Assessing the Future of Taurus Cedar (*Cedrus libani*) as a High-Value Timber Species under Climate Uncertainty

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Taurus cedar is a valuable tree species that is widely used in industrial forestry due to its high-quality, durable, and workable wood, making it preferred in furniture, construction, and wood technology sectors. Recognizing its economic and ecological importance, afforestation efforts have been carried out by the Isparta Regional Directorate of Forestry since 2009 to expand its distribution. However, climate change poses a severe threat to sustainable forestry and forest industries worldwide, with extreme events including heatwaves, irregular precipitation, water stress, and floods. This study aimed to model and map the current and future (to year 2100) distribution of Taurus cedar in the Isparta region under various climate scenarios using the MaxEnt. The model performance showed high prediction accuracy (AUC values) and the variables affecting the distribution were precipitation seasonality, elevation, precipitation of the driest quarter and landform index. Simulation results indicated that the combined percentage of suitable and highly suitable distributions currently stands at approximately 70% but is projected to decline by about 20% under the SSP 8.5 scenario. Comparing current and future projections revealed an estimated 71.5% reduction in Taurus cedar distribution. These findings stress the urgent need for conservation and adaptation measures to protect Taurus cedar from climate change and ensure its long-term survival.

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INTRODUCTION

Cedrus libani, commonly known as the Taurus cedar, is a prominent coniferous species native to the Mediterranean region. The Taurus cedar can reach heights ranging from 30 to 40 m and is characterized by its distinctive pyramid-like crown. It is renowned for its durability and resistance to decay in terms of wood structure. This has made the Taurus cedar a symbol of strength and durability. It is often used in the construction of temples, ships, and royal structures, as well as in timber trade activities (Özçelik *et al.* 2011; Abdrabou *et al.* 2020). Therefore, this species has been characterized as a highly valuable resource among cultures in the Mediterranean world from past to present (Rich *et al.* 2016; Zgheib *et al.* 2020).

From an ecological perspective, Taurus cedar thrives under a variety of bioclimatic conditions, typically at altitudes of 600 to 2,150 m with mean annual precipitation ranging from 600 to 1,500 mm (Di Matteo *et al.* 2012; Nassif *et al.* 2024). This adaptability allows Taurus cedar forests to contribute to regional biodiversity and fulfil crucial ecological roles, such as watershed management and soil protection (Sattout and Caligari 2011; Cheddadi and Khater 2022). At the same time, because of its medicinal properties attributed to the essential oils obtained from Taurus cedar leaves (Saab *et al.* 2018), it has a wide range of uses such as pharmacological research and natural therapy.

Considering this information, Taurus cedar is a tree species that has a high economic value in wood production, is used extensively in industrial forestry applications, and is preferred in the fields of furniture, building materials, and wood technologies due to its high quality, durability, and workability (Aertsen *et al.* 2010). Despite having many uses, Taurus cedar is sensitive to possible future global climate change (extreme drought) on its distribution (Hajar *et al.* 2010; López-Tirado *et al.* 2021). Therefore, today Taurus cedar symbolizes both a natural heritage and a challenge to prevent biodiversity loss and climate change. However, a study has revealed that Taurus cedar distribution is decreasing due to reasons such as anthropogenic pressures and habitat fragmentation (Bassil *et al.* 2018). Taurus cedar is listed as a vulnerable species by international conservation organizations and is at a critical point for natural ecosystems for conservation strategies aimed at preserving ecological integrity and promoting sustainable development within and outside its natural habitat (Sattout and Caligari 2011; Cheddadi and Khater 2022).

Species Distribution Models (SDMs) have become indispensable analytical tools for the protection and sustainable management of natural ecosystems. These models work by integrating species observation data with environmental and ecological variables to predict the current and potential distributions of species (Srivastava *et al.* 2019; Franklin 2023). Through SDMs, habitat preferences of species, distribution changes they will exhibit under different climate scenarios, and the possible effects of human-induced environmental changes on biodiversity can be scientifically assessed (Mert and Acarer 2021; Acarer 2024a; Acarer and Mert 2024; Kalayci Kadak *et al.* 2024; Kaya *et al.* 2025). Therefore, SDMs are important for identifying areas requiring urgent intervention and guiding strategic practices such as habitat restoration and sustainable resource management (Rathore and Sharma 2023). In addition, the integration of SDMs into decision-making processes allows ecosystems and habitats to be prioritized by considering both their biodiversity value and threat levels, thus increasing the effectiveness of conservation strategies and the efficiency of resource use (Frans *et al.* 2022).

MaxEnt, short for Maximum Entropy, is a method that works only with species-based data and is widely adopted in the field of Ecological Niche Modelling (ENM). One of the prominent features of MaxEnt is its flexibility to work with different types of environmental variables (continuous, categorical, or binary). This versatility increases its capacity to model complex habitat preferences and strengthens its applicability in the context of future simulation (Phillips and Dudik 2008; Elith *et al.* 2011; Acarer 2024c). It also shows that Maxent offers higher prediction accuracy compared to other typical distribution modelling algorithms. Especially in limited or skewed sampling conditions, the Maxent method comes to the fore due to its flexible structure and algorithmic robustness.

This study aimed to determine the current and future (year 2100) distribution of Taurus cedar, which has extraordinary properties in terms of both biodiversity and wood raw material in the Mediterranean region from past to present, within the framework of climate change scenarios. For this purpose, current and future scenarios were obtained from the WorldClim database, which supports a deeper understanding of the interactions of species with their environment and efforts to protect biodiversity during rapid climate change. In the study, SSP 2.6, SSP 4.5, and SSP 8.5 scenarios of the high-resolution climate HadGEM3-GC31-LL model for the year 2100 were preferred. As a result, this study aimed to present management plans for the conservation of Taurus cedar, which is facing the challenges of climate change and biodiversity loss. These plans will help shape the necessity of a multi-faceted (sustainable, economic, and ecological) conservation approach by considering climate change on a global scale.

EXPERIMENTAL

Study Area Features and Data Set

Cedrus libani has the world's widest and northernmost distribution in Türkiye (Boydak 2003), except for a few woodlands of Taurus cedar in Lebanon and Syria (Fady *et al.* 2003; Lopez-Tirado *et al.* 2021). In Türkiye, it is generally distributed naturally in the western, central, and eastern Taurus Mountains of Anatolia, where the Mediterranean climate prevails. The distribution of the Taurus cedar in Türkiye is more specifically in the Mediterranean Region, starting from Köyceğiz and Fethiye in the west and extending to Maraş in the east, in an area with very variable ecological characteristics. The northern border of its distribution area reaches the Sultan Mountains and the Naltaş range of the Saimbeyli Plantation and the Demiroluk location in the Alaylı Mountains. In addition, there are small stands and groups of Taurus cedar in the Erbaa and Niksar districts and their surroundings in the north of Tokat province (Boydak 2003; Karatepe *et al.* 2005; Özkan and Kantarcı 2008). Taurus cedar contributes significantly to the biodiversity and forest cover in the regions where it is distributed in Türkiye. Therefore, Taurus cedar has been defined as a keystone species that provides habitat and livelihood for many fauna in Mediterranean ecosystems while also absorbing significant amounts of carbon dioxide (Evrendilek *et al.* 2006).

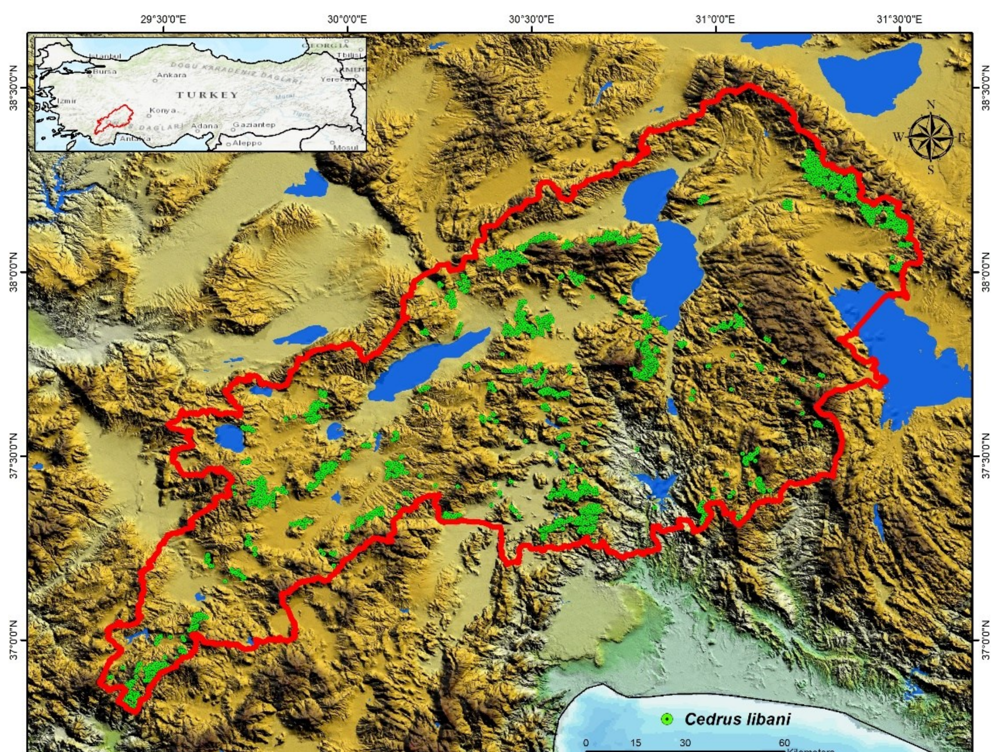

Fig. 1. Location map of the Isparta Regional Directorate of Forest and Taurus cedar presence

Taurus cedar is ecologically vital, and a primary tree species distributed in 402,319 ha in Türkiye. According to the 2022 General Forestry Directorate data (GDF 2025), its distribution ranks 8th in Türkiye with a value of 1.75% when compared to the primary forest tree species distribution in Türkiye (22,933,000). This value is quite low at 2% in the General Forestry Directorate's data for 2009. Therefore, afforestation works carried out by the forestry general directorate in some regions were carried out with Black pine first, and in the following years, with Taurus cedar. One of the afforestation works carried out intensively in large areas is at the borders of the Isparta Regional Forestry Directorate. Based on the management plans covering the years 1997 to 2017 belonging to the Isparta Regional Forest Directorate, which constitutes the current paper's study area, the areas where the cedar species is found and the small areas where the species is found have been determined. In this context, the data for 2,235 cedar species within the borders (red color) of the Isparta Regional Forest Directorate are shown in green on the map (Fig. 1).

Production of Digital Maps

The preservation of biodiversity in forest ecosystems and the effective visualization of ecological data largely depend on the creation of precise and reliable digital base maps. Digital mapping technologies have developed rapidly in recent years and have frequently taken their place in conservation studies by providing detailed representations of biodiversity and habitat distributions. Therefore, high-resolution digital base maps are important, as they support conservation targeting and help understand environmental consequences at a detailed level (Thomas *et al.* 2003). Digital Elevation Models (DEM) with a resolution of 30 arc seconds (\~1 km) are mostly preferred in species distribution models covering large areas. However, the use of data with higher spatial resolution (*e.g.*, 1 arc second \~30 m) allows for more precise and detailed analysis of environmental and climatic variables, thus significantly increasing the accuracy and reliability of model outputs (Acarer 2024b; Acarer and Mert 2024). Therefore, in this study, the high-resolution Digital Elevation Model that forms the basis of the analyses was obtained from the official website of the United States Geological Survey (https://www.usgs.gov) and converted to a format with a spatial resolution of 1 arc second \~30 m. The relevant DEM data were cut in accordance with the boundaries of the study area, converted with an appropriate projection system, and integrated into the analysis environment.

Using this base map, digital maps were produced by ArcGIS software based on various environmental variables that are predicted to shape the distribution of Taurus cedar species. These produced base maps have both categorical and continuous data structures. For example, while the slope index base map of the study area has a continuous data structure, the landform surface shape index (ayşi) base map indicates the following types: 1 = canyons, deeply incised streams; 2 = midslope drainages, shallow valleys; 3 = upland drainages, headwaters; 4 = u-shaped valleys; 5 = plains; 6 = open slopes; 7 = upper slopes, mesas; 8 = local ridges, hills in valleys; 9 = midslope ridges, small hills in plains; and 10 = mountain tops, high ridges. In addition to environmental variables, vector data including structural factors related to forestry were also included in the study. In this context, data, such as field conditions, cover closure rates, age class distributions, forest area sizes, and land cover classifications, were obtained from forest management plans prepared between 1987 and 2017. In addition, the 1/100,000 scale bedrock (lithological) map provided by the General Directorate of Mineral Research and Exploration was also evaluated and included in the modelling. All these vector data were converted to raster data structure in the ArcGIS environment. The "*polygon to raster*" tool was used for this process. Thus, all environmental data were made ready for analysis in raster format suitable for use in species distribution modelling.

After generating environmental variables for the distribution of Taurus cedar, climate data were accessed from the WorldClim website (https://www.worldclim.org/), which provides high-resolution climate data suitable for various ecological and biogeographic studies. WorldClim offers two major versions: Version 1 and Version 2, the latter of which includes significant improvements, such as higher resolution (up to 30 arc s) and more variables, and now covers 19 bioclimatic variables that are critical for ecological modelling (Cerasoli *et al.* 2022). These bioclimatic variables, representing aspects such as temperature and precipitation trends, can be downloaded directly from the WorldClim website in raster format. Data are often available for multiple time periods and can be used in a variety of formats that meet the needs of different research applications, including species distribution modelling and environmental impact assessments. For climate scenarios, such as those generated by the Hadley Center Global Environmental Model (HadGEM) within the WorldClim climate models, users can often access them from repositories hosting climate projections, including those used in the Coupled Model Intercomparison Project (CMIP) (Jones *et al.* 2011; Dike *et al.* 2015). HadGEM models provide detailed projections and can be interpolated to fit specific geographic datasets, including those from WorldClim. The use of HadGEM outputs is frequently emphasized in climate impact studies, where projections of temperature increases and precipitation changes are evaluated for various regions. As a result, both past and present data are crucial for comprehensive analysis of ecological and biological events under changing climate conditions. HadGEM climate scenarios enable valuable insights from future climate datasets. WorldClim data includes different scenarios SSP 2.6, SSP 4.5, SSP 7.0, and SSP 8.5 for 20-year periods (2040-2060-2080-2100). However, the HadGEM climate model includes only SSP 2.6, SSP 4.5, and SSP 8.5 climate scenarios. In this context, to reveal the effects of climate change on the Taurus cedar forests within the borders of Isparta Regional Directorate of Forestry, different climate envelope models (SSP 2.6, SSP 4.5, and SSP 8.5) were employed for simulations up to the year 2100. As a result, in this study, a total of 57 numerical bases, 38 environmental and 19 climate variables, were produced and the modelling and simulation phase started to reveal the effects of global climate change on the Taurus cedar species.

Assessment and Mapping of the Current and Future Distribution of Taurus Cedar

The Maximum Entropy (MaxEnt) method has become a cornerstone in the field of Species Distribution Modelling (SDM) since its development in 2006, and it has attracted significant attention (Elith *et al.* 2006). This approach is particularly valuable due to its ability to estimate the potential distribution of species using only occurrence data, which is often limited and uneven. The theoretical basis of MaxEnt lies in statistical mechanics, where it estimates the probability distribution of the maximum occurrence of a species, given the constraints imposed by known environmental variables at the locations where the species has been recorded (Elith and Graham 2009). This makes it particularly useful for ecological studies where data availability is difficult. MaxEnt operates under the maximum entropy principle, where it attempts to find the distribution that best represents the known data without making unwarranted assumptions about the underlying system. The model quantifies species-environment interactions by relating species occurrence to various environmental variables. It effectively accommodates a variety of data types, including continuous and categorical data. It can perform well even when the dataset consists of a small number of events, which is often the case in ecological research. This power is especially important in applications where data irregularity or sparsity is common, such as in the assessment of endangered species or in less scientifically explored regions. MaxEnt's versatility and high prediction accuracy have made it a preferred tool in a variety of fields, from conservation biology to climate change impact studies (Phillips *et al.* 2006; Gül 2025; Tekeş *et al.* 2025).

However, it is important to recognize that MaxEnt is not without its limitations. Relying solely on presence data could introduce bias, especially if the spatial data collected represent certain habitats unequally or disproportionately (Townsend Peterson *et al.* 2007). Therefore, the accuracy of the MaxEnt method needs to be checked. In this context, care should be taken to ensure that there are no significant deviations in the consistency graph of the main model. Another check method is to evaluate the accuracy of MaxEnt models using the Area Under the Curve (AUC) metric, which is often derived from Receiver Operating Characteristic (ROC) analysis. This provides insights into the capacity of the model to discriminate between suitable and unsuitable habitats for the target species (Phillips *et al.* 2006). Furthermore, cross-validation methods, such as Jackknife, are crucial to assess model robustness and reduce potential overfitting in MaxEnt models by evaluating performance across different data subsets (Elith *et al.* 2011). Jackknife plots show the contribution of each predictor variable to the predictive capacity of the model and provide insights into which environmental factors are crucial for habitat suitability of the species.

RESULTS AND DISCUSSION

In this study, to model changes in the future natural distribution areas of Taurus cedar with climate change, the MaxEnt algorithm was implemented employing the *cross-validation* replication strategy, with ten independent runs and 10% of the occurrence dataset reserved for model validation. The model was trained using 2,012 occurrence records, while 223 records were used for testing. The modelling process was conducted over 500 iterations, and the final prediction was obtained by averaging the outputs from ten replicate runs. In total, 48 predictor layers were utilized, including 29 environmental variable parameters and 19 bioclimatic variables from the WorldClim database, all pertaining to the Isparta Regional Directorate of Forestry. Prior to model execution, these spatial datasets were converted into ASCII format to ensure compatibility with the MaxEnt software. The modelling stage commenced with the prepared predictor layers and the present records of Taurus cedar. During the process, 47 alternative models were generated to represent the Taurus cedar current potential distribution. Variables exhibiting minimal influence – determined by their low permutation importance and contribution percentage – were progressively excluded. This iterative reduction continued until only two influential predictors remained. The optimal model was selected according to the AUC metrics, thereby ensuring stability in the omission curves and maintaining high prediction accuracy. The omission graph for the final model showed no notable deviations, indicating consistent and reliable predictions of the current potential distribution of Taurus cedar. Analysis of the modelling outcomes for the current potential distribution of Taurus cedar revealed that the omission curve exhibited no notable anomalies or inconsistencies (Fig. 2a). Among the generated models, the one yielding an AUC value of 0.832 for the training dataset and

0.824 for the testing dataset was identified as optimal (Fig. 2b). According to the performance classification proposed by Swets (1988), these values place the model within the “good” predictive accuracy category. López-Tirado *et al.* (2021) conducted an ecological niche modeling study assessing the impact of climate change on the potential distribution of *Cedrus libani*, finding a mean MaxEnt AUC of 0.64. This value is in the category of a very fair model. According to Swets (1988), AUC > 0.90 = excellent; 0.90–0.81 = good; 0.80–0.71 = fair; 0.70–0.61 = poor; and AUC < 0.60 = invalid. Furthermore, the mean AUC across all replicates was calculated as 0.832 with a standard deviation of 0.001, providing strong evidence for the model’s robustness and reliability.

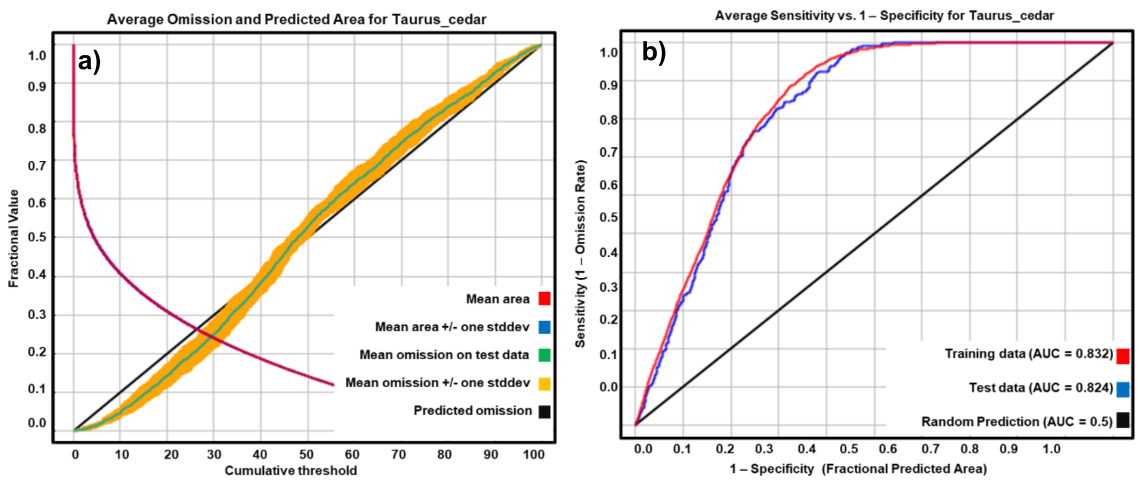

Fig. 2. Current potential distribution model of Taurus cedar: a) mean omission graph, and b) Training data set and test data set AUC graph

The high AUC values and low standard deviation obtained from both training and test data sets in shaping the current potential distribution of Taurus cedar indicate that the model had a strong predictive performance. This performance stands out as bioclimatic factors that directly or indirectly reflects the ecological tolerance ranges and habitat preferences of Taurus cedar. To increase the accuracy and validity of the model, Pearson correlation analysis was performed among 19 WorldClim bioclimatic variables. The analysis revealed a high degree of correlation between some variable pairs. To minimize the problem of multicollinearity and to prevent variable overloading in the model, factor analysis was applied to determine the variables with the highest ecological significance among the highly correlated variables. The factor analysis findings revealed that the most important variables affecting the potential distribution of Taurus cedar were consistent with the variables identified in the MaxEnt model outputs. This methodological approach supported the reliability of both the statistical analyses and the model variable contribution results. The results of the Jackknife test further supported these findings. The most influential environmental and climatic variables that contributed the highest amount of unique information when used independently of other variables were precipitation seasonality (coefficient of variation) (bio15), elevation (ykselti), precipitation of the driest quarter (bio17), and landform surface shape index (aysi). These results clearly demonstrate the sensitivity of the potential distribution areas of Taurus cedar to climatic and topographic conditions and suggest that similar trends can be predicted in future distribution projections of the species. The results of the Jackknife test further supported these findings (Fig. 3).

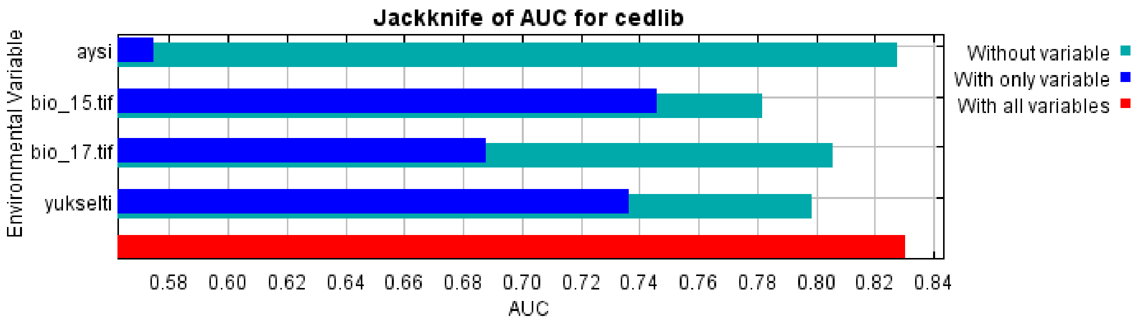

Fig. 3. Jackknife graph of current distribution model of Taurus cedar

Modeling the current potential distribution of the Taurus cedar (*Cedrus libani*) within the boundaries of the Isparta Regional Directorate of Forestry and examining the marginal response curves of environmental and climatic variables affecting this distribution are crucial for understanding the species' ecological requirements and habitat preferences. Marginal response curves visualize how each independent variable affects the model's predictive performance and probability values, holding all other variables constant. This allows for a clearer understanding of the relative importance of each factor in shaping the species' distribution. Ideally, the species-environment relationships revealed by the marginal response curves should be consistent with current distribution patterns observed in the field.

The analysis identified the precipitation seasonality (coefficient of variation) (bio15) variable as a significant determinant of the habitat suitability of the Taurus cedar. In this context, it has been determined that the distribution of Taurus cedar is high in areas where the precipitation seasonality variable is between 45 to 65 mm within the borders of the Isparta Regional Directorate of Forestry (Fig. 4a). This variable represents the variability in rainfall during the year (the level of fluctuation in the seasonal rainfall regime) and directly influences the species' water access dynamics and stress tolerance. High seasonality, particularly during dry summers, can lead to reduced soil moisture, reducing young seedling survival. Conversely, low seasonality can increase the species' growth and development potential by providing a more stable water supply. Therefore, the high contribution of the bio15 variable in the model reflects the climatic sensitivity of Taurus cedar and its dependence on the water cycle. In this context, the growth rate and general health status of the Taurus cedar are the factors that directly affect the important morphological and physiological characteristics of the Taurus cedar, such as root development and water uptake (Karataş and Özkan 2017; Bayar and Deligöz 2019; Güner *et al.* 2020).

According to the elevation, which is the second most important variable contributing to the model, the distribution of Taurus cedar is important in terms of spreading in areas with a wide altitude difference between 1,000 m and 2,000 m (Fig. 4b). In this context, it is stated that the distribution of the Taurus cedar, a coniferous species characteristic of Eastern Mediterranean Mountain ecosystems, depends largely on the interaction of topographic and climatic factors. Among these factors, elevation plays a critical role in determining the species' ecological niche (Quezel 1974; Boydak 2003). Elevation shapes the suitability of Taurus cedar habitats by directly affecting not only the temperature and precipitation regime, but also soil formation, moisture balance, and sunshine duration (Çetinkaya 2025). It is generally stated that the natural distribution of

Taurus cedar is concentrated mostly between 1,000 and 2,000 m. Quezel (1974) and Boydak (2003) state that this elevation range provides both the species' optimum temperature requirements and adequate moisture conditions. At lower elevations, increased summer temperatures and water stress limit sapling growth, while at higher elevations, low temperatures, and a short growing season reduce the species' competitiveness (Primicia *et al.* 2015). It is predicted that the lower range of the Taurus cedar may shift upwards and its upper range may expand to 2,100 to 2,200 m under the influence of climate change (Öztürk *et al.* 2010). In this context, the optimum range of 1,000 to 2,000 m revealed by the current study, while valid for current climatic conditions, may vary in future projections. Therefore, detailed examination of elevation-dependent microclimatic conditions is critical for the long-term conservation of the species.

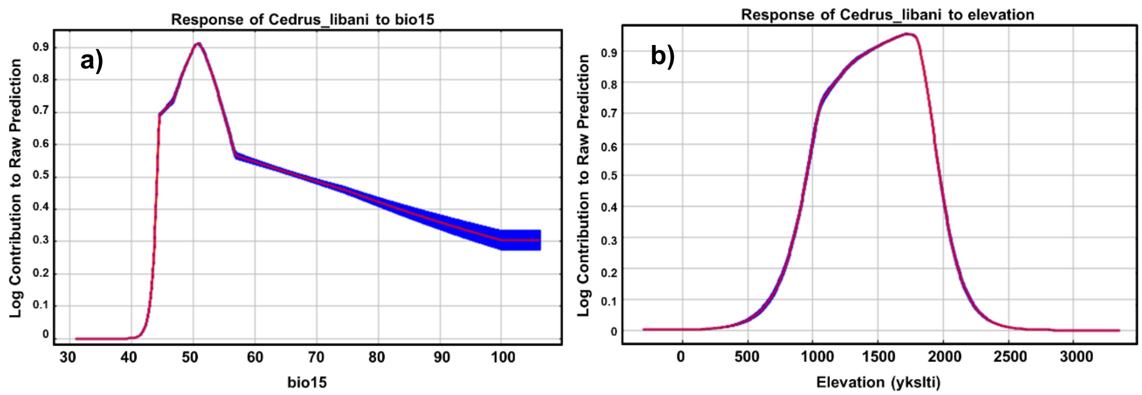

Fig. 4. Taurus cedar contributing to current potential model: a) precipitation seasonality (bio15), and b) elevation (ykslti) graph

The Precipitation of driest quarter (bio17) variable plays an important role in the current distribution model of Taurus cedar within the boundaries of the Isparta Regional Directorate of Forestry. Areas with a high probability of species presence were found to receive approximately 35 to 52 mm of precipitation during the winter (Fig. 5a). This finding is consistent with previous studies on the species' tolerance to water stress. For example, Boydak (2003) states that Taurus cedar grows better in regions within its natural range where winter precipitation is low but regular, and that its root system has a high capacity to access water during dry periods. Similarly, in an ecological assessment by Guner *et al.* (2016), it was reported that in areas where the precipitation amount of the driest quarter falls below a certain threshold, the species' growth performance and regeneration success decreases. Moreover, moderate levels of winter precipitation have a dual effect on the development of the cedar. Extremely low precipitation can lead to the death of young seedlings due to water stress, while excessively high precipitation can cause prolonged water retention in the root zone, increasing the risk of root rot (Atalay 1990). Therefore, winter precipitation in the range of 35 to 52 mm can be considered to provide an ecological optimum for the species. In addition, in their modeling study, Lopez-Tirado *et al.* (2021) emphasized that the "precipitation of driest quarter" variable makes a significant contribution to the distribution of Eastern Mediterranean cedar populations and that similar optimum ranges are observed. In future projections, expected decreases or increases in winter precipitation is predicted to lead to both habitat loss and shifts in suitable habitats for Taurus cedar ecosystems (Karataş and Özkan 2017).

Finally, according to the landform surface form index graph, which provides the least contribution to the current distribution model, Taurus cedar showed positive compatibility with all categorical land structures, while its distribution was found to be negative in areas with plains (Fig. 5b). In this context, it is revealed that Taurus cedar generally prefers mountainous and steeply sloped areas, especially areas with continuous forest cover, in its natural distribution areas (Boydak 2003; Çolak *et al.* 2010). When evaluated in terms of land use patterns, it was observed that Taurus cedar tends to avoid agricultural areas, residential areas, and plains with intense human activity. The main reason for this is that plains have mostly been converted for agricultural production and settlement, thus disrupting habitat integrity (Atalay 1990). It has been reported that both the microclimatic conditions and soil moisture regime of lowland areas are insufficient to meet the ecological requirements of Taurus cedar, and that summer drought in these areas negatively affects the species' regeneration (Lopez-Tirado *et al.* 2021). However, Karataş and Özkan (2017) emphasize that land use changes are narrowing the potential distribution areas of Taurus cedar forests, and that agricultural expansion and urban expansion are limiting the habitats at lower elevations where the species could naturally spread. This finding is consistent with the current distribution pattern identified in the current study and supports the Taurus cedar's preference for undisturbed, high-elevation forests over lowland areas. Therefore, protecting potential Taurus cedar habitats at lower elevations in land-use planning is critical for both maintaining biodiversity and strengthening the species' adaptive capacity to climate change.

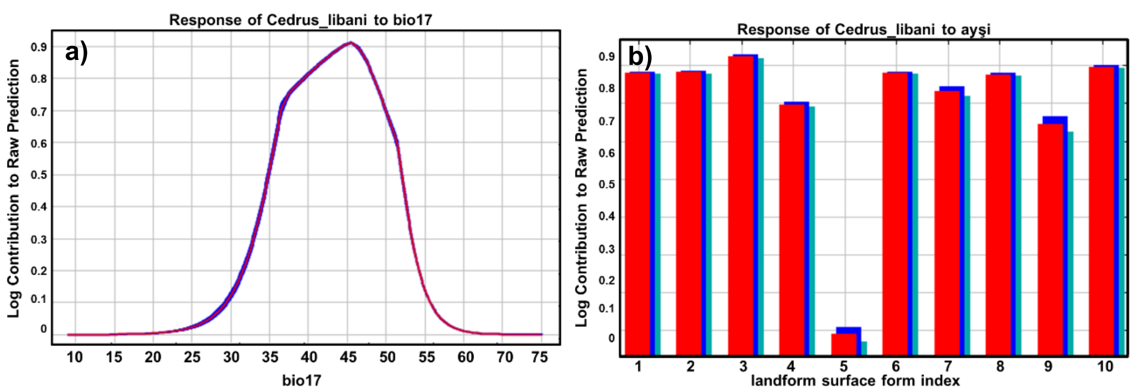

Fig. 5. Taurus cedar contributing to current potential model: a) Precipitation of driest quarter (bio17), and b) landform surface form index (ayşi) graph

The current potential distribution of Taurus cedar was determined for the boundaries of the Isparta Regional Directorate of Forestry using the MaxEnt model, considering land surface features, elevation, and two key climate variables: precipitation seasonality and precipitation of the driest quarter (Fig. 6). Mapping results indicate that areas where the species is most likely to occur are shown in red- and orange-colored areas, typically concentrated in medium- and high-altitude mountainous regions, particularly around the mountain ranges surrounding Lake Eğirdir, as well as the high slopes of Sütçüler, Aksu, and Yalvaç. In these areas, steep slopes, stony and rocky, well-drained soils prevent water from remaining on the surface for long periods, thereby reducing the risk of root rot and facilitating root access to water during dry periods. In contrast, low-altitude, flat areas with intensive agricultural activity, such as the western side of Lake Burdur and the Şarkikaraağaç Plain, are shown in blue areas, where the probability of occurrence is low. The bio15 variable corresponds to areas with balanced yet seasonally variable precipitation, which are associated with high suitability; both excessively high and very low seasonality can negatively affect the species' growth. According to bio17, Taurus cedar reaches optimal conditions in regions receiving 35 to 52 mm of precipitation during the driest quarter. High suitability values are concentrated on forested slopes at higher elevations where the optimal ranges of these two climatic variables intersect. The findings are consistent with Boydak (2003), Guner *et al.* (2016), and Lopez-Tirado *et al.* (2021), and suggest that changes in bio15 and bio17 due to climate change could lead to significant shifts in the species' distribution patterns in the future.

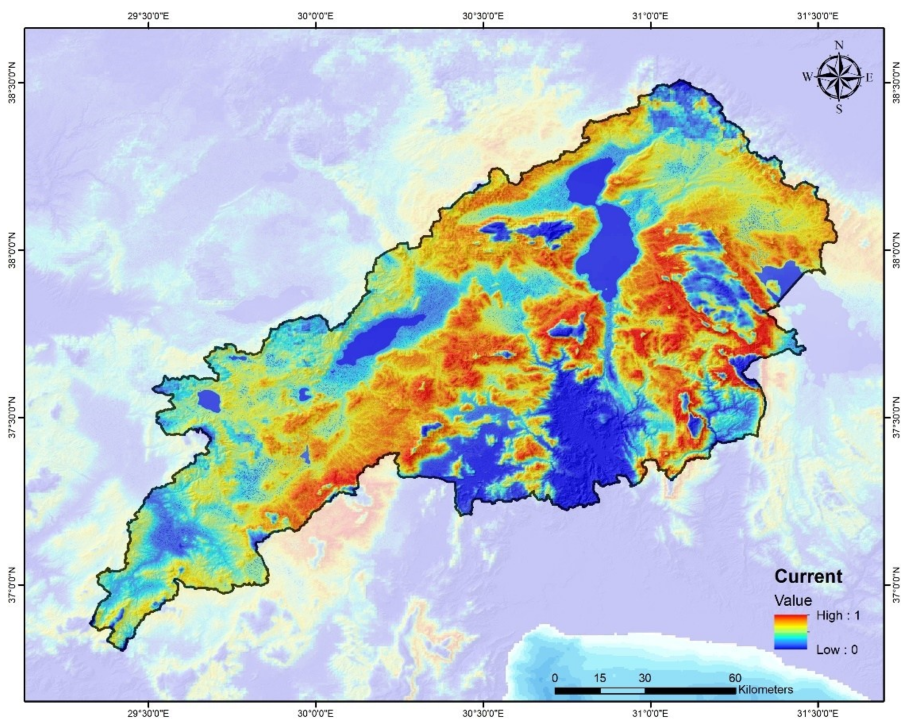

Fig. 6. Current potential distribution map of Taurus cedar

After mapping the current distribution of the Taurus cedar within the borders of the Isparta Regional Directorate of Forestry, simulations were conducted for different climate scenarios (SSP 4.5, SSP 6.0, and SSP 8.5) for the year 2100. The species distribution model, created using the MaxEnt model, reveals spatial changes in habitat suitability for the species under current climate conditions and under different climate scenarios for the year 2100. The Taurus cedar status map in Fig. 7a shows that the species has high habitat suitability, particularly in the northeastern and southeastern parts of the region; these areas, generally represented by red and orange, represent the most suitable conditions for the species' distribution. However, when examined in Fig. 7b, which represents the SSP 4.5 scenario, habitat suitability has decreased significantly despite moderate increases in greenhouse gas emissions; high suitability areas have shrunk, and low suitability areas (blue tones) have expanded. These losses are particularly pronounced in the western and central regions. The SSP 6.0 scenario, shown in Fig. 7c, projects a higher emission increase and further exacerbates the decline in habitat suitability. In this scenario, the species' range appears to be withdrawn to more limited altitudinal zones and, presumably, to more climatically stable microhabitats. The SSP 8.5 scenario, representing the most negative climate projection, reveals a dramatic shift in Fig. 7d; in this map, high suitability areas are almost eliminated, while low suitability areas, represented in blue, dominate the entire region. This suggests that the species' future existence is seriously threatened and that its habitat may be largely lost. Considering all these scenarios together, it appears that under the impact of climate change, the species will not be able to maintain the sustainability of its current habitats and will retreat to higher altitudes or climatically more suitable microregions. These findings highlight the need for urgent conservation planning measures and the importance of developing strategies sensitive to climate scenarios.

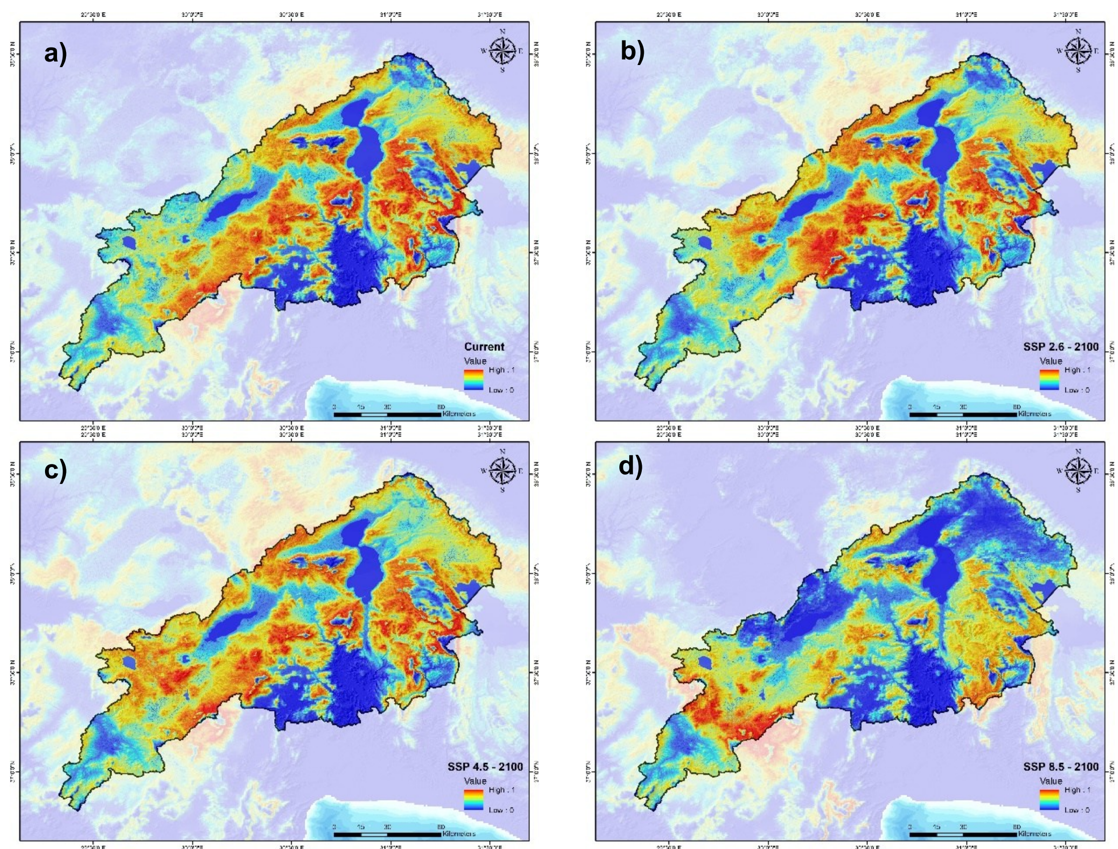

Fig. 7. Taurus cedar a) current distribution mapping and different mappings for the year 2100, b) 2.6 scenario, and c) 4.5 scenario, and d) 8.5 scenario

After mapping the current and future distribution of Taurus cedar under different climate scenarios, the habitat suitability maps were classified to make the visual analysis and spatial comparison of changes more concrete and meaningful. Suitability values were categorized into two classes: suitable areas (0.50 to 0.75) and highly suitable areas (0.75 to 1.00) (Fig. 8). The habitat suitability data obtained through the MaxEnt model were reclassified based on these thresholds, providing a clearer representation of the species' potential distribution under varying climate change scenarios. This classification clearly indicates that, with the increasing impacts of climate change, the suitable habitats for the species will be severely threatened, and a large proportion of highly suitable areas may disappear by the end of the century. The classified maps explicitly reveal the spatial contraction of the species' habitat under different climate scenarios, emphasizing the need to reassess conservation priorities considering these projected changes.

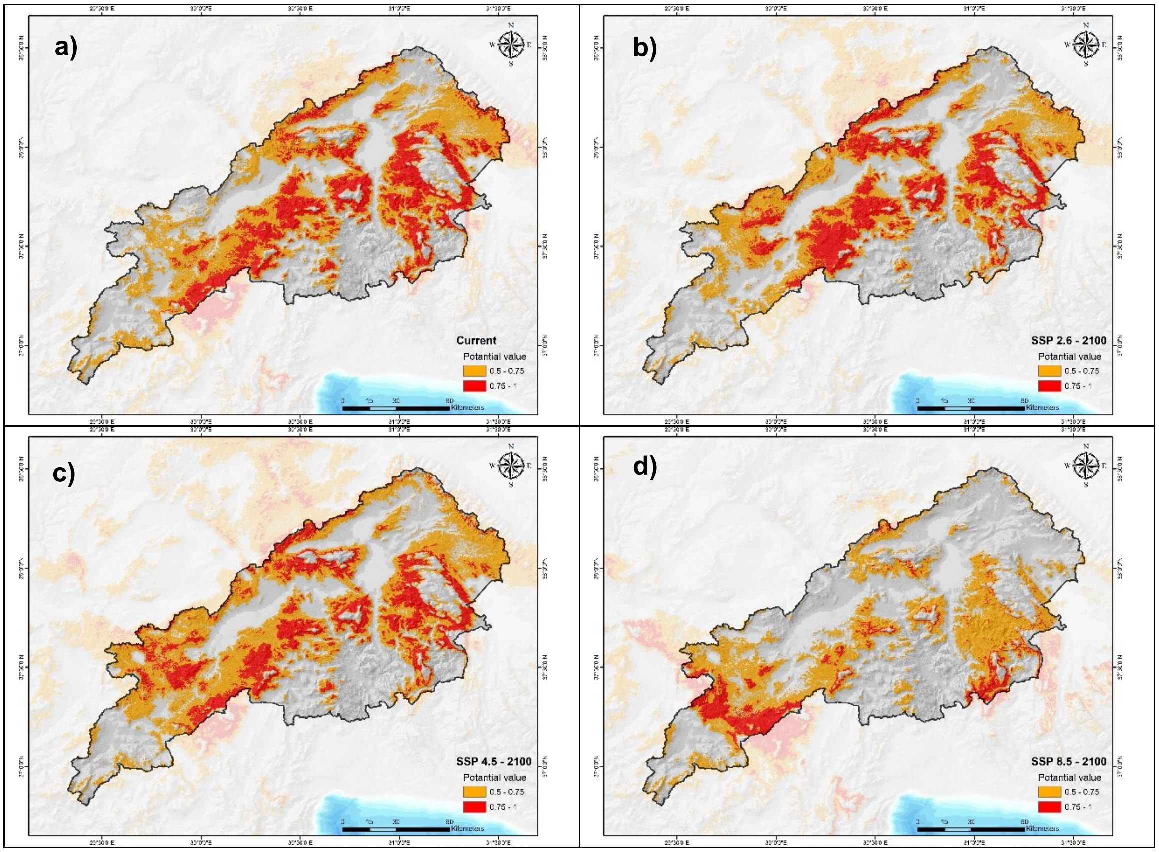

Fig. 8. Taurus cedar a) current distribution classification and different classifications for the year 2100, b) 2.6 scenario, c) 4.5 scenario, and d) 8.5 scenario

Within the boundaries of the Isparta Regional Directorate of Forestry, the classified distribution maps were analyzed to assess the spatial changes in habitat suitability under different climate change scenarios based on approximate area proportions. In the current distribution map, approximately 30% of the area consists of highly suitable habitats (potential value 0.75 to 1), 40% of suitable habitats (0.50 to 0.75), and 30% of low or unsuitable habitats (0 to 0.50). In the projection based on the SSP 4.5 scenario, the proportion of highly suitable habitats decreases to 20%, suitable habitats to 35%, while that of unsuitable areas increases to 45%. Under the SSP 6.0 scenario, the proportions of suitable and highly suitable habitats decline further to 28% and 12%, respectively, and unsuitable areas increase to 60%. In the most extreme climate scenario, SSP 8.5, highly suitable habitats drop to just 5%, suitable habitats to 15%, and approximately 80% of the study area becomes unsuitable for the species (Fig. 9). To summarize, while the current Taurus cedar distribution suitability and very suitable times are 70%; this situation has decreased to 20% in the SPP 8.5 scenario. In other words, a 71.5% decrease in the distribution area of Taurus cedar has been detected in the 2100 SSP 8.5 scenario. These proportions clearly indicate that, with increasing severity of climate change, habitats with high potential for Taurus cedar will decrease significantly, and a large part of its current distribution range is likely to become unsuitable by the end of the century. This highlights the urgent need to reassess the future management of protected forest areas and to develop effective climate adaptation strategies.

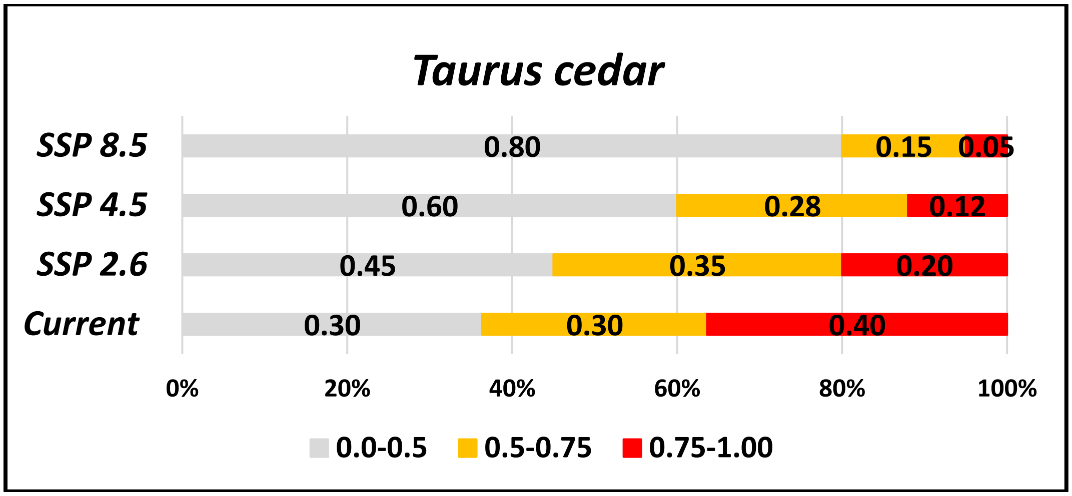

Fig. 9. The distribution of Taurus cedar according to different scenarios (2.6, 4.5, and 8.5) for current and the future (2100) years, the ratio of very suitable, suitable, and unsuitable areas

CONCLUSIONS

1. Significant declines in Taurus cedar habitats are predicted under future climate scenarios, making it essential to develop and rapidly implement effective conservation measures. Protecting existing high-quality habitats and restoring degraded areas will contribute to enhancing ecosystem resilience.
2. Based on digitally derived maps and modeling, it is important to prioritize afforestation activities with climate-resilient species in identified sensitive areas. Thus, the genetic diversity within the Isparta Regional Directorate of Forestry and the sustainability of timber production will be supported.
3. This study highlights the critical importance of developing high-resolution (approximately 30 m, 1 arc-second) digital and model-based maps for modelling the responses of species living in large geographical areas to climate change. Even at small scales, it is necessary to work with detailed and precise maps to improve the accuracy of models, which should then be applied to larger areas to enhance the reliability and validity of predictions.
4. Comprehensive monitoring systems should be established to track the health, growth, and distributional changes of Taurus cedar populations. Using remote sensing and field data, early signs of stress, pest infestations, or climate-induced impacts can be detected and addressed promptly.
5. The conservation and enhancement of habitat corridors that support gene flow and species migration between fragmented Taurus cedar areas should be ensured. This will help mitigate the negative effects of habitat fragmentation by supporting natural adaptation processes.
6. The feasibility of assisted migration strategies should be explored to introduce Taurus cedar to climatically suitable areas where it does not currently exist. Additionally, the preservation of genetic resources should be ensured through seed banks and *ex situ* conservation methods.

7. Local communities, forestry personnel, and other stakeholders should be involved in conservation efforts, sustainable use should be promoted through education and participatory management practices. This approach can help balance economic needs with ecological sustainability.
8. Climate change scenarios should be integrated into regional and national forest management plans, ensuring that future environmental conditions and species sensitivities are considered in long-term planning.
9. Collaboration between forest departments, academic institutions, climate scientists, and conservation organizations should be encouraged to facilitate data sharing, develop innovative solutions, and support evidence-based policymaking.

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