

Article

Forecasting the Impact of Climate Change on *Tetraclinis articulata* Distribution in the Mediterranean Using MaxEnt and GIS-Based Analysis

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Abstract

Climate change threatens *Tetraclinis articulata*, a Mediterranean plant endangered by habitat loss, logging, and aridification. This study used the MaxEnt model to analyze factors affecting its distribution under current and future climate scenarios (SSP1-2.6 to SSP5-8.5) for 2040–2100, highlighting its vulnerability to drought and urgent conservation needs. Results showed that: (a) the model demonstrated excellent predictive power with an AUC of 0.92; (b) the highly suitable habitat for *T. articulata* is projected to expand by 6.5%–6.7% (5.24–5.38 million km²) by 2100 under SSPs 2-4.5, 3-7.0, and 5-8.5, compared to current conditions (6.1%, 4.92 million km²); (c) the centroid of suitable habitats shifts from north-west Algeria (1.394° N, 33.538° E) to various locations under future climate scenarios: west Morocco (SSP1-2.6, −3.429° S, 33.588° E), east Tunisia (SSP2-4.5, 11.091° N, 32.501° E), northwest Morocco (SSP3-7.0, −1.947° S, 34.098° E), and southwest Morocco (SSP5-8.5, −2.985° S, 34.707° E); (d) key environmental variables influencing *T. articulata* distribution include annual precipitation (bio12, 41.7%), mean annual temperature (bio1, 27.9%), and precipitation during the driest month (bio14, 16.1%). This study concluded that climate change significantly influenced the distribution of *T. articulata* in the Mediterranean, highlighting the urgent need for conservation strategies to mitigate the risk of local extinction driven by both anthropogenic activities and climate impacts.

Keywords: biodiversity conservation; *Tetraclinis articulata*; hotspot; MaxEnt; GIS; climate change



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1. Introduction

Climate change is a significant factor profoundly affecting biodiversity at all levels [1–3]. Changes in plant distribution represent a fundamental reaction to novel climatic conditions [4,5], as has been observed in prior eras of climate change. Pollen analysis

findings suggest altitudinal and latitudinal shifts in species distribution over centuries and decades [6].

Tetraclinis articulata Vahl. Mast., commonly known as the thuya/sandarac gum tree, is a type of evergreen conifer belonging to the Cupressaceae family. It can grow to a height of 6–12 m and is characterized by its flattened branches, scale-like leaves, and reddish-brown aromatic trunk [7]. This multipurpose tree is renowned for its premium root burlwood, which renders it extremely desirable in the handicraft sector [8]. The essential oil derived from *T. articulata* has antibacterial efficacy against *Staphylococcus aureus* and *Micrococcus luteus* [9]. This monospecific species predominantly has a North African distribution, with the sole European occurrence of *T. articulata*, aside from Malta and Cyprus, in southeastern Spain, particularly in the coastal areas of the Murcia Province [10]. The inherent characteristics and restricted geographic range of the species render it particularly significant for biodiversity conservation [11]. This tree is pivotal in the socioeconomic framework of North Africa, as it offers pastureland for animals and generates items for local consumption [12]. It is ideal for the soil conservation and restoration of forests, as it can adhere to rocks on the steepest inclines owing to its robust and flexible root structure [11,13]. *T. articulata* forests offer significant benefits, including soil erosion mitigation, biodiversity preservation, and carbon dioxide sequestration, making them appropriate for afforestation initiatives in dry or semiarid regions where few species can thrive, and in places with poorly degraded soils [14].

T. articulata is a Mediterranean conifer that can survive long periods of dry weather and has many uses, including timber, resin, and essential oils, also important for controlling erosion. In a fragile ecological environment, understanding the potential spatial distribution of species and the underlying environmental conditions is crucial for resolving ecosystem management issues and predicting impacts of global change [15]. Its distribution is fragmented and relict, which means that it is only found in a few places around the world, such as its small native range in SE Spain and Malta [7,16]. The Mediterranean is a well-known area where climate change is happening quickly; it is warming about 20% faster than the rest of the world. This makes it more likely that drought-sensitive forest mosaics, where *T. articulata* grows, would be affected (MedECC/UNEP, 2020–2024) [17]. Previous studies on *T. articulata*'s predicted range responses primarily focused on the Iberian Peninsula within older climate frameworks, emphasizing its susceptibility to warming and aridification, but failing to address basin-wide, CMIP6-based evaluations [14,18].

T. articulata forests present a particularly intriguing scenario for evaluating the anticipated impact of climate change on biodiversity. A common method for evaluating the possible effects of climate change on biodiversity involves employing species distribution models (SDM) and climate change scenarios to project future habitat suitability for various species [2,19,20]. SDM predicts environmental suitability and species distribution by integrating species distribution data with environmental variables such as climate and habitat [20]. Among the prominent SDM's, CLIMAX, Biomod2, GARP, and MaxEnt, which are based on the maximum entropy model, are recognized for their accuracy, operational robustness, and efficiency [21]. It has an enhanced predictive capability compared with other models, particularly in its robustness against sample bias [20]. Most studies are based on the Coupled Model Intercomparison Project Phase 5 (CMIP5), whereas the newer version, CMIP6, demonstrates heightened climate sensitivity and enables a more comprehensive analysis of potential scenarios [22]. Thus, CMIP6 provides an improved study of the environmental factors influencing species distribution and enables a more accurate prediction of invasive alien pest spread.

Presence-only species distribution models (SDMs) like MaxEnt are well-tested for predicting climate suitability and finding the main factors that affect distributions in

Mediterranean forests [23,24]. Recent applications in North Africa validate MaxEnt's efficacy for tree taxa and advocate for its expansion to incorporate future climate scenarios and larger ensembles to mitigate bias [15]. Our study employs MaxEnt within a GIS framework integrated with CMIP6 SSPs (SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5) to provide the inaugural Mediterranean-wide, multi-horizon projections for *T. articulata*, thereby addressing the geographic and scenario deficiencies identified in previous CMIP5-era or sub-regional analyses.

T. articulata has experienced considerable fragmentation and a reduction in its population [25]. This resource is endangered by fragmentation resulting from human activities, extensive logging, and government negligence, which may result in permanent losses [26]. The effects of escalating aridification and heightened drought frequency on species tolerance and legacy responses to climate change remain unclear. Additionally, a study of its distribution pattern under different climate change scenarios has not yet been conducted. For better management of *T. articulata* forests in these semi-arid territories, knowledge of this species is essential. This information is essential for future conservation and management plans [27]. We hypothesized that, like many other species of plants and insects, climate change would have a significant influence on the distribution pattern of *T. articulata* under different climate change scenarios. This study aimed to identify the main climatic factors influencing the distribution of *T. articulata* under current and future climate change scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5) for 2040, 2060, 2080, and 2100, respectively.

2. Materials and Methods

2.1. Study Area

In the Mediterranean region, *T. articulata* is primarily located in countries such as Tunisia, where it serves as one of the main habitats for this species, especially in forests and mountainous areas. It is also found in various regions of Algeria, particularly in mountainous and arid regions. In Morocco, this species thrives in the Atlas Mountains and other elevated terrains. Additionally, *T. articulata* has been reported in other Mediterranean areas, including Spain, and islands, such as Malta (Figure 1). It is indigenous to the mountain ranges of northern Africa (Morocco, Algeria, and Tunisia, up to 1800 m a.s.l.), with scattered populations mostly found in eastern Spain (near Cartagena, the Murcia region) and Malta [28].

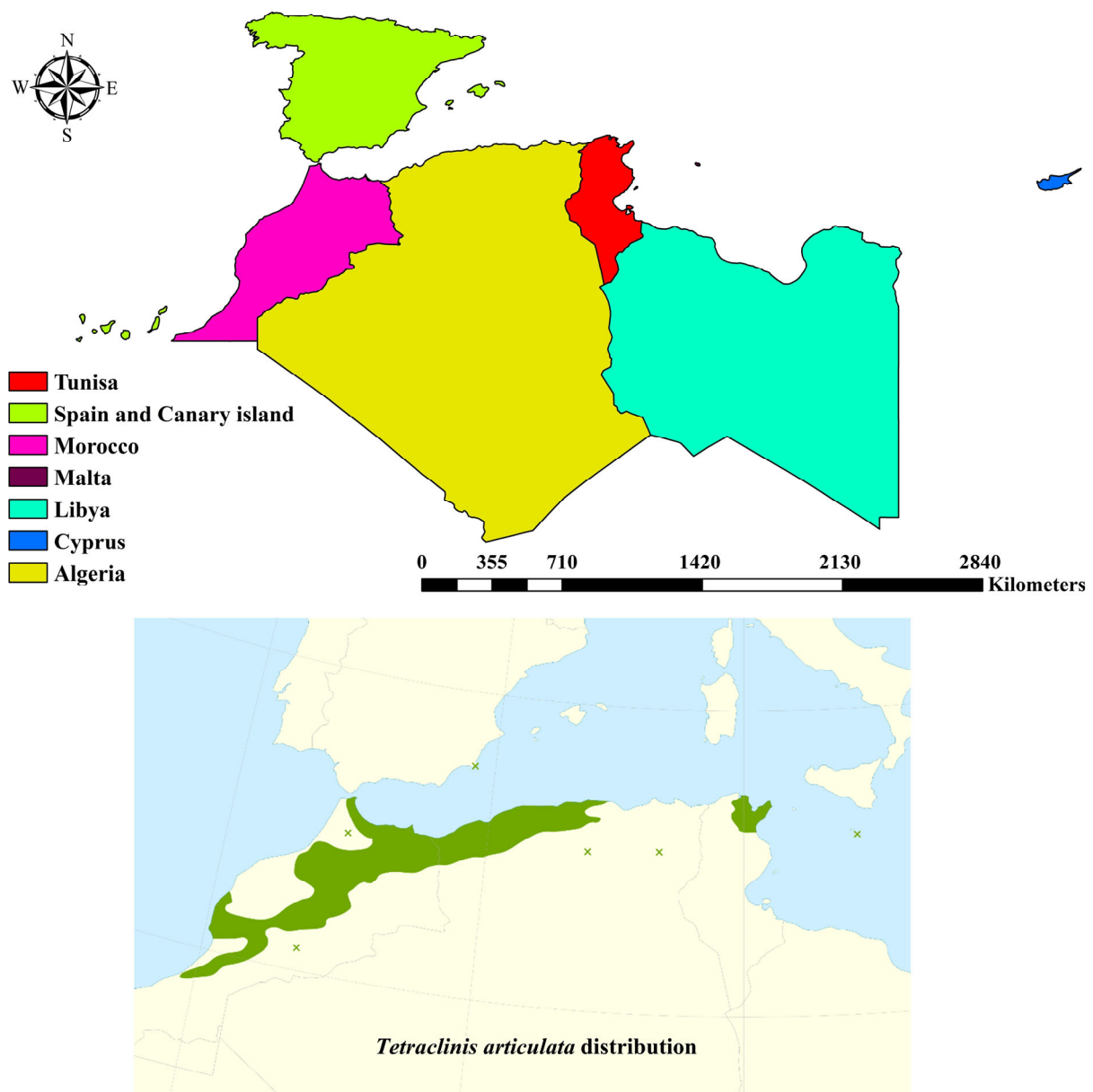


Figure 1. The study area map and known distribution of *Tetraclinis articulata* [29].

2.2. Species Occurrence Data

For occurrence data, we compiled all relevant published works from the library covering the period January 1952 to 2024. Occurrence record data were gathered from updated databases [27,30–33]. Additional data was obtained from the Global Biodiversity Information Facility (<https://www.gbif.org/>, accessed on 10 May 2025), EPPO (<https://gd.eppo.int/>, accessed on 10 May 2025), CABI (<https://www.cabi.org/>, accessed on 10 May 2025), and Euro + Med PlantBase (<https://europlusmed.org/>, accessed on 10 May 2025) databases. A total of 23,564 occurrence points were collected that were further refined to 15,000 points by applying spatial thinning of keeping one point in a 1 km radius in ArcMap (version 10.8.1).

2.3. Climatic Data

Nineteen WorldClim bioclimatic variables (Bio1–Bio19), averaged from 1950 to 2000 and possessing a spatial resolution of 2.5 arc minutes, were acquired from the WorldClim Database (<http://www.worldclim.org>, accessed on 10 May 2025) for MaxEnt modelling for

the current scenario. To thoroughly assess the alterations in the probable acceptable habitats of *T. articulata* in the future, especially in the years 2040, 2060, 2080, and 2100, we utilized the global climate model (GCM) MIROC6. We used the GCM from the Sixth Assessment Report (AR6) of the IPCC. Four shared socioeconomic pathways (SSPs) were selected for each year: SSP1-2.6 [Sustainability, low forcing: Globally cooperative, equity-focused development with rapid clean-tech adoption, efficient resource use, and strong land protection. Emissions peak early and decline fast, stabilizing at $\sim 2.6 \text{ W/m}^2$ by 2100]; SSP2-4.5 [Middle of the Road, intermediate forcing: Continuation of current trends—moderate growth, uneven progress, mixed policies. Emissions plateau mid-century then slowly decline, landing near $\sim 4.5 \text{ W/m}^2$ by 2100]; SSP3-7.0 [Regional Rivalry, high forcing: Fragmented world with weak international cooperation, slower economic growth in many regions, high population in developing areas, low tech transfer, limited mitigation. Emissions keep rising, reaching $\sim 7.0 \text{ W/m}^2$ by 2100]; SSP5-8.5 [Fossil-Fueled Development, very high forcing: Rapid, energy-intensive growth driven by abundant fossil fuel use and material consumption; strong tech progress but little mitigation. Emissions surge to $\sim 8.5 \text{ W/m}^2$ by 2100]. The reason to incorporate MIROC6 because it is an updated version of the CMIP6 GCM that has been shown to work better than MIROC5 in terms of the mean state and internal variability. This is because it has new processes for aerosols and clouds, land surfaces, and the stratosphere [34]. MIROC6 is often used in Mediterranean temperature and extreme forecasts and demonstrates satisfactory performance when integrated with conventional bias-adjustment and ensemble techniques [35].

2.4. Species Distribution Model (SDM) and Variable Selection

MaxEnt v3.4.4 was utilized to forecast the distribution range of *T. articulata* across different climatic scenarios. MaxEnt operates by identifying correlations between recorded occurrence points and background data within defined parameters, as outlined by [36]. MaxEnt is distinguished for its ability to integrate several factors such as meteorological data, provide different metrics for assessing model performance, and provide user-friendly software functionality, making it extensively utilized in species distribution prediction [37]. A complete array of 19 bioclimatic variables was obtained from the WorldClim website and first utilized as a prospective predictor. Multicollinearity among bioclimatic factors may adversely affect the relationship between species distributions [20]. To create a high-performance model with reduced variables, the Pearson correlation coefficients of the cross-correlations among the 19 bioclimatic variables were computed using the SDM toolbox (Version 2.6) extension in Arc Map (version 10.8.1) to eliminate highly correlated variables based on Pearson correlation at $p \leq 0.8$ [20]. Six variables ($p \leq 0.8$) were selected for the investigation based on Pearson correlation values (Table 1). To test the influence of variable selection, we constructed the two models, one with all 19 bio variables and the other one with the selected 6 bio variables, and to determine the statistical difference between them, we conducted the ANOVA and t-test. We quantified the contribution of the 19 predictors using MaxEnt's built-in jackknife procedure on the same dataset used for model fitting (presence records + background), with a 25% random test split and all other settings at defaults. The jackknife runs three models per predictor: (i) with only that variable, (ii) with all variables, and (iii) with that variable omitted. We examined changes in regularized training gain (and inspected AUCs) to interpret importance: a variable yielding the highest gain when used alone contains the most useful stand-alone information; a variable whose omission causes the largest drop in gain contributes the most unique information not captured by others. We report these results alongside percent contribution/permutation importance and use them to identify the dominant climatic drivers and to guide interpretation of species–environment relationships.

Table 1. Selected bioclimatic variables based on person correlation analysis of *Tetraclinis articulata* in this study.

Variable	Variable Description	Variable Retained	p-Value
Bio1	Annual mean temperature	✓	<0.8
Bio2	Mean diurnal range	✓	<0.8
Bio3	Isothermality (Bio2/Bio7) ($\times 100$)		>0.8
Bio4	Temperature seasonality	✓	<0.8
Bio5	Max temperature of the warmest month		>0.8
Bio6	Min temperature of coldest month		>0.8
Bio7	Temperature Annual Range (Bio5–Bio6)		>0.8
Bio8	Mean temperature of the wettest quarter	✓	<0.8
Bio9	Mean temperature of the driest quarter		>0.8
Bio10	Mean temperature of warmest quarter		>0.8
Bio11	Mean temperature of the coldest quarter		>0.8
Bio12	Annual precipitation	✓	<0.8
Bio13	Precipitation of Wettest Month		>0.8
Bio14	Precipitation of driest month	✓	<0.8
Bio15	Precipitation Seasonality (Coefficient of Variation)		>0.8
Bio16	Precipitation of Wettest Quarter		>0.8
Bio17	Precipitation of Driest Quarter		>0.8
Bio18	Precipitation of Warmest Quarter		>0.8
Bio19	Precipitation of Coldest Quarter		>0.8

2.5. Model Accuracy Assessment and Map Generation

The final model was run using a 10-fold bootstrapping crossover technique for current and future conditions. The efficacy of the MaxEnt model was assessed using the Receiver Operating Characteristic (ROC) curve, with the area under the curve (AUC) computed as an indicator of predictive accuracy. The area under the receiver operating characteristic (ROC) curve (AUC) was adopted for model evaluation [38]. AUC values over 0.5 indicate a superior match compared to random chance, whereas values between 0.9 and 1 denote exceptional predicting capability. To enhance species distribution modeling with MaxEnt, we evaluated eight Feature Class (FC) auto features—auto class, L: Linear, Q: Quadratic, LQ: Linear + Quadratic, LQH: Linear + Quadratic + Hinge, LQT: Linear + Quadratic + Threshold, LQHP: Linear + Quadratic + Hinge + Product, LQHPT: Linear + Quadratic + Hinge + Product + Threshold—alongside Regularization Multipliers (RM) varying from 0.2 to 2. The AUC score was used to find the most effective feature class and RM pair by assessing the degree to which the model executed [38,39].

The best model choice was centered on getting the highest AUC while still being able to generalize. After the modeling process was finished, we used MaxEnt’s results to make habitat suitability maps for *T. articulata* for both the present and the future. The maximum training sensitivity plus specificity logistic threshold (MTSS) was used to figure out how good a habitat was for species. The models’ MTSS values came out to be 0.10.

By executing lowest presence threshold (LQT) feature class to delineate the appropriate and unsuitable locations [20], we categorized habitat into four categories: unsuitable (MTSS < 0.1), moderately suitable (MTSS > 0.1–<0.3), suitable (MTSS > 0.3–<0.6), and highly suitable (MTSS > 0.6). All layers were produced in ArcMap (version 10.8.1) with ArcToolbox under Spatial Analyst Tools, namely, the Reclassify function, according to the LQT criteria.

3. Results

3.1. Model Accuracy and Contributions of Predictor Variable

To mitigate overfitting, we performed a series of screenings on the distribution sites of *T. articulata*. The efficacy of several FC combinations under varied RMs was evaluated for *T.*

articulata. AUC ratings reached a maximum of RM = 1 for all evaluated models, with LQT demonstrating the best predictive accuracy (Figure 2a). The ideal configuration was LQT at RM = 1, with an AUC of 0.92. The findings indicate that LQT is the most efficacious feature class for simulating *T. articulata* distributions across varying environmental conditions. Furthermore, the results demonstrated that the model executed with the selection of shortlisted variables by correlation analysis yielded more significant ($df = 21$; $F = 10.29$; $p < 0.01$ for AUC; $df = 21$; $F = 9$; $p < 0.01$ for TSS) and precise outcomes, achieving a higher AUC and TSS of 0.92 and 0.83 in contrast to the model utilizing all variables (AUC = 0.87 and TSS = 0.77) (Figure 2b).

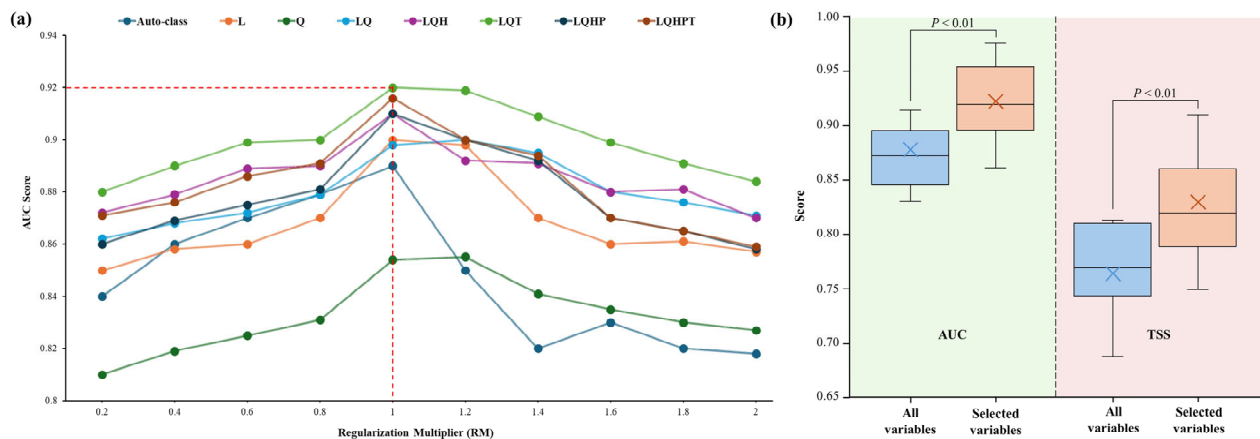


Figure 2. (a) Evaluation of AUC scores for different Feature Class (FC) combinations across Regularization Multipliers (RMs) for *T. articulata* leveraging MaxEnt modeling. Validated FCs encompass Auto Features, LQ (Linear + Quadratic), LQH (Linear + Quadratic + Hinge), and LQHPT (Linear + Quadratic + Hinge + Product + Threshold). The intersection of red dashed lines indicates the most promising model for *T. articulata*, computed according to the highest AUC value. (b) Influence of variable set all vs. selected on the SDMs' AUC and TSS scores.

The AUC values obtained from the 10-fold cross-validation of the final model with selected variables are illustrated in Figure 3. The AUC value was 0.92, indicating the robust efficacy of the MaxEnt model in forecasting the possible distribution zones of *T. articulata*. MaxEnt prediction results revealed that all occurrence records were within the anticipated range, suggesting that the model's predictions were highly accurate.

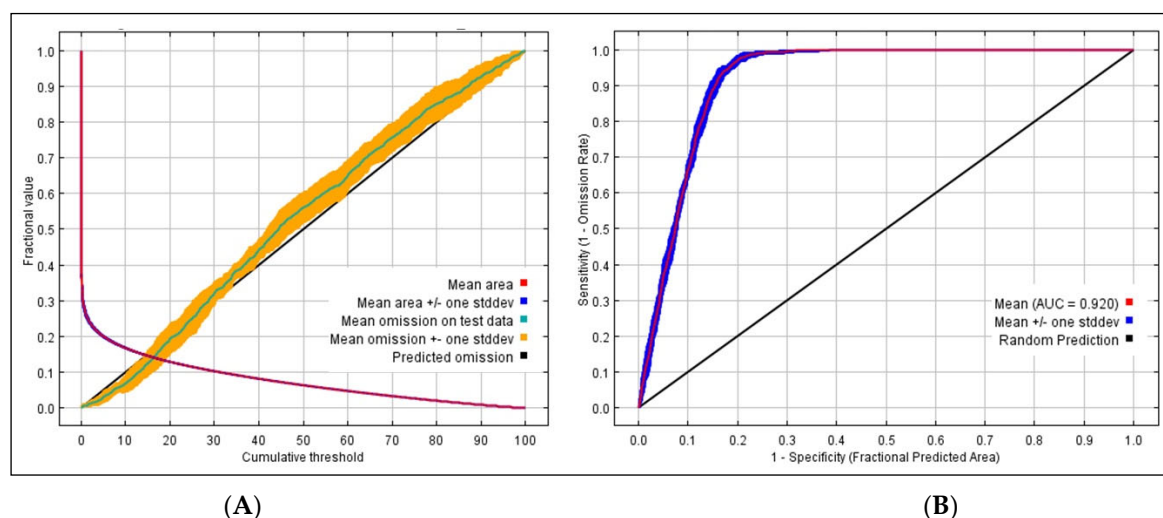


Figure 3. Model evaluation based on (A) the averaged omission and predicted area *T. articulata* and (B) the ROC curve calculated by MaxEnt as averaged sensitivity versus 1-specificity for *Tetraclinis articulata*.

The primary environmental factors correlated with the spread of *T. articulata* were rated as follows: seasonality of annual precipitation, annual mean temperature, and precipitation during the driest month. However, the overall variables contributed an average of 41.7%, 27.9%, 16.1%, 7.7%, 4.5%, and 2.1% to the model (Figure 4).

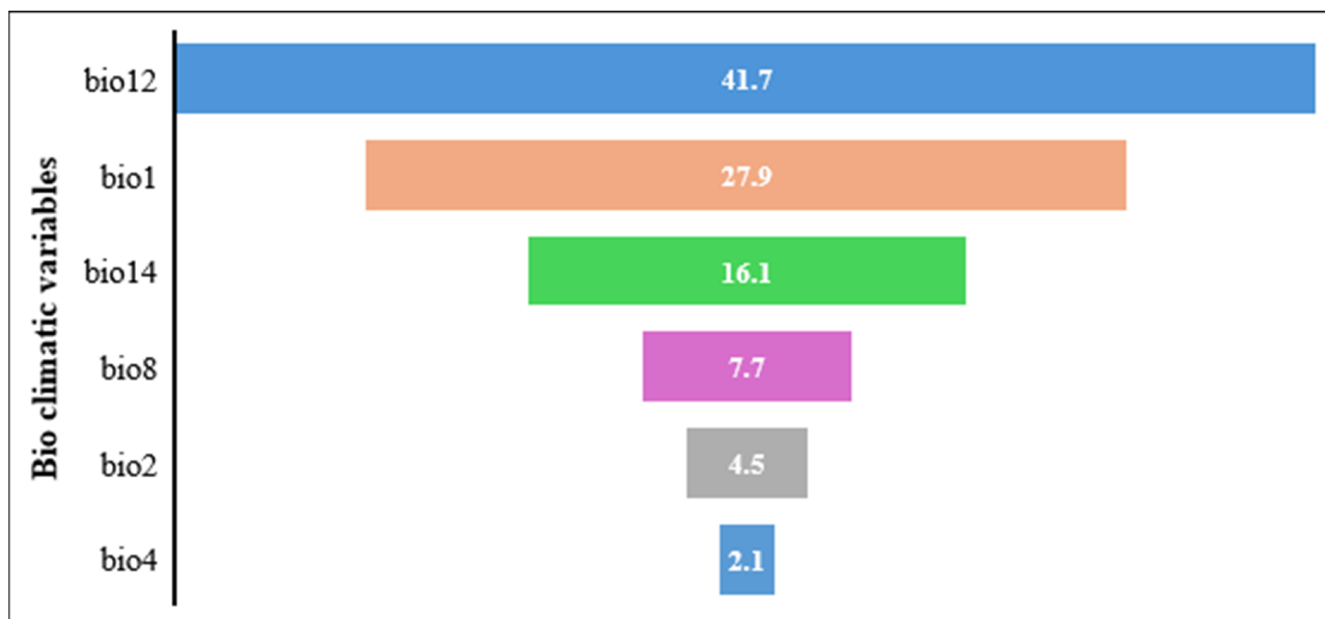


Figure 4. Percentage contribution of bioclimatic variables used for MaxEnt modelling.

The jackknife tests of variable relevance further validated that the annual precipitation seasonality (bio12), mean annual temperature (bio1), and precipitation during the driest month (bio14) had superior predictive abilities compared with the others. Their elevated training, test gain, and AUC values clearly demonstrate their substantial impact on the predictive accuracy of the model (Figures 5 and 6). The presence of *T. articulata* showed distinct trends based on mean annual temperature (bio1). It abruptly increases from 10 to 16 °C, peaks at 17 °C, and drops rapidly beyond 17.5 °C. Based on the mean diurnal range (bio2), the presence of *T. articulata* increased at 6 °C, peaked at 10 °C, and started declining at 13 °C. Furthermore, regions exhibiting moderate year-round temperature stability, where seasonal fluctuations substantially influence yearly temperature variance, have an increased probability of *T. articulata* occurrence (bio4). Areas where the mean temperature of the wettest quarter ranged between 5 and 13 °C exhibited a high presence of *T. articulata* (bio8). Similarly, regions characterized by significant differences between precipitation rates or comparatively high seasonal fluctuations in precipitation rates displayed increased probabilities of *T. articulata* presence (bio12). Areas where the precipitation rate of the driest month ranged between 0 and 10 mm displayed increased probabilities of *T. articulata* presence (bio14).

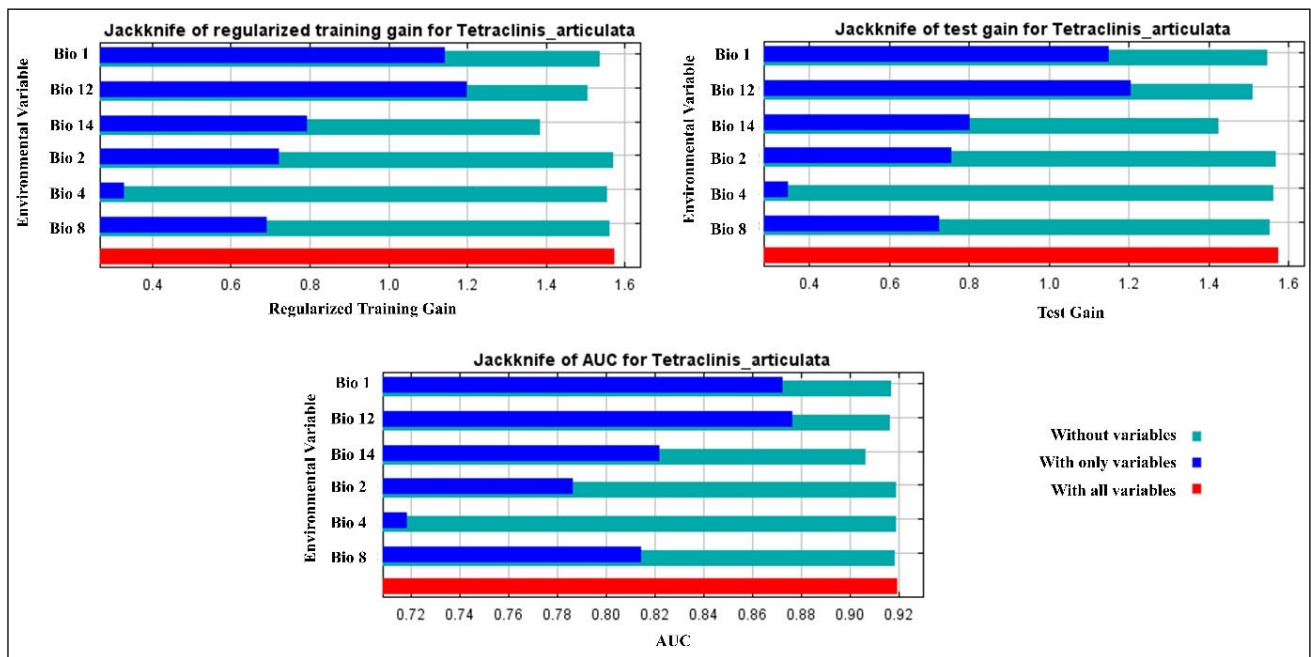


Figure 5. Relative importance of environmental variables based on the jackknife test. The figure represents the contribution of each variable to regularized training, test gain, and AUC in the *Tetraclinis articulata* model.

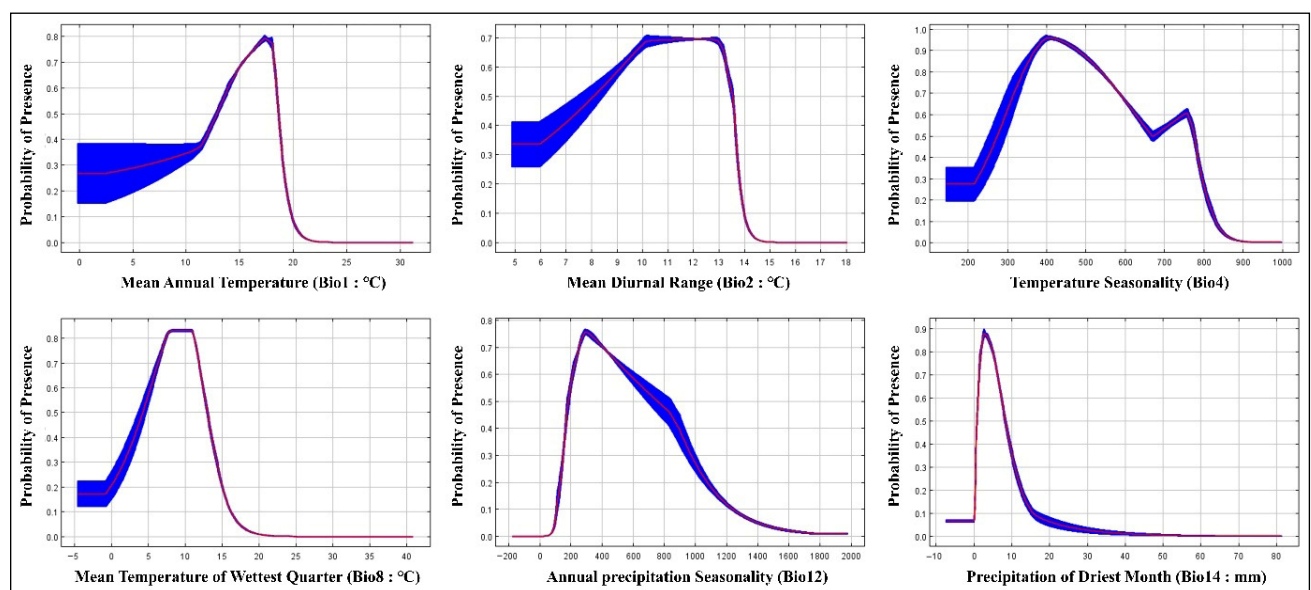


Figure 6. Response curves of predictors of *Tetraclinis articulata* in the MaxEnt model.

3.2. Current Suitable Habitats

Under present climatic circumstances, 22.02% (17.68 million km²) of the total land area of the Mediterranean areas under investigation might provide habitats conducive to the survival of *T. articulata* (Figures 7 and 8). Suitable conditions are predominantly found in the coastal regions, especially in Morocco, Algeria, and Tunisia. These locations display highly suitable environments owing to their Mediterranean climate, which is characterized by moderate precipitation and appealing temperatures. Coastal regions of these nations offer essential environmental conditions, including well-drained soil and regular humidity, which are vital for tree growth. In Algeria, the northern coastal zone has wide areas of high and moderate suitability, whereas the middle and southern parts

are deemed unsuitable because of the dry climate and insufficient precipitation. Tunisia's coastline zones also demonstrate favorable circumstances, with substantial sections rated as extremely appropriate, in contrast to the interior parts that are primarily unsuited. The Canary Islands, Cyprus, and Malta exhibit unique favorability patterns. The coastal areas of the Canary Islands are exceptionally conducive, indicating the island's consistent temperate environment. Cyprus has a significant prevalence in both suitable and extremely suitable regions, particularly in the central and southern sectors of the island. Despite its small size, Malta presents ideal conditions throughout, establishing it as a reliable habitat for *T. articulata*. Marginal areas were dispersed in the peripheries of suitable zones, signifying transitional regions in which climatic or soil conditions may restrict ideal growth. This distribution highlights the significance of coastal Mediterranean conditions in supporting *T. articulata*, whereas inland desert regions are predominantly unsuitable for their growth.

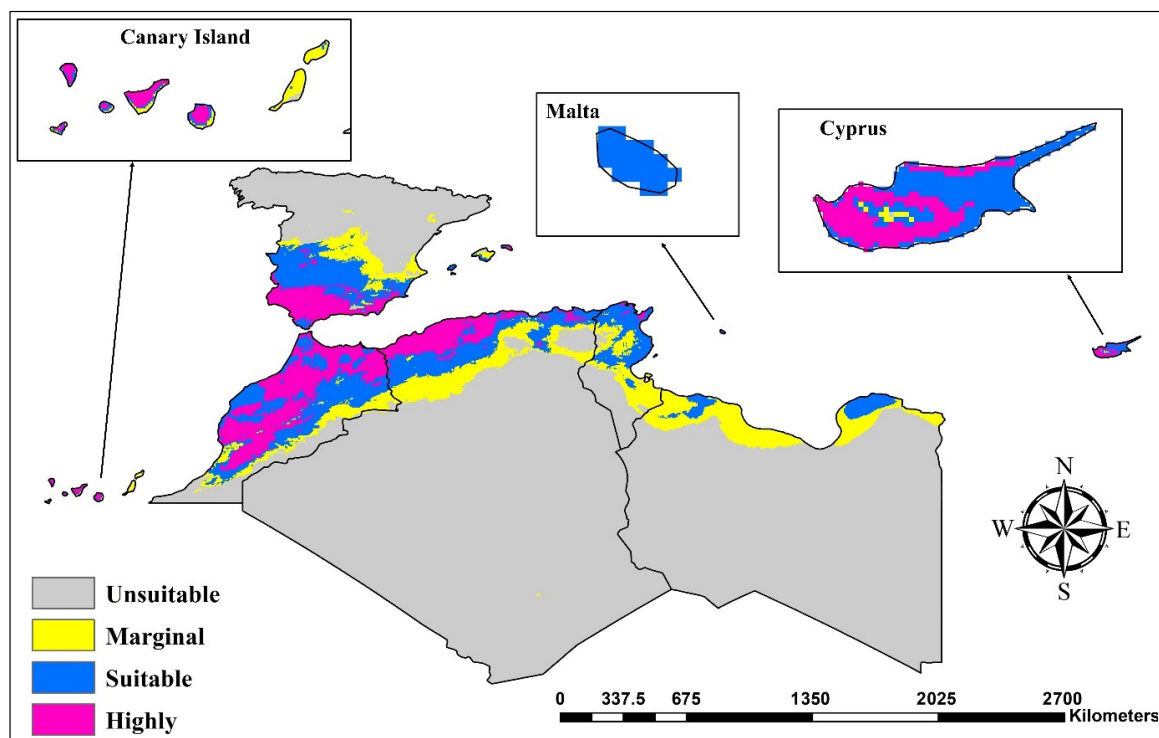


Figure 7. Potential distribution of *Tetraclinis articulata* under current climatic conditions. Habitat suitability is presented in four colors: pink, highly suitable; blue, suitable; yellow, marginally suitable; and gray, unsuitable.

3.3. Future Suitable Habitat Under Climate Change Scenarios

Habitat suitability under future climate change scenarios (SSP 1-2.6, SSP 2-4.5, SSP 3-7.0, and SSP 5-8.5) for the years 2040, 2060, 2080, and 2100 have been forecasted using MaxEnt (Figure 9). Each scenario forecasts possible alterations in habitat suitability predicted by climate change projections encompassing Northern Africa and the Mediterranean region. Throughout all the SSPs and timeframes, suitable and highly suitable locations were predominantly located in the coastal and northern regions. A distinct trend of habitat growth or shrinkage was observed based on the SSP. The suitable and highly suitable regions exhibited relative stability until 2100 in SSP 1-2.6, indicating few changes. Moderate emission scenarios indicated an expansion of highly suitable regions in SSP 2-4.5 and SSP 3-7.0, especially in the coastal region, accompanied by significant changes in the distribution pattern over time. High-emission scenarios demonstrated considerable growth in highly appropriate regions in SSP 5-8.5, indicating notable environmental advantages for the species, especially in the long-term (2100). In Algeria, the northern coastal regions

exhibited high suitability across all SSPs and periods. Under SSP 3-7.0 and SSP 5-8.5, there is a noticeable expansion of highly suitable inland areas by 2080 and 2100, respectively. The marginal areas in the central region remained largely unchanged, but coastal zones remained consistent hotspots for potential infestations. In Tunisia, the northern and eastern coastal areas show high concentrations of suitable and highly suitable habitats. Under all SSPs, the extent of the highly suitable zones increased over time, particularly under SSP 5-8.5. The inland regions remained largely marginal, but coastal areas were consistently vulnerable. In Morocco, coastal regions, particularly in the north, are highly suitable. Habitat suitability is projected to expand southward under SSP 3-7.0 and SSP 5-8.5. By 2100, significant inland shifts in suitable habitats were noted, indicating an increased risk over a larger area. In Libya, the northern coastal areas exhibit marginal to suitable habitats, with highly suitable areas limited. Highly suitable areas are projected to increase slightly along the coast, particularly under the SSP 5-8.5. However, much of the country's interior remains unsuitable. In Cyprus, the entire island showed significant suitability for habitat, with large portions categorized as highly suitable. Across all SSPs, Cyprus remained a consistent hotspot for infestation with no significant changes observed. High suitability was sustained for 2100, indicating persistent risk. In Malta, the island was highly suitable for the target species. Consistently, high suitability was maintained in all SSPs by 2100, suggesting an ongoing risk. In Spain and the Canary Islands, some islands show marginal suitability, whereas others have patches of high suitability. The marginal areas remained unchanged, but highly suitable zones persisted in specific locations, especially under higher emission scenarios. The highly suitable area coverage percentages under future climatic conditions for various scenarios, in comparison to the existing coverage (6.12%), are as follows: **SSP1–2.6**: 6.16% (2060) > 6.15% (2080) > 6.10% (2100) > 5.97% (2040); **SSP2–4.5**: 6.58%(2100) > 6.24%(2080) > 6.06%(2060) > 5.92%(2040); **SSP3–7.0**: 6.53%(2100) > 6.40%(2060) > 6.31%(2080) > 5.92%(2040); and **SSP5–8.5**: 6.70%(2100) > 6.63%(2080) > 5.97%(2040) > 5.95%(2060).

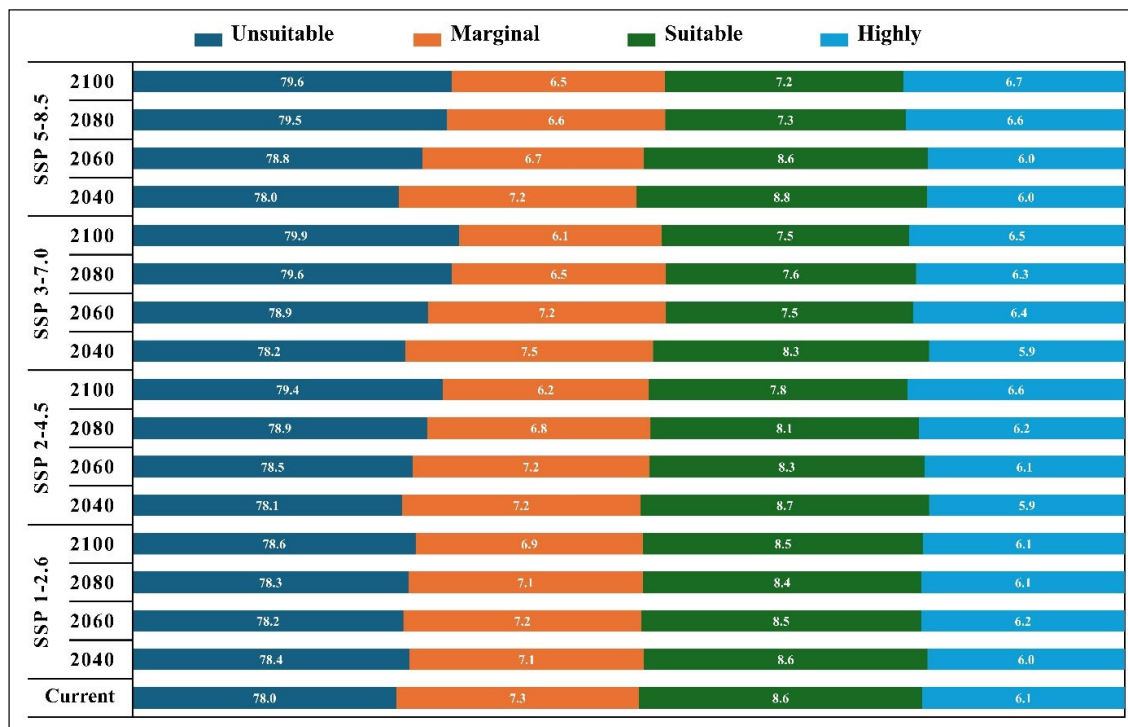


Figure 8. Predicted suitable area percentage for *Tetraclinis articulata* under present and future climatic conditions.

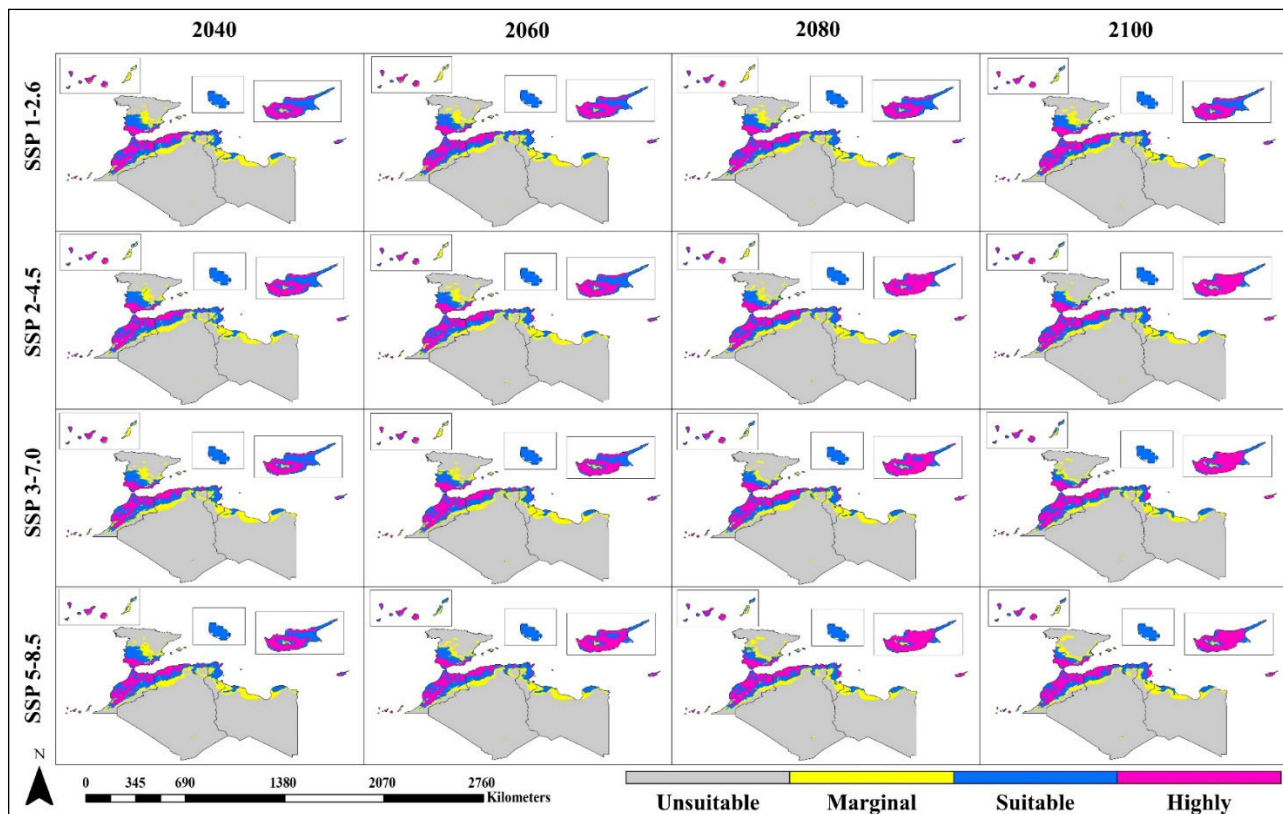


Figure 9. Potential distribution of *Tetraclinis articulata* under future climatic conditions for four climate change scenarios. Habitat suitability is presented in four colors: pink, highly suitable; blue, suitable; yellow, marginally suitable; and white, unsuitable.

3.4. Area-Wise Comparison Between Current and Future Projections

3.4.1. Algeria

Currently, the optimal areas are primarily restricted to the northern coastal zone, whereas the central and southern regions are classified as marginal or unsuitable. However, future predictions imply a progressive inland expansion of highly appropriate zones, especially under the higher-emission scenarios (SSP 3-7.0 and SSP 5-8.5). By 2080 and 2100, the range of these highly suitable habitats will expand, whereas marginal coastal zones will diminish and convert to suitable or highly suitable regions.

3.4.2. Tunisia

The northern and eastern coastal regions of Tunisia currently display a significant concentration of suitable and highly appropriate habitats; however, the middle and southern areas are predominantly unsuitable. Future projections, particularly under SSP 5-8.5, suggest a significant increase in the highly suitable areas along the coastline.

3.4.3. Morocco

Currently, Morocco's coastal and northern areas are deemed highly suitable with little inland extension. The central and southern regions of the nation are unsuitable. Future predictions suggest the progressive inland expansion of both suitable and highly suitable zones, particularly under high-emission scenarios. By 2100, the proliferation of highly suitable habitats will become increasingly evident, suggesting more available land for possible woodlands.

3.4.4. Libya

The current scenario in Libya indicates that suitable habitats are restricted to limited places along the northern coastline, whereas most inland regions are regarded as unsuitable. Future projections suggest a marginal increase in suitable areas near the coastline, particularly under elevated emissions scenarios. Notwithstanding this, inland areas remain predominantly inadequate, with a minimal increase in highly suitable regions.

3.4.5. Cyprus

Cyprus has a distinctive situation wherein the entire island is presently categorized as very appropriate, signifying considerable infestation danger. Future forecasts indicate that this high suitability remains consistent across all SSPs and timeframes, with no significant alterations in the geographical distribution. This consistency indicates that most Cyprus areas are extremely conducive to the establishment and development of *T. articulata*.

3.4.6. Malta

Like Cyprus, Malta is primarily categorized as highly suitable, with only slight variance in suitability levels. Future possibilities suggest that the island's high adaptability remains stable throughout all trajectories, highlighting its continual suitability for the expansion and development of *T. articulata*.

3.4.7. Spain and Canary Islands

The present situation in Spain and the Canary Islands indicates that several islands possess highly suitable environments that exhibit regional differences. Future forecasts suggest that these highly suited regions will either remain stable or show moderate expansion, particularly under elevated emissions scenarios. This indicates positive conditions of the Canary Islands and southwestern Spain for the development and expansion of *T. articulata*.

The area changes in the *T. articulata* suitability classes (Unsuitable, Marginal, Suitable, Highly suitable) under four climate change scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5) from the current period to 2100 are presented in Table 2. These data revealed substantial shifts in habitat suitability with increasing emissions. Under low-emission scenarios (SSP1-2.6), marginal declines were observed in highly suitable and suitable areas, while unsuitable areas expanded moderately. However, under high-emission scenarios (SSP3-7.0, SSP5-8.5), unsuitable areas increased significantly, particularly by 2100, with SSP5-8.5 showing a dramatic rise of 1.34 million km². The marginal and suitable areas declined steadily under higher emissions, indicating severe habitat degradation. Highly suitable areas exhibited mixed trends, with minor increases under SSP3-7.0, but significant reductions under SSP5-8.5. These projections emphasize the potential loss of optimal habitats for *T. articulata*, with higher emissions exacerbating the shift toward unsuitable conditions, posing a critical threat to the species' future distribution.

3.5. *Tetraclinis Articulata* Centroid Shift

The projected centroid shifts in suitable *T. articulata* habitats under different climate change scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5) by 2100 are presented in Table 3 and Figure 10. The current centroid is located at 1.394° N and 33.538° E, with notable shifts observed across all future scenarios. Under SSP1-2.6, the centroid shifted westward to −3.429° S, 33.588° E, with 536.32 km. Conversely, SSP2-4.5 predicted an eastward shift to 11.091° N, 32.501° E, spanning the longest distance of 1084.32 km. Under SSP3-7.0 and SSP5-8.5, the centroids shifted northwest, with coordinates of −1.947° S, 34.098° E (376.68 km) and −2.985° S, 34.707° E (503.96 km), respectively.

Table 2. Area change (Million km²) of *T. articulata* under different climate change scenarios.

	SSP1-2.6					SSP2-4.5				
	Current-2040	2040-2060	2060-2080	2080-2100	Current-2100	Current-2040	2040-2060	2060-2080	2080-2100	Current-2100
Unsuitable	0.31	−0.15	0.12	0.17	0.46	−0.33	0.26	0.35	0.38	1.12
Marginal	−0.19	0.09	−0.09	−0.17	−0.36	0.27	−0.04	−0.32	−0.42	−0.87
Suitable	0.00	−0.09	−0.03	0.03	−0.09	0.21	−0.33	−0.17	−0.23	−0.61
Highly Suitable	−0.12	0.15	−0.01	−0.04	−0.02	−0.15	0.11	0.14	0.27	0.37

	SSP3-7.0					SSP5-8.5				
	Current-2040	2040-2060	2060-2080	2080-2100	Current-2100	Current-2040	2040-2060	2060-2080	2080-2100	Current-2100
Unsuitable	−0.90	0.54	0.58	0.19	1.52	−1.48	0.59	0.59	0.11	1.34
Marginal	1.01	−0.23	−0.59	−0.29	−0.98	0.87	−0.41	−0.07	−0.11	−0.70
Suitable	0.43	−0.70	0.08	−0.07	−0.88	1.05	−0.16	−1.07	−0.05	−1.10
Highly Suitable	−0.53	0.39	−0.07	0.18	0.33	−0.45	−0.02	0.54	0.06	0.46

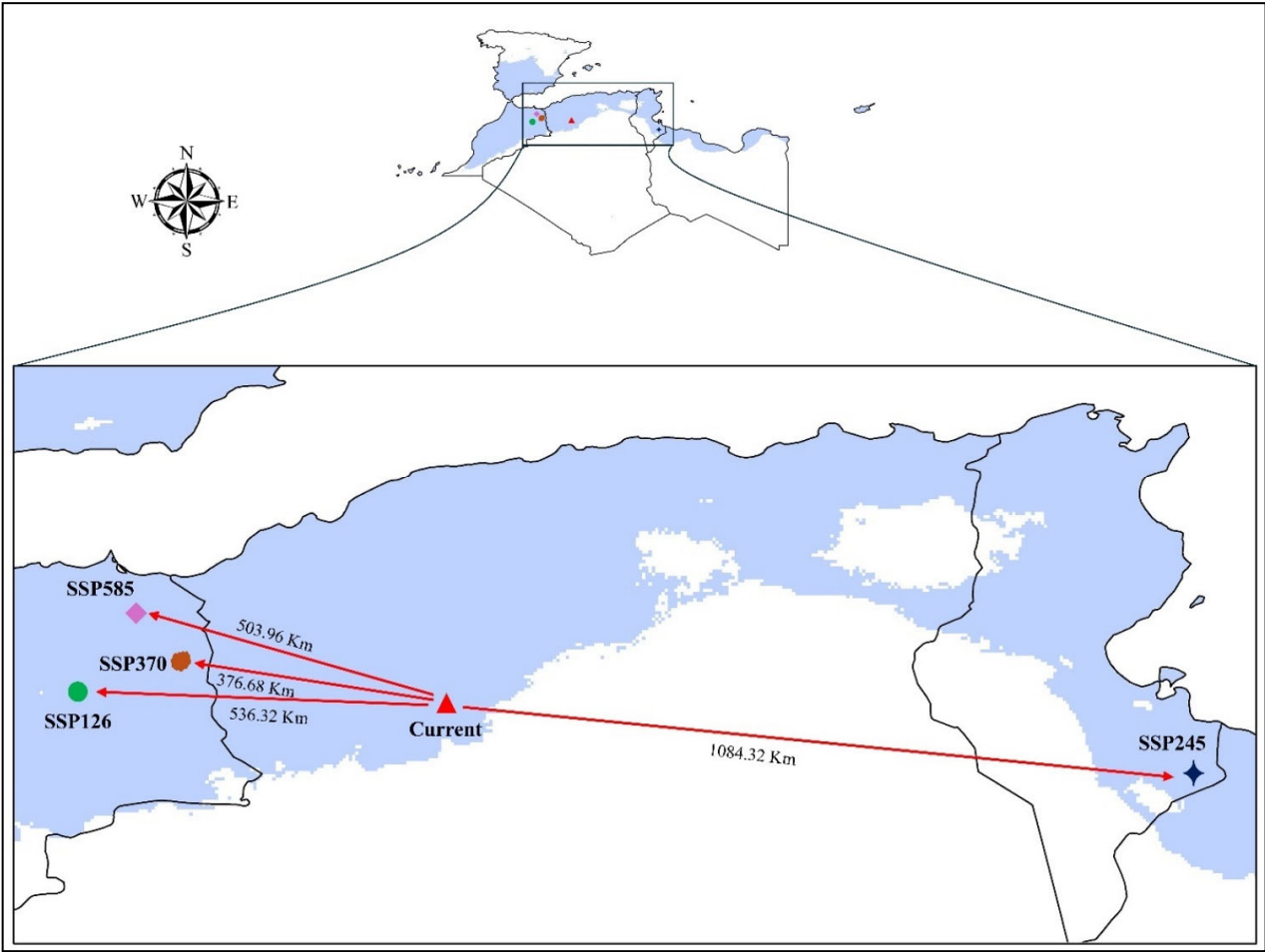


Figure 10. Centroid shift in *Tetraclinis articulata* under different climate change scenarios. For each scenario, we take an average point for 2100 as the centroid point of each year (2040, 2060, 2080, and 2100) for each scenario overlapping each other.

Table 3. Centroid shift in suitable *Tetraclinis articulata* habitats under different climate change scenarios.

Scenario	Latitude	Longitude	Region	Shift Direction
Current	1.394° N	33.538° E	Algeria	Northwest
SSP1-2.6–2100	−3.429° S	33.588° E	Morocco	West
SSP2-4.5–2100	11.091° N	32.501° E	Tunisa	East
SSP3-7.0–2100	−1.947° S	34.098° E	Morocco	Northwest
SSP5-8.5–2100	−2.985° S	34.707° E	Morocco	Northwest

These results highlight the potential redistribution of suitable habitats, driven by climate change. The eastward shift under SSP2-4.5 suggests a latitudinal expansion into northern areas, whereas the westward and northwestward shifts under SSP1-2.6, SSP3-7.0, and SSP5-8.5, indicate potential habitat contraction or displacement. The varying directions and distances emphasized the complex responses of *T. articulata* to climatic pressures, with high-emission scenarios leading to significant habitat instability. These findings underscore the urgent need for climate mitigation and conservation efforts to preserve suitable habitats of this species in the face of accelerating environmental changes.

4. Discussion

This study provides the first predicted potential habitat distribution map for a plant species (*T. articulata*) in the Mediterranean region. We conducted an initial investigation on the likely distribution range of *T. articulata* in Mediterranean regions under climate change scenarios using MaxEnt software, literature evidence, data sourced from GBIF, and an extensive field survey in these areas. The performance of the current MaxEnt model was validated to be satisfactory through pertinent screening of available occurrence records, optimization of bioclimatic variables, and adjustment of model parameters. The ROC curve, TSS, and omission rates (Figure 3) support these findings [20]. The results demonstrated a robust correlation between the performance of the MaxEnt model and modeled distributions of *T. articulata*. The predicted effectiveness of a model is influenced by species features, including geographical distribution and habitat location, as well as the nature of the model [40].

Suitable habitats for *T. articulata* are predominantly found across all countries and islands in the Mediterranean region, with the most extensive coverage in Morocco (−1.713° S, 34.128° E to −10.476° S, 28.472° E), Spain and the Canary Islands (−3.048° S, 40.091° E to −5.61° S, 36.021° E), Algeria (−1.631° S, 33.619° E to 8.266° N, 36.093° E), Tunisia (10.133° N, 37.211° E to 9.235° N, 33.934° E), Malta (14.337° N, 35.977° E to 14.542° N, 35.813° E), and Cyprus (34.559° N, 35.659° E to 34.399° N, 34.782° E) (Figure 7). Under future climate change scenarios, the current pattern of suitable distribution shifts slightly toward the Northern Hemisphere, with an increase of 0.46 million km² in the highly suitable area in SSP5-8.5, by the end of the century, compared to all other scenarios (Table 2, Figure 8). Climate change profoundly affects the distribution of *T. articulata*, as outlined by Monzón et al. [41] and Hacket-Pain et al. [42], who asserted that climate change is a global phenomenon that has severely impacted forest production along with the distribution and abundance of plant species.

Plants are particularly vulnerable to the effects of climate change, which has led to an increase in research aimed at forecasting plant responses to environmental changes [43]. Our investigation revealed that annual precipitation (bio12, 41.7%), mean annual temperature (bio1, 27.9%), precipitation during the driest month (bio14, 16.1%), and mean temperature of the wettest quarter (bio8, 7.7%) significantly affected the distribution of *T. articulata* (Figure 4). Rozas et al. [27] emphasized that the radial expansion of *T. articulata* is significantly associated with precipitation, with water availability in the preceding winter

being a crucial factor in growth. In lowland locations, growth was affected by rainfall up to 33 months earlier, whereas in mountainous areas, this influence persisted for 26 months. These data underscore the significant reliance of *T. articulata* on precipitation, demonstrating its adaptation to fluctuating water availability and its tolerance to arid conditions. Forecast temperature increases and precipitation decreases of up to 30% in certain areas within the Mediterranean basin are predicted to profoundly affect tree biology [44]. Among the climatic variables, precipitation is particularly significant, as it predominantly dictates the distribution of diverse tree species in the Mediterranean region [45,46].

This study found annual precipitation (bio12) to be a key factor influencing the potential habitat range of *T. articulata*, corroborating the observations of Salvà-Catariu et al. [47], who noted a comparable pattern for *Juniperus phoenicea*. Seasonal summer dryness has traditionally resulted in increased mortality rates in juniper populations in several Mediterranean [47,48]. Castaño-Santamaría et al. [43] identified temperature-related factors, specifically isothermality, annual mean diurnal range, temperature seasonality, and mean temperature during the wettest quarter, as the predominant variables affecting beech species in Northwest Spain. Reduced precipitation during spring and summer is anticipated to exacerbate aridity [49], perhaps leading to elevated tree mortality rates in the Mediterranean region [50].

T. articulata, a species with restricted dispersion capabilities, has difficulty adjusting to climate change, and this is exacerbated by habitat fragmentation [51,52]. These findings indicate that climate change may variably affect *T. articulata* based on the prevailing scenario, making this species a crucial indicator for assessing climate impacts on biodiversity in arid Mediterranean habitats. Owing to the effects of climate change in the Mediterranean area, both in situ and ex situ conservation strategies are strongly recommended [18].

Our CMIP6 forecasts show that the area that is favorable for *Tetraclinis articulata* to thrive in would shrink across the whole basin. In Spain, Malta, and portions of North Africa, the loss of about 8% of the area will make already patchy stands more likely to break up. The species is worldwide Least Concern, but the European subpopulations are small and very vulnerable. This means that even minor percentage losses can put local persistence and genetic representation at risk, especially in areas with a lot of fire and grazing pressure. Targeted activities include protecting existing nuclei, strengthening connections and corridors along expected shift vectors, and putting aided regeneration and ex situ seed banking at the top of the list to protect against random loss [53].

T. articulata prefers rocky, shallow, often calcareous substrates (SE Spain, Malta) and a wider mix of acidic to alkaline soils in North Africa, usually stony soils with low water-holding capacity that limit competitors but match the species' xeric adaptations [54]. When choosing reinforcing or restoration locations, management should consider climate appropriateness and edaphic filters (shallow Leptosol-like profiles, high coarse fragments/fissures). With managed browsing and post-fire erosion mitigation, pilot or enrichment plants are possible on well-drained slopes and limestone formations.

In fragile, isolated European stands, an ~8% reduction in acceptable climate space can lead to microrefugia loss or decreased recruitment windows, increasing local extinction risk despite resprouting capacity [53]. Similar decreases might diminish wood/resin yields and tighten harvest limitations in North Africa, affecting artisan income and rural employment, emphasizing the need for sustainable harvest, controlled coppice cycles, and livelihood diversification.

MaxEnt, a presence-only SDM, infers probable climatic suitability—not occupancy—and is vulnerable to sampling bias, background selection, and threshold selections. Omitting essential processes (deforestation rate, fire, land use, competition, dispersal, soil features) can decrease transferability under unfamiliar climates [55]. We used bio climatic variables

and inherited GCM/SSP uncertainty. We did not explicitly describe demography, genetics, or dispersal lags. These cautions suggest scenario-robust interpretation. We propose integrating demography/dispersal with SDMs to translate suitability into persistence, pairing models with genetic structure/provenance trials to guide seed sourcing and assisted gene flow, adding fire regime, grazing pressure, land use, and soil layers at operational scales to refine planting maps, and evaluating bias-correction and ensemble modelling to bracket structural uncertainty.

5. Conclusions

This study presents the inaugural Mediterranean-wide, CMIP6-based, multi-horizon projection of *Tetraclinis articulata* utilising a MaxEnt + GIS framework, quantifying the influence of climatic factors—particularly precipitation seasonality, mean annual temperature, and driest-month precipitation—on current suitability and prospective changes. We demonstrate a gradual reduction in climatically suitable areas from around 8.6% currently to 8.4% (SSP1-2.6) and 8.3/7.5/7.2% (SSP2-4.5/SSP3-7.0/SSP5-8.5) by the end of the century, accompanied by an increase in unsuitable zones (to around 78.6%–79.9%). We also see directional centroid movements (west–northwest for SSP1-2.6/SSP3-7.0/SSP5-8.5; eastward for SSP2-4.5), which means that key habitats are changing shape and the likelihood of fragmentation is growing.

Our analysis goes beyond just summarizing declines. It (i) finds the main climatic factors that affect *T. articulata* at the basin level, (ii) provides scenario-specific shift vectors to help with corridor design and cross-border planning, and (iii) finds relative refugia and emerging suitability that can help with assisted regeneration, seed sourcing, and ex situ conservation while putting less emphasis on edges that are very vulnerable.

We suggest the following to turn climate suitability into persistence outcomes: (1) combining SDMs with demography/dispersal (integral projection or meta-population models); (2) using genetic structure and provenance trials to help gene flow; (3) adding fire regime, land-use change, and soil constraints to make realized habitat more accurate; (4) testing model ensembles and threshold sensitivity to lower structural uncertainty; and (5) evaluating management interventions (e.g., drought-hardening, mixed-species plantings) in priority refugia and possible corridors. These efforts will make climate-smart strategies stronger so that the species' genetic diversity and ecological services can stay strong across Mediterranean regions.

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