Response of Black Pine (*Pinus nigra*) in Southwestern Anatolia to Climate Change

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Global climate change is one of the most critical challenges facing natural ecosystems. As sedentary organisms, plant communities are especially vulnerable, with climate change significantly impacting their development, productivity, and distribution. This study focuses on modelling and mapping the potential distribution of black pine (*Pinus nigra*) within the Antalya Regional Forest Directorate under the SSP1 2.6 climate scenario for the years 2040, 2060, 2080, and 2100. The MaxEnt modelling method, combined with the HadGEM3-GC31-LL climate model from WorldClim, was used to assess the impact of climate change on black pine. The current distribution model results showed "good" predictive performance, with AUC values of 0.855 for training data and 0.851 for testing data. Key variables influencing the model included precipitation during the wettest quarter, annual precipitation, maximum temperature of the warmest month, and elevation. Projections indicate that the black pine's distribution will shrink by 2040, become increasingly fragmented by 2060, and decline further by 2080, with near-total disappearance by 2100. In conclusion, this study highlights the urgent need for adaptive management strategies to address the effects of climate change on black pine forests.

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Keywords: Black pine; Climate change; Conservation and management; Maximum entropy; Modelling

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INTRODUCTION

Black pine (*Pinus nigra* Arnold), a member of the Pinaceae family, is a species with significant economic value and an extensive geographical range. Its distribution spans from North Africa and the Northern Mediterranean to the Black Sea region in the east, as well as the islands of Corsica and Sicily (Dias *et al.* 2020). The areas where it thrives are highly variable, depending on the local geography, with an optimal altitude range of approximately 350 to 2200 meters. Black pine, which has four different varieties in Anatolia, is intolerant of shade but resistant to wind and drought, requires light and can grow up to a height of about 30 to 40 m (Isajev *et al.* 2003). In addition, thanks to its adaptation abilities within forest ecosystems, black pine can endure in cold weather conditions, withstanding temperatures as low as -30 °C (Scaltsoyiannes *et al.* 2022).

Due to its ecological versatility and broad adaptability, black pine is widely utilized within the forest industry. Black pine is frequently preferred in application areas such as lumber, fiber, paper, composite board, joinery, and construction of wooden houses (Istek *et al.* 2010). The wood of black pine is distinguished by its durability, rich resin content, and ease of processing (Giovannelli *et al.* 2017). Due to its durable structure, it is used as furniture and parquet material, as well as in chemical and medical fields such as cellulose and resin production. Its high calorific value also makes black pine wood a valuable resource for firewood and biomass energy production.

Türkiye has a forest area of 23 million ha, corresponding to approximately 29.4% of the country's total land area. The most common primary tree species in these forest areas are oak, red pine, and black pine, respectively. Black pine ranks third, accounting for 18.3% of the total forest area (GDF 2022). In other words, black pine is the second most widely distributed pine species in Türkiye (Uner *et al.* 2009). Most black pine forests in Türkiye are concentrated in the Western Mediterranean Region, particularly within the borders of the Antalya Regional Directorate of Forestry.

The widespread use of black pine in the forest industry is largely attributed to its durable structure and its ability to thrive in various ecological conditions. Despite its long rotation period, which spans approximately 120 years, black pine remains a key resource for timber and wood products in the forestry sector (Uner *et al.* 2009). However, this extensive use has direct and indirect effects on the species' distribution within its natural habitats. One of the most significant threats to black pine distribution is global climate change. The adverse impacts of climate change pose a serious risk to the future potential distribution of black pine. Research suggests that rising temperatures, shifting precipitation patterns, and increasing environmental stressors could lead to a reduction in the suitable habitats for black pine in the future (Martin-Benito *et al.* 2011).

Global climate models are developed based on scenarios presented by the IPCC (Intergovernmental Panel on Climate Change). The IPCC's most recent projections are presented in the SSP (Socio-Economic Pathways) scenario group. This group predicts how future greenhouse gas emissions will be shaped by social, economic and technological developments. The most recent SSP scenarios are classified into five main scenario groups: SSP1 2.6, SSP2 4.5, SSP3 7.0, and SSP5 8.5 (Özdemir *et al.* 2020). These scenarios enable modelling studies to determine the effects of future climate conditions on species distributions due to different emission levels (O'Neill *et al.* 2016).

One of the generally preferred methods in species distribution modelling is Maximum Entropy (MaxEnt). The MaxEnt method can only work with the presence data of the species. It is well suited for the present case, since it provides a great advantage in cases where the target species is limited (Çıvğa *et al.* 2024; Özdemir 2024). It can also produce more accurate and reliable estimates with fewer observation data compared to other species distribution modelling methods (Hussein and Workeneh 2021). In addition, the ease of integration with open source (R, RStudio) and free MaxEnt software makes this method practical and accessible for researchers (Phillips *et al.* 2009). Moreover, the MaxEnt software stands out as a method used to reveal the effects of global climate change in species distribution models.

This study aims to model the current and future (2040-2060-2080-2100) potential distribution of black pine within the framework of climate change scenarios. The current and future climate data used in the study were obtained from the WorldClim database, which provides high-resolution estimates. Climate projections for the coming years (2040–2060–2080–2100) were evaluated according to the SSP1 2.6 scenario, which is accepted as the "optimistic scenario". The study aims to contribute to the development of strategic management plans for the protection and management of the Black pine. These plans will help shape the future sustainability and economic value of the species, considering climate change scenarios.

EXPERIMENTAL

Study Area Features and Data Set

Black pine occupies approximately 4.2 million hectares (ha) in Türkiye, making it the most widely distributed pine species in the country (GDF 2015; Özdemir 2022). While primarily found in Western Anatolia, it also extends to the Mediterranean region. The Antalya Regional Directorate of Forestry (ARDF) holds the largest forest assets in the Mediterranean, covering 2,065 million ha, of which 1,133 million ha are forested (GDF, 2022). Of these, 591,112 ha are productive forests, while 542,111 ha are degraded areas awaiting restoration through silvicultural interventions (Kartal and Bilir 2022).

In addition to silvicultural efforts, the effects of global climate change must be considered when managing forest productivity. The study area is rugged and mountainous, with elevations ranging from sea level to 2,917 meters. The region experiences hot, dry summers and mild, rainy winters. Although red pine (*Pinus brutia*) and cedar (*Cedrus* spp.) dominate the landscape, black pine stands are found at higher elevations. To model black pine distribution, only data from pure black pine stands, recorded in ARDF's management plans from 1987-2017, were utilized. A total of 3,037 black pine stand locations were identified across the study area and are marked in green on the accompanying map (Fig. 1).

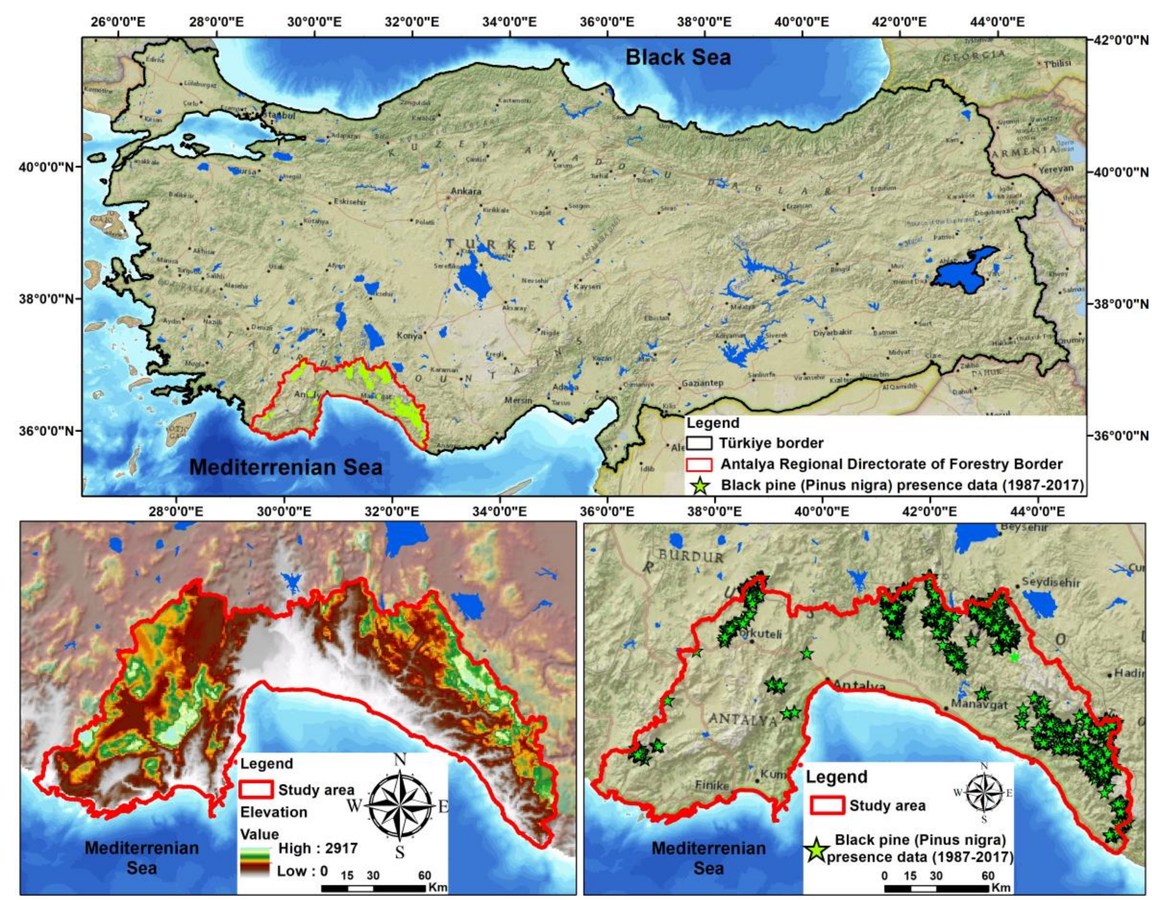

Fig. 1. Location map of the Antalya Regional Directorate of Forest and Black pine presence data

Production of Digital Maps

In forestry studies, once data on the target species are gathered from land inventory studies or management plans, the process of creating digital base maps for species distribution modelling begins. For large-scale species distribution models, digital elevation models (DEMs) with larger pixel sizes (*e.g*., 30 arc seconds ~ 1 km) are typically used. However, using smaller pixel sizes enhances the accuracy and confidence of model results, as environmental and climate variables can be understood more precisely at finer resolutions (Acarer and Mert 2024). In this study, a high-resolution DEM with a pixel size of **1 arc second (~30 m)** was downloaded from the internet address https://www.usgs.gov/ to cover the study area. Based on this DEM, which was adjusted for the study area and projected with the appropriate coordinate system, environmental base maps thought to influence black pine distribution were generated using ArcGIS Pro. Additionally, vector data on factors such as site conditions, canopy closure, age classes, area size, and land cover classes were obtained from forest management plans (1987-2017). A 1/100.000 bedrock, obtained from the General Directorate of Mineral Exploration and Research, was also included. Finally, the variables in this vector format were converted to raster format using the polygon to raster segment with ArcGIS Pro.

After producing the environmental base maps of the study area, climate variables were obtained from the internet address https://www.worldclim.org/ to determine the effect of climate change on the distribution of black pine. High-resolution climate data is essential for modelling species distribution, with WorldClim and Chelsa models being the most used due to their accuracy (Karger *et al.* 2017; Acarer 2024a). Chelsa climate variables are preferred for large-scale areas, and WorldClim climate variables are preferred for small-scale areas. WorldClim data are based on temperature and precipitation variables for 20-year periods (current-2040-2060-2080-2100) and are calculated according to their own characteristics. In addition, there are four Shared Socioeconomic Pathways (SSPs) climate envelope models for different years (SSP1 2.6, SSP2 4.5, SSP3 7.0 and SSP5 8.5). SSP126, one of the climate envelope models, is currently defined as "Sustainability – Following the Green Path" and is considered a "optimistic" scenario than other models (IPCC 2024). In this context, optimistic (SSP1 2.6) climate envelope models for different years (2040-2060-2080-2100) were preferred to reveal the effects of climate change on pure Black pine forests within the Antalya Regional Directorate of Forestry.

Current and Potential Distribution Modelling and Mapping of Black Pine

The methods used in the plant species distribution modelling phase are divided into two groups: connection and mechanistic methods. Connection methods are preferred over mechanistic methods. The reason for this is that mechanistic methods require detailed ecophysiological characteristics of the target species (Özdemir 2024). This is not the case with connection methods. Connection methods are divided into two groups: group separation techniques and profile techniques. Group separation techniques are methods that consist of binary data in the form of presence or absence of the dependent variable. Profile techniques are methods that use only the presence data of the dependent variable (Özkan 2012). One of the methods that estimates suitable and unsuitable areas for the dependent variable based on only the presence data of plant species is Maximum Entropy (MaxEnt). MaxEnt calculates the probability density to estimate the distribution of the target species with two different analyses (Phillips 2005). In these calculations, it first calculates the variable values in the areas where there are only presence data of the species (Phillips and Dudík 2008). Then, it calculates the potential distribution probability within the area by producing points like the areas where the target species has presence data in the background (Elith *et al.* 2011). It determines the relatively suitable areas for the potential distribution of the target species by revealing the difference between these two probability values (Merow *et al.* 2013). As a result, it reveals the potential distribution map for the entire area according to the variable values that affect the species distribution (Acarer 2024b).

To reveal the effects of global climate change on the black pine, the latest and most up-to-date Version 3.4.4 of the MaxEnt method, was preferred. As with other species distribution modelling, the accuracy of the model and mapping outputs produced with the MaxEnt method should be checked. For this control process, jackknife value, and contribution graph, training data set Area Under the Receiver-Operator Curve (AUC) and test data set Area Under the Receiver-Operator Curve (AUC) graph values must be examined. When examining the jackknife graph, care should be taken to ensure that the contribution of the variables contributing to the formation of the target species distribution model alone does not exceed the value results of other variables contributing to the formation of the model. Also, there are two different classifications among themselves to check the AUC. The first step to check the AUC values is that the training data AUC value of the model determined is higher than the test data AUC value. The other method is that the difference between the model training data AUC value and the test data AUC values is at the lowest level (Elith *et al.* 2011). If the training data set AUC value and the test data set AUC values are equal, then this situation can be ignored. Araújo *et al.* (2005) emphasized that to more clearly state the species-climate effect under climate change, it is necessary to evaluate the model as "fail" for 0.50 < AUC < 0.60, "weak" for 0.60 < AUC < 0.70, "medium" for 0.70 < AUC < 0.80, "good" for 0.80 < AUC < 0.90 and "excellent" for 0.90 < AUC < 1.00. Therefore, it is stated that the AUC classification of the species distribution model results under the effect of climate change obtained from the MaxEnt method can be used (Muscarella *et al.* 2014).

RESULTS AND DISCUSSION

To determine the current potential distribution of the Black pine, the MaxEnt method's subsample option was used, with 10 repetitions and 10% of the data allocated for testing (Phillips 2005). The model was trained using 2734 presence records, while 303 records were used for testing. This process involved 5000 iterations, producing an average model based on the results of 10 replications. A total of 60 environmental and climate variables-41 environmental (such as elevation class, slope, aspect, heat load index, ruggedness and roughness) and 19 WorldClim variables (such as annual mean temperature and annual precipitation within the Antalya Forest Regional Directorate) were processed. The digital base maps were converted to ASCII format for use in MaxEnt. The modelling phase was begun with the digital base maps prepared for the MaxEnt method and the presence data of the black pine. A total of 68 different models were presented for the current potential distribution model of the black pine. Among the variables contributing to the models, variables with low permutation importance and the lowest percentage value were removed from the model and the modelling process continued. The process was continued until at least two variables contributing to the model remained, and the best model was selected based on the AUC values, which had no deviations in the omission graph between the models and the degree of accuracy.

When the model results presented for the current potential distribution of black pine were examined, it was determined that there were no significant deviations in the omission graph of the model (Fig. 2a). In addition, according to these model results, the model with training dataset AUC 0.855 and test dataset AUC 0.851 was selected (Fig. 2b). The obtained model results were in the good model category according to the classification determined by Araújo *et al.* (2005). The model's average AUC value was 0.852 with a standard deviation of 0.006, confirming its reliability.

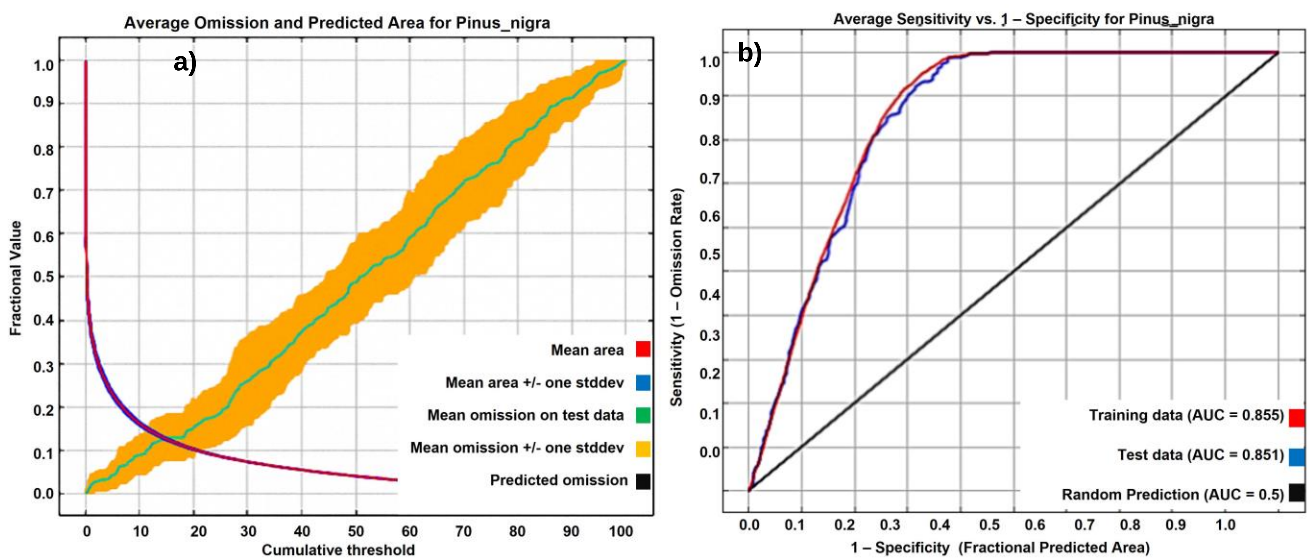

Fig. 2. Current potential distribution model of Black pine: a) Average omission chart, and b) Training data set and test data set AUC graph

The key variables shaping the current distribution model of black pine, based on low standard deviation and high AUC values from both training and test datasets, are annual precipitation (bio12), precipitation of wettest quarter (bio16), max temperature of warmest month (bio5), and elevation. The accuracy and validity of the black pine current potential distribution model created with these variable values was checked. In this context, correlation analysis was applied among 19 WorldClim climate variables. After determining the high correlation between climate variables, factor analysis was applied to determine the most significant climate variable on the black pine potential distribution. According to the factor analysis results, it was determined that the most significant variables for the potential distribution of black pine were in the same direction as the model outputs. Thus, both the statistical analysis results and the variable value results contributing to the model were shown to be accurate and reliable. In this context, according to the Jackknife graph (Fig. 3) of the black pine potential distribution, it was determined that the variables that contributed the most alone without any other variable were precipitation of wettest quarter (bio16), annual precipitation (bio12), max temperature of warmest month (bio5), and elevation (elevtin).

To effectively model the distribution of black pine within the Antalya Regional Directorate of Forests, it is crucial to examine the marginal response curves of the environmental and climate variables involved. These curves are helpful for understanding how each variable influences the model's predictions. Ideally, the marginal response curves should align with the current distribution patterns of black pine. In this context, the analysis has highlighted that the average rainfall during the rainiest quarter, particularly precipitation in the winter months (December, January, and February), plays a significant role in shaping the distribution of black pine. This finding underscores the importance of winter rainfall in influencing the habitat and distribution of this species within the region.

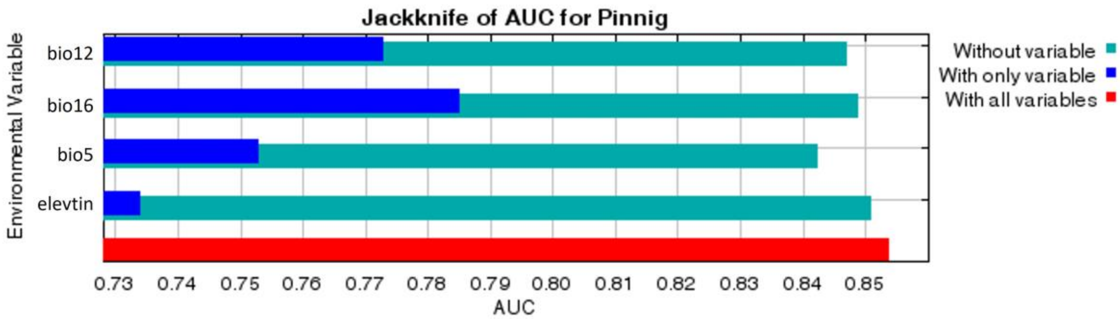

Fig. 3. Jackknife chart of current distribution model of Black pine

When the obtained variable graph is examined in more detail based on the coefficient of 0.5, areas where the amount of precipitation in the winter season is between 270 and 380 mm have a positive effect on the distribution of black pine (Fig. 4a). Giovannelli *et al.* (2017) found that black pine populations have optimum growth depending on the average precipitation of the wettest quarter in their model. It was stated that the expected average ring width of black pine was the highest in the south of the Mediterranean Basin (Antalya) compared to other regions. In addition, the same situation was observed on other pine species, as well as the effect of average precipitation of the wettest quarter on black pine populations. Previous studies have stated that some pine species tend to live in suboptimal environments due to the influence of the precipitation value of the wettest quarter (Rehfeldt *et al.* 2003; Thomson and Parker 2008). According to the annual mean precipitation variable graph contributing to the model, areas where the annual average precipitation within the area is between 630 mm and 780 mm are suitable areas for black pine species distribution (Fig. 4b).

Camarero *et al.* (2013) found that the black pine population experienced drought in areas where the average annual precipitation was approximately 630 mm. It has also been revealed that the species that will respond most to changes in annual average precipitation is black pine. It was also stated that it is important for coniferous pine species in the Mediterranean region to be able to store enough water in their soil throughout the winter before the growing season (spring) begins. From this perspective, it has been emphasized that winter precipitation in the Mediterranean region is effective relative to tree growth (Martin-Benito *et al.* 2010; Michelot *et al.* 2012; Camarero *et al.* 2013). Therefore, both the average precipitation amount during the wettest quarter and the annual average precipitation values significantly affect the distribution, growth, and development of black pine. These findings are consistent with existing literature, which highlights the crucial role of precipitation patterns in shaping the habitat and health of this species. The alignment with established research underscores the reliability of these results in understanding and predicting the black pine's ecological dynamics.

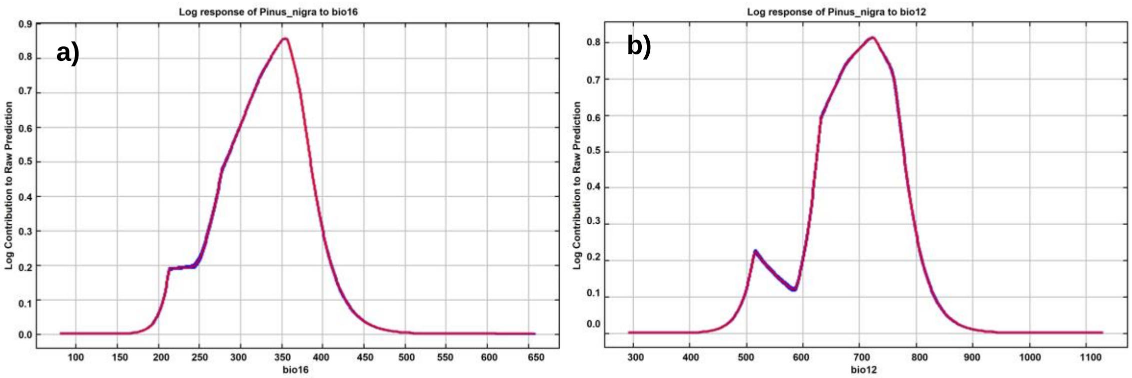

Fig. 4. Black pine contributing to current potential model: a) precipitation of wettest quarter (bio16), and b) annual mean precipitation (bio12) graph

Simultaneously, the marginal response curves for the maximum temperature of the warmest month and elevation, which contribute to the potential distribution of black pine, were analyzed. The graph for the maximum temperature of the warmest month indicates that August, the warmest month in the region, plays a critical role. Areas where temperatures in August range between 24.8 and 28.5 °C positively influence the distribution of black pine. Conversely, temperatures outside this range – either lower or higher – adversely affect the species' distribution. This finding highlights the specific temperature conditions that are most conducive to the growth and survival of black pine in the region (Fig. 5a). Marchi *et al.* (2016) stated in their model that the distribution of the marginal population of black pine will change because of climatic adaptation. Arslan and Örücü (2019) stated in their study to reveal the effect of climate change on pine species that the maximum temperature of the warmest month (bio5) variable has the greatest effect on the distribution of some pine species. Mitić *et al.* (2016) revealed the importance of the climate variable, maximum temperature of the warmest month, in the taxonomic distinction of black pine distributed in different geographies. Finally, according to the results of the altitude variable value that contributes least to the black pine potential distribution model; it was determined that areas with an altitude of 1200 m to 1900 m have a positive effect on species distribution (Fig. 5b).

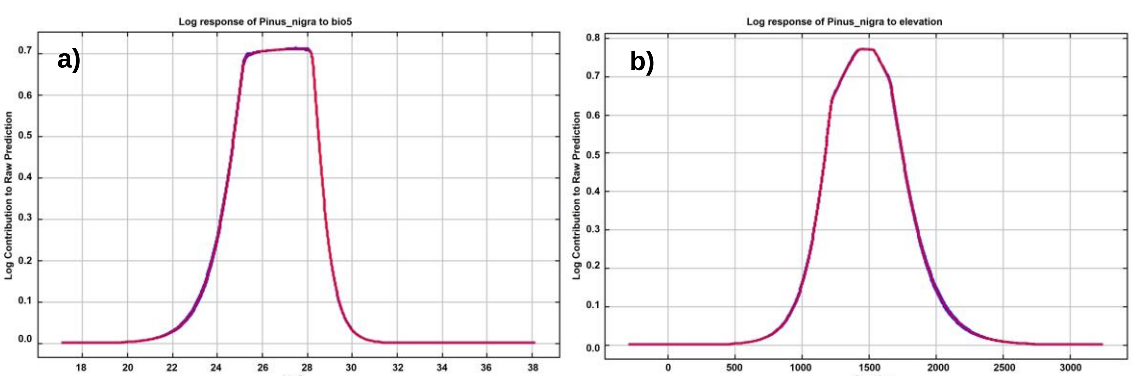

Fig. 5. Black pine contributing to current potential model: a) max temperature of warmest month (bio5), and b) elevation graph

Negiz *et al.* (2019) in their study on Productivity and Distribution Characteristics found that the black pine species was distributed between approximately 1239 to 1825 m.

Camarero *et al.* (2013) aimed to determine the effect of global climate change on the distribution of black pine. For this purpose, in addition to obtaining data on the geography where black pine is located, they found that the altitude in the sample areas generally ranged between 1500 and 1900 m. As a result, the maximum temperature of the warmest month and elevation variable value results contributing to the black pine potential distribution model are consistent with the literature.

Based on the variable values contributing to the model, the current habitat suitability map for black pine is shown in Fig. 6. When this map is examined, the potential distribution is primarily concentrated in the eastern and western regions of the Antalya Regional Forestry Directorate. Moreover, for the large-scale black pine current modelling, suitable habitats were identified in northern areas outside the study region, including the foothills of the Dedegöl Mountains, which have been recognized as ideal for black pine by Kuzugündeli and Kaya (2012). Şahan *et al.* (2021) stated that the Black pine species cones found in the Mediterranean basin have fire-spreading properties. Jansen *et al.* (2018) revealed the growth trends of the black pine within the Isparta Forest Regional Directorate, which is closest to the borders of the Mediterranean Forest Regional Directorate. Previous studies also indicated that black pine is distributed in high-altitude areas, far from settlements (Şahan *et al*. 2023). Finally, it was determined that the potential distribution of black pine was low in the coastal areas of the Mediterranean within the study area. The study confirmed low suitability in coastal Mediterranean areas, aligning with existing literature on black pine distribution.

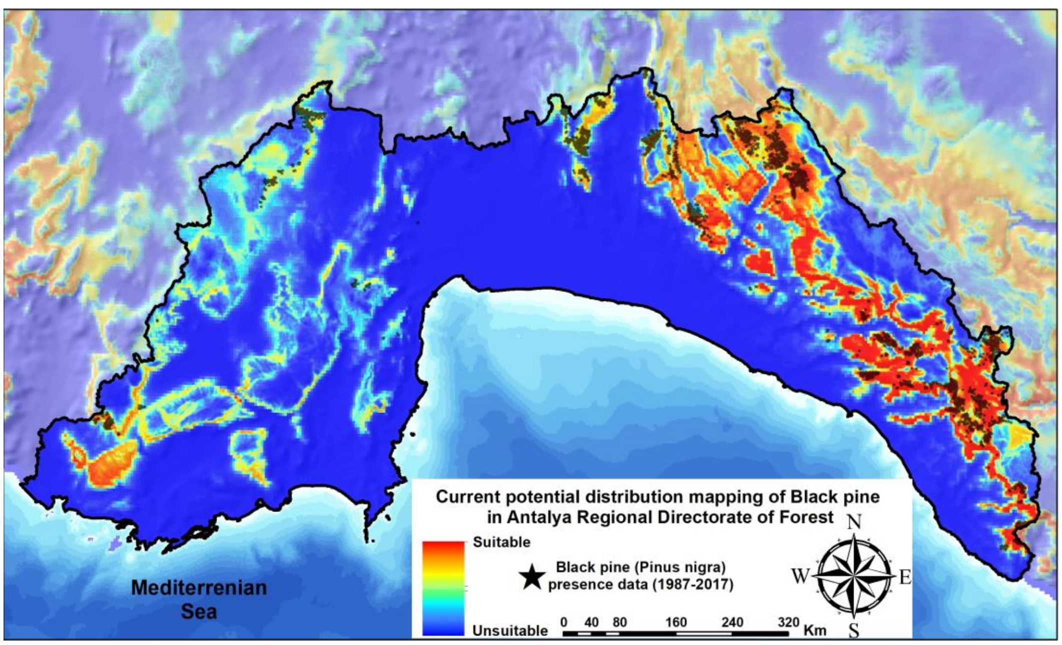

Fig. 6. Current potential distribution map of Black pine

After mapping the current distribution of black pine, the next step was to model its potential distribution for the years 2040, 2060, 2080, and 2100. To achieve this, the SSP1 2.6 (optimistic) climate scenario from the WorldClim model HadGEM3-GC31-LL was used. Simulations were conducted for these future periods based on the variables influencing black pine distribution.

According to the 2040 SSP1 2.6 scenario map (Fig. 7a), the distribution of black pine is expected to be restricted to certain areas in the eastern and western parts of the study region. By 2060 (Fig. 7b), the model predicts that suitable habitats will remain only in the eastern part of the region. In the 2080 distribution map (Fig. 7c), although some potential distribution remains in the eastern area, it is projected to be less suitable than in 2060. Finally, by 2100 (Fig. 7d), black pine is expected to nearly disappear from the study area. In conclusion, the SSP1 2.6 scenario, considered optimistic relative to other climate projections, shows a gradual shrinking, fragmentation, and eventual disappearance of black pine habitats. This study provides model-based, numerical evidence of the negative impacts global climate change will have on black pine within the Antalya Regional Directorate of Forestry. Previous research has similarly indicated that climate change will have irreversible effects on black pine distribution in the Mediterranean basin (Jansen *et al.* 2018; Aydın and Rages 2024; Cantürk *et al.* 2024).

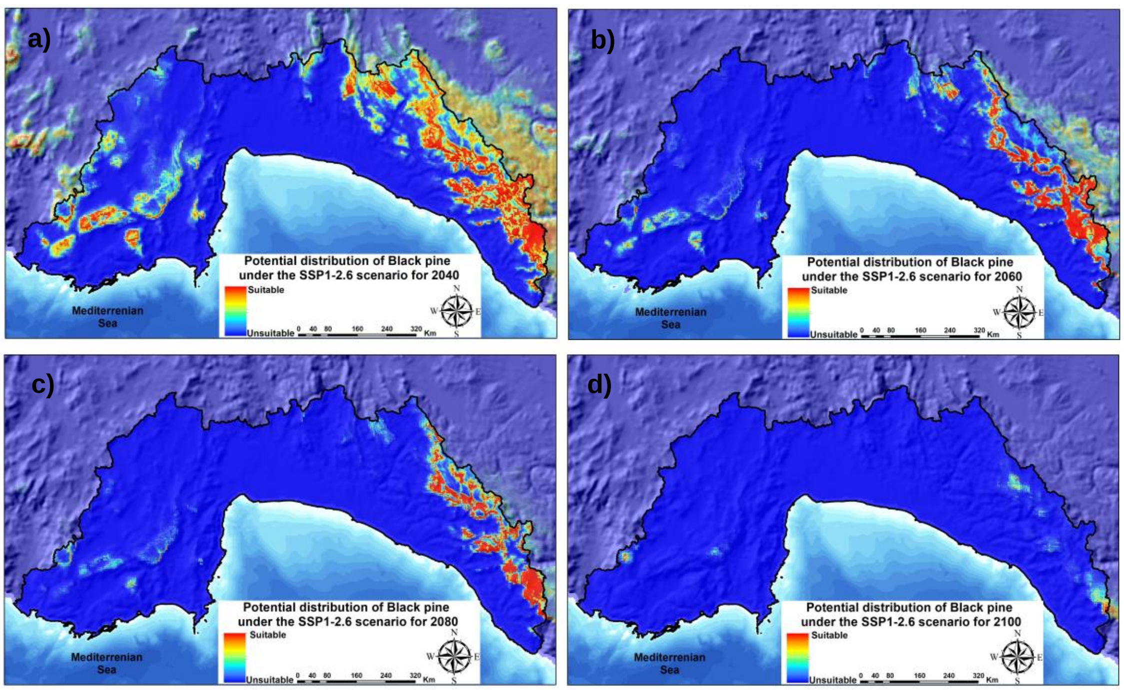

Fig. 7. Potential distribution of Black Pine in SSP1 2.6 according to the scenarios a) 2040, b) 2060, c) 2080 and d) 2100 years

The potential distribution maps of black pine obtained from this study, based on current conditions and the SSP1 2.6 climate scenario for 2040, 2060, 2080, and 2100, were classified into suitable and unsuitable areas using a threshold value of 0.5. According to this classification, black pine currently occupies 26% of the Antalya Regional Forestry Directorate, but this is projected to decrease to 23% by 2040, 17% by 2060, 23% by 2080, and just 1% by 2100 (Fig. 8). These results highlight a significant decline in the species' distribution, even under the optimistic SSP1 2.6 scenario.

The potential distribution of black pine, a species of ecological and economic importance, is highly influenced by shifts in climate, particularly changes in precipitation and temperature patterns. In fact, considering the distribution of black pine in 2100, this study indicates that climate change will cause serious problems.

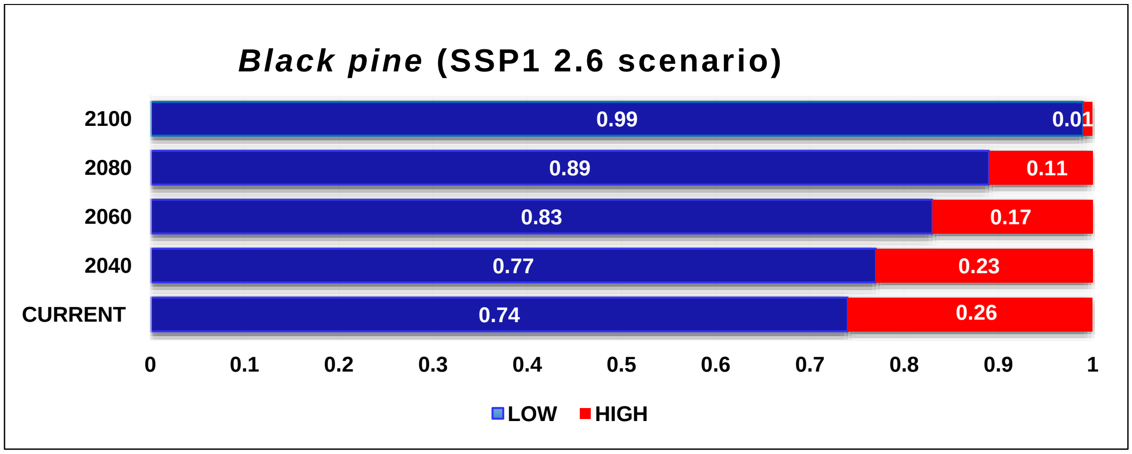

Fig. 8. Black pine potential distribution according to SSP1 2.6 scenario, ratio of suitable and unsuitable areas for current, 2040, 2060, 2080, and 2100

CONCLUSIONS

1. Although the MaxEnt method was used in this study to simulate climate change impacts specifically on black pine, this method should also be prioritized for modelling the distribution of endemic plant species. Its application can play a crucial role in biodiversity conservation, as well as in the development of effective protection and management plans for vulnerable species.
2. Cantürk *et al.* (2024) modelled the impact of climate change on the distribution of black pine using large-scale and low-resolution (30 arc second ~1 km) base maps. It has been determined that the training and test data values of the presented model are 0.866 and 0.556. Within the scope of Araújo *et al.* (2005) classification, the high difference between the test and training dataset results of the study raises doubts about the reliability of the results. This study highlights the importance of producing high-resolution **(1 arc second ~30 m)** base maps for climate change modelling of species distributed across large geographical areas. It emphasizes that, despite being small-scale, modelling should be conducted using high-resolution base maps to ensure accuracy, and then applied to broader regions for more reliable predictions.
3. Even though the SSP1 2.6 scenario is considered optimistic, priority should be given to the regions identified in the near-future black pine potential distribution maps. Since these maps predict that the distribution of black pine will nearly disappear by the year 2100, it is crucial to introduce different plant species that are well suited for temperature and precipitation changes to mitigate future losses.
4. Finally, the numerical and model-based black pine potential distribution maps, developed to help the species survive the expected impacts of climate change with minimal damage, will also assist in sustainably managing the supply and demand for wood raw materials. These maps are valuable tools that will contribute to future research on various aspects of black pine, providing a foundation for studies focused on conservation, forestry, and resource management.

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