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Modeling of the Potential Distribution Areas Suitable for Olive (*Olea europaea* L.) in Türkiye from a Climate Change Perspective

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Abstract: Türkiye is one of the first regions where olives were domesticated, and olives reflect the country's millennia-old agricultural and cultural heritage. Moreover, Türkiye is one of the leading nations in olive and olive oil production in terms of quality and diversity. This study aims to determine the current and future distribution areas of olives, which is important for Türkiye's socio-economic structure. For this purpose, 19 different bioclimatic variables, such as annual mean temperature (Bio1), temperature seasonality (Bio4), and annual precipitation (Bio12), have been used. The RCP4.5 and RCP8.5 emission scenarios of the CCSM4 model were used for future projections (2050 and 2070). MaxEnt software, which uses the principle of maximum entropy, was employed to determine the current and future habitat areas of the olives. Currently and in the future, it is understood that the Mediterranean, Aegean, Marmara, and Black Sea coastlines have areas with potential suitability for olives. However, the model projections indicate that the species may shift from south to north and to higher elevations in the future. Analyses indicate that the Aegean Region is the most sensitive area and that a significant portion of habitats in the Marmara Region will remain unaffected by climate change.

Keywords: Türkiye; climate change; *Olea europaea* L.; olive; species distribution modeling; MaxEnt; sustainability

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1. Introduction

Olive (*Olea europaea* L.), recognized as a bio-indicator species of the Mediterranean Basin [1], has ancient significance owing to its ecological, economic, and cultural importance. Within the genus Olea, *Olea europaea* L. stands out as the most distinguished member [2]. Historical evidence suggests that olives were cultivated in the Levant Region, situated in the northeast of the Mediterranean Basin, approximately 6000 years ago. Over time, they have spread across the Mediterranean Basin through domestication processes [3,4]. Cultivating in regions characterized by a Mediterranean climate, *Olea europaea* L. spans latitudes between 30° and 45° in both the northern and southern hemispheres [5,6]. Remarkably, more than 90% of olive trees worldwide are concentrated in the Mediterranean Basin [7]. This resilient species exhibits adaptability to diverse elevations and soil conditions, which are influenced by its geographical location. Additionally, the olive tree demonstrates resilience to drought stress and varying temperature regimes [8,9].

The average annual temperature for the natural growth of olives generally ranges from 15 °C to 20 °C [10]. However, in Türkiye, the lower limit for olive cultivation areas is 14.5 °C [6]. Olive trees exhibit resilience to temperatures as low as −8 °C for short durations [11], while the upper limit is approximately 40 °C [12]. The adequate annual precipitation for olive cultivation areas is considered to be above 400 mm [10], and in regions without irrigation, the minimum annual precipitation requirement is 500 mm [13]. As a dynamic system, the climate undergoes constant changes at various temporal and spatial scales. In comparison to the period of 1850–1900, the global surface temperature has reached beyond 1.1 °C during the 2011–2020 period. It is widely acknowledged that both anthropogenic activities and greenhouse gas emissions contribute significantly to this warming trend [14]. Consequently, global climate change has led to an increase in the frequency and severity of extreme weather and climate events.

The Mediterranean Basin, which includes Türkiye, has been identified as a "hotspot" of climate change [15]. Existing studies in the literature indicate a trend of increasing warmth and aridity in the Mediterranean Basin [16,17]. It is argued that there is a significant warming trend in the annual average, annual average maximum, and annual average minimum air temperatures across Türkiye [18]. Numerous studies corroborate the increasing temperature trend in Türkiye [19–21], and depending on climate projections, the country is expected to experience substantial temperature increases in the future [22].

Short-term and long-term changes in climate parameters, especially temperature and precipitation, affect biodiversity. Climate change in the past has led to the extinction of certain species, while others have altered their geographical distributions [23], indicating the vulnerability of species to climate change [24]. Climate change, a major ecological stressor on flora and fauna, is increasingly manifesting its effects on species [25]. It has been mentioned in many studies that changes observed in climate parameters may cause changes in phenology, geographical distribution, population size, and genetic diversity of species, as well as increase habitat loss and fragmentation [26–30].

Future changes in species habitat areas are anticipated due to climate change. For instance, it has been suggested that while there will not be significant habitat losses for the species *Cornus mas* L., which is distributed in Turkey, its range is expected to shift toward the northern and northwestern regions of the country in the future [31]. They have stated that the species *Juniperus excelsa* M. BIEB., which is distributed in the Göller Region, will shift toward the interior regions of Western Anatolia and the Western Black Sea by the year 2070 [32]. They have reported that the species *Carpinus betulus* L. may shift northward in the future, reducing its current distribution areas in Anatolia and surrounding regions [33].

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. Constructed using species presence data and selected environmental variables, these models facilitate the temporal and spatial prediction of current and possible future changes in species distribution, especially under various climate change scenarios [34,35]. The outputs of these models play a crucial role in identifying and mitigating the impacts of climate change on species, contributing to the formulation of sustainable management plans [30]. The influence of climate change on olive cultivation in Türkiye was examined in this study using the maximum entropy principle. The current and future distribution areas of the olive plant were investigated using MaxEnt software, utilizing bioclimatic variables. MaxEnt, relying solely on the presence records of the species and incorporating bioclimatic variables, such as temperature and precipitation, is known to deliver high-performance results [36]. Hence, MaxEnt was chosen as the preferred species distribution modeling method for this study.

Study Area

The study area, Türkiye, located in the northern hemisphere and the middle belt between latitudes 36°–42° N and longitudes 26°–41° D (Figure 1), which serves as a bridge between Europe and Asia, is divided into seven geographical regions according to its natural, human, and economic characteristics: Black Sea, Marmara, Aegean, Mediterranean, Southeastern Anatolia, Eastern Anatolia, and Central Anatolia [37].

Türkiye, positioned between temperate and subtropical belts, experiences various climate types that are influenced by its mathematical and special location. The interplay of different air masses throughout the year, the country's three-sided coastal exposure to seas, and diverse landforms over short distances contribute to this climate diversity. Temperate climate characteristics rule in the coastal regions of Türkiye, which are mainly influenced by maritime effects. However, in the country's interior, the dominance of continental climate features is notable. This is attributed to the North Anatolian Mountains and Taurus Mountain ranges running parallel to the coast, which act as barriers preventing the sea's influence from reaching the interior. The highest average precipitation in Türkiye is observed during the winter months (December, January, and February), while the highest average temperatures occur in summer (June, July, and August). Regions such as the Aegean and Mediterranean coasts, along with the Southeastern Anatolia Region, experience consistently higher temperatures throughout the year compared to others [22]. Particularly, the Southeastern Anatolia Region maintains elevated temperatures year-round, attributed to its exposure to hot and dry winds from the south. Based on long-term average temperatures for the period 1991–2020, the overall average temperature in Türkiye is 13.9 °C. In the same period, regional average temperatures are as follows: Southeastern Anatolia Region 17.4 °C, Mediterranean Region 17.3 °C, Aegean Region 16.1 °C, Marmara Region 14.6 °C, Black Sea Region 12.8 °C, Central Anatolia Region 11.1 °C, and Eastern Anatolia Region 9.8 °C [38]. The average annual total precipitation for the corresponding period is recorded at 574 mm [39].

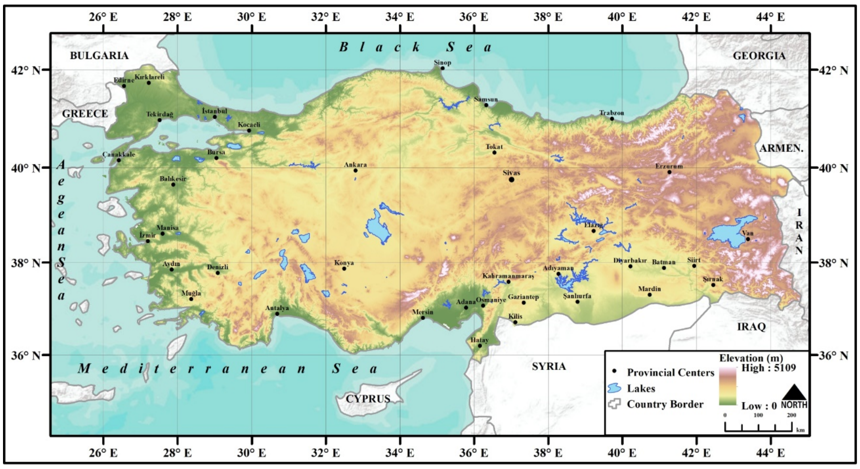


Figure 1. Location map of the study area.

Türkiye is under the influence of three main climate types, as classified by the Köppen-Geiger climate classification system: arid climate type (B), mild humid mid-latitude climate type (C), and cold humid mid-latitude type (D). The dominant climate type in the interior of the country and certain parts of the Southeastern Anatolia Region is type B. Regions such as the Aegean and Marmara experience a dominant type C climate. Type C climate is also prevalent in a significant portion of the Southeastern Anatolia Region and along the coastal areas of the Mediterranean and Black Sea Regions. The impact of the D climate type is notable at high elevations in Central Anatolia, Southeastern Anatolia, and the Black Sea Regions, as well as in a substantial part of the Eastern Anatolia Region [40].

Various factors, including short-distance variability in climatic characteristics, diverse morphological features, and soil types, contribute to the differentiation and species enrichment of plant formations within the study area. The study area hosts approximately 12,000 plant taxa [41]. Olive cultivation holds significant importance in Türkiye, with its distribution extending from the southern parts of Mardin in the Southeastern Anatolia Region, spreading along the Black Sea coasts, and continuing through the coastal and low-lying areas of the Mediterranean, Aegean, and Marmara Regions [6]. Presently, the Mediterranean, Aegean, and Marmara Regions provide optimal climatic conditions for olive cultivation, while olive cultivation activities in the Southeastern Anatolia Region face challenges due to high temperatures and drought [42]. In Türkiye, 50% of olive production occurs in the Aegean, 27% in the Mediterranean, 20% in the Marmara, and 3% in the

Southeastern Anatolia regions [43]. Key production centers for table and oil olive are Izmir, Manisa Aydın and Muğla in the Aegean Region; Balıkesir, Bursa, and Çanakkale in the Marmara Region; Mersin, Hatay, Osmaniye and Antalya in the Mediterranean Region; Gaziantep, Kilis, Şanlıurfa, Adıyaman, and Mardin in the Southeastern Anatolia Region (Figure 2).

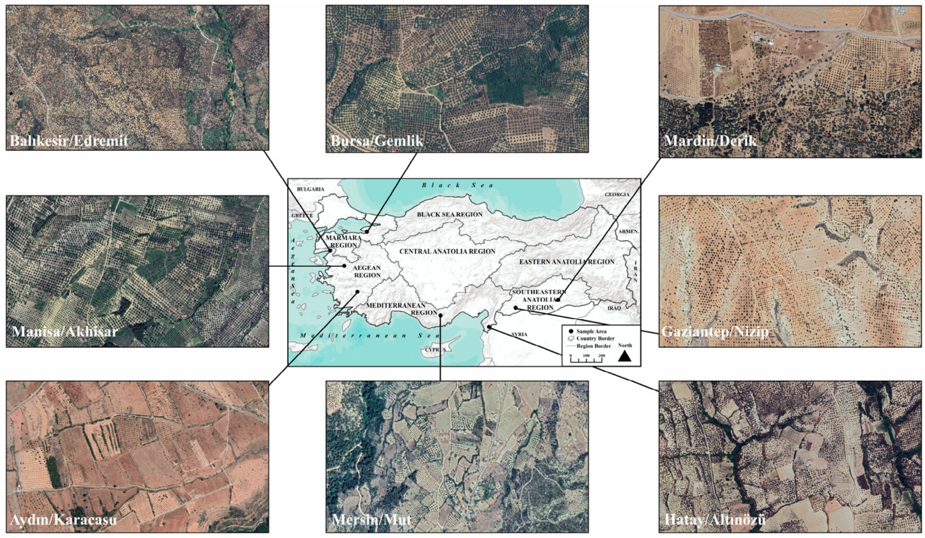


Figure 2. Satellite images of some olive orchards in the study area.

2. Materials and Methods

2.1. Species Data

The study material comprises the olive plant (*Olea europaea* L.), a species of significant importance to Türkiye's biodiversity, with substantial economic and cultural value. In this study, the presence data for olives in Türkiye and its neighboring countries were obtained from the GBIF (Global Biodiversity Information Facility) database [44], Flora of Turkey [45], and presence data compiled by other researchers [46]. We removed duplicate points, and only one point in each grid cell (1 km × 1 km) was retained, with data obtained from GBIF. A total of 512 presence records (Figure 3) were geographically coordinated using a Geographic Information System (GIS); subsequently, they were all saved in CSV format based on the requirements of the MaxEnt model. The GBIF database stands out as one of the most widely utilized databases in species distribution and ecological niche modeling studies [31,47–49].

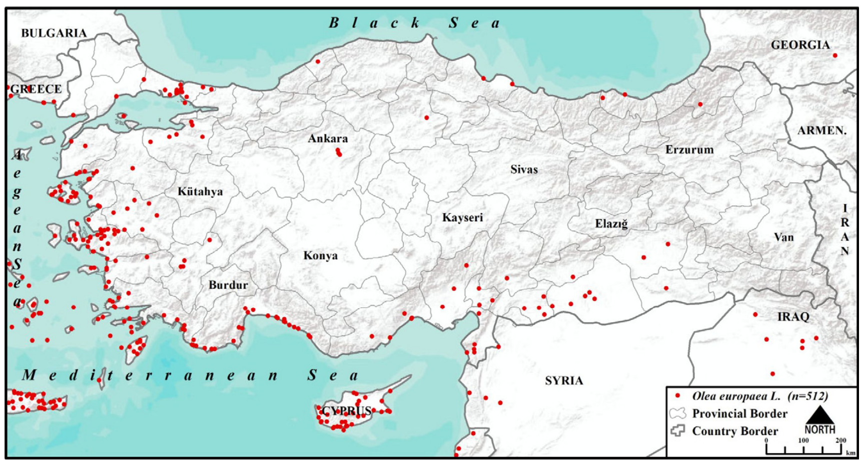


Figure 3. Distribution of the presence data used in the study (n = 512).

2.2. Bioclimatic Variables

This study employed bioclimatic variables to assess the current and projected status of olive plants both temporally and spatially, focusing on the future period of 2050–2070. To determine the present potential habitat areas, climate data for the reference period of 1960–1990 (Figure 4) were acquired from the WorldClim database (WorldClim Version 1.4), encompassing 19 bioclimatic variables with a spatial resolution of 30 s.

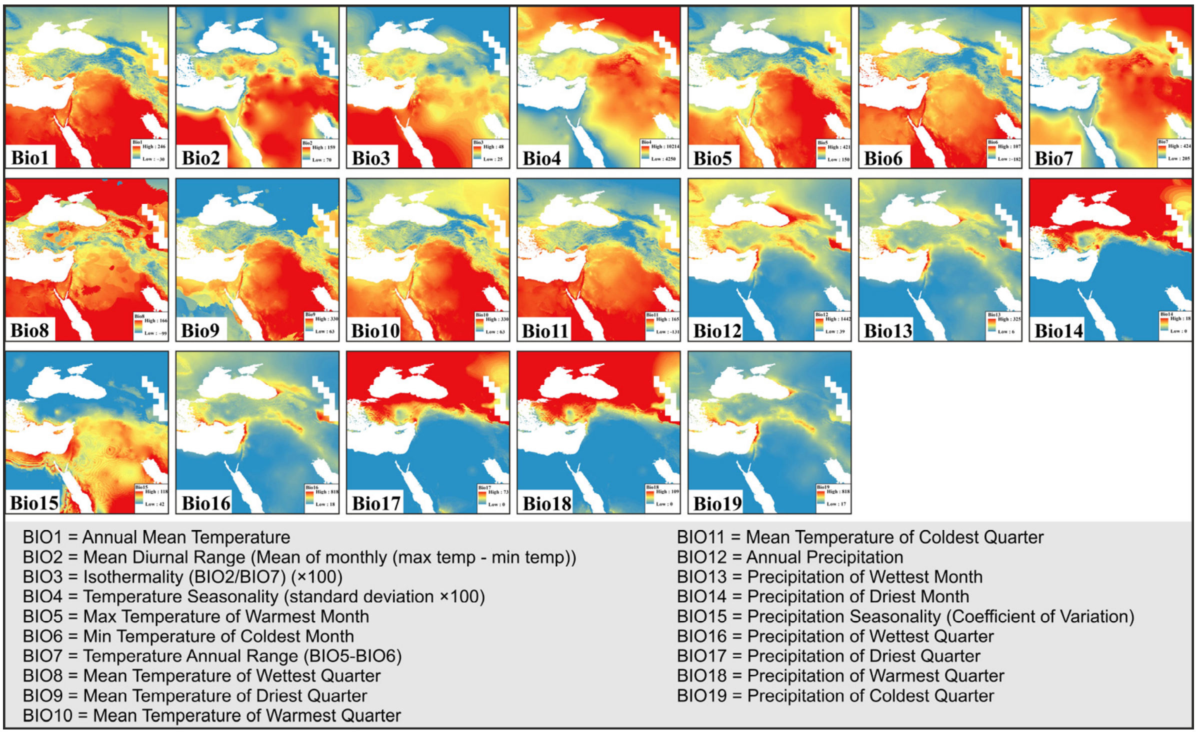


Figure 4. Bioclimatic variables with the reference period of 1960–2000 (While blue represents low values, the colors shift toward red as the values increase).

These climate data, fitted to the study area, were then converted into ASCII format and saved. For the future model, the CCSM4 model (Community Climate System Model 4) [50], part of the Coupled Model Intercomparison Project Phase 5 (CMIP5) and inclusive of the atmosphere, ocean, land, land ice, and sea ice components, was employed. Within the CCSM4 model, two distinct Representative Concentration Pathways (RCP) were considered as part of the study, namely RCP4.5 scenarios representing moderate concentrations and RCP8.5 scenarios with high atmospheric concentrations [51]. The average data for 2050 (2041–2060) and 2070 (2061–2080) under these medium and extreme RCP scenarios were retrieved from the WorldClim database, maintaining a spatial resolution of 30 s, and subsequently transformed into the ASCII format.

2.3. Statistical Analyses and Mapping

To avoid multicollinearity and improve the predictive accuracy of the model, a correlation analysis was conducted on 19 bioclimatic variables [52]. This analysis was conducted using the "Calculate Climate Heterogeneity: Principal Component Analysis" tool within the SDMToolbox v2.5, GIS software, and a correlation matrix was generated [53]. Variables with a correlation coefficient of ±0.85 or higher in the correlation matrix were excluded from the modeling process to eliminate redundancy [54,55].

MaxEnt 3.4.4. software was employed to assess both the current and possible future distribution of the olive plant. This software, operating on the principle of maximum entropy, is a preferred tool in the relevant literature due to its ability to analyze based solely on presence data, offer robust predictions with limited data, exhibit reduced sensitivity to environmental errors in location data, and facilitate the use of both categorical and continuous data [28,56,57]. In MaxEnt software, training data was set to 90%, and testing data was set to 10%; Cloglog was selected as the output type and analyzed using automatic features [36]. A cross-validation technique was applied to ensure the accuracy and consistency of the models [58]. The modeling process was repeated 15 times with 10,000 background points to ensure reliable model prediction [59,60]. The species distribution model generated in MaxEnt assigns a probability ranging from 0 (low) to 1 (high), to indicate the likelihood of the examined species being present in a given area. A value closer to 1 indicates a higher probability, while a value closer to 0 suggests a lower likelihood of the species being found in that area [61].

The performance of the models created using MaxEnt software was evaluated through the Area Under the ROC Curve (AUC) value obtained from the Receiver Operating Characteristic (ROC) analysis. The AUC is a measure used to assess how effectively it can distinguish between the asset records used in the model and a random background, and the average AUC obtained in this study was obtained after fifteen repetitions. Typically, the AUC value falls between 0.5–1. The obtained AUC value is assessed as follows: AUC ≥ 0.9 = very good, 0.9 > AUC ≥ 0.8 = good, and AUC < 0.8 = poor [62,63]. The closer the AUC value is to 1, the stronger the relationship between the variables used and the predicted geographical distribution of the studied species, indicating a more accurate model performance [64]. The Jackknife test was employed to determine the contribution of each independent variable used in the models [33,65]. Lastly, the model output was categorized into five suitability classes (Unsuitable, Barely Suitable, Suitable, Highly Suitable, and Very Highly Suitable) and visualized in the GIS environment.

3. Results

According to the correlation matrix result, the modeling process was carried out with eight independent variables: Bio2 (Mean diurnal range), Bio3 (Isothermality), Bio4 (Temperature seasonality), Bio8 (Mean temperature of wettest quarter), Bio9 (Mean temperature of driest quarter), Bio12 (Annual precipitation), Bio14 (Precipitation of driest month), and Bio15 (Precipitation seasonality) (Figure 5).

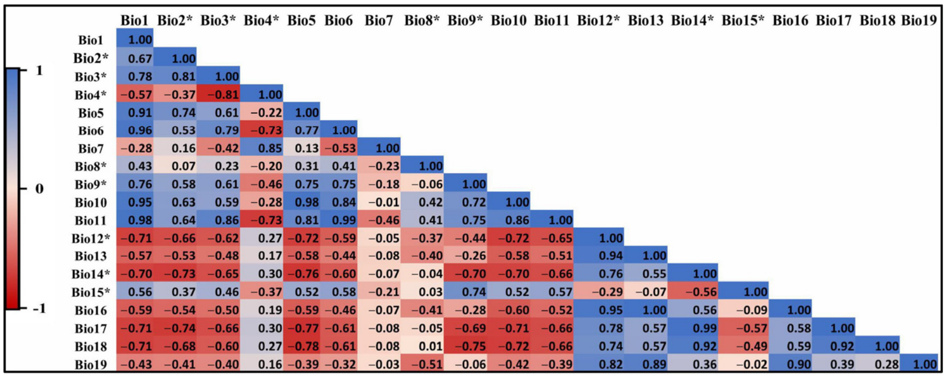


Figure 5. Correlation analysis results of the bioclimatic variables used in the modeling (*: selected variables).

The average AUC value of the model created using the determined variables was 0.925. These AUC values show that the model has very good predictive power (AUC ≥ 0.9) (Figure 6a). Bio12 (35%), Bio4 (29.3%), and Bio9 (19.9%) are the environmental variables that contribute the most to the model (Table 1). According to the Jackknife test, Bio9 is the environmental variable that increases the gain the most when used alone. When removed from the model, Bio12 is the environmental variable that decreases the gain the most. (Figure 6b).

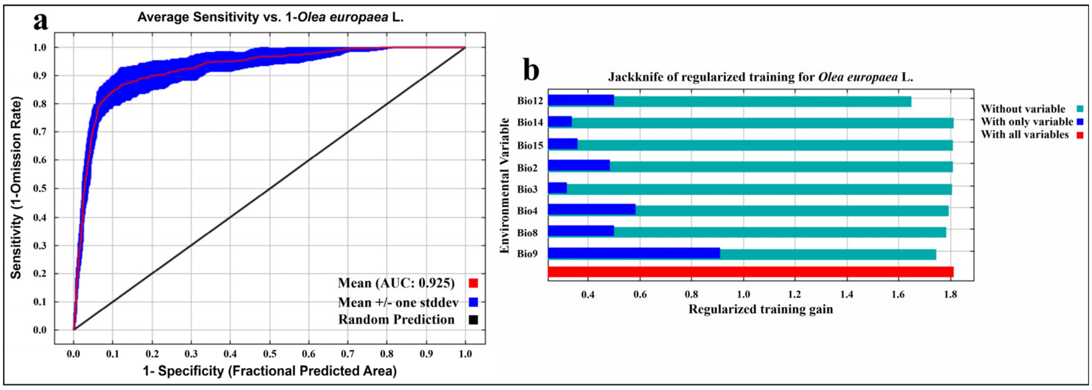


Figure 6. AUC values of the model (**a**) and Jackknife test results (**b**).

Table 1. Bioclimatic variables used as environmental inputs in the models and their percentage contribution (%).

Code	Bioclimatic Variables	Unit	Contribution (%)
Bio12	Annual Precipitation	mm	35.0
Bio4	Temperature Seasonality	C or %	29.3
Bio9	Mean Temperature of Driest Quarter	°C	19.9
Bio15	Precipitation Seasonality	%	7.9
Bio8	Mean Temperature of Wettest Quarter	°C	3.6
Bio2	Mean Diurnal Range	°C	1.6
Bio3	Isothermality	%	1.5
Bio14	Precipitation of Driest Month	mm	0.6

When examining the response curves of the bioclimatic variables with high contribution, it is observed that olive trees prefer areas where total precipitation is up to 1000 mm, and their distribution decreases as precipitation increases (Figure 7a). Similarly, their distribution increases in regions where the seasonal temperature range is up to 500, but decreases as the temperature range continues to rise (Figure 7b). Moreover, it is evident that the species declines when the mean temperature of the driest quarter exceeds 25 °C (Figure 7c).

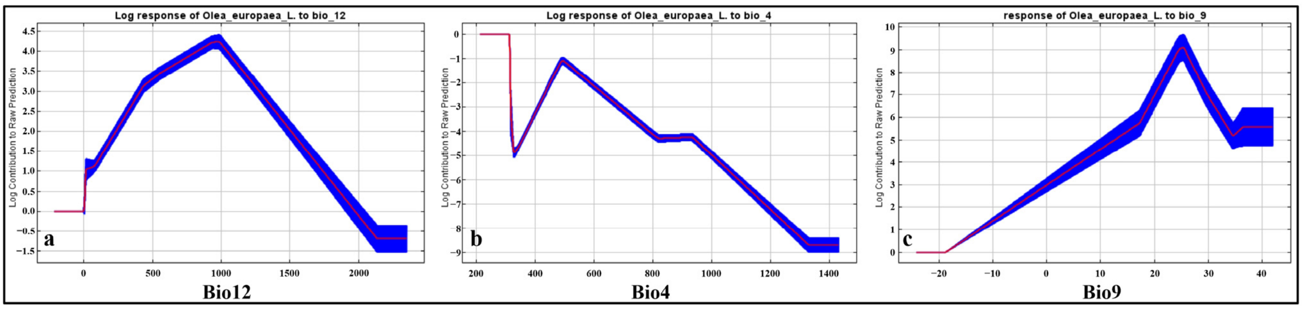


Figure 7. Response curves of bioclimatic variables with high contributions: (**a**) Bio12; (**b**) Bio4; (**c**) Bio9.

3.1. Distribution of Potential Habitat Areas Today

According to the current model designed to identify the present potential habitat areas for the olive plant in Türkiye, regions classified as suitable for the species are predominantly observed along the Mediterranean, Aegean, and Marmara coasts. While potentially suitable areas extend to the eastern part of the Mediterranean Region and the interior of Hatay, they become fragmented and interrupted where the elevation increases. The southern slopes of the Taurus Mountains, running parallel to the Mediterranean coast, present potential suitability for olives. Due to the fact that the Taurus Mountains prevent maritime influence in the Mediterranean from entering inland areas, and thus the climatic conditions differ between the south and the north of the mass, suitable areas for olives in the Mediterranean Region are limited along the coastal line. In the Aegean Region, the coastline and plains align with areas classified as suitable. However, as one moves inland from the coast and toward higher elevations, suitable areas give way to unsuitable terrain (Figure 8).

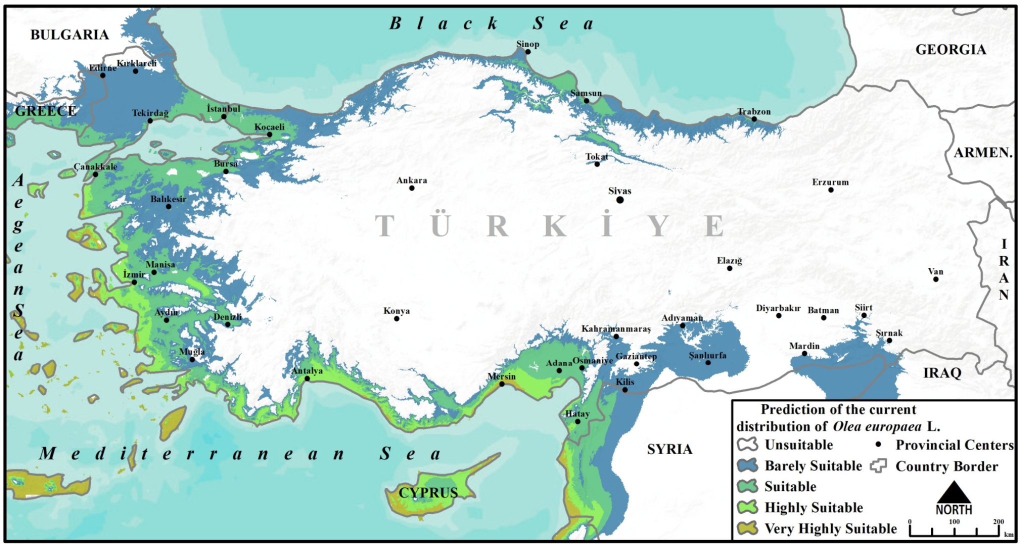


Figure 8. Potential habitat areas for the present day derived from recent historical data with the reference period of 1960–1990.

In the Marmara Region, suitable areas are identified along the coastal belts of the Aegean, Marmara, and Black Seas within the region. In Balıkesir, inland regions do not provide suitable habitats for olives, whereas the coastal area, characterized by a Mediterranean climate, offers potentially highly suitable habitats. Particularly, the northern and western parts of Balıkesir correspond to areas where the species can potentially have a suitable distribution. Regions with elevation in parallel with changing climatic conditions and geographical features are not considered potentially suitable areas under current conditions. Bursa stands out as one of the provinces with significant potential areas in the Marmara Region. Especially, due to Uludağ located to the south of Bursa, suitable potential areas can be observed in other parts of the province except the southern region. Uludağ, in the south, does not provide a suitable habitat for the species due to unfavorable topographical, edaphic, and climatic conditions. However, the lowlands of Bursa exhibit a very high potential for habitat suitability. Potentially suitable habitat areas are also observed around Lake İznik, situated in the depression between the Samanlı Mountains and Katırlı Mountains in the northeast of Bursa. According to the present-day model, suitable areas for olives are evident along the line stretching from Bursa to the Greek border of Türkiye (Figure 8).

A substantial part of Istanbul falling within this designated line presents potentially suitable habitats. However, despite their apparent suitability, considering the encroachment of urbanization and other anthropogenic effects, it can be asserted that these areas are potentially suitable but not conducive to species distribution. There are suitable habitat areas along the Black Sea coast. The most remarkable among these areas are the lowland areas of Samsun. Most of the Southeastern Anatolia Region does not harbor potentially suitable areas. Nevertheless, specific parts of Kilis, Gaziantep, Adıyaman, Şanlıurfa, Mardin, and Şırnak provinces feature a few suitable areas (Figure 8). In the model generated for the current conditions, unsuitable and barely suitable areas account for approximately 89% of the region, while roughly 11% of the area is classified as suitable (Table 2).

Table 2. Habitat area coverage according to the models (km^2).

Suitability Classes	Current	%	RCP4.5 2050	%	RCP8.5 2050	%	RCP4.5 2070	%	RCP8.5 2070	%
Unsuitable	572,445	74.7	533,092	69.6	512,279	66.9	493,359	64.4	501,641	65.5
Barely Suitable	109,133	14.2	124,418	16.2	145,387	19.0	149,462	19.5	169,486	22.1
Suitable	62,842	8.2	94,764	12.4	96,305	12.6	111,299	14.5	87,988	11.5
Highly Suitable	19,109	2.5	12,573	1.6	10,995	1.4	11,350	1.5	6974	0.9
Very Highly Suitable	2717	0.4	1399	0.2	1279	0.2	785	0.1	156	0.0

3.2. Distribution of Possible Future Habitat Areas

In the future projection based on the RCP4.5 scenario for the average period of 2050, highly suitable potential is anticipated along the Aegean coasts of Çanakkale, İzmir, and a portion of the Muğla coasts. Along the coastal line extending from Çanakkale to Hatay, interrupted by areas with suitable potential, regions with highly suitable potential are evident. Areas with suitable potential are distributed along the coast from Hatay in the Mediterranean Region to Trabzon in the Black Sea Region. Areas of suitable potential are also found in the interior of Izmir and Manisa, as well as in some lowland areas in the Black Sea Region. Habitat areas with barely suitable potential are distributed in the provinces of Adıyaman, Gaziantep, Şanlıurfa, Mardin, Kilis, and Şırnak in the Southeastern Anatolia Region in the Mediterranean Region, especially on the southern slopes of the Taurus Mountain belt; in the Aegean Region, mostly in the inland areas away from the coast; in the Marmara Region; in the southern parts of Balıkesir and Thrace, and in the Black Sea Region, along the northern slopes of the Northern Anatolian mountains (Figure 9a). Within the scope of this scenario, it was determined that 69% of the area corresponds to areas with unsuitable habitat, 16.2% to areas with barely suitable potential, 12.4% to areas with suitable potential, 1.6% to areas with highly suitable potential, and 0.2% to areas with very highly suitable potential (Table 2).

The future modeling of the RCP8.5 scenario for the period 2050 shows that very highly suitable areas are distributed in certain parts of the Çanakkale and İzmir coasts, and highly suitable areas are distributed in the Aegean and Mediterranean coasts and low-lying areas of Samsun. Areas with suitable potential are distributed on the Mediterranean, Aegean, Marmara, and Black Sea coasts as well as in some inland parts of these regions far from the coast. In the Southeastern Anatolia Region, Kilis, Gaziantep, Adıyaman, Şanlıurfa, Diyarbakır, Siirt, Batman, and Şırnak, in the Mediterranean Region; the southern slopes of the Taurus Mountains and the Göller Region, in the Aegean Region; especially in certain parts of Aydın, Denizli, and Manisa provinces, in the Marmara Region; in the south of Balıkesir and the northern parts of Edirne and Kırklareli in the Marmara Region, in the Black Sea Region; and the northern slopes of the Northern Anatolian Mountains in the Black Sea Region and the surroundings of some lowlands with suitable potential are areas where areas with very little suitable potential are distributed (Figure 9b). While 66.9% of the whole area corresponds to unsuitable areas for the potential distribution of olives, 19% corresponds to barely suitable areas, 12.6% to suitable areas, 1.4% to highly suitable areas, and 0.2% to very highly suitable areas (Table 2).

In the RCP4.5 scenario for the period 2070, the distribution of very highly suitable areas is again observed along the coasts of Çanakkale and İzmir. Highly suitable areas can be seen along the Mediterranean coastline in the Mediterranean Region. In the Aegean Region, highly suitable areas can be seen along the coasts of Izmir, Aydın, and Muğla and in the southeast of Manisa; in the Marmara Region, Çanakkale, Balıkesir, and Bursa; and in the Black Sea Region, Sinop, Samsun, and Tokat. Areas classified as suitable habitats are generally found on the Mediterranean, Aegean, Marmara, and Black Sea coasts, as well as in certain parts of Manisa and the inland areas of Çanakkale, Balıkesir, Kocaeli, and Sakarya. The areas classified as barely suitable are distributed in Adıyaman, Gaziantep, Kilis, Batman, Mardin, and Şırnak in the Southeastern Anatolia Region, in the Mediterranean Region, especially in the inland areas of Adana, Osmaniye and Kahramanmaraş, in the Aegean Region, İzmir, Aydın, Muğla and Denizli, in the Marmara Region, especially in the inland areas of Balıkesir and Edirne, Kırklareli and Tekirdağ (Figure 9c). A total of 64.4% of the area is potentially unsuitable. Barely suitable areas constitute 19.5% of the study area, suitable areas constitute 14.5% of the area, highly suitable areas constitute 1.5%, and very highly suitable areas constitute 0.1% of the area (Table 2).

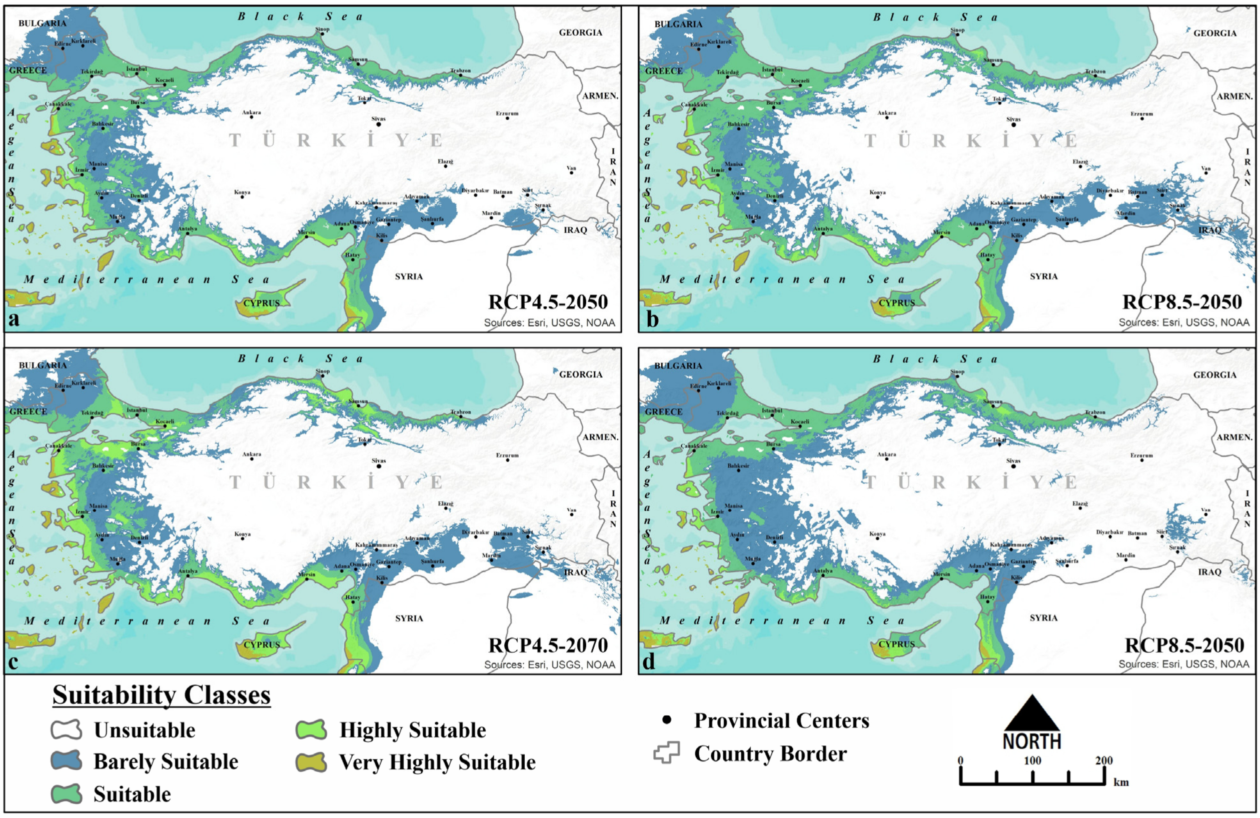
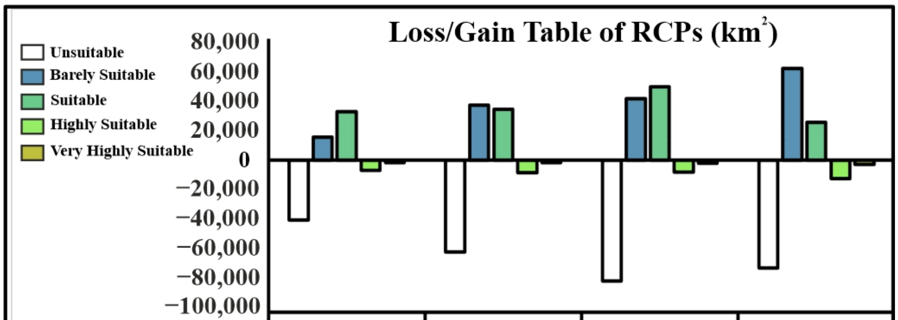


Figure 9. Possible future suitability classes for 2050 and 2070 according to RCP4.5 and RCP8.5 scenarios: (**a**) possible suitability classes for RCP4.5-2050; (**b**) possible suitability classes for RCP8.5-2050; (**c**) possible suitability classes for RCP4.5-2070; (**d**) possible suitability classes for RCP8.5-2070.

In the RCP8.5 scenario for the period 2070, very highly suitable class areas are distributed in a very small area on the Çanakkale coast. The coastal and low-lying areas of Mersin, Antalya, Muğla, Aydın, İzmir, Çanakkale, and Samsun are the areas where areas classified as highly suitable. Areas in the suitable habitat class can be seen along the coastal line from Hatay to Trabzon, as well as in the inland parts of coastal cities. Areas in this class are also distributed in Manisa and Tokat, where there is not much elevation or hilly areas. The areas that are barely suitable have an important distribution area, especially in the Aegean Region. These areas are also distributed in certain parts of Kilis, Gaziantep, Adıyaman, and Siirt in the Southeastern Anatolia Region, inland areas far from the coast in the Mediterranean Region, and in the Lakes Region (Figure 9d). Unsuitable areas in terms of olive cultivation correspond to 65.5% of the area, barely suitable areas correspond to 22.1%, suitable areas correspond to 11.5%, and highly suitable areas correspond to 0.9% of the area.

Analyzing potential habitat areas in the future from the perspective of loss/gain, a noticeable decline is observed, particularly in unsuitable areas. On the contrary, there is a consistent gain in different periods under both emission scenarios in areas deemed barely suitable. The most substantial gain in this class is anticipated in the 2070 period of the RCP8.5 scenario, amounting to 60,353 km^2. It is evident that based on the temperature change predicted by the scenarios, there will be an ongoing loss in every period in areas categorized as highly suitable (Figure 10).



		RCP4.5-2050	RCP8.5-2050	RCP4.5-2070	RCP8.5-2070
Gain	Unsuitable	39,353	60,166	79,086	70,804
	Barely Suitable	15,285	36,254	40,329	60,353
	Suitable	31,922	33,463	48,457	25,147
Loss	Highly Suitable	6536	8115	7760	12,136
	Very Highly Suitable	1318	1438	1932	2561

Figure 10. Future Loss/Gain situation according to CCSM4 model RCP4.5 and RCP8.5 scenarios (km^2).

4. Discussion

Although the olive tree is tolerant to short periods of high temperatures, prolonged high temperatures and lack of water are sensitive issues for the plant. Especially in Turkey, the increase in temperature during the summer season and the dominance of drought conditions are challenging factors for the species to realize its physiological activities. Ashraf et al. [66] and Kassout et al. [67] reported that Bio12 made the highest contribution to olive distribution in this study. This finding suggests that rainfall is an important factor limiting olive distribution.

Today, the Mediterranean, Aegean, and Marmara Regions host highly suitable areas for olive habitats, primarily located along the coastal belt and generally characterized by low elevation and relatively uneven terrain. Occasionally, lands falling within a suitable class can also be observed in the Black Sea Region. The current potential suitability model, constructed using recent bioclimatic variables (Bio2, Bio3, Bio4, Bio8, Bio9, Bio12, Bio14, and Bio15) from 1960 to 1990, aligns with the existing literature on today's olive fields. For instance, in their study employing a multi-criteria decision-making method to model existing olive grove areas, Tuğaç and Sefer [68] obtained results that generally corresponded with the findings of the present study for the Mediterranean, Aegean, and Black Sea Regions. The areas identified in this study show similarities to olive cultivation areas highlighted in the research by Efe et al. [12] and Efe et al. [6]. Similarly, the distribution areas derived in this study are in harmony with the olive cultivation regions illustrated in the studies conducted by Rodríguez Sousa et al. [69] and Chou et al. [70], with a specific focus on the Mediterranean Basin.

The future projection results indicate a continuous decrease, particularly in unsuitable and very highly suitable areas. It is anticipated that over time, unsuitable areas will predominantly transform into barely suitable land. Notably, significant habitat fragmentation and loss are expected in the future, particularly in the inner parts of the Aegean Region. This situation shows that the habitat areas distributed in the Aegean Region are quite vulnerable to future climate change. Conversely, the model results emphasize that a substantial portion of the habitat areas in the Marmara Region are less likely to be impacted by climate change. With anticipated warming, it is predicted that the current distribution of habitat areas will tend to shift northward in the future. Additionally, the model highlights that certain sections of high and rugged areas, presently unsuitable for olive habitat, may become suitable areas in the future. Gutierrez et al. [71] asserted that, with the anticipated climate warming, olive cultivation might extend to the high parts of the Apennine Mountains in Italy, which are currently unsuitable, and to regions with unfavorable climatic conditions, such as the Po Valley in the north. Moriondo et al. [72] anticipate the northward expansion of current olive cultivation areas by 2100, attributing this shift to future warm climate conditions that will render previously unsuitable regions suitable for olive cultivation. Tanasijevic et al. [8] project a movement of olive trees to higher altitudes and northern latitudes in the future, with a focus on substantial changes occurring in the Balkans, transforming currently unsuitable areas into suitable ones. Ashraf et al. [66] highlight the expected shift of *Olea ferruginea*, a wild species of olive found in Pakistan, to higher altitudes and latitudes under future climate scenarios. Öğütçü and Kıraç [73] predict the expansion of olive cultivation areas in Çanakkale toward hilly and elevated terrains in the future. Rodrigo-Comino et al. [74] observe the northward advancement of olive trees in Italy. Khan and Verma [30], based on future projections of *Olea europaea* subsp. *cuspidata* forecast a latitudinal migration of suitable habitat areas toward the north due to changing climatic conditions, particularly warming. Kassout et al. [67] anticipate an increase in the distribution area of *Olea europaea* subsp. *europaea* var. *sylvestris* plants in Morocco in the future. In this context, the findings from the literature align with the results obtained in this study.

According to the model results generated in this study, there is a forecast that olive cultivation areas will predominantly shift northward toward elevated and rugged terrains. While olive cultivation is expected to expand its habitat in the future, the shift toward more challenging and elevated areas raises questions about the economic sustainability of the species. For instance, Efe et al. [75] noted that olives cultivated on the Edremit coast of Balıkesir gradually extended to the slopes of Kaz Mountain due to urbanization, resulting in slower growth of the species in this new area and a subsequent decrease in yield.

Olive is a species that requires chilling, and insufficient chilling, both in its current cultivation areas and anticipated new regions in the future, may negatively impact fruit production. This insufficiency can lead to a significant decrease in efficiency. Furthermore, the expected rise in temperature coupled with new climatic conditions is likely to exert a substantial influence on the physiological processes, phenological timing, yield, and quality of the olive crop. The anticipated water stress in the future may also result in adverse effects on the species. The impact of pests on species in projected new habitat areas remains uncertain. It is unavoidable that these challenges will contribute to a rise in olive oil and olive prices, considering the supply-demand balance. Sectors relying on olive production are expected to be adversely affected by this situation.

It is imperative to minimize the impacts of climate change on species, anticipate possible future changes, and implement early precautionary measures accordingly. Given the significant contribution of olive species to the country's economy, it is crucial to develop suitable short- and long-term adjustment strategies. This includes formulating policies to safeguard current distribution areas, converting high-potential lands expected to expand into profitable areas in the future, and mitigating the impacts of climate change with minimal damage. Taking proactive measures now against anticipated scenarios is essential. This collaborative effort should involve decision-makers, field experts, producers, and industry stakeholders. For instance, adapting to new climate and environmental conditions involves planting the most suitable olive varieties using the correct methods, determining appropriate soil and irrigation conditions, and implementing measures to combat pests and diseases like the Olive Fly (*Bactrocera oleae* Gmelin), Olive Moth (*Prays oleae* Bern.), and Olive Scab (*Parlatoria oleae* Colv.). These precautions are anticipated to contribute significantly to the preservation and sustainability of this species under the new climate and environmental conditions projected for the future.

Adjustment for Future Climate Change Adaptation of Olea europaea L.

Olives are commercially important products with economic significance. The growth and development of olives, which are predominantly grown under traditional rainfed conditions, are primarily governed by atmospheric conditions. Therefore, it is believed that olive cultivation may face significant challenges due to changing climate conditions. Although new olive-growing areas are anticipated in the future, olive cultivation will have to contend with several threats, such as water availability, pests and diseases, and extreme weather events. Therefore, it is crucial to protect the existing olive-growing areas from climate change risks, develop adaptation strategies for future olive plantations, and encourage the implementation of such strategies in the sector. In this context, the authors plan to conduct a new study in the future on the adaptation of olive cultivation to climate change. The study will aim to address the adaptation strategies shown in Figure 11.

Figure 11. Adjustment strategies for sustainable olive cultivation.

Since olive cultivation is largely carried out under rainfed conditions, potential future droughts will adversely affect olive farming. Therefore, irrigation management is considered an extremely important management strategy in olive cultivation, both currently and especially in the future, to achieve optimal yield and high-quality, commercially valuable products. Adopting irrigation strategies, such as drip irrigation or underground drip irrigation, and combining these strategies with deficit irrigation strategies will allow for both effective and efficient use of water by saving water and ensuring sustainability for olive cultivation. Additionally, soil management, soil fertility, and proper fertilization are other important aspects to consider within the framework of climate change adaptation strategies. Determining the physical and chemical properties of the soil through soil analysis, applying the most suitable soil cultivation methods for land conditions, and choosing olive varieties that match the soil characteristics are important factors for sustainable olive cultivation. The geographical distribution, biological cycles, and levels of infestation of pests and diseases may vary with changing climate and environmental conditions. These changes may lead to the emergence of new management challenges. Therefore, it is essential to adopt an effective management strategy within adaptation measures that include biological, chemical, and cultural control of pests and diseases. Integrating technology elements such as Artificial Intelligence, the Internet of Things, Cloud Computing, Blockchain, Remote Sensing, and

Geographic Information Systems into olive production processes can contribute to the effective management of production processes and increased profitability. Satellite imagery, drones, or terrestrial platforms can be used to monitor water stress, plant nutrient status, the effects of diseases and pests, and the condition of weeds. Conditions caused by diseases and pests can be diagnosed early using artificial intelligence algorithms. In conclusion, the challenges that climate change may pose to olive cultivation are interconnected and can be managed through adaptation strategies that consider local environmental conditions.

5. Conclusions

In terms of future projections, the 2050 average of the RCP4.5 scenario suggests that areas currently deemed very highly suitable in the Mediterranean Region may transition to highly suitable. This change is particularly evident in Mersin and its surrounding areas. The Aegean Region is anticipated to experience the most significant loss in Manisa, where lands classified as suitable today are projected to shift to barely suitable in the future model. The Black Sea coast stands out for a notable increase in potentially suitable areas, especially along the coastline from Kırklareli to Trabzon. High parts of Thrace, currently unsuitable for olives habitat, transform into barely suitable areas in this model. The RCP8.5 scenario, a pessimistic outlook for the 2050 average, highlights a noteworthy feature under increasing temperature conditions: previously unsuitable high and rugged areas may transition into barely suitable areas. During this period and scenario, barely suitable areas in the Southeastern Anatolia Region expand northward, transforming unsuitable areas of today into barely suitable ones. In comparison to the present model, unsuitable fields may decrease by 5.1% in the RCP4.5-2050 model and 7.8% in the RCP8.5-2050 model. The overall prediction suggests a total increase of 6.2% according to the RCP4.5-2050 model and a total increase of 9.2% according to the RCP8.5-2050 model, compared with today, in lands classified as barely suitable or suitable (Figure 12).

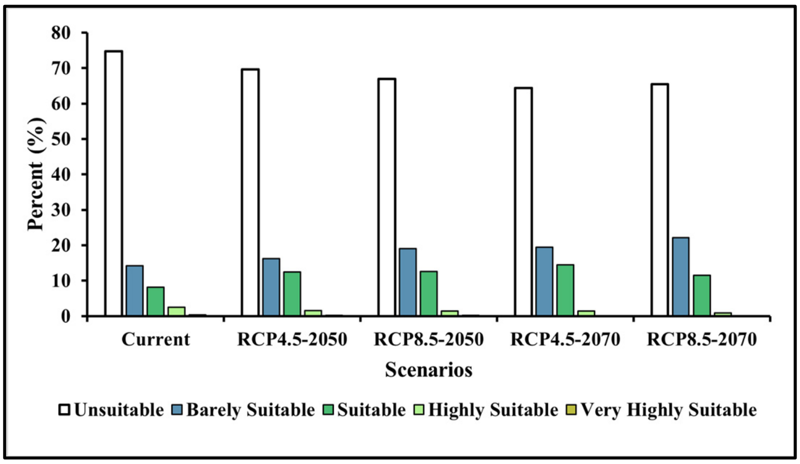


Figure 12. Percentage of suitability classes according to different emission scenarios.

The 2070 RCP4.5 scenario predicts that areas classified as barely suitable will further extend their reach northward, particularly in the Southeastern Anatolia Region. It is anticipated that flat areas with low elevation in Samsun will offer a more suitable habitat for olive cultivation under this scenario. Conversely, the RCP8.5 scenario foresees a significant decrease in potentially suitable habitat areas in the inland regions of the Aegean, away from the coast. The highly suitable habitat areas observed in the present-day Aegean Region are expected to be replaced by suitable habitat areas. Previously unsuitable high and rugged lands throughout the region may transform into barely suitable areas during this scenario and period. The high-altitude parts of Hatay, previously unsuitable as habitats, may turn into barely suitable areas in some locations under this scenario. The most substantial increase during this period is observed in barely suitable areas, with a 22.1% rise, particularly noticeable in the inland parts of the Aegean Region. Habitat areas classified as suitable in the Marmara Region are expected to largely persist even in the most pessimistic scenario. Nevertheless, significant changes in olive habitat are predicted in the Mediterranean Region and, especially, the Aegean Region due to anticipated climate change, according to the model results. The Black Sea Region is projected to be the most advantageous, with currently identified suitable areas expected to expand in the future due to changes in temperature conditions.

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