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Will Olive Groves have a Future Under Climate Change Conditions in The North Aegean Sub-Region, a Mediterranean Agricultural Ecosystem of Türkiye?

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ABSTRACT

The study is aimed at investigating future changes in sustainability of olive farming by means of climate change, and changes in agricultural climatic suitableness and phenology of olive tree cultivation in the North Aegean sub-region of Türkiye mainly characterised with dry summer subtropical Mediterranean climate. According to projected changes based on RCP8.5 scenario, projected warming reaches an average of 5-6°C increase indicating most negative condition on olive cultivation. According to RCP8.5 scenario annual precipitation projections, present suitable areas of olive groves will decrease in the period of 2049-2073, and almost the entire study area will be in the category of medium suitable. With respect to projected Emberger Bioclimate classification, for RCP 8.5 scenario, there will be a significant increase in dry-sub humid areas in the period of 2049-2073. This increase will cover up the coastal areas in the period of 2074-2098, and even all the study region will be very likely characterised with dry-sub humid and semi-arid Mediterranean bioclimatic types except for some coastal areas. An increase of about 6°C is expected in maximum values of maximum air temperatures during the bud swelling periods in the spring, especially after 2050 under RCP8.5 scenario. This increase in extreme maximum temperatures may cause olive trees to bloom earlier and prolong the growth period. By regarding the high vernalization requirement of main olive variety in the study area, a 6°C temperature increase may significantly decrease olive yields and will force farmers to transition to new varieties with relatively low vernalization requirements. According to both RCP scenarios, there is a possibility of extension of suitable areas for olive cultivation towards low to mid-elevation plateaus and mid-elevation slopes of mountainous areas and high plateaus particularly facing suitable aspects to lower negative effects of projected future warming and dryness.

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Introduction

Climate change will likely reduce crop yields in many regions of the great Mediterranean basin, mainly because of increased air temperatures affecting crop phenology and the shortening of the crop growing season (Ali et al., 2022). In this context, the shortening of the growing season is possible in some cases and in some sub-regions, agricultural basins, etc. Although it may reduce the need for irrigation, additional irrigation will be needed for many crops (Saadi et al., 2015; Tas, 2021; An et al., 2023). In Egypt, Libya, Tunisia, Algeria, Morocco, Syria, Malta and Lebanon, water availability is currently below or approaching 1,000 m^3 per capita per year, the common benchmark for water scarcity (Türkeş et al., 2011). Mediterranean countries such as Spain, Greece, Türkiye and Italy are increasingly facing regional water shortages due to the problems of climate change and increasing climatic variability and the increasing demand for water in various socioeconomic sectors (e.g. drinking water, agriculture and irrigation, energy, etc.) (Türkeş et al., 2011; Öztürk et al., 2018; Tramblay et al., 2020; Ali et al., 2022, etc.)

The olive plant probably originates from the Eastern Mediterranean region of the Middle East. *Olea europaea* L. (European olive), from the Oleaceae family, is traditionally found in the Mediterranean Basin, except for the mountainous areas with its unique mountain climate and ecosystem, characterized mainly with dry and hot summer and wet winter subtropical Mediterranean climate and semi-arid and dry subhumid step climate (Türkeş, 2020; Türkeş, 2021, 2022). Olive farming and olive-related production types are a very important agricultural activities due to its high socioeconomic, traditional and environmental importance particularly in the Mediterranean countries. Climate change causes significant changes in the natural variability of the climate and increases the frequency and severity of extreme weather and climate events and disasters. Therefore, it is expected that this negative aspect of climate change will also make itself felt in the olive growing sector.

The possible effects of climate change can affect the olive trees and the sustainability of olive farming. For productive olive cultivation, annual precipitation should be more than 600 mm (Gucci & Fereres, 2012). Low, high, and extreme values of temperature negatively affect the growth, quality, and yield of olives (Tuğaç & Sefer, 2021). Because higher temperatures and more frequent and severe heat waves around flowering will likely affect phenology, whereas suitable areas for olive cultivation could extend northward and to higher elevations under the A1B scenario in 2036–2065 (Tanasijevic et al., 2014), negative consequences of climate change for several countries are expected, including southern Spain (Gabaldón-Leal et al., 2017; Arenas-Castro et al., 2020) and Tunisia (Ouessar, 2017) under 2°C warming. Under 1.5°C to 2°C global warming levels, olive yields in the northern Mediterranean regions could decrease by up to 21% (Brilli et al., 2019; Fraga et al., 2020). On the other hand, another regional study (Bouregaa, 2019) suggests that a 3°C warming could cause a 15–64% drop of the production of rain-fed olives in Algeria.

Studies in the literature mainly focus on simulating plant growth models to investigate the climate change effects on olive biomass growth, soil properties and fruit productivity (Lorite et al., 2018; Viola et al., 2013). Also, the impacts of future changes in climate variables on olive plants is another challenging topic studied by scientists nowadays (Gabaldón-Leal et al., 2017). After determining the impacts of climate change on olive plants, researchers investigate the possible adaptation strategies against the potentially negative impacts of climate change (Fraga et al., 2021). In Türkiye, only a few studies focused on determining suitable olive cultivation areas based on ecological demands and phenological stages. Tuğaç & Sefer (2021) and Bilgilioğlu (2021) used multi-criteria decision analysis (MCDA) methods and geographic information systems (GIS) for determining suitable olive cultivation areas. In a more recent study, Ozalp & Akıncı (2023) performed random forest (RF) analysis combined with GIS to determine suitable olive cultivation areas. This is the first study in literature investigating the possible impacts of future climate change in Türkiye. The other studies in the literature focused on determining genotypes, genetic diversity, and pomological properties (Yıldırım et al., 2017; İpek, 2009, 2016; Sakar et al., 2016), demonstrating areas with olive trees (Efe et al., 2013; Öztürk et al., 2021), fruit and oil characteristics of olive plant (Özdemir et al., 2016).

However, the effect of future climate change on the olive plant in Türkiye is a very important research question and remains unanswered yet. Thus, phenological stages of oil plant were evaluated from the olive tree phenology information of the Turkish Meteorological Service (TMS) and present and future climatic suitability of olive cultivation (i.e., olive groves) lands were determined according to modified thresholds of the suitability criteria exist in the literature.

In this study, which is very likely the first peer-reviewed article study conducted in Türkiye, the future (2024-2098) changes in various precipitation and air temperature variables (i.e., climatic impact drivers) along with a bioclimatic index and various specific indicators related to olive cultivation, were examined in comparison with present conditions. First, the current climate conditions of the study area were analyzed in detail to evaluate the effects of climate change accurately. Then, olive grove lands concerning present land cover characteristics related to major geomorphological units were evaluated in detail. Later, various climate indices and indicators were calculated by making use of projected climatic time series based on the previous RCP4.5 and RCP8.5 climate scenarios of the Intergovernmental Panel on Climate Change (IPCC, 2013), and the future climate of the study area was examined for the different phenological stages of the olive trees. Unlike the studies in the literature, a very high-resolution data set was used to investigate present climate conditions and the distribution of the suitable olive (*Olea europaea* L.) cultivation areas.

Since olive trees adapt very well to the Mediterranean climate, and the olive is a climax plant of the Mediterranean climate and biome, the Mediterranean bioclimate layers of the study area were determined using Emberger's Pluviothermic Quotient (Q) and the future change was determined according to the RCP4.5 and RCP8.5 climate scenarios of the IPCC (2013). Through that, the changes in the Mediterranean bioclimate layers were examined and how olive groves would be affected in the future was evaluated. This approach provided more information about the effect of climate change because larger intervals between the thresholds defining climate classes existed in the original version of Emberger climate classification. In addition, the areas suitable for olive cultivation and the future situation were investigated based on the suitableness variables selected by Tuğaç & Sefer (2021) considering expert opinion and literature reviews. The phenological periods were considered while selecting variables and threshold values in determining the growing conditions of the olive trees.

Materials and Methods

Study Area

The study area is located between latitudes 38.9 - 39.6 and longitudes 26.3 - 27.7 (Figure 1 and 2). The influence of the dry summer and rainy winter subtropical Mediterranean climate is observed in the entire study area, which covers mainly the North Aegean sub-region of Türkiye (Türkeş, 2022). Regarding the aridity or humidity indices, the North Aegean sub-region of Türkiye is characterized mainly by moist- and dry sub-humid climates except the coastal mountainous areas like Kaz Dağı (Mount Ida) with a humid climate north of Edremit Bay (Figure 1) (Türkeş, 2022). The topographic structure of the study area shows great changes in short distance. In addition, the orographic structure of the region allows the effects of the sea to penetrate the interior through the valleys (grabens) between the mountains (Figure 1).

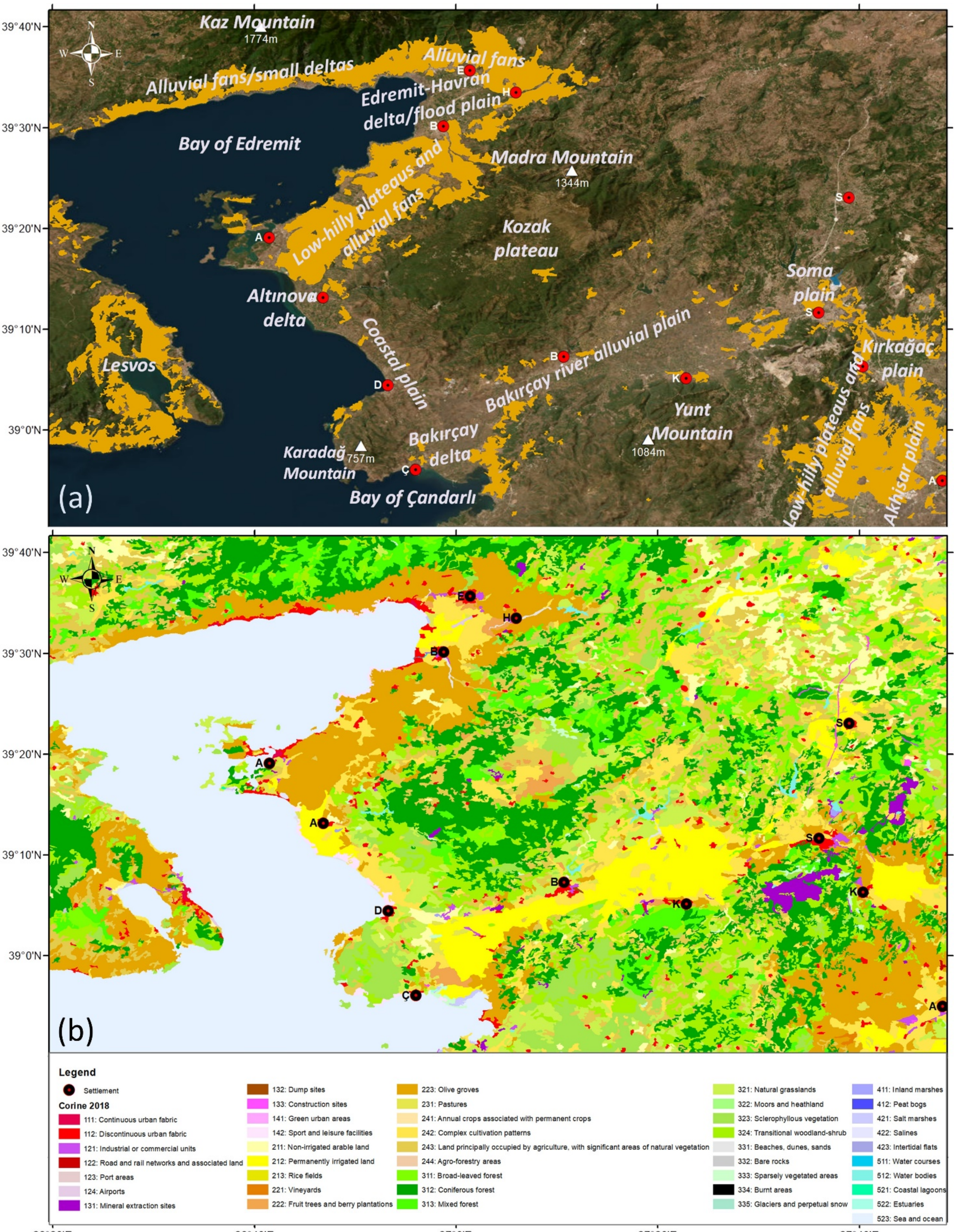

Figure 1. Geographical distribution patterns of (a) the prominent olive grove lands and associated major agro-geomorphologic units geographically belonging to mainly Balıkesir and Manisa districts of the North Aegean sub-region in Türkiye, and of (b) Corine land cover classes over the North Aegean olive groves sub-region, both of which are prepared based on the CLC2018 data.

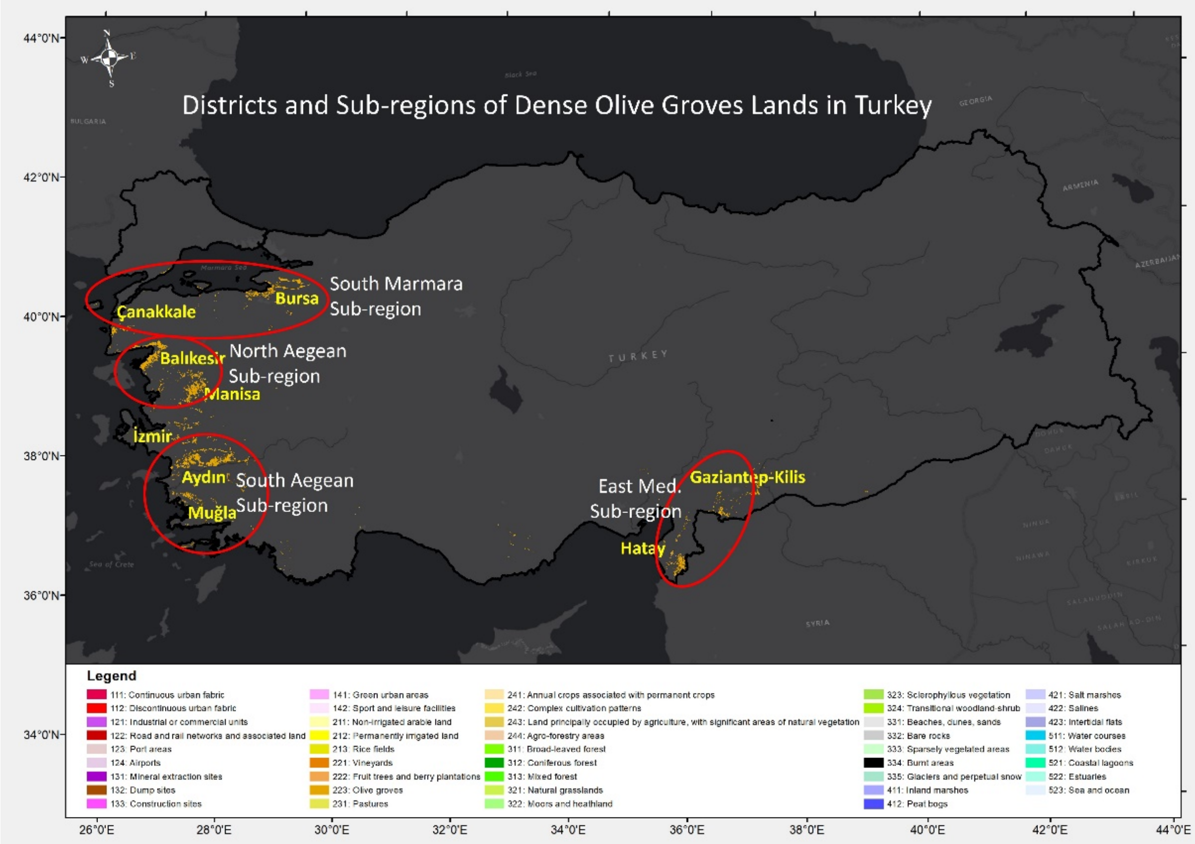

Figure 2. Spatial distribution patterns of prominent olive districts (yellow) and sub-regions (red circle) determined by dense olive groves lands in Türkiye based on the CLC2018 data.

Data Sources

Land cover data

The maps given in Figure 1 and Figure 2 were prepared by making use of the Corine Land Cover (CLC) data (CLC2018, Version 2020_20u1). CLC2018 is one of the datasets produced within the frame of the Copernicus Land Monitoring Service referring to the land cover/land use status of year 2018. CLC provides consistent and thematically detailed information on land cover (LC) and LC changes (LCC) over Europe. CLC datasets are rooted on the patterns of satellite imagery produced by researchers of participating countries; EEA members and cooperating countries (EEA39).

Present climate data

Since the study area is geographically small (North Aegean sub-region), a very high-resolution dataset is needed to spatially investigate the current and future climate variables. Since meteorology measurement stations are few, they are not preferred in this study as they will represent the study area spatially.

Re-analysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5-Land (Hersbach et al., 2020) was used to examine the current climate condition of the study area. Re-analysis is simply an approach that combines past short-term weather forecasts with observations through data assimilation. ERA5-Land provides hourly high-resolution (~9km grid interval) information on surface parameters. ERA5-Land is a better spatial resolution version of the ERA5 climate reanalysis (0.1°×0.1°). The model used in the analysis of ERA5-Land is the shared ECMWF chart for surface changes over land that includes land surface hydrology (H-TESSEL). ERA5-Land data is the most recent so-called second-generation re-analysis dataset, along with the MERRA-2 re-analysis dataset produced by NASA. The spatial resolution of the MERRA-2 dataset is $0.5^{0}x0.625^{0}$. Therefore, the ERA5-Land re-analysis dataset between 1950-2023 with much higher spatial resolution was used in this project.

Climate projection data

The Max Plank Meteorology Institute Global Model (MPI-ESM-MR) data were used to study future climate changes. MPI-ESM-MR is a new generation Earth System Model (ESMEarth System Model) developed using the European Central Hamburg Model (ECHAM5) atmosphere model and the MPIOM ocean general circulation models. To obtain higher resolution climatic variables from low-resolution global model data, dynamic downscaling was performed with RegCM4.3.4 Regional Climate Model and Nesting (Nested Simulations) method in 130x180 grid matrix with 20 km resolution, for the years 2016-2098 according to the 1971-2000 reference period, temperature and precipitation projections were produced. Daily Mean Air Temperature (°C), Minimum Air Temperature (°C), Maximum Air Temperature (°C), and Total Precipitation (mm) for the period: 1971-2000 (reference), 2024-2098 (future period) were used for the RCP4.5 and RCP8.5 scenarios of the IPCC.

Methodology

Calculation of Emberger Index

Emberger's Pluviothermic Quotient (Q) was used to determine the Mediterranean bioclimatic layers of the study area. Emberger (1930, 1932) elaborated a synthetic expression for the Mediterranean climate by classifying this climate on the base of three important climatic parameters: precipitation, temperature, and evaporation. The precipitation (P) is represented by the annual precipitation (mm). Emberger used this index to classify phytoclimatological (the relationship between climate and plant distribution) regions. Therefore, some scientists have investigated the spread of vegetation according to the Emberger index (e.g., Gavilán, 2005; Savo et al., 2012).

The Emberger's Pluviothermic Quotient (Bio-Climate) is calculated as follows:

$$Q_E = (1000 \times P) / [0.5 \times (M + m) \times (M - m)] = (2000 \times P) / (M^2 - m^2) \quad (1)$$

P = average annual precipitation total in mm,

M = average maximum air temperature of the hottest month expressed in K

m = average minimum air temperature of the coldest month expressed in K.

$$K = 273 + {}^{o}C \quad (2)$$

Mediterranean bioclimate layers are determined according to the classifications given in Table 1 with the results of the precipitation-temperature parameter (Q) value obtained by Equation (1).

Classification of phenological stages of the olive tree

Table 2 was created using the olive tree phenology map of the TMS. Future climatic conditions were investigated according to the olive tree phenological stages with the RCP4.5 and RCP8.5 scenarios. While examining the climatic conditions in the phenological stages, we also focused on the extreme climatic impact drivers including durations of the longest dry and rainy days, precipitation amounts of extreme rainy days, and maximum and minimum values of maximum air temperature, etc. were focused on.

In Table 3, the suitability values of the areas suitable for olive cultivation are given according to the main climate criterion. Variable selection and threshold values in Table 3 were compiled by Tuğaç & Sefer (2021), considering phenological periods, expert opinion, and literature information. In this study, threshold values used for determining suitable areas were modified as shown in Table 3. The medium-suitable areas according to January mean air temperature and annual air temperature were partially included in the areas suitable for olive cultivation.

The synthetic or synthesis maps of the areas suitable for olive cultivation were prepared according to the five conformity classes given in Table 3. If precipitation (constant) is suitable, other eligibility indicators will be evaluated in the following order:

- Absolute minimum air temperature in January
- January mean air temperature
- May mean air temperature
- Annual mean air temperature

In addition to precipitation, if two out of four limit conditions of the conformity classes given above were met, the related area was labelled as “suitable” for olive cultivation for the considered RCP scenario and the study period. The annual average precipitation total among the selected climatic impact drivers is the key variable here. Although other conformity classes are suitable, when the annual average total precipitation values are below the limit value, the relevant area is considered “unsuitable” for olive cultivation.

Table 1. Modified classification of the Pluviothermic Quotient (Bio-Climate) and associated biomes/ecosystem suggested for the Mediterranean Region of Türkiye (rearranged for the North Aegean Sub-region of the Western Anatolia based on Özcan et al. (2018).

Biome/Ecosystem	Modified Emberger's Q_E	Emberger's Bio-Climate Types
Humid temperate and subtropical forests (mostly coniferous)	$100 < Q_E$	Humid
Semi humid subtropical and mid-latitude coniferous, mix forests and maquis (macchia)	$75 < Q_E < 100$	Semi humid
Semi humid subtropical and mix forests and maquis	$63 < Q_E < 75$	Moist-sub humid
Dry subtropical and mid-latitude deciduous forests and bush or maquis	$50 < Q_E < 63$	Dry-sub humid
Step, grassland, and short-tall bushes	$30 < Q_E < 50$	Semiarid

Table 2. Olive Tree Phenological Stages developed for the North Aegean Sub-region by using the existing phenological observations.

Period	Phase	Time interval
Before the vegetation period	Precipitation	October – December
	Dormancy	December – January
Vegetation period	Swelling	February – April
	Blooming	16 May – 15 June
	Fruit formation	1 June – 15 July
	Ripening and harvest	16 October – 15 December

Table 3. Agricultural climate conformity classes and limit values of variables (Sys, 1993; Shalaby, 2006; Guo, 2010; Brito, 2019, Tuğaç & Sefer, 2021)

Sub Criterion	Unit	Conformity classes and values				Threshold values for suitability map
		Suitable	Medium-suitable	Less suitable	Not suitable	
Main Criterion: Climate						
Annual mean air temperature	°C	20 – 15	15 – 14	14 – 13	< 13	14 – 20
Absolute minimum air temperature in January	°C	2 – (-4)	-4 – (-6) 2 – 4	-6 – (-7.5) 4 – 6	< -7.5 > 6	2 – (-4)
January mean air temperature	°C	6 – 10.5	10.5 – 12 6 – 5	12 – 13 5 – 4	> 13 < 4	5 – 10.5
May mean temperature	°C	18 – 23	23 – 26 18 – 17	26 – 30 17 – 16	> 30 < 16	18 – 23
Annual precipitation total	mm	600 – 1100	600 – 400 1100 – 1200	400 – 300 1200 –1400	< 300 > 1400	600 – 1100

Results

Present Land Cover and Association with Major Geomorphological Units

Based on the CLC2018 database we originally prepared Figure 2 presenting geographical distribution of the prominent districts and sub-regions of dense olive grove lands in Türkiye. These districts and sub-regions, which are clearly seen on the CLC map or defined based on the geographical distribution of large and dense olive groves, show a distinct spatial clustering. With respect to ecological geography of the olive groves shown in Figure 2, our study area takes place mainly in the coastal Balıkesir district and partly in the northwest of the Manisa district of the North Aegean Sub-region of Türkiye (Figure 3a).

Olive and Olive Oil Production in The Study Area

Balıkesir and Manisa are among the most important olive and olive oil producing provinces, in Türkiye. In Figure 3, the number of olive trees in the last 11 years, obtained in the last 10 production seasons, and estimated to be obtained in the 2021-2022 production season, the olive production reserved for table olives and olive oil, and the estimated olive oil production amounts (tons) are given for Balıkesir and Manisa provinces, respectively. In the last 5-6 years, there has been an increase in the production of olive trees, and olive and olive oil in general in these two provinces (Figure 2). These statistics were compiled within the scope of olive oil product yield determination studies by official assignment of the General Directorate of Plant Production of the Republic of Türkiye Ministry of Agriculture and Forestry, under the coordination of the National Olive and Olive oil Council (NOOC, 2021). The "National Official Determination Committee of Olive and Olive Oil Harvest" determines production of table olives and olive oil for the 2021-2022 production season in all olive growing districts and regions.

Evaluation of Present Olive Grove Lands Concerning Major Geomorphological Units

Geographically, the olive groves in the study area are mainly grown on 'agro-ecologic' geomorphological units (landforms) such as low-lying plateaus and hilly lands, relatively small slope deposits or alluvial cones with unsorted mixed coarse material with low/medium slope, wider alluvial fans with low slope, and fluvial terraces at various elevation levels, and on the geomorphological units similar to piedmont, which are formed by the combination of alluvial fans developed side by side, and, to a lesser extent, coarse material accumulation cones and alluvial cones (Figure 1a) (Photo 1).

This relatively large combined alluvial fans like piedmont, are largest in front of the slopes of the Mount Ida and the Madra Mountain - Kozak Plateau (i.e., geologically a plutonic originated granite massif - granitoid) (MTA, 2022) facing the Bay of Edremit (Figure 1a). It is known that olive cultivation was traditionally grown on such geomorphological units in the past. In recent years, olive cultivation has been carried out in the alluvial flood plains such as in the Bakırçay valley and Akhisar – Saruhanlı plains, where tobacco and cotton were cultivated widely until 30-40 years ago, and on the lowest terraces immediately surrounding the current floodplain.

The geomorphological units where olive groves are grown in the largest areas over the study area are the low-sloping alluvial plains similar to the piedmont plain, which are mainly formed by the combination of the alluvial fans and cones located in the front parts of Mount Ida, Madra Mountain and the high Kozak plateau overlooking the Edremit Gulf (Figure 1a). These alluvial geomorphology-origin landforms were highly fragmented by streams at the mid to late Miocene, the Pliocene and Pleistocene epochs during the geomorphological evolution of the north-west Anatolia throughout the Upper Tertiary period and turned into low plateaus and hills in some places. Low-lying plateaus and low hilly landforms located between Ayvalık and Burhaniye in the Northern Aegean coastal zone can be added to these geomorphological units (Figure 1a).

In addition to these, the geomorphological units where olive groves cover large areas are low plateaus, terraces and alluvial cones or fans located in the north and east of the Bakırçay River delta and generally in the south and east parts of the Soma and Kırkağaç plains (Figure 1a). Apart from the large olive plantations surrounding the Bay of Edremit, the other largest olive plantations in the study area are distributed in the alluvial flood plains of Saruhanlı and Akhisar plains in the south-east of the study area and on the alluvial fans and fluvial terraces (Figure 1a).

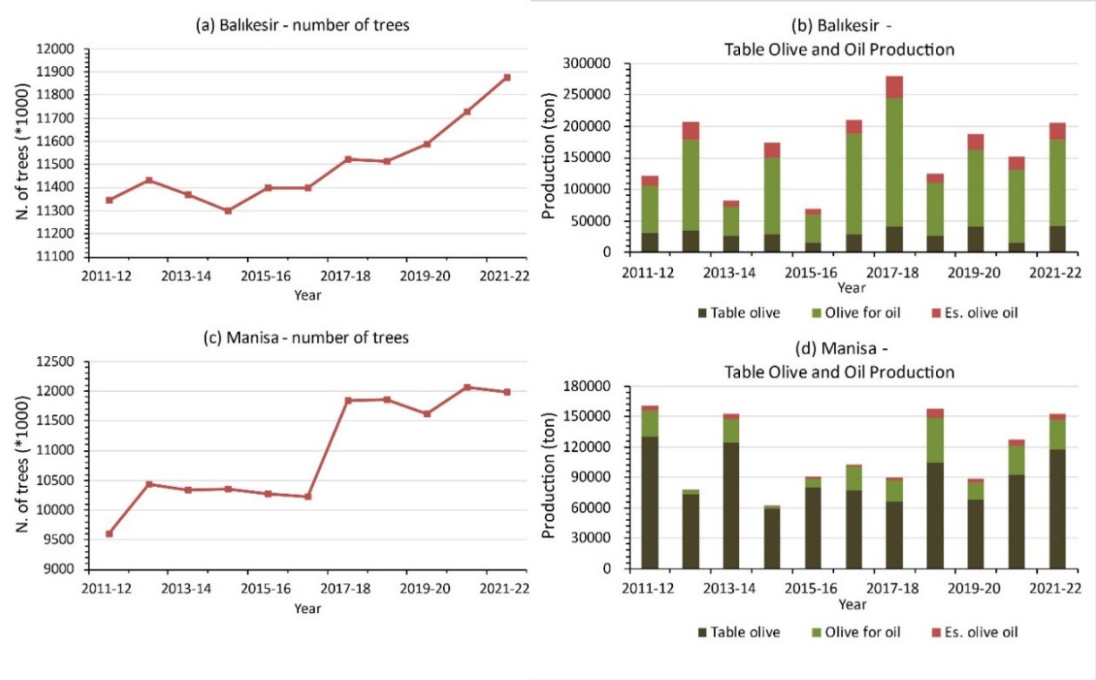

Figure 3. The number of olive trees obtained in the last 10 production seasons and estimated to be obtained in the 2021-2022 production season, the olive production allocated for table olives and olive oil, and the estimated olive oil production amounts for (ab) Balıkesir and (cd) Manisa provinces.

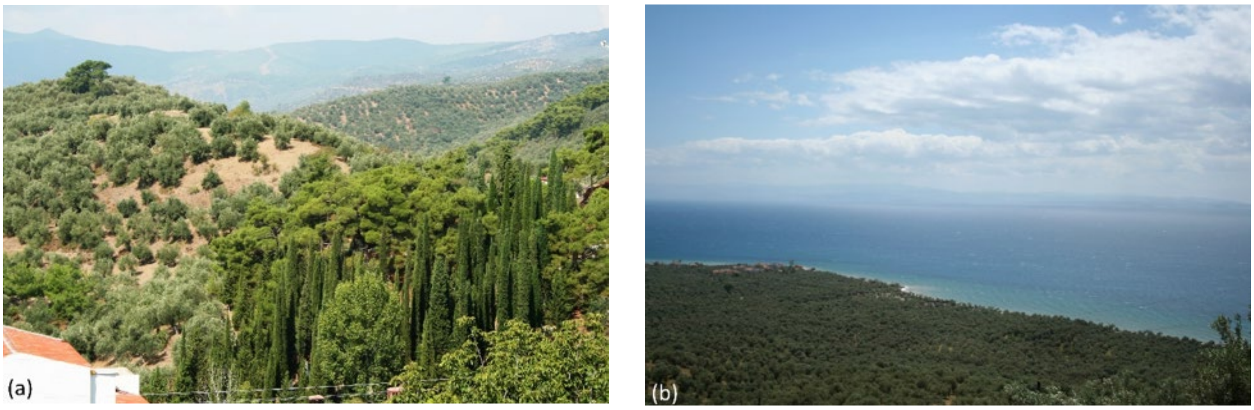

Photo 1. Some examples of the Mediterranean ecogeography from the southern part of the Kaz Mountain exposed to the Edremit Bay (a) An ecogeography including pistachio pine (*Pinus pinea*), red or Turkish pine (*Pinus brutia* Ten) and the Mediterranean tall cypress (*Supressus sempervirens* var *pyramidalis*) and olive groves in the historical Nusratlı Village, which was established on a low plateau and hilly geomorphological landscape on the southern skirts of Kaz Mountain overlooking the Edremit Bay; (b) Dense olive groves grown on the geomorphological unit of an alluvial fan extending to the sea, near the district of Altınoluk town, on the southern skirts of Kaz Mountain overlooking the Edremit Bay.

On the other hand, although it is not clearly visible on the CLC2018 map, on the edges of the alluvial flood plain of the Bakırçay River, which is also a tectonic-origin depression, that is, a graben, like the Edremit Gulf, a wide area extending from the Çandarlı (Bakırçay) delta to the tectonic-origin Soma plain, which is the largest plain at the end of the Bakırçay valley, there are olive groves with a somewhat scattered distribution. In addition, olive groves take up large areas in the eastern and southeastern parts of the Greek island of Lesvos facing Türkiye (Figure 1a).

Other Present Land Cover Characteristics

Except for the olive groves, in the remaining part of the study area, forest ecosystems consisting of broad-leaved, coniferous, and broad-leaved/coniferous mixed trees and stands, as well as vineyards, orchards, and annual agricultural products such as vegetables and grains, some of which are also permanently irrigated as in the Bakırçay valley, are distributed (Figure 1b). Mediterranean stone pine (*Pinus pinea* L.), the largest agro-forestry product in the study area, is grown in private and state-owned plantations on the Kozak Plateau (Figure 1b). In the study area, the largest and most densely native/naturalized and managed pure (broad-leaved and/or coniferous) and broad-leaved/coniferous mixed Mediterranean and mid-latitude (paleo boreal relicts) mountain forest biotopes are distributed in the Mount Ida (Türkeş, 2021; Türkeş et al., 2023), and pure and mixed Mediterranean forest ecosystems are distributed in the Madra Mountain - Kozak Plateau ecoregion (Figure 1b).

Present Climatology of The Study Area

Winter season

In Figure 4, the contour lines show the total precipitation variability (mm/month), the vectors and the vector colors show average wind speed (m/s) and mean air temperature (°C), respectively. Since the effect of friction is significant in winds blowing 10 meters high, these winds are boundary layer gradient winds, not true geostrophic or gradient winds. While examining the seasonal climate of the study area, mid-season months and seasonal average maps were used.

The air temperature of the mountainous areas of Kozak plateau and Kınık district, where the altitude is high, is below 4°C. In winter, the land is colder, and the sea is cooler and warmer than the land, so the winds blow from the land to the sea. Figure 4a shows this clearly. As seen in Figure 4a and 4b, the air temperature is 4-5°C higher in the coastal areas both in January and in winter. Total precipitation reaches its highest value towards Mount Ida and in the gulf region. In general, the total precipitation is higher in the coastal areas and the precipitation decreases significantly towards the continental interior. In Figure 4a and 4b, the effect of orography on precipitation distribution according to the total precipitation pattern is clearly seen.

Spring season

The spatial relationships of air masses and frontal mid-latitude cyclones in western Türkiye (especially the Aegean region) have effects on spring precipitation variability (Türkeş et al., 2009). While mid-latitude cyclones are active in the Aegean and Marmara regions in spring, their effect decreases towards the Mediterranean region.

As seen in Figure 4c, due to the decrease in the temperature difference between the seas and the land, much lighter winds blow over the study area compared to January. It is noteworthy that the air temperature is higher than the surrounding area in the low-altitude flat area between Kozak plateau and Kınık district. This region is like the bottom of a somewhat depression surrounded by mountains, and the precipitation of convective instability is also seen here. In Figure 4d, this situation is clearly seen in the total precipitation patterns in both April and spring.

Summer season

The most blowing local scale wind in the Aegean region, especially in İzmir and Aydın, is the wind coming from the west (İmbat or Günbat in Turkish). This breeze starts to blow in the hottest hours of the day in the afternoon and continues gently until late at night. Since the İmbat wind (cool Aegean summer sea breeze) is cool and humid, it provides the transfer of moist and warm air masses to the interior as well as its cooling effect in summer. However, as can be seen in Figure 4e, due to the large-scale pressure and wind pattern that is effective in summer in the region (from the Azores high pressure to the Monsoon low pressure area), a very strong north-eastern summer breeze blow. Such winds are generally seen in the Eastern Mediterranean sub-region in summer in Türkiye (Türkeş, 2022).

A wind from relatively colder seas to warmer land and therefore an effective moisture transport from the sea to the land is not observed in the region. Therefore, it can be interpreted that the humidity rate is relatively lower than the southern districts (İzmir, etc.) close to the study area.

As seen in Figure 5f, very low summer precipitation, which is typical of the Mediterranean climate, is seen in the total precipitation map of the study region. In general, as in other seasons, the northeast of the study area is colder. This temperature difference appears to be around 5-6°C.

Autumn season

Figure 4g shows the map of total precipitation (mm/month), average temperature (°C) and average wind (m/s) for the mid-autumn month and autumn season. Considering the temperature distribution, the difference between the relatively cold northeastern parts of the study area and the relatively warm southwestern parts is around 3°C.

In Figure 4g, it is seen that a relatively low-strength northerly wind blows very regularly according to the average wind distribution pattern. The effect of orography on the precipitation distribution in the winter season (see Figure 4b) is also seen in the autumn season. Similarly, the coastal areas receive higher precipitation, and this situation continues to decrease towards the continental interior areas where the altitude is low. In terms of wind force, the least strong winds blow in this season after the spring season. In terms of total precipitation, the region generally has higher precipitation in autumn than in spring, and lower precipitation than in winter.

Present and Future Areas Suitable for Olive Cultivation

The following vegetation classification by the International Geosphere–Biosphere Programme (IGBP) shown in Figure 5 is derived from the Terra and Aqua combined Moderate Resolution Imaging Spectroradiometer (MODIS) Land Cover Climate Modeling Grid (CMG) (MCD12C1) Version 6 data product (Friedl and Menashe, 2020).

In Figure 5, the vegetation types of the study area are classified according to IGBP. The green areas labelled with the number 18 represent the current olive cultivation areas. This map will be used to evaluate the future suitability of olive production areas. The results show that future suitable areas according to modified thresholds (Figure 14) are in very good agreement with the present olive cultivation areas as shown in Figure 5. This resemblance with present olive cultivation areas and determined suitable areas with modified thresholds is the key factor for accurate evaluation of future changes in olive cultivation areas.

Analysis of Selected Climate Impact Drivers According to the Phenological Stages and RCP Scenarios

Precipitation conditions

In Figure 6, seasonal annual total precipitation amounts according to the reference period are shown. Although it is not regular according to the RCP8.5 scenario, there is a decrease in seasonal total precipitation in general over the years. According to the RCP4.5 scenario, there is an increase in spring and autumn precipitation in the last quarter of the century and an increase in winter precipitation in the middle quarter of a century. Since winter precipitation constitutes the most important part of the annual total precipitation in the study area, the decrease or increase in precipitation is very important in this period. Therefore, in Figure 7, the spatial distribution of winter precipitation according to the RCP scenarios has been specifically examined.

In Figure 7, the spatial variation of the winter precipitation totals calculated according to the working periods of the RCP scenarios is shown. Total precipitation varies greatly in the study area. Therefore, it is not preferred to show the precipitation changes as a percentage in Figure 7, because changes in quantity will not be seen and the distinction between coastal and terrestrial sections will not be discernible.

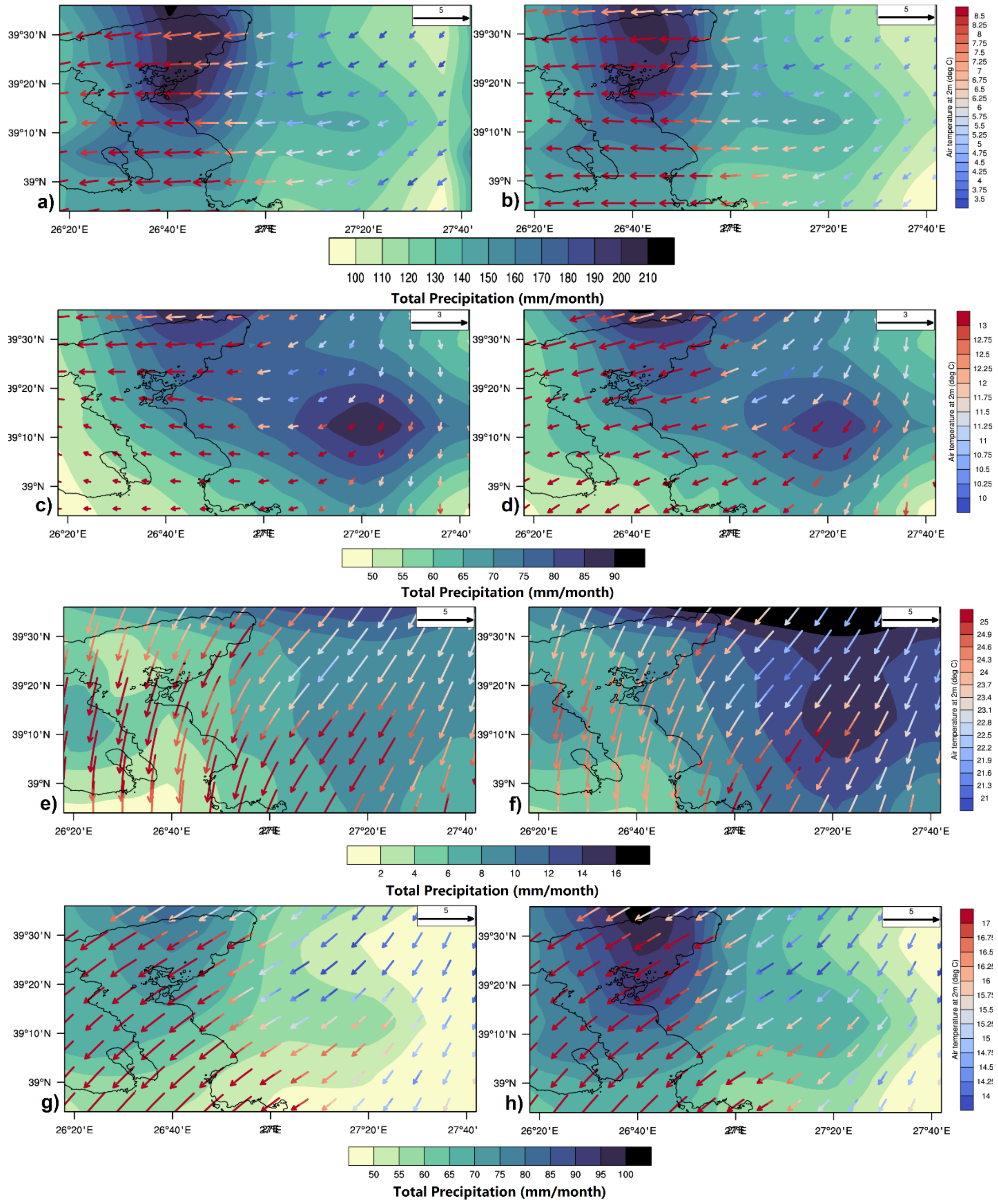

Figure 4. Geographical distribution patterns of average precipitation total (mm), mean air temperature (°C) and average wind velocity (m/s) in the North Aegean Sub-region for the period of 1950-2023 a) January, b) winter season, c) April, d) spring season, e) July, f) summer season, g) October and h) autumn season.

First, when looking at the areal distribution map of winter precipitation calculated with current data for the study region (Figure 4a and 4b), it is seen that the coastal regions receive more precipitation than the continental interior. According to the RCP4.5 scenario, the increase in winter precipitation compared to the 2049-2073 period is seen, and, according to the RCP4.5 scenario, there is an increase in precipitation compared to the inner parts, with the coastal areas being slightly higher for the 2049-2073 period (Figure 7). Decrease in precipitation towards the continental interior, especially the coastal areas, decreases according to both scenarios and for all other periods. The significant decrease seen in coastal areas shows its effect towards terrestrial interior areas in the RCP8.5 scenario 2074-2098 period. However, an increase in precipitation is observed in all RCP8.5 periods, albeit very slightly, in the innermost continental parts.

In Figure 8, the longest dry and rainy periods for the swelling, flowering, maturation, and harvest phases are calculated for the years 2024-2048, 2049-2073 and 2074-2098, according to the reference period. Here, the longest dry period represents the days without precipitation and the longest precipitation variable represents the longest period with precipitation. According to the RPC scenarios, the longest dry period during the flowering phase changes by 2-3 days at most. RCP4.5 scenario shows a decrease in the dry period for the years 2049-2073 during the maturation period. In addition, a significant increase is observed in the swelling period between RCP8.5 (2074-2098). As can be seen in Figure 7, according to the RCP 8.5 scenario, there is a serious decrease in total precipitation between 2074 and 2098. In Figure 8, the longest rainy days do not show any significant change except for the post-2050 RCP8.5 scenario.

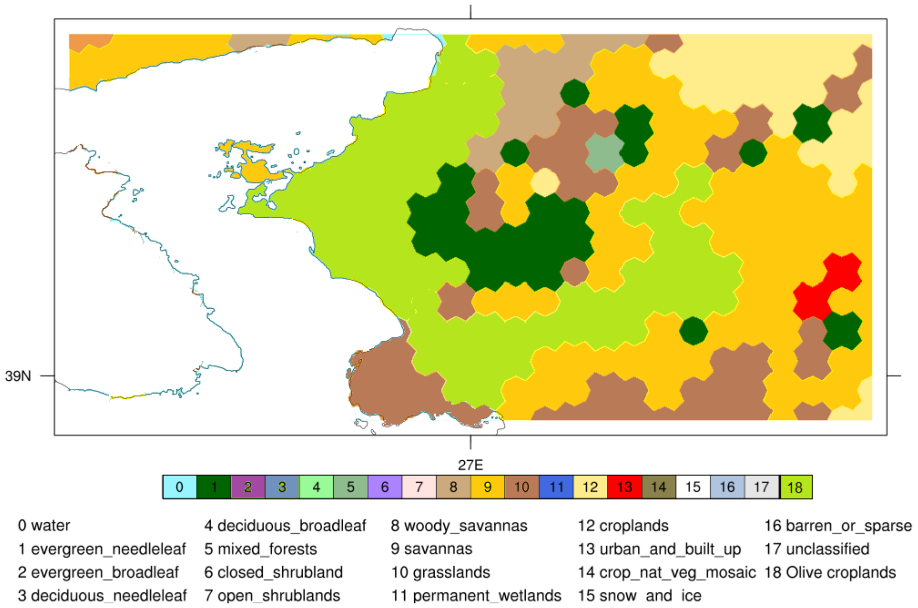

Figure 5. Geographical distribution pattern of the vegetation types of the study area according to the (IGBP) (MCD12C1, https://doi.org/10.5067/MODIS/MCD12C1.006)

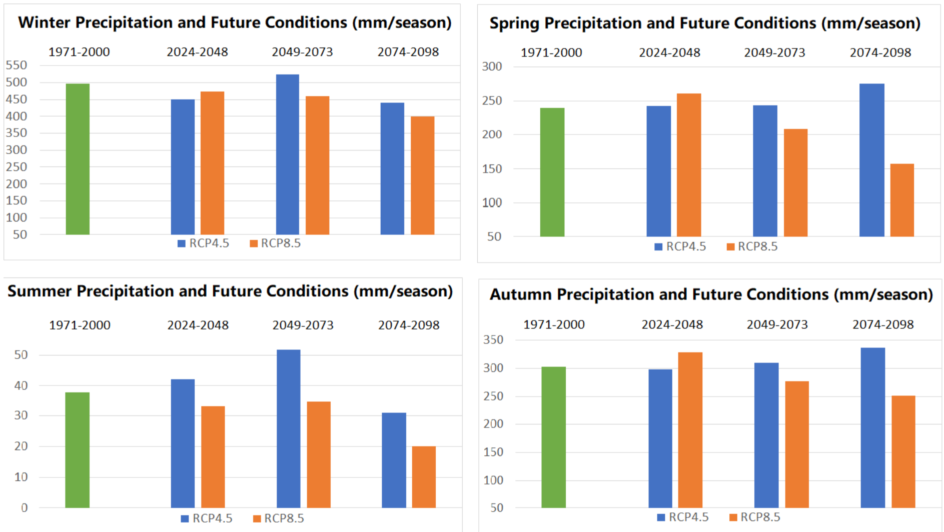

Figure 6. Projected changes in seasonal total precipitation amounts (mm) of the North Aegean Sub-region under two RCP scenarios for three future periods (2024-2048, 2049-2073 and 2074-2098) in comparison with the reference period (1971-2000).

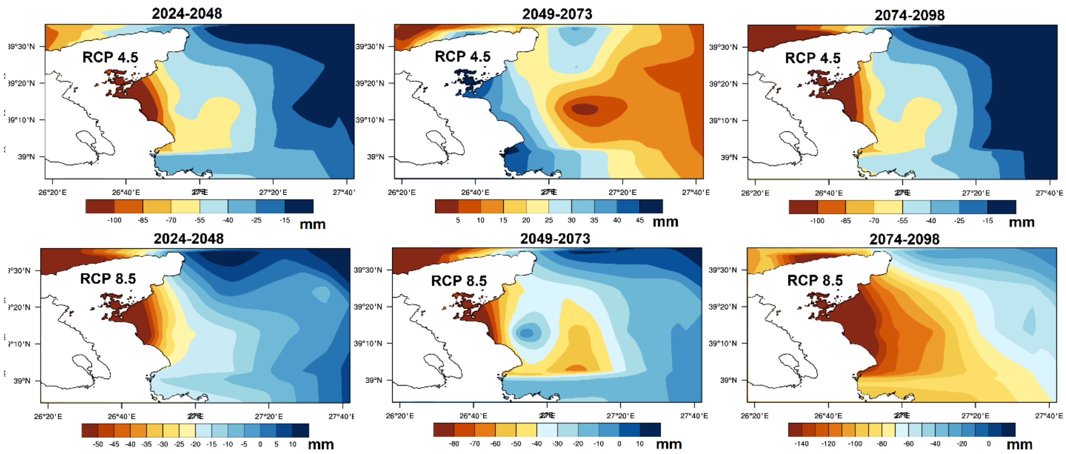

Figure 7. Changes in winter season total precipitation amounts (mm) of the North Aegean Sub-region under two RCP scenarios for three future periods (2024-2048, 2049-2073 and 2074-2098).

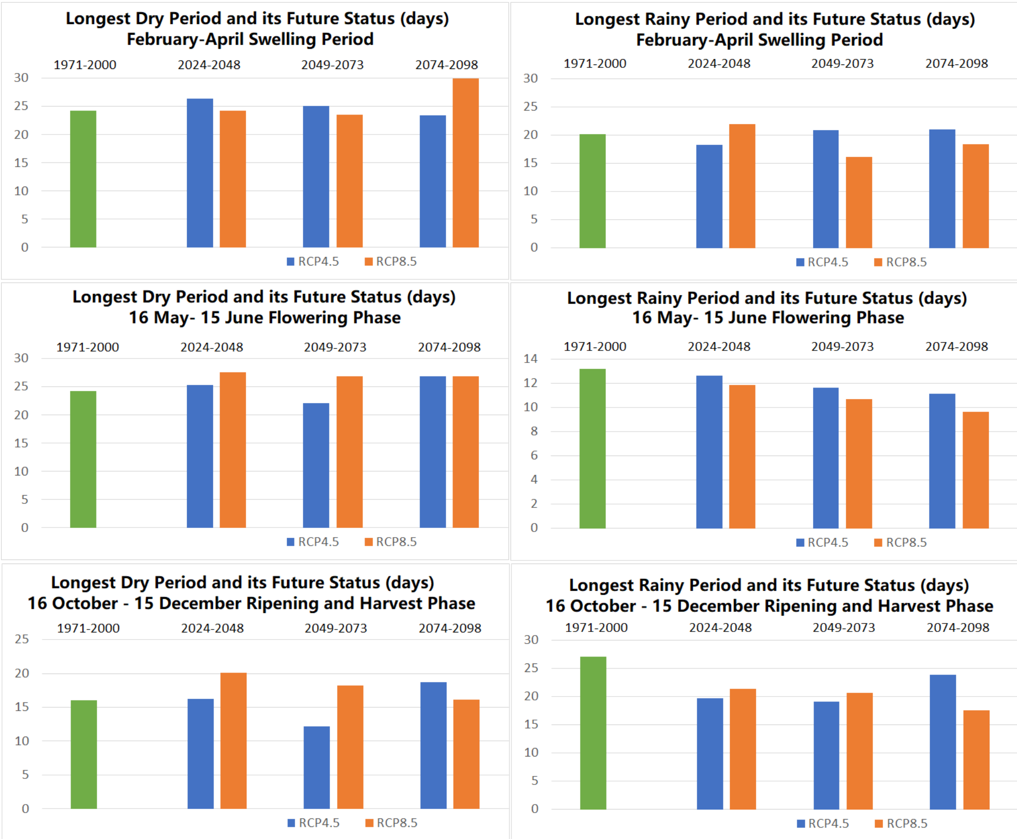

Figure 8. Projected changes of longest dry and wet periods (days) in three phenological stages of olive tree for the North Aegean Sub-region under two RCP scenarios for three future periods (2024-2048, 2049-2073 and 2074-2098) in comparison with the reference period (1971-2000).

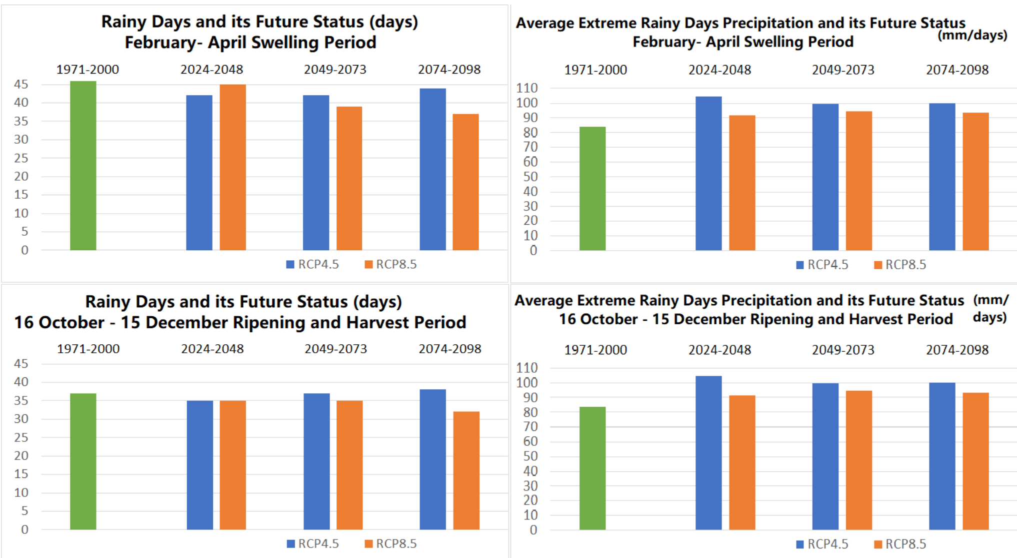

Figure 9. Projected changes in rainy days and precipitation amounts of extreme rainy days in two phenological stages of olive tree for the North Aegean Sub-region under two RCP scenarios for three future periods (2024-2048, 2049-2073 and 2074-2098) in comparison with the reference period (1971-2000).

Especially according to the RCP8.5 (2049-2073) scenario, the longest rainy days decrease by 10 days. Longer rainy days delay the harvest, lower the polyphenols, and decrease the amount of swelling and pollination (EBRD project report, 2023). Expected rainy days in the future according to the reference period are given in both days and amount (mm) (Figure 9). Although there is a slight decrease in the rainy days according to both scenarios, an increase in the amount of precipitation is observed during the ripening and harvesting phases and the swelling period. However, it is considered that this increase will very slightly affect fruit quality and number of fruits. As predicted by many climate projection models, a decrease in precipitation and an increase in precipitation intensity are expected in the study region in the future.

Expected changes of extreme temperature events in the olive tree swelling period according to the reference period in the future are shown in Figure 10.

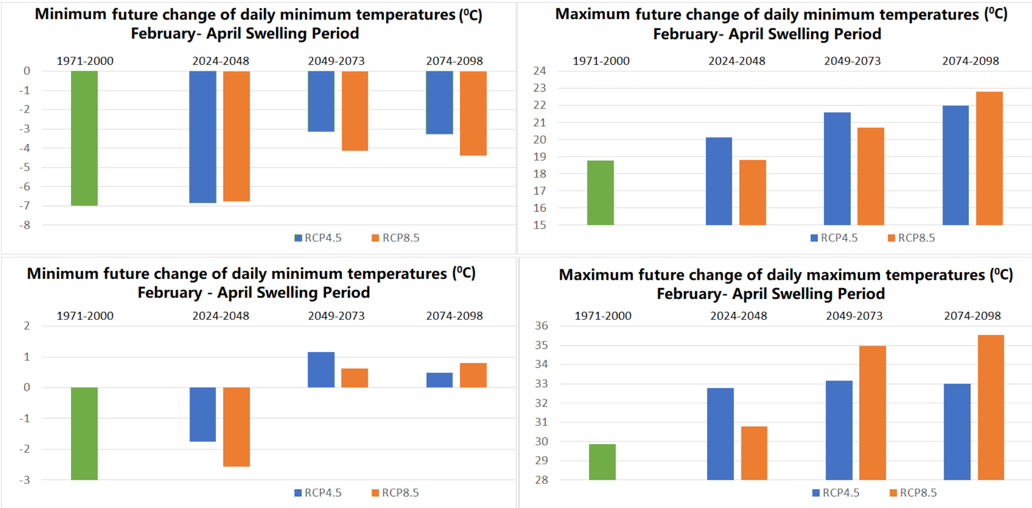

Figure 10. Projected changes in minimum and maximum values of maximum and minimum air temperatures (°C) in the swelling phenological stage of olive tree for the North Aegean Sub-region under two RCP scenarios for three future periods (2024-2048, 2049-2073 and 2074-2098) in comparison with the reference period (1971-2000).

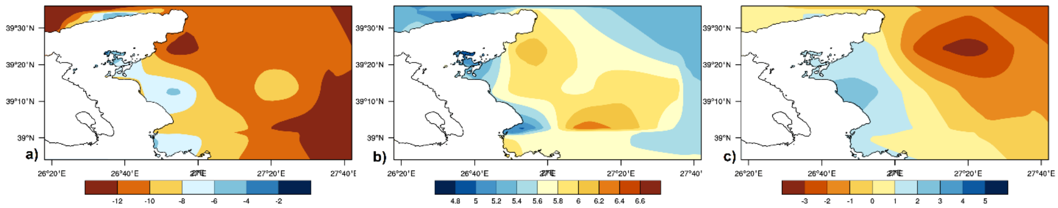

Figure 11. Spatial distribution patterns of projected future climatic changes in the olive tree swelling phase
(a) changes in the longest rainy days according to the RCP8.5 (2049-2073) scenario, (b) changes in the maximum values of the daily maximum air temperatures (°C) according to the RCP8.5 2074-2098 scenario, and (c) changes in the minimum values of daily maximum air temperatures (°C) according to RCP4.5 2049-2073 scenario.

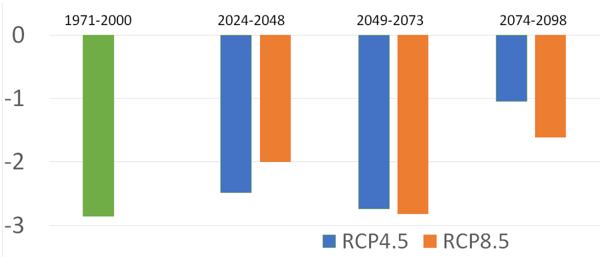

Figure 12. Projected changes in minimum values of minimum air temperatures (°C) in the ripening and harvesting phenological stages of olive tree for the North Aegean Sub-region under two RCP scenarios for three future periods (2024-2048, 2049-2073 and 2074-2098) in comparison with the reference period (1971-2000).

There is an overall increase in the maximum and minimum values of the minimum and maximum temperatures which may cause earlier bloom and increase chilling requirements. Therefore, it can be said that colder extreme weather conditions are not expected in terms of minimum temperatures in the study area. However, at the maximum values of the maximum temperatures, a maximum temperature increases of up to 6°C is observed, especially in the periods after 2050 in the RCP8.5 scenario. The increase in temperature during the swelling period in the study area causes the olive trees to bloom earlier and the growth period to prolong the growth period (Pérez et al., 2008). Therefore, the spatial distribution of this situation will be examined specifically in Figure 11.

While describing the climate of the study region, it was shown that coastal areas receive more precipitation than continental interiors. As seen in Figure 11a, the longest rainy days decrease in coastal areas that receive more precipitation than inland areas. The number of the longest rainy days decreases even more in the interior areas that already receive less precipitation. Therefore, this may increase the effect of possible water stress.

Air temperature conditions

When the graph of minimum of maximum air temperatures is examined, although the reference period is around -3°C on average, positive values appear after the 1950s according to both RCP scenarios. Therefore, this situation is also examined as spatial distribution in Figure 11b, which shows the variation of the maximum values of the daily maximum temperatures in the area.

Especially, the least temperature increase is seen in the coastal areas. It can be said that the increase in temperature is partially seen in higher areas where olive cultivation is mostly done. For this reason, it is seen that the olive trees in the interior areas far from the coast will be more affected by the temperature increase in the swelling stages compared to the coastal areas.

As can be seen, where the climate of the study area is explained, the temperature of the study area is colder in the northeastern part and the air warms up towards the southwest. According to the map of the minimum of the maximum temperature in Figure 11c, the air gets colder in the relatively cold regions, while the warmer coastal and south-southeastern parts are warming. However, it is thought that this situation will not pose a problem for the olive tree during the swelling period.

According to the minimum values of the ripening and harvesting period minimum temperatures given in Figure 12, there is a warming according to both RCP scenarios.

Especially in the last quarter century, an average of 1.5-2°C warming is predicted according to both scenarios. Since the coldness that the olive tree can withstand is around -7 degrees, this predicted increase in minimum temperatures can be viewed positively in terms of olive agriculture.

Determination of Current and Future Bioclimate Layers of the Study Area According to the Emberger Bioclimate Classification

Figure 13 shows the Mediterranean bioclimate layers calculated for the study area according to the Emberger index. The dashed red line in Figure 13 indicates the threshold value modified for this study. According to today's climatic conditions (1950-2023), the northern coastal zones of the study area are rainy and almost all the remaining areas are classified as the Mediterranean bioclimate with low precipitation. According to the RCP4.5 scenario, there is no significant change in the Mediterranean bioclimate type of the study area. There is a decrease in rainy areas in the northeast of the study area and a slight increase in semi-arid areas in the southwest (Figure 13). According to the RCP8.5 scenario, similar changes are seen in the RCP4.5 scenarios in the first quarter-century period. However, in the middle quarter period (2049-2073), there is a significant increase in semi-arid areas from the eastern and southeastern regions to the western parts, although the rainy Mediterranean bioclimate is almost absent (Figure 13).

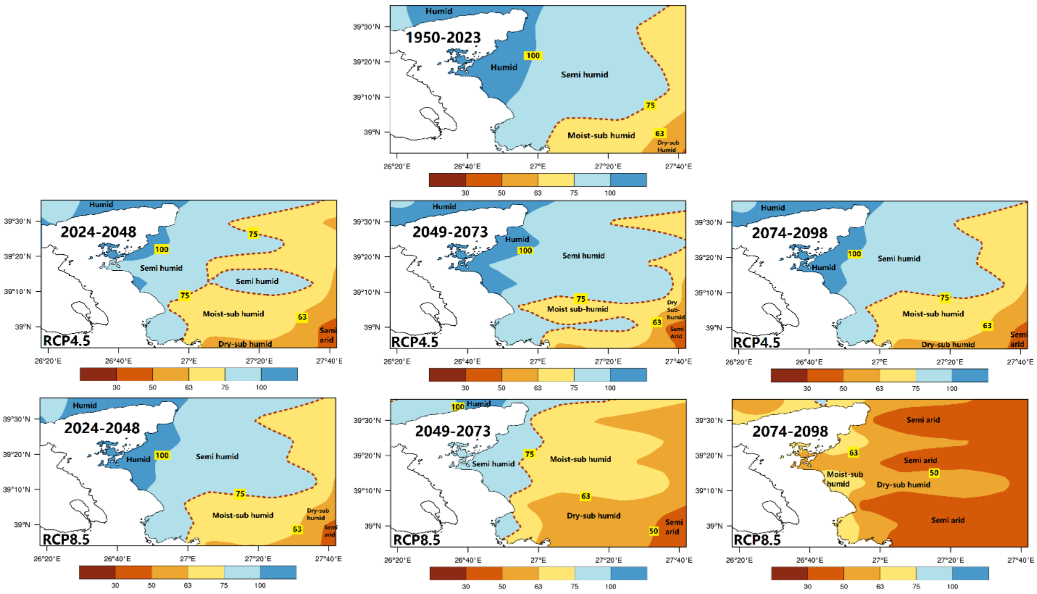

Figure 13. Geographical distribution patterns of the present and future Mediterranean bioclimate classes of the North Aegean Sub-region according to the Emberger Bioclimate Classification.

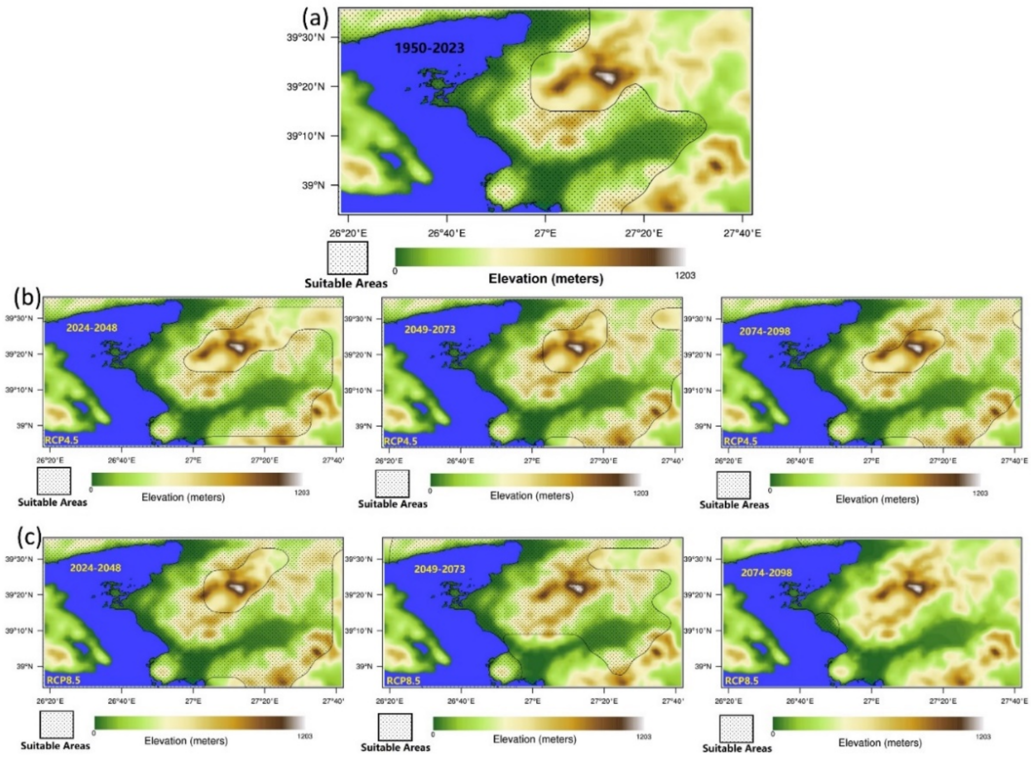

Figure 14. Geographical distribution patterns of (a) present suitable areas for olive cultivation, and future changes in the suitable areas for olive cultivation according to five conformity classes for the periods of 2024-2048, 2049-2073 and 2074-2098 under (b) the RCP 4.5 and (c) RCP8.5 scenarios.

This increase reached up to the last quarter-century variable (2074-2098) coastal areas, and even the entire study area was determined as the semi-arid Mediterranean bioclimate layer, except for some coastal areas. In arid conditions, olive trees can stop crown growth and build drought resistance by reducing photosynthesis and transpiration. However, water stress during the growth periods negatively affects production and development, causing significant changes in fruit quality, maturity, and oil content (Ayaz and Varol, 2015). For this reason, water stress, which is likely to occur after 2050 in much warmer and semi-arid climatic conditions than today, should be examined in detail and precautions should be taken against it, according to the RCP8.5 scenario.

Figure 14a is the synthesis map of the present and predicted future conditions of the areas suitable for olive cultivation calculated with the proposed methodology in this project. Dashed areas in Figure 14a indicate "suitable", and the other areas show "unsuitable" fields for oil cultivation. The suitable areas in Figure 14a consist of low-lying plateaus and low hilly landforms and low-sloping alluvial plains. The unsuitable areas are mostly relatively colder areas like high plateaus and mountainous regions. The areas suitable for oil cultivation determined with the methodology proposed in this project are very similar to the present oil cultivation areas shown in Figure 5. This shows that the proposed methodology and the selected conformity classes are very appropriate for determining areas suitable for olive cultivation for the study area. In addition, determining future changes according to present conditions (1950-2023) will be significant because of the consistency of the results in Figure 14a.

Figures 14b and 14c clearly depict the expected future changes in suitable olive cultivation areas according to study periods for RCP 4.5 and RCP8.5 scenario, respectively. The areas suitable for olive cultivation (dashed areas) increased according to present conditions due to slightly decreased average annual total precipitation and projected warming in temperature variables in relatively colder (mountainous) areas. Altitude is one of the restriction factors for olive growing. For example, 900-1200 meters is a border for the Mediterranean region. Therefore, the expansion of the suitable areas for olive cultivation won't be affected by the increased altitude in the suitable areas in Figure 14b-c. The suitable areas slightly change with the study period. This result is in scope with the results in Figure 13 showing the change in Mediterranean climate classes.

Because of the slightly increased average annual total precipitation for the period 2024-2048 RCP8.5 scenario and expected warming in temperature variables in high altitudes, the study area becomes much more suitable for olive cultivation as seen in Figure 14c. However, the expected decrease in average total precipitation and relatively higher warming in temperature variables for the period 2049-2073 resulted in a decrease of the suitable olive cultivation areas. Nevertheless, suitable olive cultivation areas increased for the period 2049-2073 according to present conditions. As seen in Figure 6 the total precipitation significantly decreases for the period 2074-2098. Also as shown in Figure 13, the Mediterranean climate of the study area becomes mostly semi-arid according to Emberger climate classification for the period 2074-2098. Therefore, there is no suitable area left for olive cultivation in almost all the study area for the RCP8.5 (2074-2098) scenario (Figure 14c). It must be noted that the unsuitable areas for olive cultivation are in good agreement with areas classified as semi-arid according to Emberger bioclimatic classes.

Conclusions

This study is aim at investigating future changes in sustainability of olive farming by means of selected climatic impact drivers and a bioclimatic index, and the climatic suitableness variables and various specific indicators including phenology related to olive tree cultivation compared with present conditions in the North Aegean sub-region of Türkiye mainly characterised with dry and hot summer subtropical Mediterranean macro climate.

Generally, there are no significant differences observed between RCP4.5 and RCP8.5 in terms of warming trends in air temperatures in the 2024-2048 period. However, according to the RCP8.5 scenario, the warming will increase regularly, and this warming reaches an average of 5-6°C in the far future period of 2073-2098. As expected, the most adverse effect of predicted warming will occur in the last quarter of the century under the RCP8.5 scenario.

Regarding the present climate, the coastal areas in the north of the study area are rainy during the cold months of the year from the November to April, and almost all the remaining areas are classified as Mediterranean bioclimate with low precipitation according to the Emberger Bioclimate Classification. In RCP4.5 scenario, there is no significant change is expected in the Mediterranean bioclimate type of the study area. However, according to the RCP 8.5 scenario, in the middle quarter period (2049-2073), there will be a significant increase in dry-sub humid areas from the east and southeast to the west. This increase will cover up to the coastal areas in the last quarter-century period (2074-2098), and even the entire study area was determined as the dry-sub humid and semi-arid Mediterranean bioclimatic layer, except for some part of Aegean Sea coastal zone.

According to the annual total precipitation projections in the RCP8.5 scenario, it is predicted that the areas suitable for olive production will decrease in the period of 2049-2073, and almost the entire study area will be in the category of medium suitable for olive production in the period of 2073-2098. An increase of about 6°C is expected in the maximum values of the average maximum temperatures during the swelling periods, especially in the periods after 2050, according to the RCP8.5 scenario. The increase in the extreme maximum temperatures in the study area may cause the olive trees to bloom earlier and prolong the growth period (Pérez et al., 2008). Also, by considering the high vernalization requirement of the main olive variety in the study area a 6°C temperature increase might significantly decrease the olive yields and will force farmers to transition to new varieties with relatively low vernalization requirements.

Water stress from decreased precipitation amounts in RCP 8.5 scenario will also very likely cause heat stress due to increased air temperatures and evapotranspiration rates. This stress might physiologically damage olive trees, cause flower shedding and thus reduce olive yields. Also, of possible water stress and changing temperature and precipitation regimes on olive pests (e.g., olive fly pests) and diseases (e.g., fungal diseases) might be increased and therefore, necessary precautions should be taken, especially after 2050.

As a result, it can be assessed briefly that even though the North Aegean sub-region of Türkiye will be likely more suitable for olive cultivation because of a small increase in annual total precipitation amounts in the period 2024-2048 under the RCP8.5 scenario and expected warming in air temperature drivers in high altitudes, an evident projected decrease in total precipitation amounts and relatively higher warming levels in air temperature drivers in the period 2049-2073 will very likely lead a substantial decrease in the suitable olive cultivation areas. Further, the Mediterranean climate of the study area will very likely face mostly semi-arid environmental conditions according to the Emberger climate classification for the period 2074-2098. Consequently, there would not be a climatically suitable area left for olive cultivation in majority of the study area under the RCP8.5 (2074-2098) scenario conditions.

On the other hand, according to both RCP scenarios, there is a possibility of extension of suitable areas for olive cultivation towards low to mid-elevation plateaus and mid-elevation slopes of mountainous areas and high plateaus particularly facing suitable aspects to lower negative effects of projected warming and dryness. These areas are presently characterized mainly by pure and mixed Mediterranean forest ecosystems consisting of broad-leaved and coniferous mixed trees and stands (Türkeş, 2021; Türkeş et al., 2023). In the future, considering the difficulty of adaptation of present forest ecosystems to changing climate conditions, these areas can be replaced with olive orchards.

Declarations

Ethical Approval Certificate

This article does not contain any studies with human or animal participants performed by any of the authors.

Author Contribution Statement

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Sinan Sahin and Murat Türkeş. All authors commented on previous versions of the manuscript, and all authors read and approved the final manuscript.

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Conflict of Interest

The authors declare no conflict of interest

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