Unlocking the Habitat Suitability of Wild Olive to Improve Its industrial Potential: A Comprehensive Distribution Modeling Study

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Wild olive (*Olea europaea* L.) is a highly significant forest tree species, both in Türkiye and globally. Its oil and other extracts from the fruits and leaves are vital to various industries, including culinary, cosmetics, pharmaceuticals, and healthcare, making it a valuable non-timber forest product. However, its natural distribution is restricted to Mediterranean climates, emphasizing the need for conservation efforts to support its growth and expansion. Potential distribution modelling is one of the best studies to be done to protect a species and ensure its survival. In this study, the MaxEnt method, which relies exclusively on presence data, was used to generate a potential distribution map for wild olive. The environmental variables to be included in the modeling method were determined using the Analytic Hierarchy Process (AHP), one of the multi-criteria decision-making methods. From an initial set of 29 variables, AHP selected the top 11 for the final model. The resulting model demonstrated high accuracy, with an AUC value of 0.922, successfully identifying and mapping the potential distribution areas for wild olive across Türkiye.

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Keywords: Olea europaea; MaxEnt; Species distribution modeling; Analytical hierarchy process; Multiple decision making

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INTRODUCTION

Forests are ecosystems that contain some of the most crucial natural resources of our planet. Since the early 19^{th} century, a great deal of interest has been focused on scientific research on forests because of their importance as a resource for humanity. Specifically, there has been a dramatic rise in the quantity of research done on forest tree species. It is clear from looking at these research that the original emphasis was mostly on the growth environment and ecological needs of tree species. Studies on different types of forest utilization, however, have become more and more common in recent years (Gülsoy *et al*. 2022). The wood industry, food, cosmetics, medicine, pharmacy, and industrial applications stand out among these many uses.

Because of its ecological, economic, and cultural significance, the wild olive (*Olea europaea* L.), the study's subject, has long been valued as a bio-indicator plant in the Mediterranean Basin (Uzun and Ustaoğlu 2022). Among the members of the *Olea* genus, wild olive (*O. europaea* L.) is the most distinguished member (Hashmi *et al.* 2015). Wild olive is a tree with a broad crown that can reach a height of approximately 10 to 15 meters or grow as a shrub with a height of 1.5 to 2 meters. Its trunk is finely fractured and grayish-brown in appearance. The fruit has dimensions of 5 to 20 mm in diameter and 6 to 33 mm in length. The fruits are bright green when they are immature and turn dark green or black when they are ripe. For this species, flowers usually bloom in May, and the fruits ripen in August and September (Yaltırık 1978). Remarkably, the wild olive species grows in areas with a Mediterranean climate, and the Mediterranean Basin is home to over 90% of the world's olive trees (Fraga *et al.* 2020). Also in Türkiye, wild olive is a major non-wood forest product as well as a notable tree species. Because of the species' economic significance, several breeding research have been carried out on it in Mediterranean nations. Although wild olive is not currently categorized as an endangered species globally, its distribution may show a declining trend in the future due to unconscious harvesting and consumption in certain regions (Çıvğa *et al*. 2023). For this reason, considerable research has been carried out in Tunisia (Trigui 1996), Israel (Lavee *et al.* 1999), Spain (Rallo *et al.* 2008; Morales-Sillero *et al.* 2012), Greece (Pritsa *et al.* 2003), Italy (Bellini *et al.* 2000), and our own nation (Arsel and Cirik 1994; Özdemir *et al.* 2013). The most valuable olive tree product, olive oil, has been shown to have positive health effects. Notable research on this subject has demonstrated the effectiveness of olive oil and its constituents in the treatment of metabolic, autoimmune, and cardiovascular disorders. It is also advised for the prevention of breast and colon cancers (Alarcón de la Lastra *et al.* 2001; Antoniou and Hull 2021). Furthermore, in Southern Europe, olive oil has been utilized as a folk medicine for diabetes and hypertension (Komaki *et al.* 2003). Olive leaves also have a variety of medicinal applications. According to reports, olive leaf extract can prevent muscular spasms, control intestinal rhythm abnormalities, and be used to treat allergies (Nishibe *et al.* 2001; Scheffler *et al.* 2008). According to Singh *et al.* (2008), it enhances blood circulation throughout the body, control blood clotting, raise blood flow in blood vessels, and protect against heart disease. Moreover, it is used therapeutically for illnesses including high blood pressure, diabetes, hypertension, and cholesterol (Susalit *et al.* 2011; Alesci *et al.* 2022). It also controls the bacteria in the stomach (Sudjana *et al.* 2009). It has been reported that olive leaf extract can boost immunity, function as an antibacterial, and have anti-aging effects in herbal medicine (Long *et al.* 2010).

When the climate requirements of the species are examined, for olives to develop naturally, the average yearly temperature typically ranges from 15 to 20 °C (Brito *et al.* 2019). However, the lower limit for olive growing areas in Türkiye is 14.5 °C. Olive trees have a maximum temperature tolerance of about 40 °C (Efe *et al.* 2009), with short-term tolerances down to -8 °C (Krishna 2014). Over 400 mm of annual precipitation is sufficient for olive growing areas each year (Brito *et al.* 2019), while 500 mm of annual precipitation is the minimum required in non-irrigated areas (Ponti *et al.* 2014). Türkiye is located in the Mediterranean Basin, which has been called a "hotspot" for climate change (Giorgi 2006). Studies that are currently available in the literature demonstrate the Mediterranean Basin's trend toward rising temperatures and droughts (Cramer *et al.* 2018; Zittis *et al.* 2022). Türkiye's temperature trend has been confirmed by numerous research (Kızılelma *et al.* 2015; Dün and Gönençgil 2021), and the country is predicted to have notable temperature rises in the future (Bağçaci *et al*. 2021) based on climate projections. The possible distribution areas of wild olive species that are resistant to heat waves, frost, and drought must thus be identified, and their distribution must be expanded into places that are ideal for their growth.

As was already indicated, studies to increase the number of wild olive species—which are widely utilized for their fruits and leaves in medicine—have gained popularity recently. Accordingly, research has been done to model possible distribution regions and ascertain the species' appropriate ecological needs, setting the groundwork for more efficient and sustainable use. The best approach for this is thought to be species distribution modeling (Lissovsky and Dudov 2021).

Species distribution modeling has been utilized, particularly in recent years, to create conservation and management strategies as well as to forecast possible distribution regions of rare and endangered species (Zhang *et al.* 2021; Acarer 2024). Species distribution models, including Bioclim, Climex, Domain, Garp, and MaxEnt, are widely employed to investigate the impact of climate elements and environmental variables on species (Qin and Li 2023). In this study, the effect of topographic and climate variables on wild olive distribution in Türkiye was investigated using the maximum entropy (MaxEnt) principle. It is known that MaxEnt, which is based only on species occurrence records and includes bioclimatic variables such as temperature and precipitation, gives high-performance results (Phillips *et al.* 2017). In addition, in this study, the analytical hierarchy process (AHP) method, which is one of the multiple decision-making methods, was used for the selection of environmental variables to be included in the model. Previously, the AHP method has various areas of use in many fields, including natural sciences (Salwa *et al.* 2019; Erdoğan Yüksel *et al*. 2024; Singer 2024). It has even become popular. However, it has not been used for variable selection in species distribution modeling studies. As a result, this study aimed to identify the variables affecting the potential distribution areas of the wild olive species with AHP and to map suitable areas using the MaxEnt method.

EXPERIMENTAL

Digital maps of environmental variables were prepared for Türkiye, and bioclimatic maps were obtained from the CHELSA database. Once all variables were prepared, occurrence data consisting of 416 records for the target species wild olive were obtained from the GBIF database. Expert judgement was used for a weighting process among all variables (including 10 topographic variables and 19 bioclimatic variables) using the Analytic Hierarchy Process (AHP) approach (Wind and Saaty 1980; Bertolini and Bevilacqua 2006). The most significant variables affecting the species' distribution were determined using this approach.

The AHP method establishes hierarchy. Next, it is decided which option is better than the others. The procedure is carried out in three phases by numerical scoring (Ömürbek *et al.* 2014; Özgür 2020). The first step in creating a hierarchy is deciding the goal. Variable selection is the study's defined aim. Lower in the hierarchy should be the criteria in charge of deciding the quality of the decisions. The lowest level of alternatives is what's needed. The table of significance degrees used in pairwise comparisons, as indicated in Table 1, should be prepared following the formation of the hierarchy. For every criterion, the options are ranked in pairwise matching in this table by Wind and Saaty (1980). For example, in this study, the elevation criteria is evaluated by comparing it with slope and aspect first, and then all the options are compared again with each other. When comparing the variable with itself in the decision matrix, the significance degree "1" ought to be applied. When doing pairwise comparisons, it is important to consider how important one alternative is relative to the others. The AHP method's application steps and formulae are determined by Özbek (2017) and Yıldırım and Önder (2018).

Table 1. Table of Importance Levels used in Pairwise Comparison (Wind and Saaty 1980)

Importance Level	Definition	Explanation
1	Equally Important	Both factors are of equal importance.
3	Moderately Important	According to experience and judgment, one factor is slightly more important than the other.
5	Strongly Important	One factor is significantly more important than the other.
7	Very Strongly Important	One factor is strongly more important than the other.
9	Absolutely Important	One of the factors is highly important than the other.
2, 4, 6, 8	Intermediate Values	They are intermediate values of the degrees in the lines above in the choice between two factors.

As mentioned above, each environmental variable that may have an impact on the distribution of the target species was weighed using the AHP approach. To determine its relative significance in affecting the distribution of the species, for instance, the elevation variable was weighted against the other variables. Each variable was subjected to this procedure. After that, they were reassessed using alternatives in order to assign a score to each of them (Fig. 1). The findings and recommendations of specialists studying the species' ecology were taken into consideration during this grading phase.

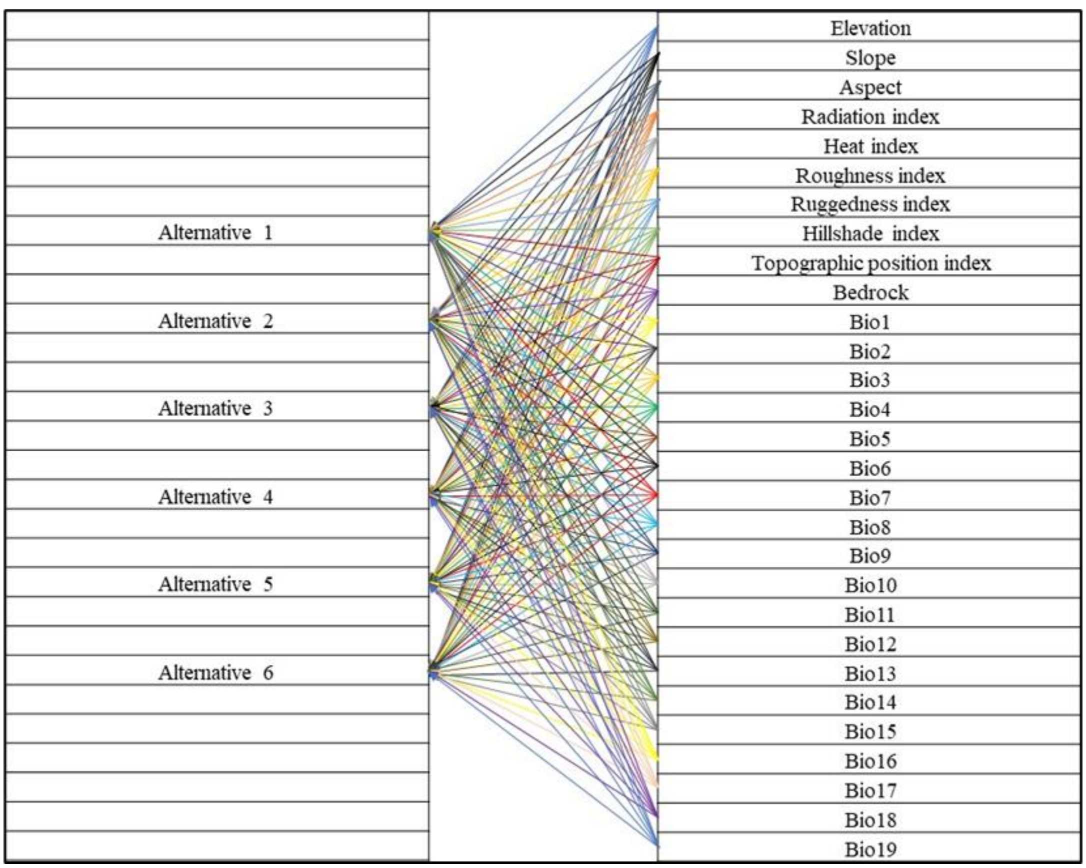

Fig. 1. Weighting of variables over alternatives

AHP calculations were performed in Microsoft Excel following the scoring of the environmental factors. The first row of matrix A12 represents the second column, while A21 represents the second column first row of the matrix. This notation is preferred as it allows for an infinite number of columns and rows, denoted by Ann. The AHP methodology consists of three fundamental ideas. Firstly, the framework of the model is established, followed by the comparison of alternatives and criteria, and finally, the determination of priorities. The pairwise comparison matrix shown in Table 2 is used to evaluate the relative suitability weights of n number of criteria.

Table 2. A Pairwise Comparison Matrix

Criteria	C1	C2	C3	Cn	Eigenvector ()	Criteria Vector (W)
C1	1	a_{12}	a_{13}	a_{1n}	$V_i = \prod_{i=1}^{n} a_{ij}^{\frac{1}{n}} \sum V_i$	$W_i = V_i / \sum V_i$
C2	$^1/_{a_{12}}$	1	a_{23}	a_{2n}		$W_i = V_i / \sum V_i$
C3	$^1/_{a_{13}}$	$^1/_{a_{23}}$	1	a_{3n}		$W_i = V_i / \sum V_i$
Cn	$^1/_{a_{1n}}$	$^1/_{a_{2n}}$	$^1/_{a_{3n}}$	1		$\sum W_i = 1$
Eigenvalue λ_{max}	$\sum C_{ji} \, x \, W_i$					
Consistency Ration (CR)	$\frac{(\lambda_{max} - n)/(n-1)}{RI}$					

Elevation (C1), slope (C2), aspect (C3), radiation index (C4), heat index (C5), roughness index (C6), ruggedness index (C7), hillshade index (C8), topographic position index (C9), bedrock (C10), bio1 (C11), bio2 (C12), bio3 (C13), bio4 (C14), bio5 (C15), bio6 (C16), bio7 (C17), bio8 (C18), bio9 (C19), bio10 (C20), bio11 (C21), bio12 (C22), bio13 (C23), bio14 (C24), bio15 (C25), bio16 (C26), bio17 (C27), bio18 (C28), and bio19 (C29) were all weighted and compared to each other. The pairwise comparison matrix of the criteria was made according to Eq. 1.

$$A = \begin{bmatrix} a_{11} & \cdots & a_{1j} & \cdots & a_{1n} \\ \vdots & & \vdots & & \vdots \\ a_{i1} & \cdots & a_{ij} & \cdots & a_{in} \\ \vdots & & \vdots & & \vdots \\ a_{1n} & \cdots & a_{nj} & \cdots & a_{nn} \end{bmatrix}, a_{ij} = 1, a_{ij} = 1/a_{ji}\,, a_{ji} \neq 0 \quad (1)$$

The conditions for this method are a_1, a_2, ... a_n. The total number of criteria is denoted by "n". A scale from 1 to 9 was used to measure the relative relevance of the two criteria. One point on this scale denotes "low importance," while nine points indicate "definitely more important." The process of determining the eigenvector (□) that fulfills the formula A_w = λ_{max} w—where λ_{max} is the biggest eigenvalue of matrix A—leads to the derivation of the comparison weights (Ozturk 2018). Here, the corresponding λ_{max} and the eigenvector w are determined for the condition (–A − λ_{max}) w = 0. To guarantee consistency of subjective perception and correctness of comparable weights, consistency ratio (CR) and consistency index (CI) were computed as follows,

$$CI = (\lambda_{max} - n)/(n-1) \quad (2)$$

$$CR = CI/RI \quad (3)$$

where *n* is the quantity of criteria. The RI is calculated for matrices of varying sizes, and for 29 × 29 matrices, its value was 1.68. For a reliable result, the CR value must be below 0.1 (Table 3).

Table 3. Random Value Indices

Number of criteria (N)	1	2	3	4	5	6	….	29
Random Value Index (RI)	0.00	0.00	0.58	0.90	1.12	1.24		1.68

After the variables that are effective in the distribution of wild olive species were determined by the Analytic Hierarchy Process (AHP) approach based on expert opinions, the model was run in the MaxEnt program utilizing only these variables.

RESULTS AND DISCUSSION

Wild olive was modeled and mapped using the variables determined *via* the AHP method. The cumulative increase values of the variables weighted and the weight of each criterion by the AHP method are presented in Figs. 2 and 3, respectively.

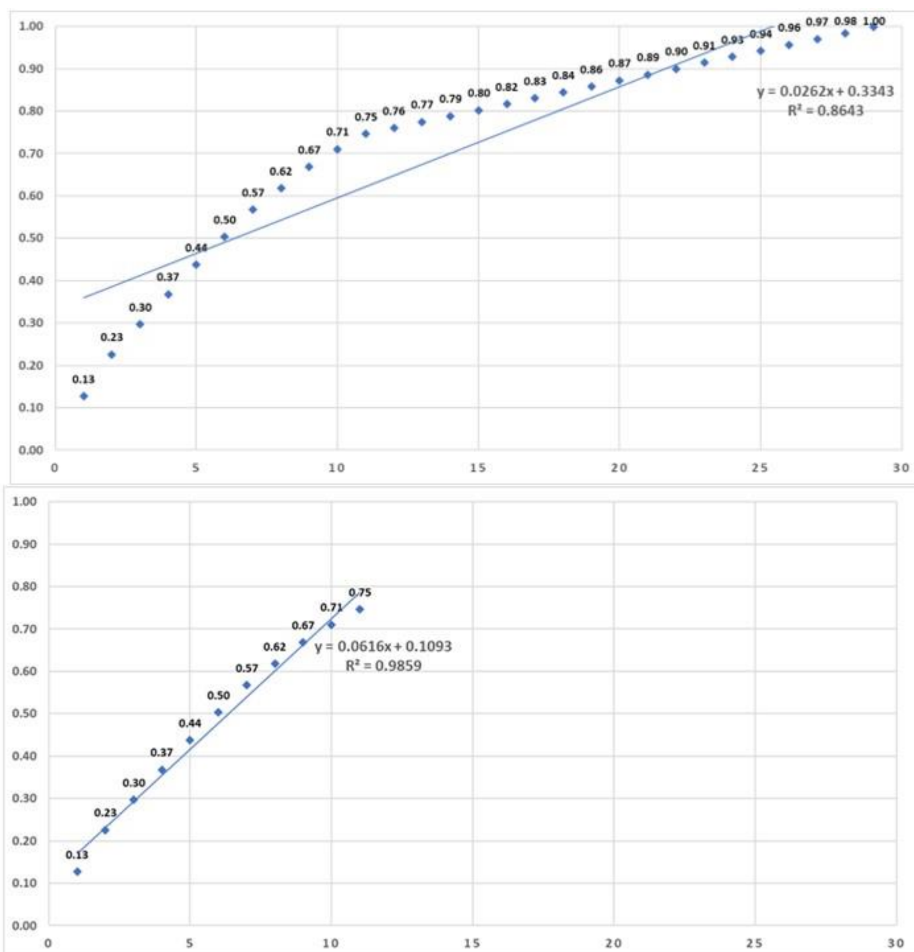

Fig. 2. The cumulative increase trend of the weighted average values of the criteria and R^2 values

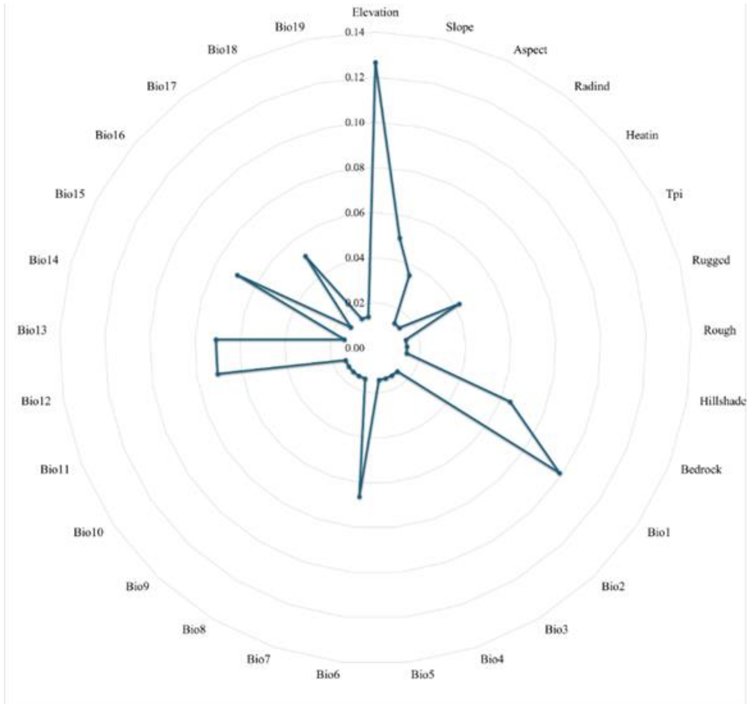

Fig. 3. Weight of each criterion

In Figs. 2 and 3, it can be observed that the first 11 weighted variables reached the 0.75 level. In other words, according to expert evaluations, the top 11 criteria, which play a significant role in determining the distribution of wild olive, accounted for 75% of the total cumulative weighted percentage. This result was derived from the sum of the calculated weights of each variable.

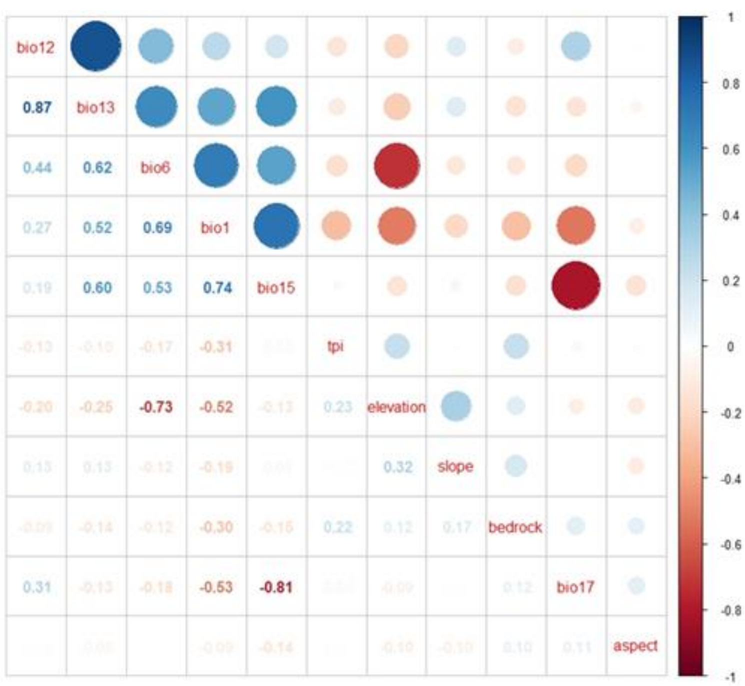

Fig. 4. Correlation analysis results of the environmental variables

After the first 11 variables, the cumulative increase showed a declining trend. The influence of the remaining variables is minimal and uniform. Additionally, the highest R^2 value was also achieved with these first 11 variables. Thus, these 11 criteria are considered to represent the majority of the variables' overall impact. To mitigate potential multicollinearity during the modeling process, a correlation analysis was performed among these 11 variables (Fig. 4).

After the correlation analysis, high correlation ($p>0.80$) was observed between bio12 - bio13 and bio15 - bio17. Among the climate variables with high correlation, it was determined that bio12 and bio15 would play a more active role in the distribution of wild olive (Kassout *et al.* 2022; Çıvğa *et al.* 2023). Therefore, bio13 and bio17 were not included in the modeling phase.

The modeling process was conducted with 9 variables that were selected by correlation analysis. The variables that created the model and their contribution rates are given in Table 4, respectively.

Table 4. Variables Constituting the Model and their Contribution Rates

Variable	Percent Contribution
elevation	68.1
bio15	12
bedrock	5.4
bio1	4.2
slope	3.7
bio6	3.5
bio12	2.3
aspect	0.7
tpi	0.1

The omission curve and ROC curve of the species distribution model generated using the above variables are presented in Figs. 5 and 6.

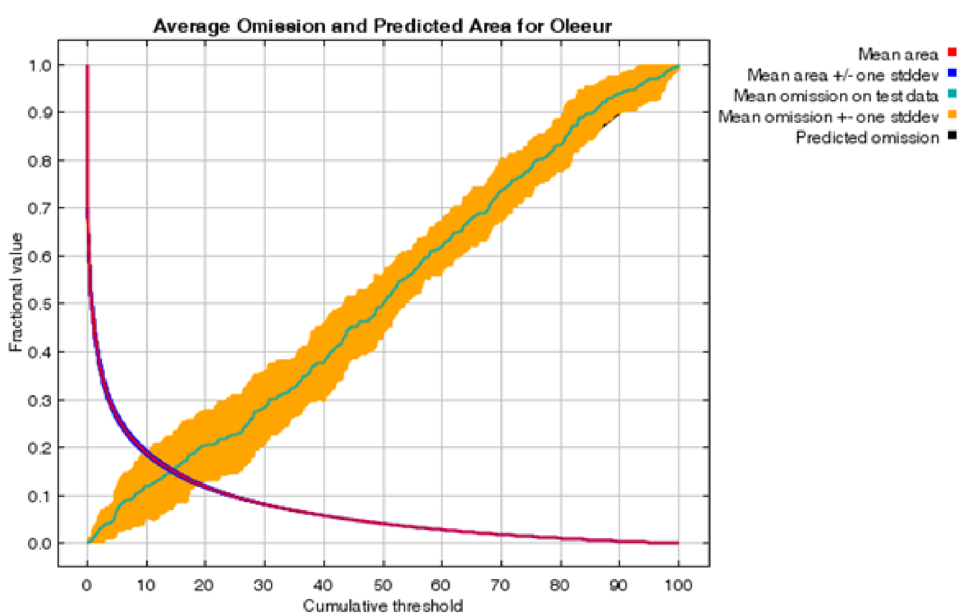

Fig. 5. Omission curve of the model

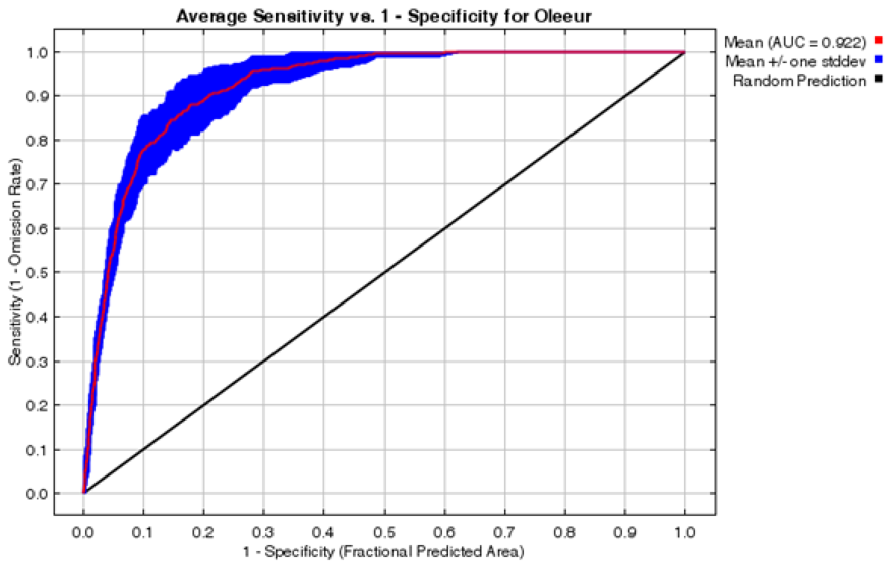

Fig. 6. ROC curve of the model

Figure 5 shows that averaged over repeated runs, the test omission rate and anticipated area as a function of the cumulative threshold. The receiver operating characteristic (ROC) curve for the identical data, once more averaged over the duplicate runs, is shown in Fig. 6. The standard deviation was 0.014, and the average test AUC for the duplicate runs was 0.922. The graph representing the jackknife test, which is another parameter considered during the validation of the model for the target species, is provided in Fig. 7.

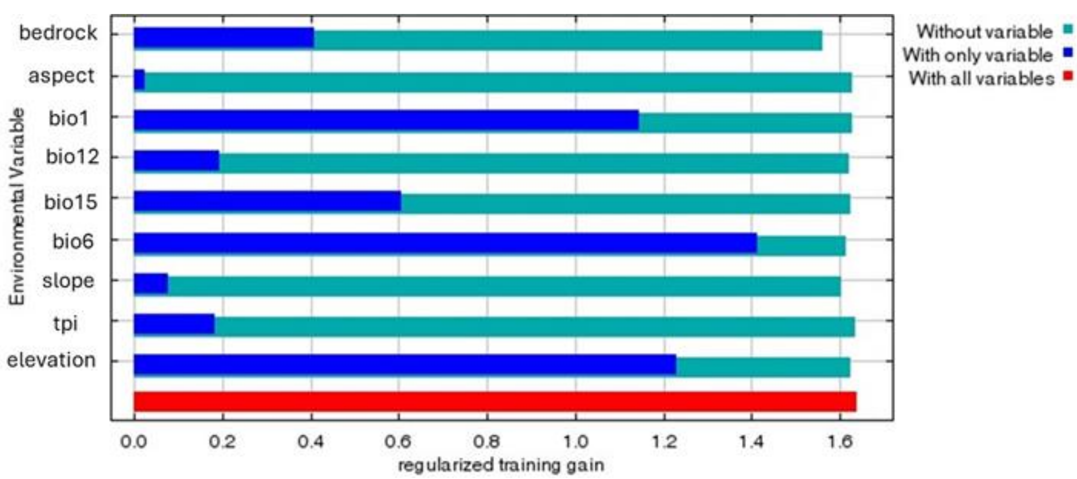

Fig. 7. Jackknife graph of the model

Bio6 emerged as the most informative environmental variable when used independently, providing the greatest benefit in isolation. Conversely, bedrock was the variable whose exclusion resulted in the largest reduction in model gain, indicating that it contained unique information not captured by the other variables. The reported values are averages over multiple runs. The potential distribution map acquired by MaxEnt is presented in Fig. 8.

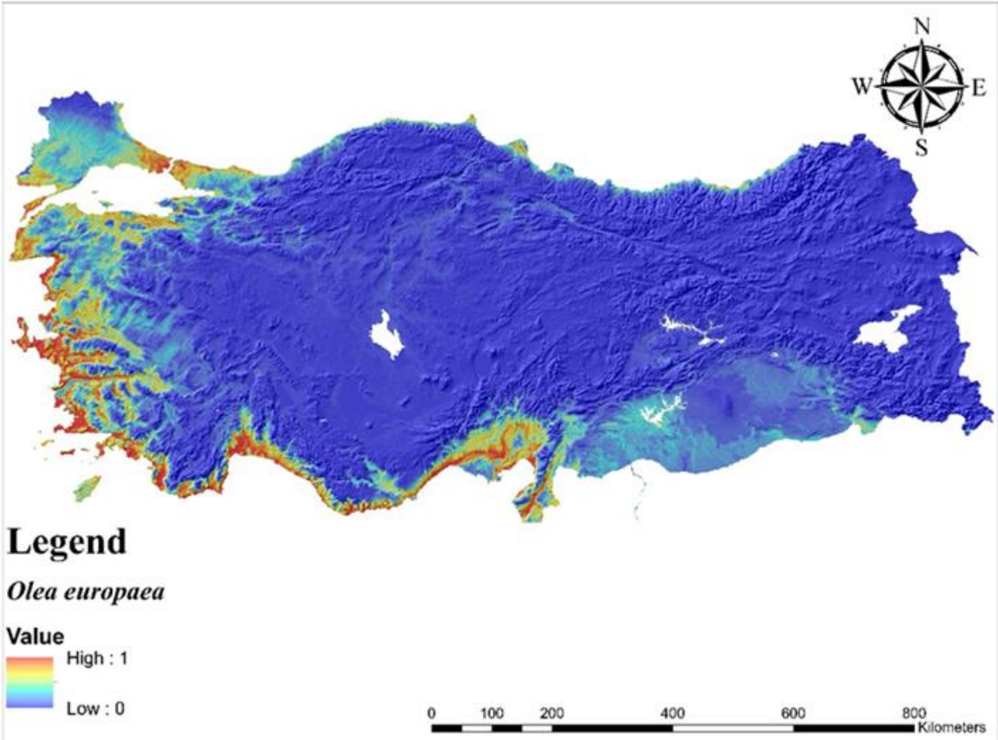

Fig. 8. The potential distribution map created by MaxEnt

The potential distribution map for wild olive indicates that the most suitable habitats for the species are predominantly found in the southern, western, and northwestern regions of Türkiye. These areas share a common feature: they are all influenced by the Mediterranean climate, which provides favorable conditions for the growth of wild olive trees. The Mediterranean climate is characterized by mild, creating an environment that supports the ecological requirements of wild olive.

The first result of the study indicates that the variables affecting the potential distribution of wild olive are elevation, bio15, bedrock, bio1, slope, bio6, bio12, aspect, and tpi. The AUC value of the model created with these variables was 0.922. According to Swets (1988), AUC values of distribution models are classified as follows: AUC ≥ 0.90 is considered excellent, 0.90 > AUC > 0.81 is good, 0.80 > AUC > 0.71 is fair, 0.70 > AUC > 0.61 is poor, and AUC < 0.60 is considered a failure. Accordingly, the model of this study corresponds to the "excellent" model class.

The results of the variables creating the model in the present study coincided with the results of many studies on the ecological requirements of wild olive. In a study by Efe *et al.* (2009), it was mentioned that temperatures throughout the year affect the growth and yield of the species. Similarly, another study indicated that the species avoids high-altitude areas with harsh and drying winds during flowering time and can be productive up to a maximum altitude of 600 m (Ayaz and Varol 2015). In another study, the distribution and yield of the species decrease on steep terrain (Tunalıoğlu and Gökçe 2002). Another study aimed at determining suitable areas for olive production in Türkiye using the AHP method emphasized the role of temperature and precipitation variables in determining suitable production areas. According to the results of the study, the optimal annual average temperature for olive cultivation was determined to be between 14.4 and 19.2 °C. Moreover, the study indicated that compared to many other plants, the olive species is more tolerant in terms of soil requirements; however, fruit quality and yield increase are particularly better in loamy and sandy loam soils (Tuğaç and Sefer 2021). Additionally, soil reaction, organic matter content, lime content, and soil water-holding capacity were highlighted as crucial factors for the olive species (Galán *et al.* 2008; Aguilera and Ruíz-Valenzuela 2009). As can be understood from both this study and various studies, it is seen that wild olive are not very wide in terms of ecological requirements. In other words, its ecological requirements are within certain limits. Therefore, this species can find its temperature requirement, altitude suitability, and suitable soil properties in the Western and Southern regions of Turkey. The inner parts of Turkey are higher in altitude, lower in temperature, and different in terms of soil properties. Due to one or more of these reasons, wild olive cannot find a suitable growing environment in the Northern and inner parts of Türkiye.

In summary, when it comes to olive trees, the first thing that comes to mind is olive oil. Olive oil has been used for centuries in the treatment of various diseases, and there are numerous studies on this subject. Olive oil and its components have been indicated to be used in cardiovascular and metabolic diseases, breast and intestinal cancers, hypertension, and diabetes (Alarcón de la Lastra *et al.* 2001; Komaki *et al.* 2003; Mushtaq *et al.* 2020). The use of olive tree leaves for the treatment of various diseases is also quite common. Olive leaf extracts are widely used in conditions such as stomach, lung, and bowel cancer, gum inflammation, middle ear infection, intestinal rhythm disorders, muscle spasms, hypertension, and cholesterol (Haloui *et al.* 2010; Susalit *et al.* 2011; Tekin *et al.* 2022). *O. europaea* is important as a food and for human health. The contribution of the species not only to human health but also to natural ecosystems is undeniable. With the impact of climate change, significant increases in temperature are projected globally, including in Turkey.

The wild olive is also a species that exhibits resilience to heatwaves, salinity, and drought (Belaj *et al.* 2007). In this case, it can be considered that climate change is not the main factor threatening the distribution of wild olive. However, two critical considerations emerge. The first is productivity, that is, the quality of the olives produced. It has been seen that there is not enough work on this subject and comprehensive studies need to be conducted.

The second and more pressing issue is the potential indirect effects of climate change such as diseases, parasites, and pests. For instance, a study by Akçay *et al.* (2014) on 60 different olive varieties derived from wild olive cultivation did not find genetic variation. In other words, the results indicated that the expanded cultivars most likely originated from clones of a single tree, showing 100% genetic identity among the samples. This lack of genetic variation indicates that the species is highly vulnerable to threats such as diseases, parasites, and pests. In other words, if these threats were to materialize, the wild olive could face a significant risk of extinction. Additionally, climate change may indirectly trigger these threats by creating conditions that favor the spread of diseases, parasites, and pests.

Therefore, to ensure the species' long-term survival, it is crucial to identify its ecological requirements and potential distribution areas. In addition, doing the species to the identified potential areas sowing or planting and expanding its distribution represents the most effective measure that can be implemented in practice.

CONCLUSIONS

1. In this study, the potential distribution of wild olive has been determined using the MaxEnt method, and its potential distribution areas have been identified.
2. This study provides valuable outputs for management plans aimed at meeting the demand for the fruit, leaves, and wood resources of wild olive, which has extensive use in conservation, development, sustainability, and industrial sectors.
3. Modeling and mapping the potential distribution of wild olive for the present can be combined with future studies on climate change and biodiversity, offering valuable contributions to researchers.
4. The results obtained from this study may be useful and guiding in terms of measures that can be taken to address the aforementioned potential problems (diseases, parasites, and pests).

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