11).

The jackknife test (Fig. 3) confirms the importance of the "coldest quarter precipitation" variable in modelling the distribution of carob trees. This variable shows the best gain and seems to have the most valuable information when used independently in the model. This test also shows the importance of the variable "Mean diurnal variation" (bio2), which, when omitted, results in the greatest reduction in gain and appears to provide the model with information not captured by the other variables.

In light of the above, the environmental variables with the greatest influence on the spatial distribution of carob were precipitation in the coldest quarter (bio19), altitude, mean temperature in the coldest quarter (bio11) and mean monthly daily variation (bio2). The remaining environmental variables contributed minimally to the model's prediction.

Response curves allow us to examine the probability of carob presence in response to variations in the values of each variable. If we focus solely on the variables with the greatest impact on the distribution of carob (Fig. 4), we see that the probability of distribution is high, with bio19 values between 250 mm and 350 mm (Fig. 4a). In terms of altitude, the carob tree has a relatively high percentage of presence at altitudes between 700 m and 1200 m (Fig. 4b). In certain areas, it grows at higher altitudes, as long as the appropriate exposure is present (Rima, 2021).

The bio11 variable appears to limit the range of this species to a bio11 range of 0 °C to 14 °C (Fig. 4c). This is consistent with the idea that the carob tree has very little resistance to cold (Batlle and Tous, 1997). Fig. 4d shows that the carob tree tolerates daily temperature fluctuations up to a value of 14 °C, at which point the suitability of the habitat begins to decline until a value of 18 °C is reached, marking the upper limit of the carob tree's presence).

These results are consistent with the ecology of the carob tree, considered to be a species that grows between 300 m and 1400 m above sea level, not resistant to cold and fears lack of water outside the summer period, but can tolerate severe summer drought and irregular rainfall (Sbay and Abrouch, 2006).

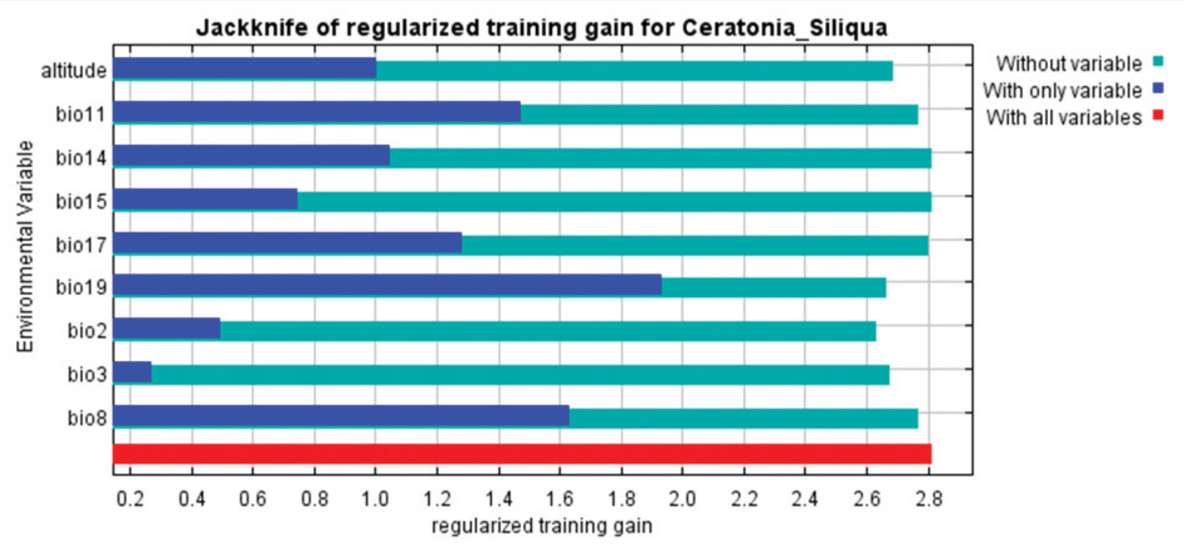

Figure 3. Results of the jackknife test on the contribution of the variables selected to predict carob tree distribution

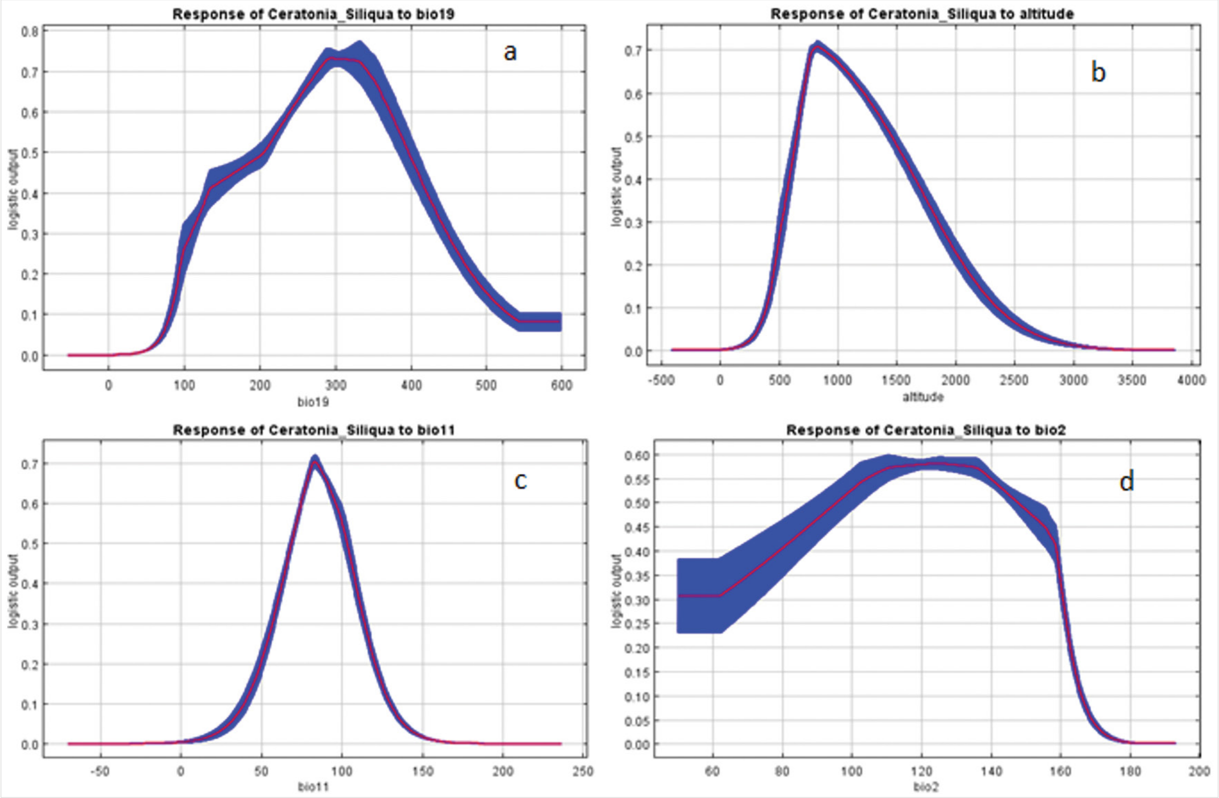

Figure 4. Response curve of the presence probability to environmental variables. a bio19 (mm), b Alt (m), c bio11 (*10) °C, d bio2 (*10 °C)

Potential Distribution Area of the Carob Tree

The model developed allowed us to construct a map depicting the potential distribution range of the carob tree in Morocco under current climatic conditions (Fig. 5). Using the 10th percentile training threshold of 0.311, carob should be present in an environment with a total area of approximately 5,816,858 ha (58,168 km²).

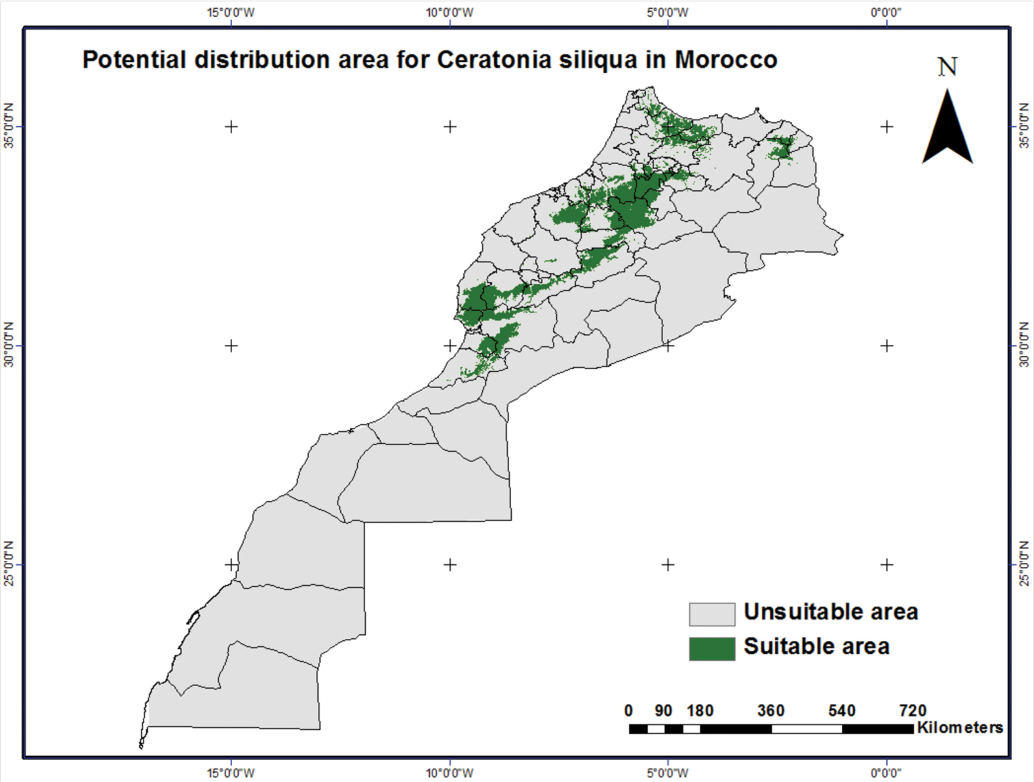

Figure 5. Potential geographical distribution of the carob tree in Morocco

This potential area is much larger than the current area of 80,000 ha (800 km^2) (Chaabi, 2023). Favourable areas for carob represent 7% of the Moroccan territory. These areas are consistent with the literature and confirm the species' affinity for the plains and mid-mountains of the Rif, Middle Atlas, High Atlas and Anti-Atlas (Fig. 5). In particular, the model predicts the presence of the carob tree in a small area in the east of the country (between Taourirt, Berkane, Oujda and Jerada), although there are no model inputs for this zone. On the other hand, the model does not predict the presence of carob in the south, south-east and east of Morocco, or in the coastal areas from the Atlantic to the north.

Discussion

Today, predicting species distributions is central to numerous applications in ecology, agriculture, horticulture, forestry, and conservation (Corsi et al., 1999; Welk et al., 2002; Elith et al., 2006).

Several types of models exist to model the distribution of a species or the zones favourable to its spread, with the aim of reproducing the environmental determinism of the species' distribution. The aim is to identify the optimal conditions that allow a species to persist and/or to study the ecological impact of certain factors on the species (anthropization, climate change, etc.) (Ben Rhouma and Ben Mariem, 2022). It has been shown that there is a strong relationship between the environment and species distribution (Pulliam, 2000; Araújo and Guisan, 2006), which gives weight to modelling based on environmental variables (Delforge, 2020).

The complexity of a model lies in being able to provide both a mathematical answer to the role and contribution of each of the explanatory variables (environmental variables) on a response variable (the species studied) (Guisan et al., 2002), but also to be able to assess, through different parameters, the effectiveness of the fit between these predictor variables and the expected response, that is, the strength of the relationship between these producers and the responses (significance), in order to evaluate the relevance and the degree of confidence to be placed in a final mapping of the potential habitat of the species (Bargain and Fabri, 2016).

MaxEnt has a clear edge over other models when it comes to predicting species distributions (Peterson et al., 2007). It performs well in modelling the geographic distribution of species with only presence data (Xiaomin and Guangsheng 2018). It can make predictions or inferences from incomplete information (Phillips et al., 2006).

SDMs typically incorporate a broad range of environmental factors as explanatory variables that help describe species' behaviour (Damaneh et al., 2022). Climate is the main factor determining the distribution and life of living beings. The distribution of species within a geographical area reflects the presence of a particular climate, which also serves as an indicator of the region's biodiversity (Xiaomin and Guangsheng, 2018). Different climatic factors are chosen to model the connection between species and climate, enabling the prediction of a species' distribution. In most studies, the choice of climatic factors was based on subjective criteria. There are no standardized criteria or methods for selection (Xiaomin and Guangsheng, 2018). The selection was mostly driven by study experience, which was a source of uncertainty and incomparability of results (Matsui et al., 2004). In general, the selection is guided by the availability of data for the study area. The 19 bioclimatic variables (Table 1) are the most commonly used in species distribution modeling studies. They are closely connected to the physiological factors of plant growth (Li et al., 2016; Moukrim et al., 2018; Kassout et al., 2021) and are available for the whole world at different spatial resolutions.

The precision of MaxEnt in predicting the geographic distribution of *C. siliqua*, based on the environmental variables selected for modelling, reached an excellent level of precision (Fig. 2), showing that the chosen climatic factors can represent the climatic conditions of the carob tree's geographic distribution. In addition, each environmental variable has a percentage contribution to the distribution of the carob tree in Morocco. Among them, precipitation of the coldest quarter (bio19), average temperature of the coldest quarter (bio11), mean diurnal deviation (bio2) and altitude are the variables that have contributed most to this distribution (Table 2, Fig. 3). The selected variables influence the distribution of the carob tree to different degrees and are all essential. When these factors interact together within a specific threshold, the area may be conducive to the growth of *C. siliqua* (Chapin et al., 1987). *C. siliqua* can adapt morphologically and physiologically to environmental stress, especially water shortage (Rejeb, 1995), making it a drought-resistant species. Trees can limit water loss by controlling root hydraulic conductivity and leaf water dynamics (Ouzounidou et al., 2012).

The carob tree has adapted to efficiently draw water from the soil to make up for atmospheric water loss, supported by its deep root system and swift adjustments in water potential (Nardini et al., 2002; Lo Gullo et al. 2003). Additionally, the carob tree can withstand drought by effectively regulating water through stomatal adaptation, as well as its leaf structure and anatomy (Catarino et al., 1981; Lo Gullo et al., 1986). During drought, leaf wax production increases, which lowers cuticular permeability and helps protect the plant from excessive transpiration (Baker and Procopiu, 1980). Given that this species can survive and reproduce with just 250 mm of rainfall, it can be inferred that it has developed particular mechanisms to cope with water stress (Martins et al., 2024). However, a rainfall range of 400-500 mm annually is necessary to achieve good fruit production. (Marti and Caravaca, 1990).

In general, the distribution of fruit trees such as *C. siliqua* is limited by cold stress (Mitrakos, 1981). Frost sensitivity is a major issue for this crop. The severity of frost damage is influenced by the temperature in the orchard and the trees' physiological condition (Batlle et Tous, 1997). Extreme temperatures can stunt tree growth or even ruin the harvest due to freezing conditions (Von Haselberg, 2000). Moukrim et al. (2018) showed that the lack of a cold season (frost) throughout the year is regarded as the primary factor enabling the establishment and growth of the carob tree in the province of Azilal, Morocco. The carob tree favours regions with an absolute minimum temperature above 3 °C and an altitude between 0 and 500 m. It is unusual for it to grow at elevations of 900 m or even 1600 m (Gharnit et al., 2005).

Kassout et al. (2023) emphasized notable correlations between the morphological traits of the carob tree and the environmental conditions in its current distribution area in Morocco. Seed yield was positively correlated with altitude and the average temperature of the warmest month, while it showed a negative correlation with the mean temperature of the coldest month.

Our results indicate that a large part of Morocco is bioclimatically suitable for the development of the carob tree. However, this species is not present in all potential environments, despite the a priori favourable climatic conditions. This could be due to a perceptual bias related to the species' status as a forest species until 2008, when it became a fruit species, but also, in highly anthropized environments, to the mismatch between the natural potential of spaces and their arbitrary allocation to agricultural activities (Moukrim et al., 2018). Other factors (biotic, geographical and anthropogenic) very probably play a role in limiting the extension of the carob tree. These include interspecific competition, geographical barriers and human disturbance (Phillips et al., 2006).

The government of Morocco, through the National Agency for Water and Forests (ANEF), has launched a strategy in 2020 to strengthen the resilience of forests in the face of climate change by promoting drought-resistant species such as carob trees (Chaabi, 2023). This strategy is in line with the more global strategy of sustainable agriculture, which aims to limit the expansion of water-consuming crops. Currently, the aim of the "Moroccan Forest 2020-2030" program is to increase the area of carob trees in the forest estate by 5,100 hectares per year. At the same time, in order to promote crops adapted to the new climate, the "Green Generation" strategy calls for the planting of 125,000 ha of carob trees by 2030. Future plantings should take into account the physiological and phytosociological aspects of the species as well as its requirements (xerophilous, thermophilous and heliophilous) by planting it in a mixture with other deciduous or bushy species (Eddabbeh, 2024).

The map of the potential range of the carob tree (Fig. 5) can provide decision-makers and land managers with a decision-making tool for rational and sustainable management of the species. In this way, areas predicted to be favourable, but currently unoccupied, can be preserved for its development and expansion.

Conclusion

Species distribution modelling is a crucial tool for defining the geographic extent of favourable areas for species and identifying the environmental variables that influence their distribution. Areas predicted by models to be favourable for the establishment of a species may reveal sites that have not yet been explored. Overall, the presence of the species in the predicted favourable areas will improve our knowledge of this species, while its proven absence in these areas could highlight the anthropic or natural pressures (interspecific competition, geographic barriers, etc.) that the environment is enduring.

The model developed for the carob tree allowed us to identify the main variables conditioning the distribution of the carob tree in Morocco, namely bio19, bio11, bio2 and altitude, in accordance with the ecology of the species.

Our results have shown that the potential range of *C. siliqua* in Morocco is larger than its current range and that it has even greater potential for expansion. These results could provide valuable support to decision makers in guiding and orienting new plantations of the carob tree, which is considered as a resilient alternative species in the context of shifting climate patterns. This modeling approach can serve as an effective tool for managing and conserving the carob tree in the face of climate change.

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CRediT Authorship Contribution Statement

Amal Labaioui: Conceptualization, supervised the work, analyzed the data and drafted the manuscript. **Ahmed Elbakkali**: Conceptualization, collected data on points of presence.

Declaration of Competing Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

AgriMaroc (2023). Le Maroc est le 2ème plus grand producteur de caroube au monde. Available at: https://www.agrimaroc.ma/, [Accessed: 15 June 2024], (in French)

Ait Chitt M., Belmir M., Lazrak A. (2007). Production des plantes sélectionnées et greffées du caroubier. Transfert de technologie en Agriculture 153: 1-4

Aouinti H., Moutahir H., Touhami I., Bellot J., Khaldi A. (2022). Observed and Predicted Geographic Distribution of *Acer monspessulanum* L. Using the MaxEnt Model in the Context of Climate Change. Forests 13(12): 2049. doi: 10.3390/f13122049

Araújo M. B., Guisan A. (2006). Five (or so) Challenges for Species Distribution Modelling. J Biogeogr 33:1677–1688. doi: 10.1111/j.1365-2699.2006.01584.x

Asseh E. E., Ake-Assi E., Koffi K. J. (2019). Diversité biologique et influence des changements climatiques sur la distribution géographique de quelques espèces d'Acanthaceae en Côte d'Ivoire. Int J Biol Chem Sci 13 (2): 676 692. doi: 10.4314/ijbcs.v13i2.9

Austin M. P., Belbin L., Meyers J. A., Doherty M. D., Luoto M. (2006). Evaluation of Statistical Models Used for Predicting Plant Species Distributions: Role of Artificial Data and Theory. Ecol Model 199: 197-216. doi: 10.1016/j.ecolmodel.2006.05.023

Baker E. A., Procopiou J. (1980). Effect of Soil Moisture Status on Leaf Surface Wax Yield of Some Drought-Resistant Species. Research Note. J Hortic Sci 55(1): 85-87. doi: 10.1080/00221589.1980.11514907

Baldwin R. A. (2009). Use of Maximum Entropy Modeling in Wildlife Research. Entropy 11 (4): 854 866. doi: 10.3390/e11040854

Batlle I., Tous J. (1997). Carob Tree. *Ceratonia siliqua* L. International Plant Genetic Resources Institute, Rome, Italy, 92pp

Bargain A., Fabri M. C. (2016). Guide méthodologique de modélisation prédictive d'habitats profonds en Méditerranée. Département Océanographie et Dynamique des Ecosystèmes, Laboratoire Environnement Ressources Provence Azur Corse (LER-PAC). 128 pp, (in French)

Baum N. (1988). Arbres et arbustes de l'Egypte ancienne. Peeters Publishers, France, 381p

Benmahioul B., Kaid-Harche M., Daguin F. (2011). Le caroubier, une espèce méditerranéenne à usages multiples. Forêt méditerranéenne XXXII: 51-58.

Ben Rhouma T., Ben Mariem H. (2022) Identification des principaux déterminants environnementaux et modélisation de la distribution potentielle de pin d'Alep et impact du changement climatique en Tunisie. Revue marocaine des sciences agronomiques et vétérinaires 10 (1): 157-168. (in French)

Bianchini M., Tarhouni M., Francioni M., Fiorentini M., Rivosecchi C., Msadek J., Tlili A., Chouikhi F., Allegrezza M., Tesei G., Deligios P. A., Orsini R., Ledda L., Karatassiou M., Ragkos A., D'Ottavio P. (2025). Modeling Climate-Driven Vegetation Changes under Contrasting Temperate and Arid Conditions in the Mediterranean Basin. Ecol Evol 15 (1): e70753. doi: 10.1002/ece3.70753

Foughali B., Fghire R., Anaya F., Oudou I.A., Tahrouch S., Wahbi S. (2021). Bioclimatic Impact on the Carob Seeds Morphological Diversity in Morocco. Biosci Biotechnol Res Asia 18 (1): 207. doi: 10.13005/bbra/2908

Brambilla M., Caprio E., Assandri G., Scridel D., Bassi E., Bionda R., Celada C., Falco R., Bogliani G., Pedrini P., Rolando A., Chamberlain D. (2017). A Spatially Explicit Definition of Conservation Priorities according to Population Resistance and Resilience, Species Importance and Level of Threat in a Changing Climate. Diversity Distrib 23 (7): 727-738. doi: 10.1111/ddi.12572

Breiman L., Friedman J. H., Olshen R. A., Stone C. J. (1984). Classification and Regression Trees. Monterey, Calif., 432 p.

Catarino F. M., Correia O. A., Webb E., David M. (1981). Morphological and Physiological Responses of the Mediterranean Evergreen Sclerophyll, *Ceratonia siliqua*, to Different light Intensities. In: Components of Productivity of Mediterranean Climate Regions. Basic and Applied Aspects (Margaris N. S., Mooney H. A., eds), Junk Publishers, The Hague, pp. 5-15.

Chaabi C. (2023). Stress climatique : L'état mise sur le caroubier avec 100 000 ha d'ici 2030. Available at: https://medias24.com/2023/01/12 [Accessed: 1 August 2024], (in French)

Chapin F. S., Bloom A. J., Field C. B., Waring R. H. (1987). Plant Responses to Multiple Environmental Factors. Bioscience 37: 49–57. doi: 10.2307/1310177

Corsi F., Dupre E., Boitani L. (1999). A Large-Scale Model of Wolf Distribution in Italy for Conservation Planning. Conserv Biol 13: 150–159.

Damaneh J. M., Ahmadi J., Rahmanian S., Sadeghi S. M. M., Nasiri V., Borz S. A. (2022). Prediction of Wild Pistachio Ecological Niche Using Machine Learning Models. Ecol. Informatics 72: 101907. doi.org/10.1016/j.ecoinf.2022.101907

Delforge A. (2020). Prédiction des zones favorables à l'installation de l'espèce exotique envahissante Ambrosia artemisiifolia L. en région wallonne. Mémoire de fin d'étude, Université de Liège. Available at https://matheo.uliege.be/bitstream/2268.2/10622/4/MEMOIRE_DelforgeAdrien.pdf, [Accessed: 12 January 2024], (in French)

Direction Générale de la météorologie (DGM) (2023). Maroc: Etat du Climat en 2022. Available at: https://www.marocmeteo.ma/sites/default/files/climat_report/pdfs/Maroc_Etat_Climat_2022.pdf, [Accessed: 12 January 2024], (in French)

Doffou S. C., Kouadio K., N'Da Dibi H. (2021). Effets des variations climatiques à l'horizon 2050 sur la distribution phytogéographique de *Tieghemella heckelii* Pierre ex A. Chev. (*Sapotaceae*) en Côte d'Ivoire Int J Biol Chem Sci 15 (2): 679-694. doi: 10.4314/ijbcs.v15i2.23

Eddabbeh F. E. and Eddabbeh L. (2024). Le caroubier naturel au Maroc : Importance, superficie, production et recommandations. Agriculture du Maghreb. Available at: https://www.agri-mag.com/2024/04/21/caroubier-naturel-maroc/, [Accessed: 18 April 2024], (in French)

Elith J., Graham C. H., Anderson R. P., Dudík M., Ferrier S., Guisan A., Hijmans R., Huettmann F., Leathwick J., Lehmann A., Li J., Lohmann L., Loiselle B., Manion G., Moritz C., Nakamura M., Nakazawa Y., Overton J., Peterson A., Zimmermann N. (2006). Novel Methods Improve Prediction of Species' Distributions from Occurrence Data. Ecography 29:129-151. doi: 10.1111/j.2006.0906-7590.04596.x

Elith J., Phillips S. J., Hastie T., Dudík M., Chee Y. E., Yates C. J. (2011). A Statistical Explanation of MaxEnt for Ecologists. Diversity Distrib 17:43-57. doi: 10.1111/j.1472- 4642.2010.00725.x

Evans J. S., Murphy M. A., Holden Z. A., Cushman S.A. (2011). Modeling Species Distribution and Change Using Random Forest. In: Predictive Species and Habitat Modeling in Landscape Ecology (Drew C., Wiersma Y., Huettmann F., eds), Springer, New York, pp. 139-159

Feeley K. J., Silman M. R. (2011). Keep Collecting: Accurate Species Distribution Modelling Requires More Collections than Previously Thought. Diversity Distrib 17 (6): 1132-1140. doi: 10.1111/j.1472-4642.2011.00813.x

Garah K., Bentouati A. (2019). Using the MaxEnt Model for Assessing the Impact of Climate Change on the Aurasian Aleppo Pine Distribution in Algeria. Afr J Ecol 57(2). doi: 10.1111/aje.12630

Gharnit N., El Mtili N., Ennabili A., Sayah F. (2005). Caractérisation foliaire du caroubier (*Ceratonia siliqua* L.) originaire de la province de Chefchaouen (Nord-ouest du Maroc). J Bot 31: 75–84. (in French)

Graham C. H., Elith J., Hijmans R. J., Guisan A., Townsend Peterson A., Loiselle B. A. (2007). The Influence of Spatial Errors in Species Occurrence Data Used in Distribution Models: Spatial Error in Occurrence Data for Predictive Modelling. J Appl Ecol 45 (1): 239 247. doi: 10.1111/j.1365-2664.2007.01408.x

Guisan A., Zimmermann N. E. (2000). Predictive Habitat Distribution Models in Ecology. Ecol. Model 135 (2): 147-186. doi: 10.1016/s0304-3800(00)00354-

Guisan A., Edwards T. C., Hastie T. (2002). Generalized Linear and Generalized Additive Models in Studies of Species Distributions: Setting the Scene. Ecol. Model 157: 89-100. doi: 10.1016/S0304-3800 (02)00204-1.

Hanley J. A., McNeil B. J. (1982). The Meaning and Use of the Area under a Receiver Operating Characteristic (ROC) Curve. Radiology 143 (1): 29-36

Hernandez P. A., Graham C. H., Master L. L., Albert D. L. (2006). The Effect of Sample Size and Species Characteristics on Performance of Different Species Distribution Modeling Methods. Ecography 29 (5): 773-785. doi: 10.1111/j.0906-7590.2006.04700.x

Hijmans R. J., Cameron S.E., Parra J. L., Jones P. G., Jarvis A. (2005). Very High Resolution Interpolated Climate Surfaces for Global Land Areas. Int J Climatol 25: 1965-1978. doi:10.1002/joc.1276

Kassout J., Ater M., Ivorra S., Barbara H., Limier B., Ros J., Girard V., Paradis L., Terral J. F. (2021). Resisting Aridification: Adaptation of Sap Conduction Performance in Moroccan Wild Olive Subspecies Distributed Over an Aridity Gradient. Front Plant Sci 12: 663721. doi: 10.3389/fpls.2021.663721

Kassout J., Hmimsa Y., Fatehi S. E., Kadaoui K., Houssni M., Chakkour S., Sahli A., El Chami M., Ariza, D., Palacios G., Navarro Cerrillo R., Ater M. (2023). Aridity Gradients Shape Intraspecific Variability of Morphological Traits in Native *Ceratonia siliqua* L. of Morocco. Plants 12(19): 3447. doi: 10.3390/plants12193447

Khouas A., Hamamou M. (2020). Caractérisation morphologique, anatomique et biochimiquede l'éspèce *Ceratonia siliqua* L. (Caroubier) provenant des régions Blida et Tipaza. Mémoire de fin d'étude, Université Blida. Available at: https://di.univ-blida.dz/jspui/handle/123456789/10557, [Accessed: 17 May 2024], (in French)

Lahssini S., Hajib S., Lahlaoi H., Mharzi Alaoui H., Khattabi A. (2015). Modelling Spatial Distribution of the Carob Tree (*Ceratonia siliqua* L.) in Azilal Province, Morocco. J Geogr Geol 7: 33-44. doi: 10.5539/jgg.v7n4p33

Lehmann C. E. R., Archibald S. A., Hoffmann W. A., Bond W. J. (2011). Deciphering the Distribution of the Savanna Biome. New Phytol 191: 197– 209. doi: 10.1111/j.1469-8137.2011.03689.x

Li G. Q., Du S., Wen Z. M. (2016). Mapping the Climatic Suitable Habitat of Oriental Arborvitae (*Platycladus orientalis*) for Introduction and Cultivation at a Global Scale. Sci Rep 6: 30009. doi :10.1038/srep30009

Lo Gullo M. A., Salleo S., Rosso R. (1986). Drought Avoidance Strategy in *Ceratonia siliqua* L., a Mesomorphic Leaved Tree in the Xeric Mediterranean Area. Ann Bot 58: 745–756.

Lo Gullo M. A., Nardini A., Trifilo P., Salleo S. (2003). Changes in Leaf Hydraulics and Stomatal Conductance Following Drought Stress and Irrigation in *Ceratonia siliqua* (Carob Tree). Physiol Plant 117(2): 186–194. doi: 10.1034/j.1399-3054.2003.00038.x

Mahmoud A. R., Farahat E. A., Hassan L. M., Halmy M. W. A. (2025). Predicting the Future Impact of Climate Change on the Distribution of Species in Egypt's Mediterranean Ecosystems. BMC Plant Biol 25 (1):644. doi: 10.1186/s12870-025-06630-7

Martins-Loução M. A., Correia P. S., Romano A. (2024). Carob: A Mediterranean Resource for the Future. Plants 13(9): 1188. doi: 10.3390/plants13091188

Marti J. T., Caravaca I. B. (1990). El Algarrobo. Ediciones Mundi-Prensa, Spain (in Spanish)

Mas B., Riera S., Allué E. (2023). Modelling Mediterranean Oak Palaeolandscapes Using the MaxEnt Model Algorithm: The Case of the NE Iberia under the Middle Holocene Climatic Scenario. Ecol Inform 74:101984. doi: 10.1016/j.ecoinf.2023.101984

Matsui T., Tsutomu Y., Tomoki N., Nakaya T., Taoda H., Yoshinaga S., Daimaru H., Tanaka N. (2004). Probability Distributions, Vulnerability and Sensitivity in Fagus Crenata Forests Following Predicted Climate Changes in Japan. J Veg Sci 15: 605–614.

Merow C., Smith M. J., Silander J. A. (2013). A Practical Guide to MaxEnt for Modeling Species' Distributions: What It Does, and Why Inputs and Settings Matter. Ecography 36: 1058-1069. doi: 10.1111/j.1600-0587.2013.07872.x

Mitrakos K. (1981). Temperature Germination Responses in Three Mediterranean Evergreen Sclerophylls. In: Components of Productivity of Mediterranean-Climate Regions - Basic and Applied Aspects (Margaris N.S., Mooney H.A., eds), Dr.W. Junk Publishers, London, pp. 277-279.

Moukrim S., Lahssini S., Mharzi Alaoui H., Rifai N., Arahou M., Rhazi L. (2018). Modélisation de la distribution spatiale des espèces endémiques pour leur conservation : cas de l'*Argania spinosa* (L.) Skeels. Revue d'Écologie 73: 153-166 (in French)

Nardini A., Lo Gullo M., Salleo S. (2002). Competitive Strategies for Water Availability in Two Mediterranean Quercus Species. Plant Cell Environ 22(1): 109–116. doi: 10.1046/j.1365-3040.1999.00382.x

Ouzounidou G., Vekiari S., Asfi M., Ozturk M., Sakcali M., Gork M. G. (2012). Photosynthetic Characteristics of Carob Tree (*Ceratonia siliqua* L.) and Chemical Composition of Its Fruit in Diurnal and Seasonal Basis, Pak J Bot 44 (5): 1689-1695.

Pearson R. G., Raxworthy C. J., Nakamura M., Townsend Peterson A. (2007). Predicting Species Distributions from Small Numbers of Occurrence Records: A Test Case Using Cryptic Geckos in Madagascar. J Biogeogr 34: 102-117. doi: 10.1111/j.1365-2699.2006.01594.x

Peterson A. T., Papes M., Eaton M. (2007). Transferability and Model Evaluation in Ecological Niche Modeling: A Comparison of GARP and Maxent. Ecography 30 (4): 550–560.

Phillips S. J., Anderson R. P., Schapire R. E. (2006). Maximum Entropy Modeling of Species Geographic Distributions. Ecol Model 190: 231-259. doi: 10.1016/j.ecolmodel.2005.03.026.

Phillips S. J. and Dudík M. (2008). Modeling of Species Distributions with Maxent: New Extensions and a Comprehensive Evaluation. Ecography 31 (2): 161-175. doi: 10.1111/j.0906-7590.2008.5203.x

Pulliam H. R. (2000). On the Relationship between Niche and Distribution. Ecol Lett 3: 349–361. doi: 10.1046/j.1461-0248.2000.00143.x

Rejeb M. N. (1995). Le caroubier en Tunisie : Situations et perspectives d'amélioration. Dans: Quel avenir pour l'amélioration des plantes ? Edit. AUPELF-UREF, Paris (in French)

Rima K. (2021). Morpho-Ecological and Phytochemical Characterization of Carob Tree (*Ceratonia siliqua* L.) in Algeria. Ph.D. Thesis, University Ziane Achour, Djelfa, Algeria

Ripley B. D. (1996). Pattern Recognition and Neural Networks. Cambridge University Press, 390 p.

Rupprecht F., Oldeland J., Finckh M. (2011). Modelling Potential Distribution of the Threatened Tree Species *Juniperus oxycedrus*: How to Evaluate the Predictions of Different Modelling Approaches? J Veg Sci 22: 647-659.

Sbay H., Abourouh M. (2006). Apport des espèces à usages multiples pour le développement durable: cas du pin pignon et du caroubier. Centre de Recherche Forestière Haut-Commissariat aux Eaux et Forêts et à la Lutte Contre la Désertification, Rabat: 1-9. (in French)

Sbay H. E. (2008). Le caroubier au Maroc un arbre d'avenir. La Collection Maroc Nature, Centre de Recherche Forestière du Haut Commissariat aux Eaux et Forêts et à la Lutte contre la Désertification: Rabat, Morocco, pp7, (in French)

Sbay H. (2022). Tout savoir sur le caroubier. Hortimédia. Available at: https://hortimedia.ma, [Accessed: 25 March 2024], (in French)

Swets J. A. (1988). Measuring the Accuracy of Diagnostic Systems. Science 240: 1285 1293

Von Haselberg C. (2000). Vegetative Growth and Flower and Fruit Development in Carob Trees (*Ceratonia siliqua* L.) with Special Emphasis on Environmental Conditions at Marginal Production Sites in South Portugal. PhD. doi: 10.13140/2.1.3414.3048.

Welk E., Schubert K., Hoffmann M. H. (2002). Present and Potential Distribution of Invasive Mustard (*Alliara petiolata*) in North America. Diversity Distrib 8: 219–233

Wisz M.S., Hijmans R.J., Li J., Peterson A.T., Graham C.H., Guisan A. et al (2008). Effects of Sample Size on the Performance of Species Distribution Models. Diversity Distrib 14: 763-773.

Xiaomin L., Guangsheng Zhou (2018). Climatic Suitability of the Geographic Distribution of *Stipa breviflora* in Chinese Temperate Grassland under Climate Change. Sustainability 10: 3767. doi: 10.3390/su10103767

Ye P., Zhang G., Zhao X., Chen H., Si Q., Wuet J. (2021). Potential Geographical Distribution and Environmental Explanations of Rare and Endangered Plant Species through Combined Modelling: A Case Study of Northwest Yunnan, China. Ecol Evol 11 (19): 13052-13067. doi: 10.22541/au.160734246.63375336/v1

Young N., Carter L., Evangelista P. (2011). A MaxEnt Model v3.3.3e Tutorial (ArcGIS v10). Available at : https://www.coloradoview.org/wp-content/coloradoviewData/trainingData/a-maxent-model-v8.pdf, [Accessed: 25 February 2024], (in French)

Zouhair O. (1996). Le caroubier, situuation actuelle et perspectives d'avenir. Document interne, Eaux de Forêt, Maroc, 22p

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