



Effects of climate trends and variability on tree health responses in the Black Sea and Mediterranean forests of Türkiye

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Abstract

To adapt forest ecosystems and forest management to climate change, it is essential to know which forest regions and which tree species are resilient to climate variability and which ones are possibly affected most by past and anticipated future changes. In this contribution, for the main forest regions of Türkiye and six tree species, recent climate variability and trends were quantified and statistically correlated to record tree defoliation and vitality. Climate variables considered are maximum temperature (*Tmax*), minimum temperature (*Tmin*), mean temperature (*Tmean*), and total precipitation (*Prcp*), which are compared to forest health responses recorded as part of the International Cooperative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests) on 277 plots across forests along the Black Sea and Mediterranean regions. In addition, long-term data on satellite measurements of the normalized difference vegetation index (NDVI) were extracted for the same 277 plots for the period 2008–2020. Firstly, 30 years (1991–2020) of reanalysis of climate variables from ECMWF were extracted for all plots; secondly, individual correlations and cross-correlations of climate variables and tree health and vitality were computed for the period 2008–2020 (significance level of 95%) for the four most dominant species from the Black Sea forests (*F. orientalis*, *Q. cerris*, *P. sylvestris*, *P. orientalis*) and two species from Mediterranean forests (*P. brutia* and *C. libani*). Temperature showed a stronger effect on most species than precipitation. Finally, time-lagged correlations were analyzed for seven-time lags (significance level of 95%) to evaluate legacy effect. The analysis revealed that different tree species from the two regions show different responses to climate variables. Species in the Mediterranean region are more resistant to droughts and climatic variations. Legacy effects of *defoliation* and *NDVI* have lasted for at least 2 years.

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1 Introduction

Climate variability and extremes have been shown to increasingly pose a risk to forest ecosystems (Haynes et al. 2014; Sanchez-Salguero et al. 2017; Seidl et al. 2017; Limaki et al. 2021; Song et al. 2018). There are numerous studies that link climatic factors to forest health and vitality through abiotic (climate and weather extremes, air pollutants, forest fires) and biotic (pests, disease) factors (Marco et al. 2014; Gea-Izquierdo et al. 2019; Gottardini et al. 2020). Prediction of these factors is important for adapting future forest plans and sustainable forest ecosystem management (Deng et al. 2021). Beside investigating climatic conditions, use of remote sensing and defoliation data is crucial for assessing forest health. Many studies for many regions on different tree species have been conducted to improve the assessment of defoliation and tree responses to climate variability using remote sensing (Fernandez-Manso et al. 2011; Townsend et al. 2012; Zhu et al. 2018; Pasquarella et al. 2021) A study by Kovalev

et al. 2021 shows that use of seasonal normalized difference vegetation index (NDVI) dynamics makes it possible to classify plots according to the tree conditions. Results of assessing impact of extreme climatic events on aspen defoliation using NDVI note that there are predictable patterns of aspen defoliation that identify aspen stands vulnerable to climate extremes (Currit and St Clair 2010).

Türkiye also faces a number of forest stressors including fires, climate change, droughts, insects, and fungi, the part where the fires are most intense is the coastline from Antalya to Istanbul (Ozturk et al. 2010). Since the 1970s droughts due to the decreasing trend in total amount of precipitation in the Mediterranean region has been one of the confronted problems (Turkes 2012). There were 2.793 forest fires in 2021, resulting in the loss of 139.503 hectares of forest in Türkiye, which is approximately eleven times greater than the average loss for the period 2017–2020 (GDF 2022). Since the early 1980s, daily maximum and minimum temperatures in Türkiye have increased (Toros 2012b). Changes in the frequency, intensity, and duration of weather extremes with droughts and flash floods caused by extreme temperatures and precipitation events were experienced (Tayanç and Toros 1997; Kömüşçü et al. 1998; Toros 2012a; Baltacı 2017). The number of hot days, the number of heatwaves, and the duration of heatwaves were found to be significantly correlated (95% significance level) with fire occurrences in the period 1997–2006 in the western part of Türkiye (Unal et al. 2013). According to a recent trend analysis of heatwave characteristics, the frequency and length of heat waves in Türkiye have increased since 1950, and the Black Sea and the Mediterranean coasts have experienced the most significant changes in heat wave characteristics since the 1980s (Erlat et al. 2021). As given above, despite the abundance of literature showing climate variability and extreme behaviors in Türkiye, the studies that explain how these results effect on forest dominant tree species are insufficient. Some of the available studies related to this subject; a study by Ayan et al. (2022) based on the prediction of warmer conditions in the future with different scenarios, *Fagus orientalis* Lipsky. populations of the southern slopes of the North Anatolian Mountains were predicted to shrink and the populations in main distribution areas of Istranca Mountains and Northern Anatolia would be reduced, particularly populations in transition zone Central Anatolia. Also, it would lose its isolated-marginal populations in the southeast of Türkiye. The global habitat suitability area of *Cedrus libani* would enlarge in the forecasted scenarios with respect to the present, although it would be more restricted in 2070 due to the altitudinal shift (López-Tirado et al. 2021). This paper aims to explore which climate variables impact forest health in Türkiye for the period 2008–2020, so unlike

previous studies, NDVI, defoliation and climate variables were conducted together for dominant tree species in the Black Sea and Mediterranean forests.

The International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forest (ICP Forests), ICP monitored plots in Türkiye provide a unique dataset to analyze the details of forest health responses to climate and their changes over time. In this study, collected data at the ICP sites combined with climate and remote-sensed data could contribute to understand the drivers of forest health conditions in Türkiye; hereby, provide crucial knowledge towards sustainable and climate-adapted management of Turkish forests. No such studies have been conducted in the Mediterranean and Black Sea regions. These forest regions are the backbones of commercial forestry in Türkiye and their health conditions are of concern in Türkiye (GDF 2020).

In this study, we investigate how observed climate variability and change impacted tree crown defoliation in different geographic regions of Türkiye through the three main points as follows:

- Identify recent climate trends in the main forest regions and for the distribution areas of different tree species in Türkiye
- If the climate changed recently identify which forest regions and which tree species are sensitive to climate variability, expressed by defoliation and vitality (using NDVI)
- If a sensitivity is identified and determine which climate variables (precipitation temperature) explains over which time span most of the observed defoliation or change in NDVI.

To address those questions we aim to explain surveyed tree crown conditions assessed at ICP plots and also changes in satellite-derived NDVI for 277 plots across Türkiye for the period 2008–2020. We focus on six dominant tree species including Oriental beech (*Fagus orientalis*), Türkiye oak (*Quercus cerris*), Scots pine (*Pinus sylvestris*), Oriental spruce (*Picea orientalis*), Turkish pine (*Pinus brutia*), and Lebanese cedar (*Cedrus libani*). We focus on the two main forest regions, the Black Sea coast and the Mediterranean coast. Within the scope of this work, we will use individual correlations between short term climate variability and tree responses in terms of defoliation and NDVI, cross-correlations between climate variables and defoliation and NDVI, respectively, and finally time-lagged correlations to assess legacy effects and the time-scale of climate variables on forest health. Results will be analyzed both in a spatial (geographical) and temporal (decadal) context.

2 Data and methodology

For Europe and beyond, the International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forest (ICP Forests) has provided an international comprehensive framework and monitoring system since 1985 to assess the spatio-temporal variation of forest conditions at selected plots (Lorenz 1995). The goal of the ICP forest network is to provide a comprehensive compilation of information on the condition of forests (health, productivity) in Europe, including Türkiye. ICP assesses the impacts of natural and human-induced disturbances in order to understand cause-effect relationships between these factors and the condition of forest ecosystems (Lorenz 2010). The ICP Forest assessments exist at two monitoring intensity levels: In 2020, there were 5852 Level I plots across Europe on a grid of 16 × 16 km and 623 Level II plots that are a selected forest ecosystem. Forty-two countries including Türkiye have participated in the program. Initially, ICP assessments in Türkiye were launched in the 1990s, but they were discontinued due to lack of qualified staff and funding (Tolunay et al. 2010; Karakas et al. 2007; Koray et al. 2007). Since 2007, continuous observation has been implemented in Türkiye with 597 Level I plots and 52 Level II plots as of 2019 (Michel et al. 2020).

Defoliation is measured at Level I sites. Defoliation is regarded as a measure of tree health because it represents the percentage of leaves missing in the current crown in comparison to a fully foliated reference tree (Potočić et al. 2021). In the ICP forest plot surveys, there are two types of reference trees: local reference trees and absolute reference trees. Most countries including Türkiye have adopted local reference trees as standards (Eichhorn et al. 2016). Local reference trees or conceptual trees are the most suitable trees with full foliage for a particular site, considering factors such as altitude, latitude, tree age, site conditions, and social status. Their defoliation is set to 0%. Defoliation based on local reference trees is the most assessed variable in forest monitoring and international field exercises dating back to the 1980s (Michel et al. 2020). Even though accepting crown defoliation as a core parameter of forest health, it has also caused some critics due to the bias that can be caused by the observer and different measuring methods (Innes 1993; Eichhorn et al. 2010). Nevertheless, it is commonly considered an approved indicator for forest health (De Marco et al. 2014; Zierl 2004).

2.1 Study area

2.1.1 Ecology of forests

Fundamental studies were conducted to categorize phyto-geographical regions in Türkiye. Three types of

phyto-geographical regions are defined for Türkiye which are the Euro-Siberian, Mediterranean, and Irano-Turanian (Davis 1971; Zohary 1971, Avcı 1996). These regions have a particular vegetation and climatic characteristic. The Euro-Siberian region covers the entire Black Sea coast and the Black Sea coast of Thrace, climate throughout the year with high precipitation ratio and low seasonal temperature differences and foggy weather are climatic conditions (Çolak and Rotherham 2006, Atalay 2002). The Mediterranean region includes western and southern part of the Anatolia and the Amanos mountains. Maquis and dry forests at high elevations and dry, hot summers with warm and rainy winters are the characteristics of the region (Çolak and Rotherham 2006, Atalay 2002). These two regions are mostly forested, and also the most densely populated areas (Atalay et al. 2014). There are different types of forests with more than 450 tree species and shrubs (Çolak and Rotherham 2006). The detailed investigations mentioned above into forest structure groups according to ecological regions in Türkiye, which helped to determine our study areas. Hence priority was given to the tree species of the Black Sea/northern Marmara ecological regions (hereafter “Black Sea Forests”) and Mediterranean/western Aegean ecological regions (hereafter “Mediterranean Forests”). Based on the most common trees found (Bahadır and Emet 2010), four species from the Black Sea forests (*F. orientalis*, *Q. cerris*, *P. sylvestris*, *P. orientalis*) and two species from Mediterranean forests (*P. brutia* and *C. libani*) were selected. A study by are cited in text but not provided in the reference list.

Please provide references in the list or delete these citations. Eşen et al. (2015) notes that *F. orientalis* is the principal commercial tree in Türkiye and mostly growing in Black Sea Region. *Q. cerris* is a native and widely distributed species and oak species constitute 76.4% of broadleaf forests in Türkiye (Özer 2014). One main distributional areas of *P. sylvestris* in Türkiye are the western and eastern part of Black Sea region and mixed *P. sylvestris*, forests are commonly associated with *F. orientalis* and *P. orientalis* in the eastern part of Black Sea region (Atalay et al. 2014). *P. orientalis* is a native species in the Eastern Black Sea Region (Tüfekçioğlu et al. 2011). *P. brutia* is one of the important forest trees of the Mediterranean Region, reaches its greatest distribution in southern Türkiye and one of the most valuable commercial trees (Kayacık 1980). *C. libani* naturally distributed in Türkiye, Syria, Lebanon, and Southern Türkiye has the largest forest area of *C. libani* in the world with 324,453 hectares (Boydak and Çalikoğlu 2008). Of the 277 plots, 138 plots were attributed to Black Sea forests and 139 plots to Mediterranean forests (Fig. 1). Two plots from the Mediterranean, and 25 from the Black Sea forests, in total 27 plots out of 277 had two of the species present, *F. orientalis*

(73), *Q. cerris* (25), *P. sylvestris* (50), *P. orientalis* (16), *P. brutia* (118), *C. libani* (22) as seen in Fig. 1.

According to GDF (2009), the forested areas in Türkiye cover 21.2 million hectares, constituting 27.2% of the total land area. The forested areas in Türkiye are mostly concentrated in the Black Sea region (BSR), Marmara region (MR), Aegean region (AR), and Mediterranean region (MeR), while Central Anatolia (CAR), East Anatolia (EAR), and Southeastern Anatolia (SEAR) regions are forest-poor regions (Fig. 1). The forests in Türkiye are separated into roughly 50% productive and 50% unproductive. Sixty percent of the forests in Türkiye are coniferous and 40% are broad-leaved dominated trees. The majority of broad-leaved trees are *Quercus* sp (oak) tree species, which constitute 30.2% of the total forestry regions and the majority of conifers are *Pinus nigra* (black pine) and *P. brutia* (red pine), which constitute 19.8% and 25.2% of the total forestry regions. Regarding the geographical areas of Türkiye, the forested area by region is as follows: Black Sea (24.4%), Mediterranean (19.6%), Aegean (15.9%), Marmara (12.8%), Middle Anatolia (13.8%), East Anatolia (8.3%), and Southeast Anatolia (5.8%). In Türkiye, ICP Forest level I plots are found mostly in the Black Sea and Mediterranean regions since most forested areas are located here (GDF 2020).

2.1.2 Climate of the study area

The plots in the Black Sea forests experience dominantly temperate climates that are year-round humid with warm summers (Cfb); the plots in the Marmara ecological regions are also found with climates that experience hot summers (Cfa) while the higher-altitude mountain forests and forests of the Backward Black Sea Plateau experience continental cold climates with warm summers (Dfb) (Kottek et al. 2006). Generally, most of the Black Sea forest plots are wet in every season, the share of summer (sum of months June, July, and August, hereafter “JJA”) precipitation in the annual total is about 19.4%. In contrast, the Mediterranean forests are in temperate climates with dry and hot summers (Csa), partially also continental cold climates with dry and warm summers (Dsa) in the interior. For the plots in the Mediterranean forests, summer precipitation (JJA) in the annual accounts for only about 5.7% (Atalay 1997).

2.2 Data sources

2.2.1 Defoliation data

In 2020, 607 plots are available over Türkiye. In this study 277 plots out of 607 were selected considering only the six

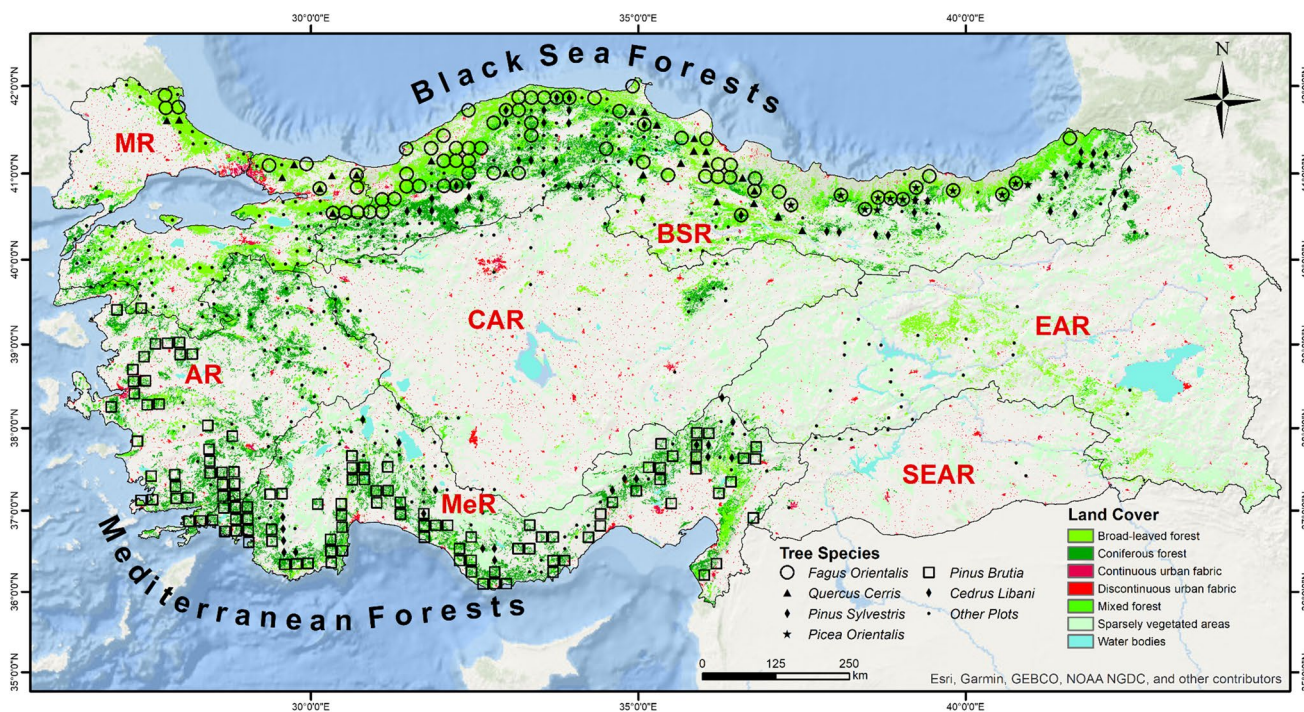


Fig. 1 The locations of forests (green areas), ecological regions (red labels refer to the climate regions as called in the text) and the 304 ICP plots in Türkiye with the 277 plots contain at least one of the six dominant tree species in the study highlighted by different symbols: *F. orientalis* (73), *Q. cerris* (25), *P. sylvestris* (50), *P. orientalis* (16),

P. brutia (118), and *C. libani* (22). 27 ICP plots contain more than one selected tree species. Land Cover was retrieved from CORINE Land Cover data (© European Union, Copernicus Land Monitoring Service 2018, EEA)

most dominant tree species (Table 1) from main forestry regions of Türkiye. For defoliation data in the 277 plots were provided by the Ministry of Agriculture and Forestry for the period 2008–2020 which is the longest available period for defoliation. Defoliation is categorized into five classes, from 0% (no defoliation) to 100% (dead tree). It has five different classes based on reference trees on the plots such as Class 0 up to 10% (none), Class 1 > 10–25% (slight), Class 2 > 25–60% (moderate), Class 3 > 60–100% (severe), and Class 4 = 100% (standing dead trees only) (Michel et al. 2020). Class 4, namely dead trees, is not included in this study. Measurement of defoliation is conducted only once each year during the months of June, July, August, and September. In this study, the plots whose measurements were completed in the summer season (June, July, August; hereafter JJA), were used. September is an autumn month that has different characteristics than the summer months and was not considered in this study. In addition, the percentage of missing data in the defoliation data as follows by tree species; *F. orientalis* is 12.8%, *Q. cerris* 25%, *P. sylvestris* 16%, *P. orientalis* 6%, *P. brutia* 14%, and *C. libani* 16%.

2.2.2 Climate data

Climate variables were obtained from the fifth generation ECMWF reanalysis data ERA5-land (C3S 2017) obtained for the period 2008–2020 at a spatial resolution of $0.25^\circ \times 0.25^\circ$ and an hourly temporal resolution. For each plot, data from the grid cell containing the coordinates of the corresponding ICP plot were extracted. For each ICP plot, daily maximum air temperature at 2 m (*Tmax*), daily minimum air temperature at 2 m (*Tmin*), and daily mean air temperature at 2 m (*Tmean*) were calculated from hourly ERA5 data over the entire period 2008–2020. Similarly, daily precipitation (*Prcp*) was calculated as the sum of hourly ERA5 precipitation data for each ICP plot.

The standardized precipitation index (SPI) and standardized precipitation evapotranspiration index (SPEI) were used similar to other studies investigating drought effects on vegetation (Sirdaş and Sen 2003; Polong et al. 2019; Danandeh Mehr and Vaheddost 2020). Previous studies showed that temperature has a critical role in drought severity (Stagge et al. 2015; Abbasi et al. 2019; Eris et al. 2020). While SPI (McKee et al. 1993) works solely based on precipitation, SPEI (Vicente-Serrano et al. 2010) additionally includes maximum and minimum temperature to estimate evapotranspiration (Frank et al. 2017). Hargreaves (Hargreaves 1994) was used to estimate reference evapotranspiration since besides maximum and minimum temperature data, latitude data is also available for ICP plots. SPI and SPEI calculations were conducted using R packages SPI and SPEI (Beguieria and Vicente-Serrano 2023) for each ICP plot separately over different periods, including 1, 2, 3, 6, 9, 12, and 24-month backwards based on ERA5 *Tmax*, *Tmin*, and *Prcp* data for the period 2008–2020.

2.2.3 Remote sensing data

In addition to ground-based defoliation assessments as surveyed at ICP plots, satellite-based metrics such as normalized difference vegetation index (NDVI) can also show responses of vegetation vitality at the stand-level to varying climate variables. NDVI has been used to assess how climate variability affects vegetation growth especially in climate-sensitive areas (John et al. 2013; Zhang et al. 2016). Studies on climate change and its responses of NDVI of vegetated areas have been conducted globally over the past few decades (Pravalie et al. 2014; Schmidt et al. 2014; Shawul and Chakma 2020; Salvador and de Brito 2018), and the number of the studies for Türkiye due to its location, intricate climate, climate change sensitivity, and unique topography has increased (Arekhi et al. 2018; Akkoyunlu et al. 2019; Koç

Table 1 Ecological properties of the tree species

Species ecological properties	<i>F. orientalis</i>	<i>Q. cerris</i>	<i>P. sylvestris</i>	<i>P. orientalis</i>	<i>P. brutia</i>	<i>C. libani</i>
Climate	Temperate climate	Temperate climate	Continental and temperate climate	Tropical climate	Mediterranean climate	Mediterranean climate
Altitude (m)	200–2000	500–2000	0–2600	300–2100	0–1650	1300–3000
Shade	Shade tolerant	Semi-shade tolerant	Shade intolerant	Shade tolerant	Shade intolerant	Semi-shade tolerant
Moisture	Moist tolerant	Moist tolerant	Moist intolerant	Moist tolerant	Moist intolerant	Moist intolerant
Weakness	Late-frost		Drought			
Strength		Air pollution, relatively drought tolerant		Air pollution, wind exposure, drought	Drought, fire resistant	Drought, fire resistant

Refer to Atalay (1997); Kandemir and Kaya (2009); Mátyás et al. (2004); Fady et al. (2003); Messinger et al. (2015); Simeone et al. (2019)

et al. 2020). For satellite-based metric, we used MOD13A3 version 6 at 1×1 km resolution to retrieve monthly NDVI for the period 2008 to 2020 from application for extracting and exploring analysis ready samples (AppEEARS) (<https://lpdaac.usgs.gov>). AppEEARS provides an efficient way to use spatial temporal and layer parameters.

2.3 Statistical analysis methodologies

2.3.1 Trend analysis

Long-term in *Tmean*, *Tmax*, *Tmin*, and *Prcp* were calculated for the 30-year climate period 1991–2020 using linear regressions on the ERA5 reanalysis data separately for each grid cell in which an ICP plot was located and separately for the full-year and the summer (JJA) period. Long-term trends in NDVI and mean plot defoliation (defoliation) per species were calculated over the 13-year period 2008–2020 (summer only), due to limited data availability.

2.3.2 Correlation analysis

Pearson correlation coefficients (Rodgers and Nicewander 1988) were computed to assess linear relationships between summer (JJA) average *Tmean*, *Tmax*, *Tmin*, *Prcp*, NDVI and summer defoliation to check for correlations between inter-annual climate variability and tree responses for the period 2008–2020. Statistical significance was evaluated according to linear regression results at a 95% confidence interval (p -values ≤ 0.05 (*)), and were evaluated at three different levels with p -values ≤ 0.05 (*), p -values ≤ 0.01 (**), and p -values ≤ 0.001 (***)).

2.3.3 Principal component analysis

For analyzing cross correlations between the above climate variables, NDVI and defoliation for the period 2008–2020 (summer only), additionally principal component analysis (PCA) was used (Anderson 1958; Kendall 1968). The method has aimed at the selection of significant components and the dimensionality reduction. Specifically, PCA identifies the directions of maximum variance in high-dimensional data and projects it onto a smaller dimensional subspace while retaining most of the original information (Hartmann et al. 2018). PCA has been widely adopted in various fields such as meteorology, climatology, and forestry to detect elementary features of physical phenomena by simplifying data sets (Camperlin and Diop 2003; Sneyers et al. 1989; Pandžić et al. 2009; Tadić et al. 2019). This study has applied PCA to identify the main components of climate affecting forest health conditions of different tree species.

2.3.4 Time-lagged correlations

To test if there are delayed effects or legacy effects of climate extremes on tree health, time-lagged correlations were performed. Correlations with a moving window were calculated using the Pearson correlation coefficients between *Tmax*, *Tmean*, *Tmin*, *Prcp*, and *Tmean* anomalies over periods of increasing length back from a measurement when NDVI/defoliation was measured. Time-lagged correlations were performed for the period 2008–2020 using seven different time windows backwards from a date when defoliation and/or NDVI were measured. These time windows are considering the time from the defoliation/NDVI measurement date back to the previous 1, 2, 3, 6, 9, 12, and 24 months (here after T1, T2, T3, T6, T9, T12, T24) with respect to the defoliation date of the year based on plots from each species. For each time window *Tmax*, *Tmean*, *Tmin*, *Prcp*, and *Tmean* anomalies were calculated relative to the same period of the year in the entire 2008–2020 period. The significant tests of the partial correlation coefficients were based on the Student *t*-tests at a significance level of 95%.

3 Results

3.1 Climatic conditions

3.1.1 Annual averages, variability, and change

The average annual total precipitation (*Prcp*) in the period 1991–2020 in the Black Sea forest plots was 1033 mm (range 559–2453 mm). Generally, highest annual *Prcp* is found on the forest plots along the Eastern Black Sea coast. Annual average air temperature (*Tmean*) in the Black Sea forest plots was 9.90 °C (3.42–15.04 °C). The average annual *Prcp* in the forest plots of the Mediterranean forests for the same period is 810 mm (356–1275 mm). Annual *Tmean* in the Mediterranean forest plots was on average 14.68 °C (7.81–19.73 °C).

The average interannual variability as assessed by the standard deviation of annual *Tmean* from 1991 to 2020 is 0.92 K (0.69–1.26 K) for the plots of the Black Sea forests, and 0.74 K (0.56–1.07 K) for the plots of the Mediterranean forests. Average interannual *Prcp* variability is 122.45 mm or 11.8% of the average annual total (66.67–297.10 mm) for the plots of the Black sea forests, and 144.73 mm or 17.8% (63.80–255.69 mm) for the plots of the Mediterranean forests. The interannual variabilities in *Tmean* and *Prcp* by tree species are shown in Table 2.

Over the period from 1991 to 2020, for $n = 277$ plots, namely all investigated plots a statistically significant positive trend of annually averaged *Tmean* was found (Fig. 2a). Averaged over all plots of the Black Sea forests,

Table 2 Climate variability and change for the 1991–2020 period averaged for all plots containing the listed tree species. Square brackets refer to the proportion of interannual variability of JJA *Prcp* totals to JJA *Prcp* totals

Tree species	Annual average air temperature (<i>Tmean</i> , 2 m, °C)			Annual total precipitation (<i>Prcp</i> , mm)			Annual averaged monthly <i>Tmax</i> (2 m)		
	Annual average of <i>Tmean</i> (1991–2020)	Interannual variability of <i>Tmean</i> (1991–2020)	Trend of annual <i>Tmean</i> (1991–2020)	Annual <i>Prcp</i> total (1991–2020)	Interannual variability of <i>Prcp</i> totals (1991–2020)	Trend of annual <i>Prcp</i> (1991–2020)	Annual average of <i>Tmax</i> (1991–2020)	Interannual variability of <i>Tmax</i> (1991–2020)	Trend of annual <i>Tmax</i> (1991–2020)
<i>F. orientalis</i> (n=73)	10.86 (6.28–14.96) °C	0.88 (0.69–1.13) °C	0.66* K/decade	1102.33 (584.00–2453.27) mm	131.82 (77.24–267.10) mm (11.9%)	No significant trend	15.41 (10.74–18.29) °C	1.04 (0.71–1.42) °C	0.85* K/decade
<i>Q. cerris</i> (n=25)	11.91 (7.71–15.04) °C	0.87 (0.87–1.08) °C	0.66* K/decade	868.63 (559.37–1109.3) mm	109.25 (75.03–152.76) mm (12.6%)	No significant trend	16.65 (13.19–19.20) °C	1.01 (0.77–1.30) °C	0.80* K/decade
<i>P. sylvestris</i> (n=50)	7.91 (3.42–11.72) °C	1.00 (0.83–1.26) °C	0.77* K/decade	982.37 (559.53–2315.08) mm	112.59 (66.67–222.41) mm (11.5%)	No significant trend	13.09 (8.79–17.30) °C	1.21 (1.00–1.50) °C	1.00* K/decade
<i>P. orientalis</i> (n=16)	7.76 (10.57–4.33) °C	0.95 (1.17–0.89) °C	0.70* K/decade	1645.20 (1174.90–2453.27) mm	150.76 (108.88–251.40) mm (9.2%)	No significant trend	12.12 (8.79–14.07) °C	1.06 (0.95–1.40) °C	0.73* K/decade
<i>P. brutia</i> (n=118)	15.24 (19.73–8.34) °C	0.73 (1.076–0.55) °C	0.56* K/decade	813.95 (355.90–1273.32) mm	148.82 (68.78–255.69) mm (18.3%)	No significant trend	20.10 (12.90–24.42) °C	0.75 (0.52–1.11) °C	0.54* K/decade
<i>C. libani</i> (n=22)	11.46 (15.09–7.81) °C	1.01 (0.85–0.64) °C	0.62* K/decade	798.33 (535.30–1238.58) mm	129.31 (64.79–191.00) mm (16.2%)	No significant trend	16.61 (12.49–20.74) °C	0.88 (0.62–1.07) °C	0.6* K/decade

*p-value is less than 0.05

annual *Tmean* experienced a statistically significant trend of +0.70 K/decade. For the Mediterranean forests annual *Tmean* experienced a statistically significant trend of +0.57 K/decade. Only for $n = 7$ plots (four from the Eastern Black Sea region, three from the Western Mediterranean region) a statistically significant positive trend of annual total *Prcp* was found. A total of $n = 31$ plots, all from the Middle Black Sea region, experienced a statistically significant negative trend of annual total precipitation and $n = 239$ plots had no statistically significant trend (Fig. 2e). Averaged over all plots of the Black Sea forest plots, annual *Prcp* had no statistically significant trend. Similarly, averaged over all Mediterranean forest plots, annual *Prcp* had no statistically significant trend. The trends in *Tmean* and *Prcp* separated by tree species are shown in Table 2.

3.1.2 Summer season averages, variability, and change

The average summertime (JJA) total precipitation (*Prcp*) in the period 1991–2020 in the Black Sea forest plots was 239.62 mm (range 71.32–744.38 mm). Again, highest summertime *Prcp* is found on forest plots along the Eastern Black Sea coast. The average summertime *Prcp* in the forest plots of the Mediterranean forests for the same period is 53.07 mm (3.21–214.86 mm). The share of JJA *Prcp* in the annual total *Prcp* for the Black Sea and Mediterranean are 6.53% and 21.49%, respectively. Summertime average (JJA) average air temperature (*Tmean*) in the Black Sea forest plots was 18.80 °C (14.07–23.93 °C) and in the Mediterranean plots it was 24.17 °C (18.71–28.13 °C).

Figure 3 contrasts summer (JJA) *Tmean* and total *Prcp* individually from all 277 selected plots; the tree species are shown in different colors. Clear ecoclimatic differences for different tree species and regions are revealed: Generally highest JJA *Tmean* and lowest JJA *Prcp* are experienced by forest plots containing *P. brutia*, while *C. libani* is found in similarly dry (Mediterranean) conditions, but with generally lower *Tmean*. The forest species of *F. orientalis*, *Q. cerris*, and *P. sylvestris* are found over a range of summertime climatic conditions of the western Black Sea region, while forests with *P. orientalis* experience clearly more humid conditions of the eastern Black sea with highest summertime *Prcp*.

The average interannual variability of summer air temperatures as assessed by the standard deviation of JJA *Tmean* from 1991 to 2020 is 0.86 K (0.68–1.30 K) for the plots of the Black Sea forests, and 0.73 K (0.54–0.97 K) for the plots of the Mediterranean forests. Average interannual summer precipitation variability based on JJA *Prcp* is 65.08 mm or 27.16% (22.05–163.61 mm) for the plots of the Black sea forests, and 25.83 mm or 48.67% (3.66–77.63 mm) for the plots of the Mediterranean

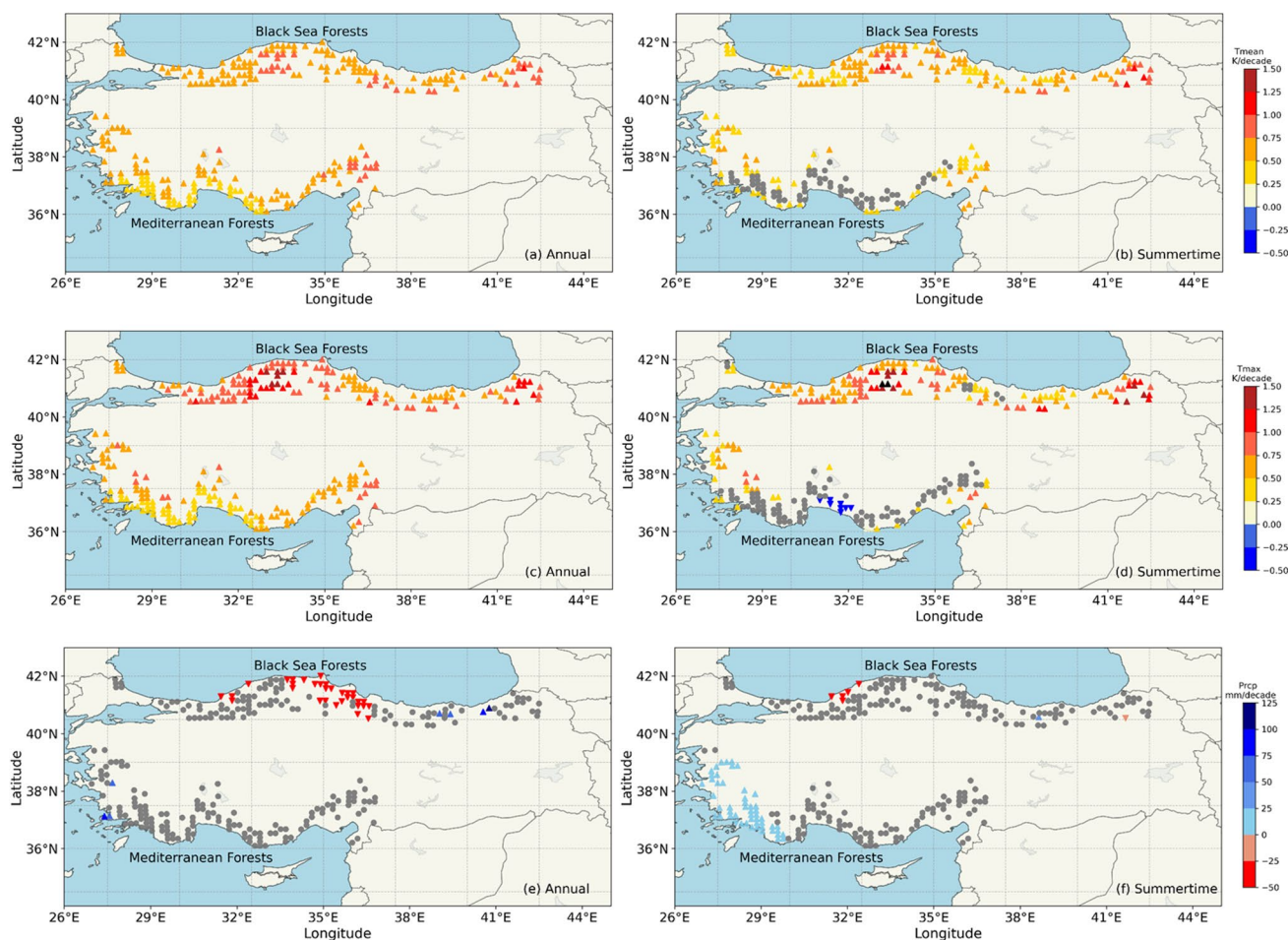


Fig. 2 a–e Statistically significant trends (95% confidence interval) are shown for the 1991–2020 period in **a** annual mean temperature, **b** summertime mean temperature, **c** annual max temperature, **d** sum-

meritime max temperature, **e** annual total precipitation, **f** summertime total precipitation. Gray points refer to the plots having no significant trend for the period

forests. The interannual variability in *Tmean* and *Prctp* by tree species is shown in Table 3.

Over the period from 1991 to 2020, for $n=209$ plots a statistically significant positive trend of summer (JJA) *Tmean* was found and $n=68$ plots had no statistically significant trend (Fig. 2b). Averaged over all plots of the Black Sea forests, JJA *Tmean* experienced a statistically significant trend of $+0.61$ K/decade. For the Mediterranean forests, JJA *Tmean* experienced a statistically significant trend of $+0.30$ K/decade. Similarly, for $n=53$ plots a statistically significant positive trend in summertime (JJA) total *Prctp* was found. $n=6$ plots had a statistically significant negative trend of JJA total *Prctp* and $n=218$ plots had no statistically significant trend (Fig. 2f). Averaged over all plots of the Black Sea forests, summer (JJA) *Prctp* has no statistically significant trend. For the Mediterranean forests JJA *Prctp* has no statistically significant trend. The trends in JJA *Tmean* and *Prctp* by tree species are shown in Table 3.

3.2 Forest health indicators

3.2.1 Defoliation

Defoliation was assessed on all 277 plots from 2008 to 2020 on more than 4300 individual trees (Table 4). Overall, *Q. cerris* had the highest fraction of trees with strong defoliation. 20% of all *Q. cerris* trees assessed were in defoliation Class 2 or 3. This is followed by *P. brutia* (12% of all *P. brutia* trees assessed are in defoliation Class 2 or 3) and *F. orientalis* (12%) and *P. sylvestris* (10%), *P. orientalis* and *C. libani* showed the lowest fraction of trees in defoliation Classes 2 and 3 among the six species studied with 7 and 3%, respectively. *P. orientalis* had 67% of all trees in Class 0 (no defoliation). *F. orientalis* (44%), *C. libani* (48%), *P. sylvestris* (47%) experienced about half of the trees in Class 0 (no defoliation), *Q. cerris* (29%) and *P. brutia* (21%) had fewest trees with no defoliation.

Table 3 Summer time climate variability and change for the 1991–2020 period. Square brackets refer to the proportion of interannual variability of JJA *Prcp* totals to JJA *Prcp* totals

Tree species	Summertime (JJA) air temperature (2 m)				Summertime (JJA) precipitation				Summertime (JJA) max temperature (2 m)			
	Average of JJA <i>Tmean</i> (1991–2020)	Interannual variability of JJA <i>Tmean</i> (1991–2020)	Trend of JJA <i>Tmean</i> (1991–2020)	JJA <i>Prcp</i> total (1991–2020)	Interannual variability of JJA <i>Prcp</i> totals (1991–2020)	Trend of JJA <i>Prcp</i> (1991–2020)	Average of JJA <i>Tmax</i> (1991–2020)	Interannual variability of JJA <i>Tmax</i> (1991–2020)	Trend of JJA <i>Tmax</i> (1991–2020)			
<i>F. orientalis</i> (n = 73)	19.47 (15.25–23.37) °C	0.79 (0.68–1.12) °C	0.55* K/decade	232.17 (79.38–744.38) mm	69.67 (30.09–163.60) mm (30.0%)	No significant trend	24.23 (19.24–27.39) °C	0.96 (0.6–1.58) °C	0.6* K/decade			
<i>Q. cerris</i> (n = 25)	20.69 (17.24–23.93) °C	0.80 (0.68–1.03) °C	0.56* K/decade	155.54 (86.82–236.00) mm	54.71 (32.07–89.41) mm (35.1%)	No significant trend	25.71 (22.95–28.38) °C	0.94 (0.71–1.48) °C	0.6* K/decade			
<i>P. sylvestris</i> (n = 50)	17.53 (14.07–21.23) °C	0.97 (0.75–1.39) °C	0.72* K/decade	224.43 (71.32–699.03) mm	58.92 (22.05–129.25) mm (26.2%)	No significant trend	23.32 (18.86–27.96) °C	1.24 (0.82–1.74) °C	0.90* K/decade			
<i>P. orientalis</i> (n = 16)	16.68 (14.14–18.39) °C	0.86 (0.73–1.16) °C	0.57* K/decade	452.41 (330.008–744.38) mm	92.57 (70.32–163.60) mm (20%)	No significant trend	21.08 (18.82–22.71) °C	0.90 (0.71–1.45) °C	0.53* K/decade			
<i>P. brutia</i> (n = 118)	24.65 (18.72–28.12) °C	0.72 (0.54–0.97) °C	No significant trend	50.03 (3.21–190.64) mm	24.71 (3.65–67.71) mm (49.3%)	No significant trend	29.98 (24.11–34.65) °C	0.89 (0.57–1.22) °C	No significant trend			
<i>C. libani</i> (n = 22)	21.58 (18.73–25.59) °C	0.76 (0.63–0.91) °C	No significant trend	69.39 (39.61–214.86) mm	32.09 (22.71–77.63) mm (46.2%)	No significant trend	27.24 (23.27–30.50) °C	0.91 (0.70–1.06) °C	No significant trend			

**p*-value is less than 0.05

Table 4 Fraction of trees based on defoliation classes for the period 2008–2020

Species	Def. class	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2008–2020 average
<i>Fagus orientalis</i>	Class 0	10%	24%	31%	38%	33%	47%	31%	65%	57%	62%	63%	61%	50%	44%
	Class 1	39%	54%	55%	55%	59%	47%	49%	31%	39%	35%	35%	35%	46%	45%
	Class 2	47%	21%	13%	6%	6%	5%	19%	4%	4%	3%	2%	4%	4%	11%
	Class 3	4%	1%	0%	1%	1%	1%	1%	1%	0%	0%	0%	0%	0%	1%
No. of trees		611	655	749	740	742	781	801	849	877	872	815	858	836	
<i>Quercus cerris</i>	Class 0	8%	21%	11%	21%	16%	39%	42%	51%	36%	32%	45%	30%	24%	29%
	Class 1	46%	51%	47%	48%	72%	46%	48%	39%	49%	52%	45%	57%	65%	51%
	Class 2	36%	27%	28%	20%	8%	15%	8%	9%	14%	13%	9%	12%	10%	16%
	Class 3	10%	2%	14%	11%	4%	0%	3%	1%	1%	3%	1%	1%	1%	4%
No. of trees		83	63	88	71	75	107	77	112	147	141	149	161	148	
<i>Pinus sylvestris</i>	Class 0	37%	34%	35%	32%	35%	53%	53%	56%	64%	59%	57%	50%	47%	47%
	Class 1	38%	49%	51%	51%	54%	39%	39%	40%	29%	36%	35%	43%	46%	42%
	Class 2	21%	16%	14%	15%	11%	7%	7%	3%	5%	4%	7%	6%	6%	9%
	Class 3	4%	1%	1%	1%	0%	1%	1%	0%	1%	1%	2%	1%	1%	1%
No. of trees		346	565	539	618	529	603	435	489	593	524	525	596	608	
<i>Picea orientalis</i>	Class 0	53%	57%	40%	46%	54%	52%	61%	77%	80%	86%	83%	89%	90%	67%
	Class 1	27%	25%	41%	44%	39%	41%	34%	21%	19%	12%	16%	9%	9%	26%
	Class 2	19%	17%	17%	9%	6%	6%	4%	1%	0%	0%	0%	0%	1%	6%
	Class 3	1%	2%	2%	2%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%
No. of trees		100	126	133	133	134	134	134	134	134	140	139	140	140	
<i>Pinus brutia</i>	Class 0	19%	17%	15%	22%	22%	26%	19%	25%	21%	30%	25%	16%	20%	21%
	Class 1	69%	66%	65%	65%	70%	69%	74%	65%	66%	60%	63%	69%	63%	66%
	Class 2	12%	16%	19%	13%	7%	5%	6%	10%	13%	9%	12%	15%	17%	12%
	Class 3	0%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
No. of trees		804	2301	2208	2112	2140	2078	1679	2089	2248	2280	2170	2188	2098	
<i>Cedrus libani</i>	Class 0	16%	47%	37%	43%	59%	62%	59%	64%	65%	55%	51%	42%	27%	48%
	Class 1	83%	50%	62%	54%	36%	35%	40%	33%	31%	42%	45%	53%	67%	49%
	Class 2	2%	2%	1%	2%	2%	3%	1%	4%	3%	3%	4%	5%	7%	3%
	Class 3	0%	0%	0%	1%	2%	0%	0%	0%	0%	0%	0%	1%	0%	0%
No. of trees		109	177	176	169	162	173	174	200	208	166	166	167	166	

The number of trees into each defoliation class by year are given in Table 4.

Defoliation of all selected tree species during the 2008–2020 period was 17.14% in the Black Sea forests and 18.36% in the Mediterranean forests. Separated by species, the defoliation during the 2008–2020 period was 16.68% for *F. orientalis*, 22.67% for *Q. cerris*, 17.47% for *P. sylvestris*, 13.51% for *P. orientalis*: 19.03% for *P. brutia*, and 15.40% for *C. libani*. Interannual variation in summertime defoliation was recorded as follows: *F. orientalis*, 6.48%; *Q. cerris*, 7.73%; *P. sylvestris*, 5.31%; *P. orientalis*, 4.93%; *P. brutia*, 4.60%; *C. libani*, 4.04%.

Over the 13 years of the dataset, four tree species experienced a statistically significant trend in summertime defoliation, namely *F. orientalis* (− 9.8%/decade**),

Q. cerris (− 8.7%/decade**), *P. sylvestris* (− 5.8%/decade**), and *P. orientalis* (− 3.9%/decade**), *P. brutia* (0.4%/decade) and *C. libani* (1.6%/decade) experienced no statistically significant trends.

3.2.2 NDVI

The 13-year summertime (JJA) NDVI averages for the 2008–2020 period for plots containing the species are as follows: Plots containing *F. orientalis* 0.84 (0.70–0.91), *Q. cerris* 0.72 (0.49–0.87), *P. sylvestris*: 0.70 (0.39–0.90), *P. orientalis*: 0.81 (0.63–0.89), *P. brutia*: 0.52 (0.26–0.74), *C. libani*: 0.47 (0.29–0.63). The NDVI interannual variability for the summertime (JJA) 2008–2020 period by species are as follows: Plots containing *F. orientalis*, 0.02 (0.01–0.07); *Q. cerris*, 0.03 (0.02–0.07); *P. sylvestris*,

0.02 (0.01–0.05); *P. orientalis*, 0.02 (0.01–0.04); *P. brutia*, 0.03 (0.01–0.06); and *C. libani*, 0.03 (0.02–0.04).

The following trends in summertime (JJA) *NDVI* were identified for the 2008–2020 period for plots containing the corresponding species: *F. orientalis*, +0.03***;* *Q. cerris*, +0.04**;* *P. sylvestris*, +0.04***;* *P. orientalis*, +0.03****;* *P. brutia*, +0.04***;* *C. libani*, +0.05 ** per decade.

3.3 Individual correlations between climate variables and tree health

Correlations between summertime (JJA) averaged climate variables (*Tmax*, *Tmean*, *Tmin*, *Prcp*) and tree health indicators (*defoliation*, *NDVI*) were calculated for each tree species separately; all plots containing a species were combined to calculate correlations irrespective of geographic location in Table 5. As shown in Fig. 4, it is evident that average *Tmax*, *Tmean*, *Tmin*, total *Prcp* of JJA, and *defoliation* values for each species have also varied considerably between plots.

In addition, correlations between climatic variables and forest health conditions (*defoliation*, *NDVI*) were calculated for each individual plot; and the Pearson correlation coefficient (*r*) values between the average JJA *Tmax* and total JJA *Prcp* plot averaged *defoliation* and *NDVI* are shown in Fig. 5. All correlations are calculated for the 2008–2020 period. In addition to *Tmax*, *r* values have also been calculated for *Tmean* and *Tmin*, however, *Tmax* results have been highlighted because results were more pronounced. Although it has been found that summertime (JJA) *Tmax* and total *Prcp* vary with geographic location, a clear regional distinction in the climate variability is

found between Mediterranean forests and Black Sea forests: *P. brutia* and *C. libani* have mainly varied in total precipitation of JJA between 25 and 250 mm, in average maximum temperature of JJA between 23 and 34° C. *F. orientalis*, *Q. cerris*, *P. sylvestris*, and *P. orientalis* have changed between 100 and 800 mm in total precipitation of JJA and changed between 19 and 29 °C for the average maximum temperature of JJA.

Figure 5 also gives the opportunity to interpret the ranges of climate variability in which tree responses are higher. It is seen that some plots with low precipitation values are highly correlated with *NDVI*. Part of the *P. orientalis* plots, which experience higher total *Prcp*, show low/negative correlation with values > 500 mm between *NDVI* and *Prcp*.

3.4 Cross-correlations between climate variables and tree response

For the PCA, the initial variables are *Tmean*, *Tmax*, *Tmin*, *Prcp*, *defoliation*, and *NDVI* (Fig. 6). The target variable is *defoliation* class. Each dot in Fig. 6 refers to a plot and single year (2008–2020), the number of dots is different for the species since the number of plots varies for each tree species and for each year. Selected plots containing *Q. cerris* and *P. sylvestris* had *defoliation* values reported up to Class 3, while the other four species showed maximum *defoliation* only up to Class 2. The most common *defoliation* values reported are in classes 0 and 1, which means that none or slight *defoliation* are more frequent at a plot level.

Aside from *C. libani* and *P. sylvestris*, other species show a negative correlation between *defoliation* and *NDVI*. In

Table 5 Pearson correlation coefficient (*r*) of summertime (JJA) averaged climate variables (*Tmax*, *Tmean*, *Tmin*, *Prcp*) and forest health indicators (*NDVI*, *Defoliation*) for the same periods based on tree species for the period 2008–2020

<i>F. orientalis</i>	<i>Prcp</i>	<i>NDVI</i>	<i>Defoliation</i>	<i>P. orientalis</i>	<i>Prcp</i>	<i>NDVI</i>	<i>Defoliation</i>
<i>Tmax</i>	−0.81***	−0.28*	0.19	<i>Tmax</i>	−0.43	−0.03	0.57*
<i>Tmean</i>	−0.59***	−0.22	0.08	<i>Tmean</i>	0.22	0.27	0.2
<i>Tmin</i>	−0.26*	−0.13	−0.03	<i>Tmin</i>	0.54*	0.33	−0.07
<i>Prcp</i>		0.27*	−0.15	<i>Prcp</i>		0.32	−0.36
<i>NDVI</i>			−0.22	<i>NDVI</i>			−0.16
<i>Q. cerris</i>	<i>Prcp</i>	<i>NDVI</i>	<i>Defoliation</i>	<i>P. brutia</i>	<i>Prcp</i>	<i>NDVI</i>	<i>Defoliation</i>
<i>Tmax</i>	−0.64***	0.19	−0.31	<i>Tmax</i>	−0.40***	0.04	0.13
<i>Tmean</i>	−0.57*	0.46*	−0.60*	<i>Tmean</i>	−0.55***	0.18*	0.05
<i>Tmin</i>	−0.49*	0.54*	−0.67***	<i>Tmin</i>	−0.49***	0.25*	0.00
<i>Prcp</i>		−0.06	0.21	<i>Prcp</i>		0.13	−0.07
<i>NDVI</i>			−0.62***	<i>NDVI</i>			0.09
<i>P. sylvestris</i>	<i>Prcp</i>	<i>NDVI</i>	<i>Defoliation</i>	<i>C. libani</i>	<i>Prcp</i>	<i>NDVI</i>	<i>Defoliation</i>
<i>Tmax</i>	−0.76***	0.28	−0.18	<i>Tmax</i>	−0.52*	−0.11	0.06
<i>Tmean</i>	−0.58***	0.40*	−0.11	<i>Tmean</i>	−0.42*	−0.06	−0.01
<i>Tmin</i>	−0.2	0.50***	0.03	<i>Tmin</i>	−0.21	0.03	−0.1
<i>Prcp</i>		−0.03	0.40*	<i>Prcp</i>		0.18	0.08
<i>NDVI</i>			0.03	<i>NDVI</i>			0.31

p*-value is less than 0.05; *p*-value is less than 0.01; ****p*-value is less than 0.001

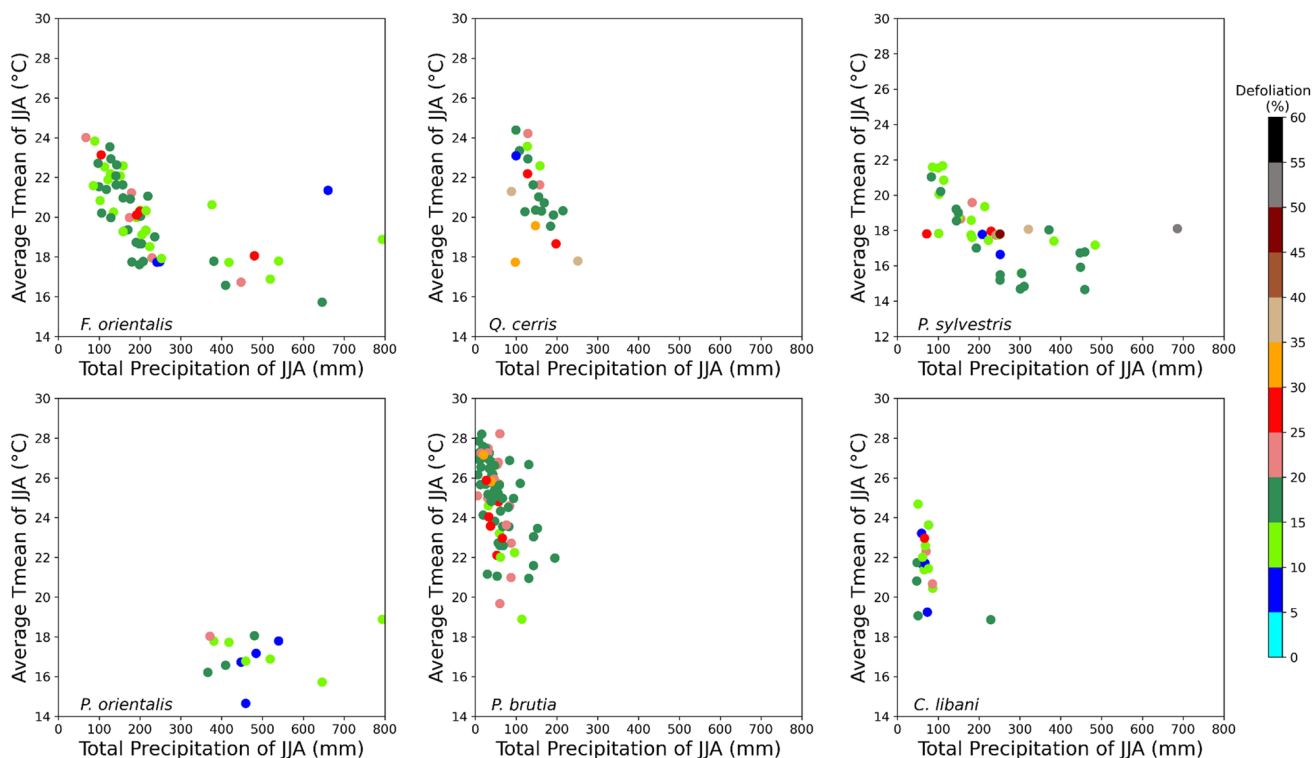


Fig. 3 Total summer (JJA) precipitation vs average summer (JJA) T_{mean} ($^{\circ}\text{C}$) for all 277 plots for the 2008–2020 period (includes 304 dots)

cases where *defoliation* and *NDVI* are positively correlated, as in *C. libani* and *P. sylvestris*, the defoliation class is 2, meaning that defoliation has increased by 25–60%.

Except for *P. sylvestris*, the correlation between *NDVI* and *Prcp* is positive or strongly positive. *P. orientalis* has the smallest angle between *NDVI* and *Prcp*, showing a strong positive correlation.

NDVI correlates positively with T_{min} for *P. orientalis*, *P. sylvestris* and *P. brutia* and also correlates positively with T_{mean} for *Q. cerris*, *P. sylvestris*, and *P. orientalis*. Except for *P. Sylvestris* and *F. orientalis*, *NDVI* has right angles with T_{max} so there is no correlation between *NDVI* and T_{max} . Similarly, *F. orientalis* and *C. libani* also have right angles between *NDVI* and T_{mean} . Where *Prcp* and *NDVI* correlate positively, the defoliation degree is either none or slight as in *P. orientalis*, *F. orientalis*, and *Q. cerris*. As a result of the PCA, differences in the variables behaviors based on species become more evident, which demonstrates that the relationships between variables are species-specific.

3.5 Spatio-temporal correlation analysis

3.5.1 Climate variables, drought indices and defoliation

Pearson correlation coefficients (r) between defoliation and drought indices, and climate variables on the 277 plots for the period 2008–2020 are shown in Fig. 7. On the maps it

is evident that the correlation between T_{max} or T_{mean} and defoliation is generally positive in the Mediterranean and along the western Black Sea Coast, on the other hand there is generally a negative correlation between *defoliation* and drought indices in these regions. The eastern Black Sea and the eastern Mediterranean regions show the most positive correlations between *Prcp* and *defoliation*, furthermore the same behavior is valid for the correlations between drought indices and *defoliation*.

3.5.2 Climate variables, drought indices and NDVI

Based on the analysis of the relationship between climate variables and *NDVI*, the plots and the species in the Eastern Black Sea region have different correlation values than the rest of the region. For the Eastern Black Sea, correlations between *average Tmax*, T_{mean} , T_{min} and the *NDVI* are high; however, the correlations between the total *Prcp* and the *NDVI* are lower than the rest of the Black Sea region. Also, the correlations between T_{min} and *NDVI* show a different pattern for both of the regions (Fig. 8). The number of the plots with positive correlation have increased greatly for the species in the Black Sea forests and for the Mediterranean forests, the strong negative correlation seen in T_{max} and T_{mean} was replaced by weak negative values in T_{min} . Unlike in the Black Sea forests, there is no regionally differentiated behavior in Mediterranean forests. The

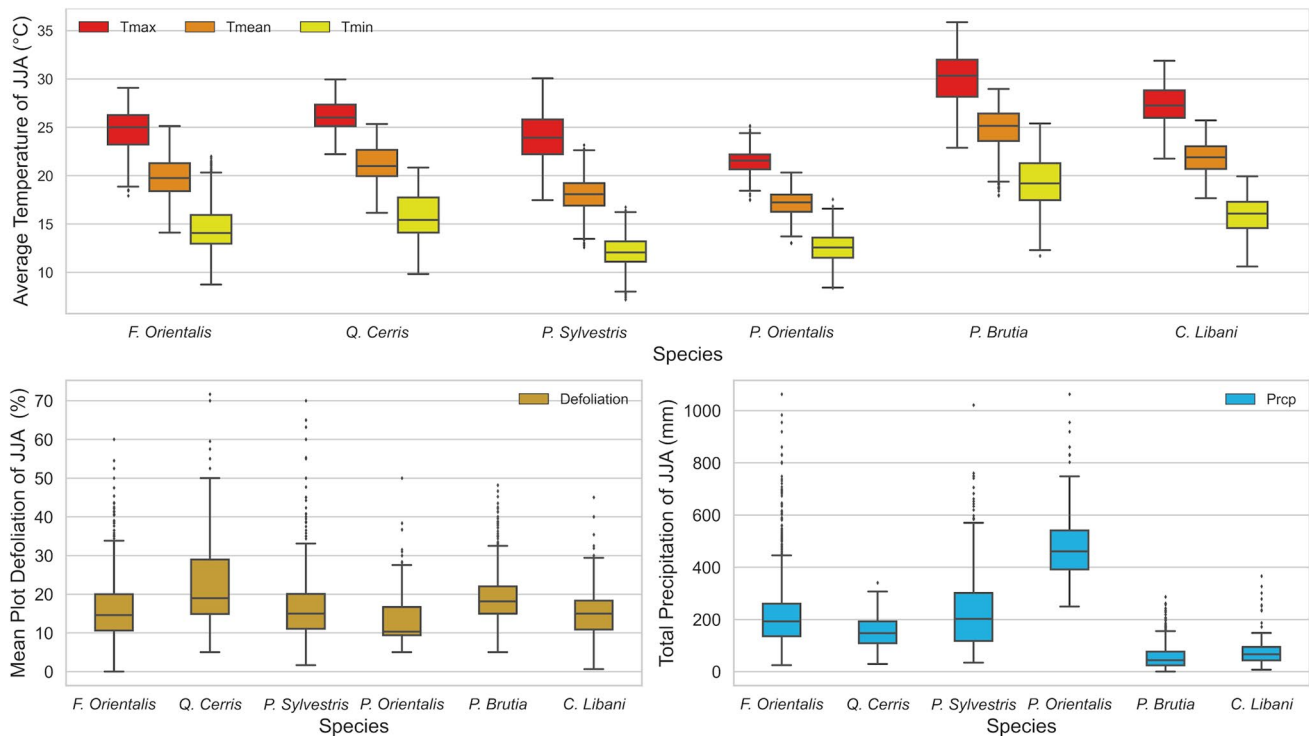


Fig. 4 Box plot graphs of average *Tmean*, daily *Tmin*, and daily *Tmax* for JJA (°C), total precipitation of JJA (mm), and *defoliation* of JJA (%) for 2008–2020 period based on tree species from 277 plots over Black Sea and Mediterranean regions

NDVI has mostly positive correlation with *Prcp* (91% of the plots), but has negative correlation with *Tmean* (70% of the plots), *Tmax* (79% of the plots), and *Tmin* (52% of the plots). For the relationships between *NDVI* and monthly, 3-month SPEI, SPI is mostly positive by 90%, 92%, 90%, and 93% of the plots, respectively. Most of the negative correlations belong to the plots found in the Eastern Black Sea Region.

3.6 Evaluation of time lagged correlations

In order to determine on which time-scales the climatic drivers have strongest correlations with measured *NDVI*, *defoliation* and *drought indices*, correlations between climate variables and tree health/vitality indicators were analyzed for seven different time lags. First, monthly mean *Tmax*, monthly mean *Tmean*, monthly mean *Tmin*, total *Prcp* over the entire period, monthly *Tmean* anomaly, and monthly *Prcp* anomaly were determined for the previous 1, 2, 3, 6, 9, 12, and 24 months (here after T1, T2, T3, T6, T9, T12, T24). The time windows were chosen based on the measurement date of defoliation as reported for each plot separately, back 1, 2, 3, 6, 9, 12, and 24 months from the date of the defoliation measurement. For *NDVI* and *drought indices*, correlations were calculated for the month of the defoliation measurement and compared to the climate variables in the variable windows (Figs. 9 and 10). Significance tests of the

correlation coefficients were separately calculated for each time window based on the Student *t*-tests at a significance level of 95%.

F. orientalis and *Q. cerris* experienced the strongest legacy effect in correlation *Prcp* anomalies and *NDVI*. Median values for *F. orientalis* and *Q. cerris* in T1, T2, T3, T6, T9, T12, and T24 are -0.06 , 0.04 , 0.10 , -0.16 , 0.15 , 0.16 , and 0.20 and 0.02 , 0.10 , 0.17 , 0.20 , 0.10 , 0.14 , and 0.38 , respectively. However, for all time-lags there is no significant correlation. *P. sylvestris* experienced the strongest legacy effect for the correlation between *Tmean* anomalies and *NDVI*, median values in T1, T2, T3, T6, T9, T12, and T24 were 0.26 , 0.35 , 0.38 , 0.20 , 0.15 , 0.16 , and 0.33 , respectively. In this case, correlations are significant in all time-lags. *P. orientalis* which has the wettest conditions, experienced the strongest legacy effect in correlation between *Tmean* anomalies and *NDVI*; median values in T1, T2, T3, T6, T9, T12, and T24 were 0.17 , 0.37 , 0.33 , 0.17 , 0.20 , 0.27 , and 0.48 , respectively. *P. brutia* and *C. libani* experienced the strongest legacy effect in correlation *Prcp* anomalies and *NDVI*; however, correlations are not significant except for *P. brutia* in T2, T3, and T6 (SI). Median values for *P. brutia* and *C. libani* in T1, T2, T3, T6, T9, T12, and T24, respectively, were 0.12 , 0.22 , 0.27 , 0.11 , 0.21 , 0.19 , and 0.30 and -0.15 , 0.24 , 0.29 , 0.11 , 0.24 , 0.17 , and 0.21 .

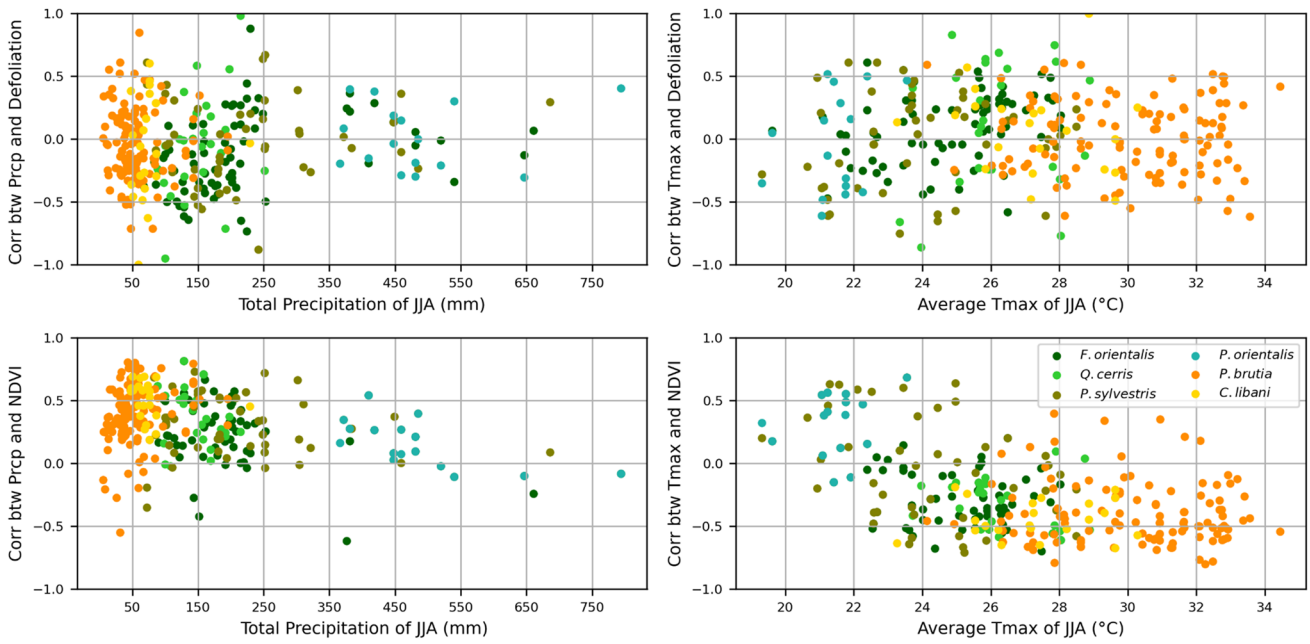


Fig. 5 Results of the Pearson correlation coefficient (r) between total *Prcp* of JJA-average *Tmax* of JJA defoliation and *NDVI* based on tree species for the 2008–2020 period

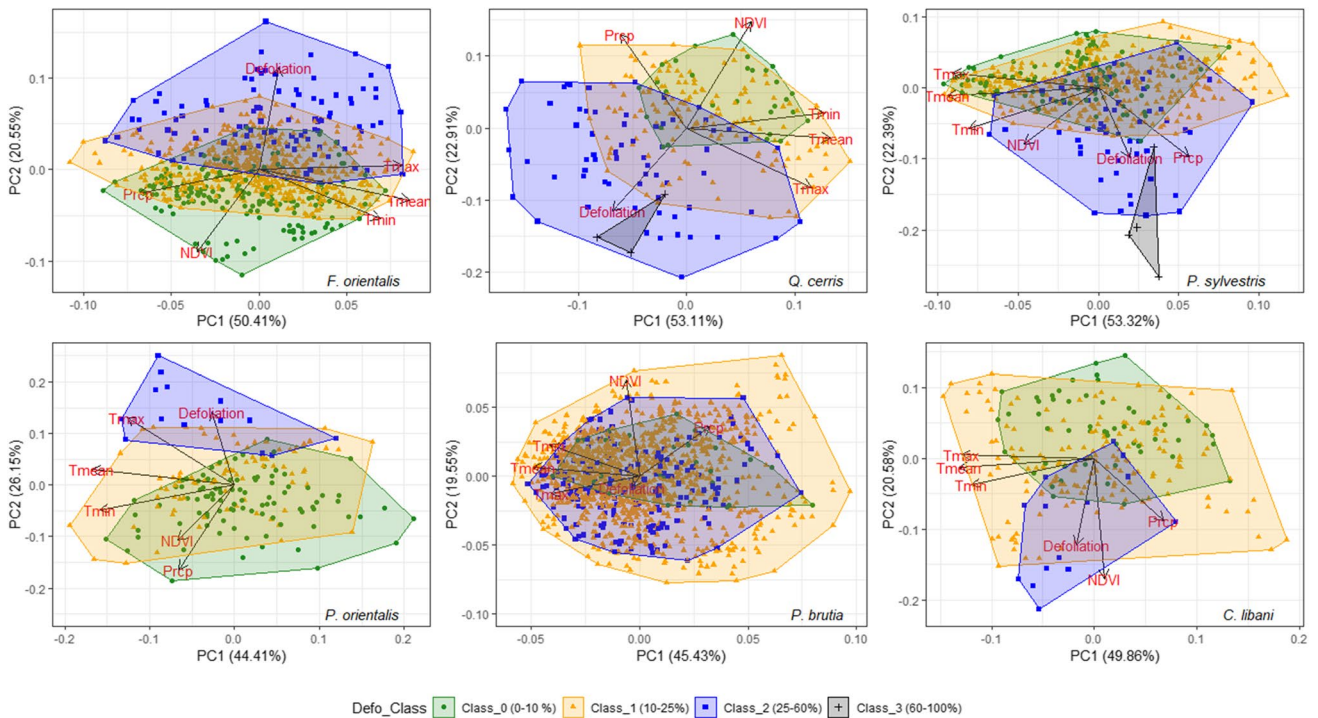


Fig. 6 PCA results for the annual 2008–2020 period based on total precipitation of JJA, average *Tmean*, *Tmin*, *Tmax* of JJA, *defoliation*, and *NDVI*. The colored areas show the range of the four defoliation classes (*Defo_Class*) with respect to climate variables for each species. The arrows in PCA represent the vectors that correspond to

the initial variables from which principal components have been computed. An angle between two vectors represents the correlation between the variables: small angles show a strong positive correlation, right angles indicate a lack of correlation, and opposite angles indicate a high negative correlation (Rossiter 2014)

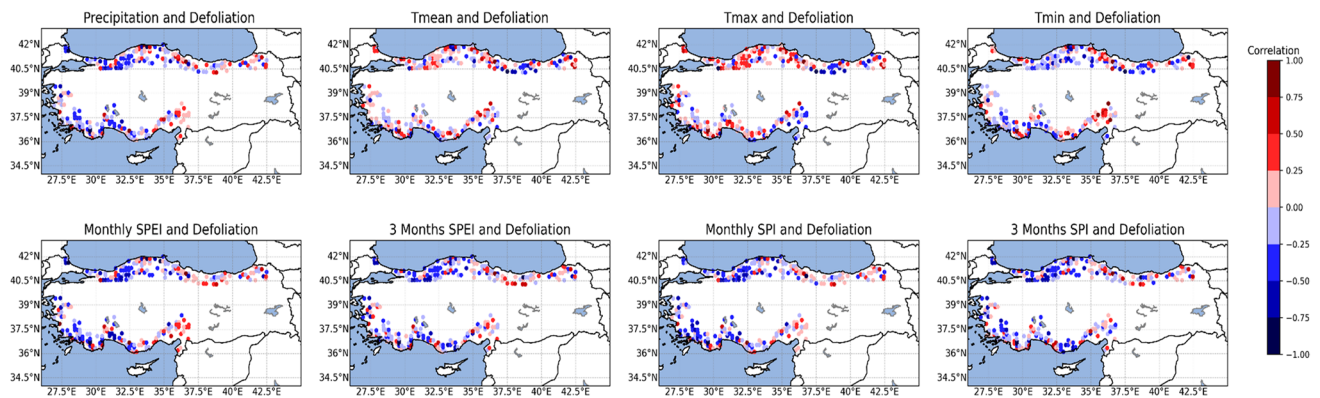


Fig. 7 Pearson correlation coefficient (r) values between climate variables anomalies (total Prcp of JJA and average $Tmean$, $Tmin$, and $Tmax$ of JJA)—drought indices and *defoliation* for the 2008–2020 period for all 277 plots

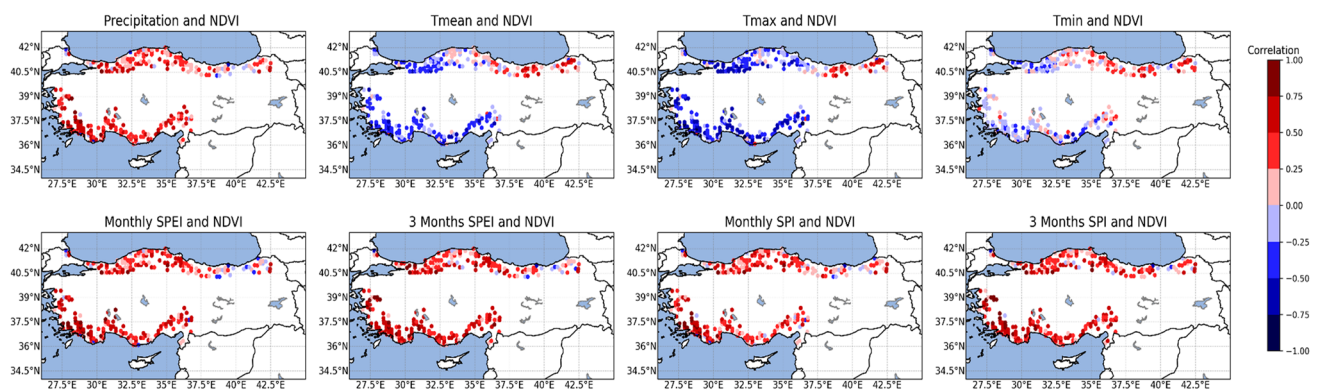


Fig. 8 Pearson correlation coefficient (r) values between climate variables anomaly (total precipitation of JJA and average $Tmean$, $Tmin$, and $Tmax$ of JJA)—drought indices and NDVI for the 2008–2020 period for all 277 plots

Overall *P. brutia* experienced the strongest legacy effect for the correlations (Figs. 9 and 10). Also Mediterranean species, *P. brutia* and *C. libani* showed stronger and more consistent correlations than Black Sea species. Regarding the median line of the time lag, the majority of the tree species showed different behaviors in T6 and beyond compared to T1, T2, and T3.

In addition, there is no significant correlation for *Prpc* anomaly and NDVI for all species and time lags except for *P. brutia* in T2, T3, and T6, for *Prpc* anomaly and defoliation in T2, T3, T6, T9, T12, T24 for *P. orientalis*, and in T6, T9, T12, T24 for *C. libani*. For some of the time-lagged correlations, *F. orientalis*, *Q. cerris*, and *P. sylvestris* have no statistically significant correlation between $Tmax$, $Tmean$, $Tmin$, and *defoliation*.

4 Discussion

All tree species experience higher variability of summertime *Prpc* than annual *Prpc* proportionally to the total summer and annual precipitation. The Black Sea forests experience

higher summertime *Prpc* and lower interannual relative summertime *Prpc* variability. Also the Black Sea region has a slightly higher interannual summertime temperature variability, with values of 0.79 K, 0.80 K, 0.97 K, 0.86 K for plots containing *F. orientalis*, *Q. cerris*, *P. sylvestris*, and *P. orientalis*, respectively. When considering selected tree species, tree species common for the Black Sea forests (e.g., *F. orientalis*, *Q. cerris*, *P. sylvestris*, *P. orientalis*) show a higher rate of defoliation than Mediterranean forests tree species (e.g., *P. brutia*, *C. libani*) which experiences significantly lower summertime precipitation. Overall defoliation rate, when all species were included in the analysis, the average *defoliation* of plots in the Mediterranean forest was slightly higher than in the Black Sea forests. Despite the large differences in precipitation and temperature values between the two forests, the fact that the defoliation rate difference is very low, indicates that the species of the Mediterranean region; *C. libani* and *P. brutia* are better adapted to climate variability (Sevik and Ertürk 2015; Messinger et al. 2015).

All four tree species dominantly found in the Black Sea forests show a statistically significant decreasing trend in

Fig. 9 Pearson correlation coefficients (r) between average T_{mean} , cumulative P_{prcp} and $NDVI$ for the previous 1, 2, 3, 6, 9, 12, and 24 months (time lags were calculated based on plot location from the day defoliation was measured in summertime) for the entire 2008–2020 period

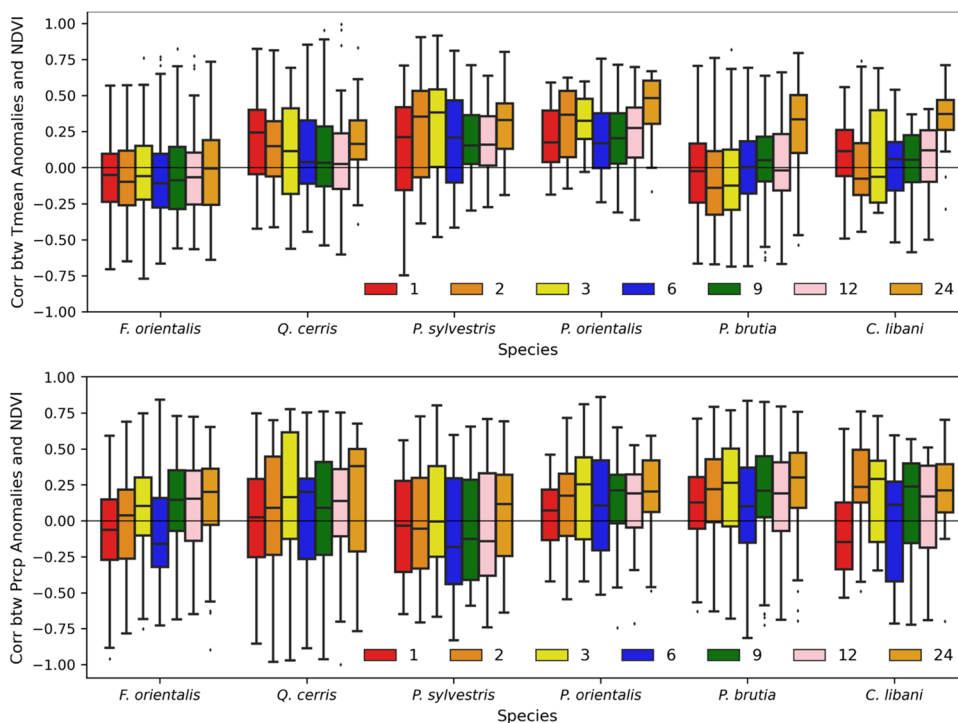
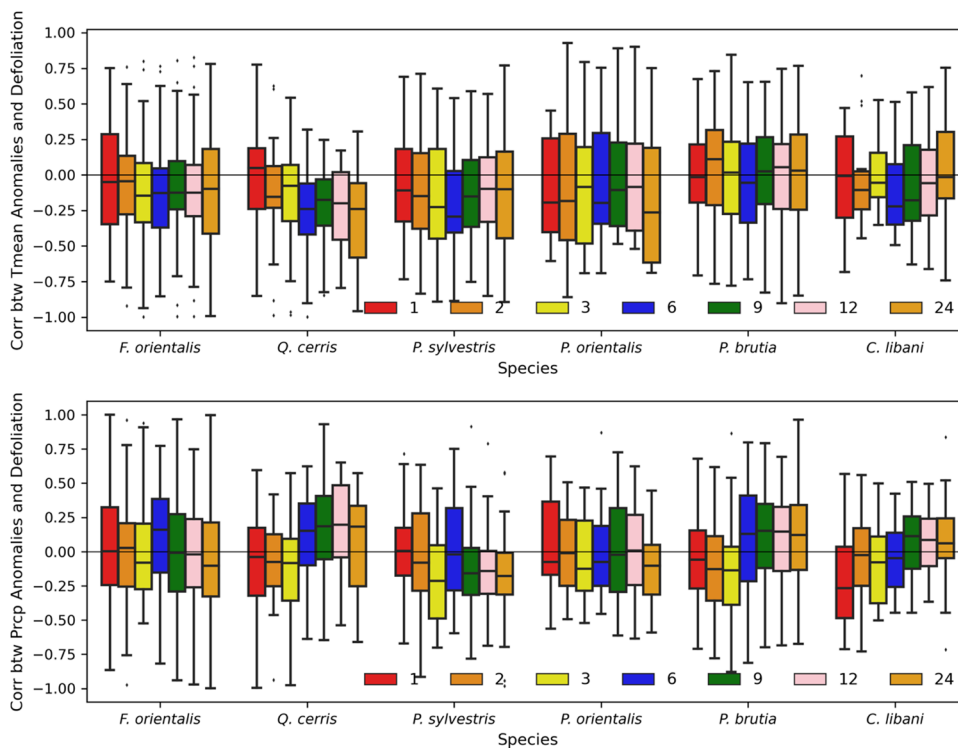


Fig. 10 Pearson correlations coefficient (r) between climate variables and $defoliation$ for windows of 1, 2, 3, 6, 9, 12, and 24 months backwards (the windows are calculated from the day the $defoliation$ is measured) for the 2008–2020 period



defoliation over the 2008–2020 period. Simultaneously, the plots containing these species show concurrently a statistically increasing trend in $NDVI$. This means that changes in the tree-level indicators are also reflected in changes to plot-level data over decadal scale. However, on an interannual

scale only *Q. cerris* showed a statistically significant correlation between annual summertime $NDVI$ at plot level and annual summertime *defoliation* measurements at tree level.

For the Mediterranean climate, the natural vegetation of the coastal zone consists of pine species, which have a high

demand for warmth and light and are resistant to drought, and, in places where they are destroyed, maquis cover the place which consists of small trees or shrubs with an average height of 1–2 m and always green. In high places, coniferous larch, cedar and fir forests dominate, for the Black Sea climate; the natural vegetation consists of broad-leaved moist forests in the coastal areas and coniferous forests that grow in cold and humid conditions in the higher elevations (Atalay 1997, 2010; Günel 2013; Dönmez 1985). A study by Efe and Sönmez 2015 state that most of the broad-leaved forest trees are humid species and form “humid forests.” These are mostly spread in the Black Sea Region. Conifers, especially *P. brutia*, which is a common species of the Mediterranean region, are considered a “dry forest” element. As a result, Mediterranean forests are generally more drought and less dense than Black Sea forests, which is an explanation why *NDVI* could statistically significantly increase but defoliation does not show a significant trend.

Regarding *defoliation* and *NDVI* trends for the 2008–2020 period, there is a decrease in *NDVI* and an increase in *defoliation* across most plots in 2008–2009 and 2013–2014 (SI) which is explained by extreme drought conditions at the beginning of the study period in 2008 and also during the year 2013. 2008 experienced the lowest total annual precipitation of the last 40 years across Türkiye. Mediterranean forests experienced the lowest and second lowest total annual precipitation of the last 20 years in 2008 and 2013. For the Black Sea forests, conversely 2013 was the year with the lowest and 2008 was the year with the second lowest total annual precipitation over the last 20 years (TSMS 2022). In line with this, the temperature and precipitation values at the forest plots showed that 2008 is one of the driest years for the summertime for the forests as well. In summer 2008, the Mediterranean forest plots experienced a compound effect namely very low precipitation and unusually high temperatures at the same time. For the Black Sea forest plots, 2008 and 2013 were on average the third and fifth driest years for the summertime over the 1991–2020 period. For the Mediterranean forest plots, the JJA period in 2008 and 2013 were the second and fourth driest summer periods over the 1991–2020 reference period. In addition, summer 2008 was the third hottest summer for the Mediterranean forest plots over the reference period. The years following the droughts, 2009 and 2014, had a higher amount of precipitation than the long term average but still a lower *NDVI* and a higher *defoliation* compared to the 13-year average. Tree damages in 2008 and 2013 were severe and 2009 and 2014 showed legacy effects from the previous year’s drought as expected, even though they did not experience severe conditions. From 2010 to 2020, 91.7% of the plots (254) show an upward trend in *NDVI* and regarding each plot; 55% for *F.orientalis*, 50% for *Q.cerris*, 46% for *P. sylvestris*, 69% for *P. orientalis*, 34%

for *P. brutia*, and 36% for *C.libani* show either decreasing or no trend in defoliation (SI, Fig. S11).

F. orientalis showed statistically significant trends between mean plot *NDVI* and *Tmax* and *Prcp*. With increasing precipitation and decreasing maximum and mean temperature on plots (SI, Fig. S2–S5), *NDVI* of *F. orientalis* plots significantly increased during the 2008–2020 period. For *Q. cerris*, *P. sylvestris*, *P. brutia* significant correlations between *NDVI* and *Tmin* and *Tmean* were found, but no influence on precipitation variability could be detected. *P. orientalis* and *C. libani* tree species did not show any direct correlations between climate variables and *NDVI*.

Regarding *Tmax*, *Tmean*, *Tmin*, and *Prcp* variables, *P. brutia* and *C. libani* have a different range from the four tree species from the Black Sea region. At this point, the ecological characteristics of the species reveal themselves. *F. orientalis* and *Q. cerris* do not need very special conditions to grow, *F.orientalis* has a wide distribution along with the Black Sea Region (Kandemir and Kaya 2009). *Q. cerris* exhibits strong morphological variability and ecological adaptability (Simeone et al. 2019). *P. orientalis* exists in more specific conditions. It actually reflects the characteristics of extreme wet conditions in the Eastern Black Sea (Atalay et al. 2014). *P. brutia* is one of the light-tree species and has a very high-temperature demand. It is the most resistant pine species to temperature and drought (Fady et al. 2003). A study by Messinger et al. (2015) concluded that the exceptional drought tolerance of *C. libani* was confirmed by comparing tree ring growth in natural stands at Elmali, southwest Türkiye. Although the rainfall total at Elmali was very low (68 mm) and mean air temperatures were high (18 °C) during summertime. *C.libani* tolerates extreme cold in winter and prolonged droughts during summer. Semerci et al. (2017) studied drought stress of *P. sylvestris* in different regions from Europe and Türkiye, there are significant differences among populations of *P. sylvestris*, while populations in northern Europe have significantly weaker tolerances to drought compared to southern and high-elevation populations, which exhibit generally lower growth rates and more resistance to drought. In addition, *P. brutia* has been found to be highly drought-resistant and can effectively be used for reforestation in disturbed areas (Sevik and Ertürk 2015). Recently, there has already been an increase in the mean annual temperature and severity of summer droughts in the Mediterranean region (Abbasnia and Toros 2018). Having drought-resistant tree species in the Mediterranean region is really promising since future climate scenarios indicate that the Mediterranean region will be among the most heavily affected parts of the world in terms of increased frequency and intensity of drought events (Ozturk et al. 2015; Türkeş et al. 2018).

The correlations between climate variables and defoliation and drought indices have revealed that the temperature effect in the regions is stronger than the precipitation. However not only climate variables are affecting defoliation in the forests but also ecological factors such as insect calamities (Ataman 1967; Yüksel and Akbulut 2005; Ülgentürk et al. 2012; GDF 2022), non-sustainable forest management (Baskent et al. 2008), illegal logging (Gunes and Elvan 2005) may cause defoliation. The results of our study are subject to these uncertainties.

The spatial variability in JJA average *Tmean* and *Prcp* is larger for the tree species in the Black Sea region, which is due to the fact that they can be found over larger geographic areas and are adaptive to different climates (Fig. 3). While the Black Sea forests are more suitable for the species with lower summertime temperature and higher summer precipitation demand, the Mediterranean forests are mainly suitable for species with high summertime temperature and low summer precipitation demand. A detailed study by Günel (2013) has reported similar climate evaluation for the regions.

In 2009, defoliation was assessed on 563 plots including 12,290 trees over Türkiye. The mean defoliation was 18.9% for conifers, and 21.5% for broadleaves, respectively. In 2009, on 18.7% of the monitored trees, defoliation was more than 25%. *P. brutia* had the highest defoliation among conifers (Fischer et al. 2010). Similarly, in this study *P. brutia* had the highest defoliation (19.03%) for the 2008–2020 period among the assessed conifers including *P. brutia*, *C. libani*, *P. sylvestris*, and *P. orientalis*. The altitude of the distribution area of *P. brutia* is lower than other coniferous species (Table 1), The Mediterranean region has high average and maximum temperatures (Atalay 1997). The shortlength of the growing period (Boydak 2004) and the high average and maximum temperatures may encourage this species to reduce water loss by transpiration as a precaution against drought. On the other hand, it is the most important conifer species from the commercial perspective; its wood is used for many purposes: construction, industry, carpentry, firewood, and pulp in Türkiye (Fady et al. 2003; Petrakis et al. 2007; Tolunay et al. 2008).

In particular, forest fires in the western Mediterranean are considered a great risk (Özcan et al. 2018); however, this may not be the case in the Black Sea region. Tüfekçioğlu et al. (2011) based on RegCM3, reported that temperatures will increase 2–4 °C in the Black Sea region, and precipitation will increase 200–300 mm in the eastern part of the region in the next century. They also concluded that while fire could pose a threat to the western part of the Black Sea region, it does not threaten the eastern part—*P. orientalis* ecosystems, since their ecosystems have a humid climate through the summer. According to Bilgili (1997), fires in Türkiye are distributed as follows: 41% in the Aegean, 25% in the Mediterranean, 22% in the Marmara, and 13% in the rest. Summer is the season of most forest fires in Türkiye where extreme temperature and drought are observed,

followed by spring with 48%, (Bahadır 2010). In Fig. 4, the findings support previous studies on forest fire tendency in the Mediterranean region mentioned earlier due to the low precipitation and high temperatures of the plots.

In this study, PCA confirmed the climatological results of previous studies (Türkeş 2012; Kadioglu 2000; Toros 2012a) that explained the general characteristics of precipitation and temperature in Türkiye. Relationships between the parameters are species-specific due to spatial factors like altitude, latitude, distance from sea (Usta et al. 2018) along with ecosystem differences (Atalay 2002). PCA results have revealed the correlation differences between climate variables and forest responses for the six tree species.

In this paper, the geographic distribution of the species (Günel 2013) and the exposure to different climatic features (Atalay et al. 2014) in local environments may have influenced the individual correlation results to have low correlation values. The occurrence of defoliation can be the result of weather extremes, air pollution, or biological factors (Popa et al. 2017), so tree responses to climate variability can be different even in the same subregion due to compounding factors or factors not even linked to weather extremes. Defoliation is also one of the most difficult and expensive data to collect, the ICP network (Level I) provides an opportunity to investigate the relationships between tree defoliation and climate variables, considering a large number of species and large spatial variations of species (Fischer et al. 2012).

The Student *t*-test (95% significance level) was performed for the seven time lags (T1, T2, T3, T6, T9, T12, T24) with climate variables including *Tmean*, *Prcp*, *Tmax*, *Tmin*, *Prcp* anomalies, *Tmean* anomalies, drought indices including the SPI, the SPEI and *defoliation* and *NDVI*, respectively. A study by de la Cruz et al. (2014) for the period similarly also reported that there is a relationship between climate variables and defoliation was proved by statistical methodologies and previous years' thermal conditions determine current year defoliation conditions for the 1987–2012 period. Similarly, to other studies (Wu et al. 2018; Li et al. 2020) in the past, the results revealed that the legacy effect of parameters continued even for at least the previous 2 years, except for *Prcp* anomaly and *NDVI*. The studies conducted on relatively similar regions also showed there was no significant correlation between *Prcp* anomaly and *NDVI*. For instance, no significant correlations were found in the forest of the northeast, in some parts of southern China as well as in some desert areas of the northwest (Chen et al. 2020). No significant correlations between *Prcp* anomaly and *NDVI* were found in major parts of the mountain ranges, in some semi-desert and desert areas of southern Kazakhstan and Turkmenistan as well as in the forest steppe in northern and northeastern Kazakhstan (Gessner et al. 2013). Detailed information about the topography and climate properties is provided by Atalay et al. (2014) and Günel (2013).

In this study, defoliation analyses have been done with 13 years of data (2008–2020). It is the longest available period for the ICP plots across Türkiye however historical knowledge and climate responses of tree species could be presented better with longer data periods of data. So the survey should be continued to get precise results. Also timely coordinated defoliation observation for the same tree species can be one of contributions to better understanding correlation with climate variables and satellite metrics.

5 Summary and conclusion

The most important findings of this study are the following:

- Tree level *defoliation* and plot-level *NDVI* show concurrent trends in Black Sea forests species *F. orientalis*, *Q. cerris*, *P. sylvestris*, and *P. orientalis*.
- Forest health as assessed by *NDVI* and *defoliation* in the Black Sea region is statistically linked to climate variability, strongest effects were detected for *F. orientalis*.
- Forest health assessed by *NDVI* and *defoliation* could not be linked to climate variability in the Mediterranean forests.
- Legacy effect of climate variabilities on *NDVI* and *defoliation* was observed for up to 2 years. This is a fundamental result to better understanding of the tree species responses.
- Regarding defoliation rate and interannual variabilities, Mediterranean species, *P. brutia* and *C. libani*, are more resistant to drought and climate variabilities.

Annual climate variables trends showed that *Tmean* and *Tmax* have statistically significant and remarkable trends for each species for the 1991–2020 period. Summer climate variables trends showed that *F. orientalis*, *Q. cerris*, *P. sylvestris*, and *P. orientalis* in the Black Sea region have statistically significant trend in *Tmean* and *Tmax* for the 1991–2020 period however the tree species in the Mediterranean region have no statistically significant trend. On the other hand, *Prcp* has a significant trend for none of the tree species in annual and summertime trends for the 1991–2020 period.

According to the individual correlations and PCA result of this study, it was concluded that correlation assessment between ground-based (*defoliation*)-satellite-based (*NDVI*) data and climate variables made on the basis of the tree species regarding defoliation classes is more reliable than the individual correlation assessment based on the tree species.

Although the highest interannual *Prcp* variability was seen in the Mediterranean region there was no increasing trend for defoliation. It means *P. brutia* and *C. libani* have higher adaptive capacity to drought. Similarly, statistically significant

positive *NDVI* trends were seen in the Mediterranean region and the trend value is slightly higher than the Black Sea region on average per decade. Additionally, the tree species in the Black Sea region experienced a decreasing defoliation trend in a range – 3.9 to – 9.8%/decade.

Regarding tree species, while the Black Sea region is more sensitive to precipitation than temperature, the Mediterranean region is more sensitive to temperature than precipitation. However, regarding both our statistically significant correlation results for different time lags and the extreme events and climate projections based on the previous studies, for the long run, the temperature has a greater influence on tree species in the regions due to expected temperature rises. In terms of the time lag, the results show that the legacy effects of climate variables, satellite-based data (*NDVI*), and ground-based data (*defoliation*) last for 2 years. Nevertheless, no significant correlations between *Prcp* anomaly and *NDVI* were found for the species except for the *P. brutia* in T2, T3, and T6. Similarly, the earlier studies conducted similar results for the densely populated and mountainous regions. While there are clear correlations found between *NDVI* and climatic anomalies, there was no clear relationship found on the plot-level between *NDVI* and *defoliation* data. This paper is one of the first to apply the subject of climate variability and forest health to the ICP Forest plots in Türkiye, highlighting the importance of integrating these fields together. Similar to the studies in the past, it has been shown once again that due to the special topographic structure of Türkiye and climate variabilities, further studies on tree species and vegetation should be conducted by taking into consideration sub-climate zones.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s00704-024-04853-6>.

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Author contributions Author contribution All four authors were involved in the conception of the idea. Data collection was performed by NDC and ADŞ. The first analysis was performed by NDC and reviewed by AC. The first draft of the manuscript was written by NDC and AC. The results were reviewed and analyzed by NDC under the supervision of AC and RY. All authors were involved in the development of the manuscript. All authors read and approved the final manuscript.

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Data and materials availability Available after request.

Code availability Available after request.

Declarations

Competing interests The authors declare no competing interests.

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