European Journal of Forest Research (2023) 142:61–89
https://doi.org/10.1007/s10342-022-01506-z

ORIGINAL PAPER

Analyzing climate-induced mortality of Taurus fir based on temporal forest management plans and climatic variations and droughts in the Central Mediterranean sub-region of Turkey

Can Vatandaşlar[1] · Murat Türkeş[2] · Akkın Semerci[3] · Alptekin Karahan[4]

Received: 30 August 2021 / Revised: 3 June 2022 / Accepted: 26 September 2022 / Published online: 15 October 2022

Abstract

Fir species have been threatened by extreme weather and climate conditions in many parts of the Mediterranean Basin. However, there are almost no studies focused on the mortality of Taurus fir in the Eastern Mediterranean basin and Turkey. This study aims to quantify the mortality pattern of Taurus fir stands in Hadim Forest Enterprise from 1971 to 2016 and to assess this pattern considering the long-term trends and fluctuations in the observed climate data. To this end, spatiotemporal changes in forest cover were analyzed using historical stand type maps in GIS. Statistical and graphical time-series analyses were performed on observed climate data. As a result, rapid areal losses were detected in pure fir stands, even though the annual rate of forestation is 0.5% for the entire forest. More than half of the stands transformed into pure or mixed stands dominated by black pine. Both fir stands and the entire forest became much more fragmented and drought-induced deadwood remarkably increased in almost all fir stands. Regarding the climatic analyses, statistically significant increased trends ($p < 0.01$) were detected particularly in annual, summer, and autumn mean and average maximum and minimum air temperatures of the Hadim station; strong decreased trends were observed in all relative humidity series; and rapid warming in the surrounding region along Hadim was observed. In addition, series of the Aridity Index and the Standardized Precipitation-Evapotranspiration Index revealed that more arid conditions and significant droughts have dominated the study district since the 1990s. This period has been characterized mostly by long-term agricultural and hydrological droughts. We conclude that selective tree mortality events in the Hadim's forests are likely caused by adverse impacts of observed climate variations and long-term droughts in the sub-region.

Keywords *Abies cilicica* · Climate change · Drought indices · Forest vulnerability · Landscape metrics · Ecosystem structure

Introduction

Increased anthropogenic greenhouse gas concentrations in the Earth's atmosphere have substantially changed the world's climate. Since the 1950s, the global air temperature has increased by 0.13 ℃ every ten years (IPCC 2018). Climate model projections have revealed that it will further increase at least 1.0–1.5 ℃ toward the mid-century (IPCC 2018; Stocker et al. 2013). Besides, water availability will likely be limited due to changing rainfall patterns resulting in more extreme droughts, heatwaves, and hot extremes in many biogeographic regions (Allen et al. 2010; Sterl et al. 2008). Therefore, it is crucial to understand the past, current, and future responses of forest ecosystems to such changes. Thus, forest managers may be able to formulate sound adaptation strategies and control the ecosystem dynamics under

Communicated by Arne Nothdurft.

✉ Can Vatandaşlar
canvatandas@hotmail.com

1 Department of Forest Engineering, Faculty of Forestry, Artvin Coruh University, 08100 Artvin, Turkey

2 Department of Physics, Center for Climate Change and Policy Studies, Bogazici University, Istanbul, Turkey

3 Niksar Technical Sciences Vocational School, Tokat Gaziosmanpaşa University, Tokat, Turkey

4 Forest Management and Planning Department, General Directorate of Forest, Ankara, Turkey

global climate challenges (Jandl et al. 2019; Pederson et al. 2014).

Climate-induced tree mortality is one of the frequent consequences observed in forest ecosystems in response to global warming (Wang et al. 2020). Many studies report widespread tree mortalities from different parts of the world (i.a., Allen et al. 2010; Bolte et al. 2009; Breshears et al. 2009; Gazol et al. 2015; McDowell et al. 2020; Özcan et al. 2018; Türkeş et al. 2018). Some researchers highlight that these phenomena have accelerated in the past decades. Van Mantgem et al. (2009) and McDowell et al. (2020) attributed this increase to the climatic changes. Many other studies showed that certain tree species were more sensitive to drought. Such species might be subjected to intensive mortality events in the next decades (Allen et al. 2010; Fosso and Karahalil 2020; Pederson et al. 2014). Norway spruce, for example, is one of the sensitive tree species to warm and dry conditions. Bolte et al. (2009) stated that salvage logging operations became widespread in European spruce forests due to a considerable increase in insect outbreaks (i.e., bark beetle) as a secondary factor after warming in central Europe. It is assumed that bark beetle attacks will further increase in the next decades. Anatolian black pine is another drought-sensitive tree species native to Turkey. A dendrochronological study by Janssen et al. (2018) shows that the radial growth of black pine has been significantly declining in the Eastern Mediterranean sub-region of the country since the 1970s. The researchers attribute this phenomenon to the increased temperatures and summer droughts experienced in the region. In another dendrochronological study conducted in Turkey's Mediterranean region, high summer temperatures were a significant limiting factor for tree growth of the same species (Doğan and Köse 2019). The researchers stated that black pine forests located at their lower distribution range were more sensitive to climate change than those in the upper forest zone.

It is thought that some conifers generally suffer more from tree mortality (Williams et al. 2013) because their stomata are larger than broadleaved species, which in turn causes more water loss (Adams et al. 2017; Choat et al. 2018; Wang et al. 2020). While most conifers regulate their stomatal aperture using high abscisic acid levels during water deficit (Brodribb et al. 2014), broadleaved species' stomatal behavior is largely driven by genetic factors related to Ca^{2+}-dependent stomatal signaling. This mechanism seems to provide broadleaves the ability to resist drought (Brodribb and McAdam 2013). Among conifers, climate-induced tree mortality is ubiquitous in some fir species. In the southern Siberian Mountains, for example, the mortality of fir was induced by water stress coupled with the insect and fungi outbreaks. Kharuk et al. (2016) concluded a periodical process triggered by climatic variations based on the dendrochronological data. The authors state that Siberian fir forests may partly disappear from their current distribution range and are likely to be replaced by more drought-tolerant species. In another study, Gazol et al. (2015) analyzed tree mortality events in silver fir ecosystems across Europe. They reported a substantial growth decline for Spain and southern Italy since the 1980s due to water deficit. This finding confirms the Camarero et al. (2011)'s study reporting similar events in Pyrenean silver fir forests. Moreover, some projection studies predict a 30% growth decline in circum-Mediterranean fir forests by 2050 (Sanchez-Salguero et al. 2017). The researchers point out that fir populations currently subjected to drought conditions will be more vulnerable to tree mortality, probably resulting in local extinctions. In particular, the quaternary populations' refugia located at the warmer end of the fir distribution range are at great risk. *Abies tazaotana*, and *A. pinsapo* in general, *A. cilicica*, and *A. cephalonica* in their lower distribution ranges, can be considered among these fir species (Sanchez-Salguero et al. 2017).

As for Turkey, widespread tree mortality events were reported for Taurus fir (*Abies cilicica* (Antoine & Kotschy) *Carrière*) forests in the last decades (Allen et al. 2010; Aytar and Hızal 2012; Carus 2010; Öztürk et al. 2010; Semerci et al. 2004, 2008). Although the Taurus fir species is native to Turkey's Mediterranean region (Janssen et al. 2018), it gradually shifts near mixed oak stands in central Anatolia (Keleş et al. 2012). Moreover, habitat models point out an extinction risk for this species due to aridity, especially for its lower distribution range (Aussenac 2002; NCC 2011). Based on the long-term dendrochronological data, Akkemik (2000) reported that high temperatures in summer and low precipitation in spring and early summer were major limiting factors for the survival of Taurus fir. Low radial growth in the previous year also affected the survival rate of this species. Bozkuş (1986), on the other hand, stated that the natural distribution range of Taurus fir in Turkey was vaster in the past than today. The researcher attributed it to more favorable climate conditions in the region at that time. He also asserted that large Taurus fir stands had been subjected to forest fragmentation in the last decades. Such studies support the idea that Taurus fir cover has recently decreased in Turkey (i.a., Carus 2010; Semerci et al. 2018). This is also the case for the rest of the Mediterranean Basin (Collins et al. 2012). Because of such changes and fragmentation in the forest cover, Taurus fir now naturally grows only at glacial refugia of the Tertiary flora in different mountainous lands isolated from each other (Sanchez-Salguero et al. 2017). In this regard, Bolte et al. (2009) suggest that current and retrospective data about sensitive tree species' performances (i.e., mortality, regeneration, development) can be utilized to assess the species' adaptability to climate change. However, there is still a lack of information about how the Taurus fir has been affected by climate-induced tree mortality at the forest (landscape) level. Besides, the stand dynamics of this species have been poorly understood so far. The scientific knowledge of these phenomena will support future conservation strategies in the country and the Mediterranean region, each of which is a climate change hotspot (Janssen et al. 2018). This is also essential for preparing adaptive forest management plans (FMPs) with an ecosystem-based multifunctional management approach (Baskent et al. 2005; Bolte et al. 2009; GDF 2008), which has been nationally adopted in Turkey in recent years (Asan 2017; GDF 2017).

The aim of this study is to describe the mortality pattern of Taurus fir species by analyzing the spatiotemporal changes in forest cover under the responsibility of Hadim Forest Enterprise between the years 1971 and 2016. The study area is a prominent region in Turkey for the natural distribution of this species (Bozkuş 1986) and the obvious impacts of climate change, such as increasing temperatures and the increased stress on water resources (Tayanç et al. 2009). For this, spatial and tabular information from temporal FMPs and their associated data (e.g., historical stand type maps, forest inventory information, logging statistics) were analyzed in a GIS environment. Moreover, long-term trends and variations in the climate data were thoroughly examined using statistical tests. Through this study we aim to find answers to the following research questions: (i) *Which forest stands have been most affected in Hadim over the past 45 years between 1971 and 2016?* (ii) *What proportion of Taurus fir forests has been lost in this period at the landscape level?* (iii) *How has the ecosystem structure changed over time?* and perhaps most importantly (iv) *Does climate change have an impact on the possible changes in the Taurus fir forests?* It is believed that having this information will make it easier for natural resource managers to mitigate the negative impacts of climate change on forest ecosystems of fir. It may also help to understand these ecosystems' structure and combat biodiversity losses, both in Turkey and in other Mediterranean countries.

Materials and methods

Study area

The study area, Hadim Forest Enterprise, is located 100 km south of Konya Province (Turkey), with a total area coverage of about 90,290 ha (Fig. 1). It is on the north border of Antalya Province, showing a typical Mediterranean climate (GDF 2016). According to the Turkish Meteorological Service (TMS 2016), differences in air temperature throughout the year are considerable. Precipitation mostly falls in the cold months. The high topography includes mountainous lands, with a mean terrain slope of 36%. The altitude ranges between 850 and 2500 m asl. The main tree species in the forest are Anatolian black pine (*Pinus nigra* J.F. Arnold *subsp. pallasiana* (Lamb.) Holmboe), Lebanon cedar (Ce*drus libani* A. Rich.), Taurus fir (*Abies cilicica*), juniper (*Juniperus foetidissima* Willd*., Juniperus excelsa* M. Bieb., and *Juniperus drupacea* Labill.), and oak (*Quercus sp.*). They form pure or mixed stands depending on site conditions. Besides, maple (*Acer sp.*), Oleaster-leaf pear (*Pyrus elaeagnifolia*), and plane (*Platanus sp.*) individually exist in the study area. *Maquis*, a typical Mediterranean shrub formation, is common on degraded lands, especially at lower altitudes (GDF 2016). Regarding land use/land cover (LULC) classes, about one-third of Hadim Forest Enterprise consists of forestlands. However, half of them are degraded, with a canopy cover of less than or equal to 10%. Degraded grasslands, openings (e.g., rocky areas and bare lands), agricultural lands, settlements, and water bodies are other LULC classes sorted in descending order by area coverage. Local communities generally engage in agriculture, animal husbandry, and forestry (Bozkuş 1986; GDF 2016).

Geodatabase development

A GIS database was developed for compiling multiple data from different periods in one place. Temporal FMPs and their stand type maps belonging to the planning years of 1971, 1993, and 2016 were used (GDF 1971, 1993, 2016). Additionally, climate data from surrounding meteorological stations and several official statistics were among the data sources utilized in the present study. The specification of the multi-source data can be seen in detail in Table 1.

First, we scanned the historical maps of Hadim Forest Enterprise and registered them into 1/25000-scaled topographical maps using the affine transformation method with Universal Transverse Mercator (UTM) projection. Then, registered maps were visually digitized on-screen. Finally, stand type codes on historical maps were entered into the corresponding attribute tables of GIS geodatabase based on the national forest management guidelines (GDF 2017). Table 2 shows the stand classification and coding system used in this study and by the Turkish General Directorate of Forestry (GDF).

The current stand type maps can be directly transferred to the GIS database since they are presented in digital format. However, tabular data from the management plans such as standing volume, deadwood volume, and volume increment were manually entered into attribute tables at the stand type level. Thus, spatial (graphical) and non-spatial (tabular) information on the study area were integrated into a single geodatabase in ArcGIS 10.2 software (ESRI 2012). In addition, official statistics for wildfire and salvage logging operations were also collected at the landscape (forest enterprise) level (Table 1). As for the salvage logging records, we only

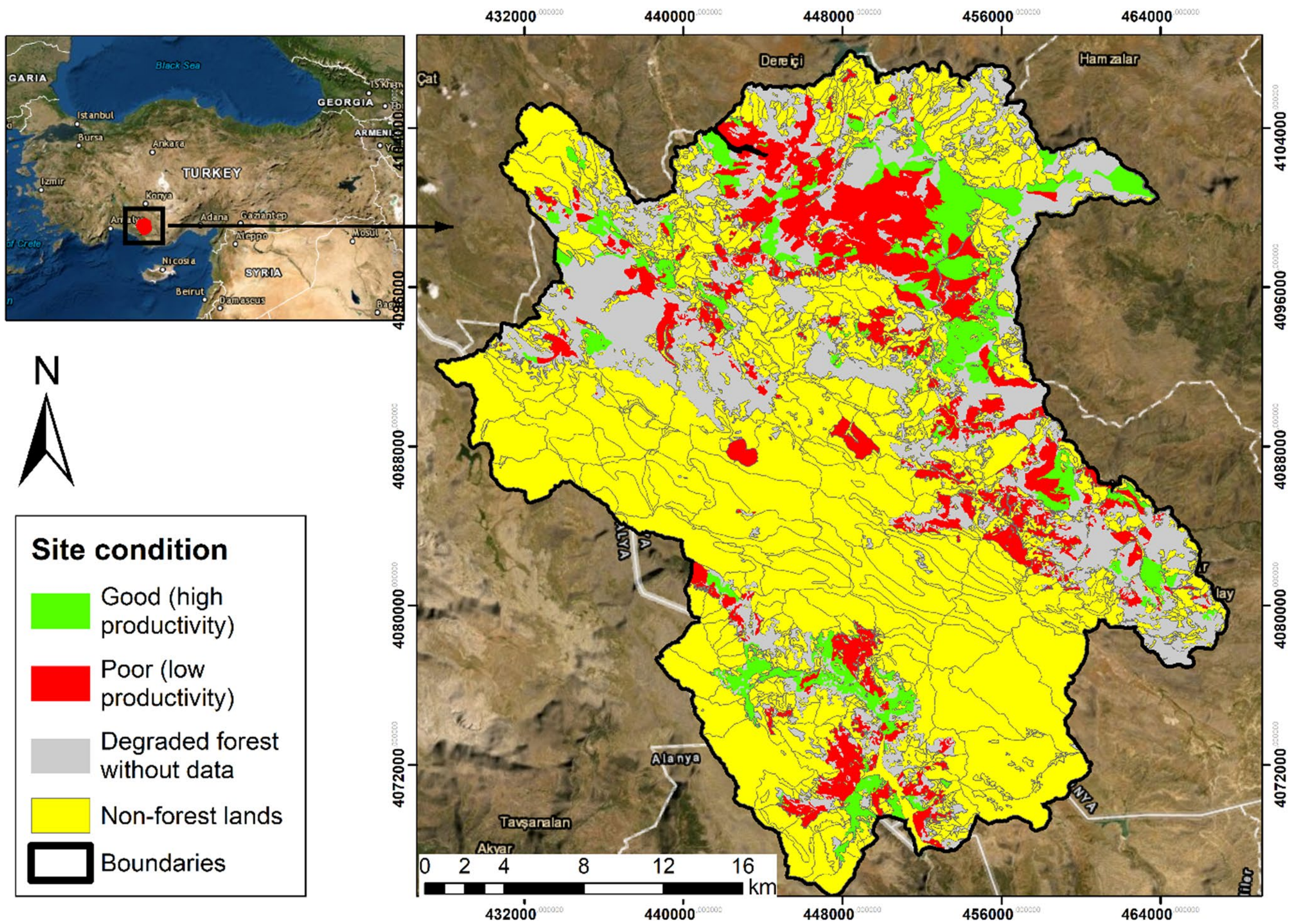

Fig. 1 Location of Hadim Forest Enterprise with growing site condition

focused on the infected fir species since the insect outbreak was considered a secondary factor after drought stress for the region (Allen et al. 2010; Semerci et al. 2018).

Spatiotemporal analyses

After geodatabase development, a series of GIS tools and functions, including overlay, reclassification, generalization, field calculator, summary, raster clip, aspect, slope, and zonal statistics, were used for quantifying the landscape structure and analyzing the possible spatiotemporal changes in it. The landscape structure of Hadim Forest Enterprise was analyzed in ArcGIS using the FRAGSTATS add-on both at the class- and the landscape level (McGarigal et al. 2002). The number of patch, the mean patch size, the largest patch size, and the mean edge length metrics were used as quantitative indicators of landscape fragmentation. Their units and brief explanations are given in Table 3.

Areal transitions among the significant forest covers were documented by several stand parameters, such as species mix and canopy cover between the three planning periods covering 1971 to 2016. For this, many stand types were generalized into one LULC class in the stand type maps. For example, all stands consisting of fir species were aggregated into one multipart polygon for documentation in the transition matrix. Similarly, non-forested areas were aggregated into one class.

The formula proposed by FAO (1995) was used to better understand forest dynamics changing over time. Accordingly, the annual rate of forestation is calculated using Eq. (1) between the years 1971 and 2016. Within this framework, special attention was paid to forest covers, consisting of Taurus fir species rather than other LULC classes. By doing so, the tree mortality pattern of fir forests was documented in detail.

$$q = [\left(\frac{A_2}{A_1}\right)^{\frac{1}{t2-t1}}] - 1 \quad (1)$$

where q is the annual rate of forestation (percentage per year), A_1 and A_2 are the forest cover at times t_1 and t_2.

Table 1 Different types of data sources used in the study

Data type	Data source	Date	Spatial resolution	The purpose of use
Spatial data	Stand type map from the FMP covering 1971 to 1993	1971	Vector data with minimum shape area of 1 ha	Areal statistics, forest cover change, growing site, and fragmentation analyses
	Stand type map from the FMP covering 1993 to 2016	1993	Vector data with minimum shape area of 1 ha	Areal statistics, forest cover change, growing site, and fragmentation analyses
	Stand type map from the FMP covering 2016 to 2035	2016	Vector data with minimum shape area of 1 ha	Areal statistics, forest cover change, growing site, and fragmentation analyses
	Forest inventory data from the FMP covering 1971 to 1993	1971	Stand level	Structural change, and standing deadwood analyses
	Forest inventory data from the FMP covering 1993 to 2016	1993	Stand level	Structural change, and standing deadwood analyses
	Forest inventory data from the FMP covering 2016 to 2035	2016	Stand level	Structural change, and standing deadwood analyses
	Digital Elevation Model	2016	173-m cell size	Slope, aspect, and elevation analyses
	Natural and artificial regeneration sites	1971–2016	Vector data with minimum shape area of 1 ha	Analyzing the impact of forest management on fir stands
	Climate data from the Hadim, Karaman, and Mut stations	1960–2018	Vector data with point feature	Analyzing the impact of climate change on Hadim's forests
	The Standardized Precipitation-Evapotranspiration Index	1960–2020	0.5° gridded cells	Analyzing the impact of long-term droughts on Hadim's forests
Non-spatial data	Salvage logging statistics	2007–2018	Landscape level	Extracted deadwood volume, analyzing the impact of forest management on fir stands
	Wildfire statistics	2007–2018	Landscape level	Analyzing the impact of wildfires on Hadim's forests

Table 2 Stand classification scheme used in Turkey (GDF 2017)

Stand parameter	Criterion	Code	Definition	Class interval
Tree species	Dominant species in stand	G	Fir sp.	–
		S	Cedar sp.	–
		Çk	Anatolian black pine	–
		Ar	Juniper sp.	–
		Mn	Macedonian oak	–
Canopy cover	Percent of ground covered by tree canopies (%)	B	Degraded	1–10
		1	Loosely-covered	11–40
		2	Moderate-covered	41–70
		3	Fully-covered	71–100
Stand developmental stage	Average diameter at breast height (DBH) (cm)*	a	Regeneration	< 8.0
		b	Poletimber	8.0–19.9
		c	Thin-tree	20.0–35.9
		d	Medium-tree	36.0–51.9
		e	Large-girth-tree	≥ 52.0

(*) Only the trees ≥ 8 cm in DBH (merchantable tree size) are recorded during inventory surveys

In Eq. (1), positive q values indicate forestation, whereas negative values indicate an areal loss.

Kriging interpolation method was used for producing the climate types map described in the next subsection. The method was based on the ordinary Kriging with a spherical semi-variogram model. We used a variable search radius with a number of points of 12. No maximum distance was determined for the nearest input sample points. After the

Table 3 The patch metrics used for fragmentation analysis (McGarigal et al. (2002) and Paudel and Yuan (2012))

Metric name	Abbr	Unit	Definition
Number of patch	NP	#	Refers to patch (polygon) density. The NP may increase as a result of forestation or fragmentation (or both)
Mean patch size	MPS	ha	The function of the number of patches and total area. The MPS decreases as the individual stands become smaller
Largest patch size	LPS	ha	The largest patch in size for the entire landscape. The LPS increases as the forest become more compact
Mean edge length	MEL	m	The mean amount of perimeter for all the patches. The MEL generally increases with fragmentation

map generation, it was reclassified based on the Aridity Index (*AI*) values.

Independent samples t-test was used for analyzing whether there are any significant differences between changed and steady-state stands (in terms of species mix) based on four ecological factors: (i) surface slope, (ii) slope aspect, (iii) altitude, and (iv) growing site (aka bonitet) class ($p < 0.05$). The spatially explicit data for the growing site class was extracted from the FMP (Fig. 1). It was based on species-specific site indices which could be determined by stand top-height measurements at a reference age (e.g., 100 y/o) (GDF 2017; van Laar and Akça 2007). All data sets were tested for normality using Kolmogorov–Smirnov analysis ($p < 0.05$).

Analysis of climate type

Climate types of the study area were determined by a well-known climate and dry-land type classification method, namely the *AI* of the United Nations Environmental Program and the United Nations Convention to Combat Desertification (UNEP/UNCCD). The UNEP/UNCCD *AI* is one of the fundamental methods for determining climate and related dry-land types in Turkey. It is also used as a useful tool for assessing the vulnerabilities of dry-land types to the desertification processes. According to UNEP (1993), *AI* is calculated as:

$$\mathrm{AI} = \left(\frac{P}{\mathrm{PET}}\right) \tag{2}$$

where P is the annual precipitation (mm) and PET is the potential evapotranspiration totals (mm). The PET values were calculated using the method of the WATBUG program, which was written by Willmott (1977) based on Thornthwaite's approach (1948). The *AI* values below 1.00 generally indicate a climatic moisture deficit because precipitation amounts in such a climate location do not meet the water (or soil moisture) lost due to evapotranspiration (Table 4).

Table 4 Classification of climate types in Turkey based on the UNEP/UNCCD Aridity Index (*AI*) (Türkeş 2013; Turkes 2020)

Aridity criteria	Climate type
> 0.20	Arid
$0.20 \leq AI < 0.50$	Semi-arid
$0.50 \leq AI < 0.65$	Dry sub-humid
$0.65 \leq AI < 1.00$	Semi-humid
$1.00 \leq AI < 2.00$	Humid
$2.00 \leq$	Per humid

Observed climate change and variability analyses

Unfortunately, only a few stations represent the study area. Consequently, to reveal the main climatological causes (i.e., drought and heat or increased air temperature induced) of tree mortality and tree drying in the Taurus fir individuals and communities in the Hadim district, long-term series of climatic observations from Hadim, Karaman, and Mut climatological and meteorological stations were selected (Fig. 2). These observations were recorded by the Turkish Meteorological Service (TMS) from 1960 to 2018. Although we have only limited time-series data, our results show a good agreement with various country-based or regional studies, which cover or are nearby our study area (i.a. Türkeş and Akgündüz 2011; Özcan et al. 2018; Türkeş 2013; Turkes 2020; Türkeş and Erlat 2018; Türkeş et al. 2009, 2018, 2020; Erlat and Türkeş 2013, 2016, 2017; Erlat et al. 2021). In this respect, both individual and district-averaged annual and seasonal averages of minimum, maximum and mean air temperatures (°C), total precipitation (mm) and mean relative humidity (%) time-series of the Hadim, Karaman, and Mut stations were investigated by using statistical and graphical time-series analysis techniques and the below hypothesis test:

(i) The non-parametric Mann–Kendall (M–K) rank correlation test ($u(t)$) and its sequential analysis were used to detect any long-term non-linear trend, change points and significant warmer or colder (or drier or wetter) periods in the series of climatological observations, and to test whether these trends are statistically significant or not. The methodologic details of the M–K technique can be found in Sneyers (1990) and Türkeş et al. (2002).

(ii) The least-squares linear regression (LSLR) equations were computed to detect possible long-term linear

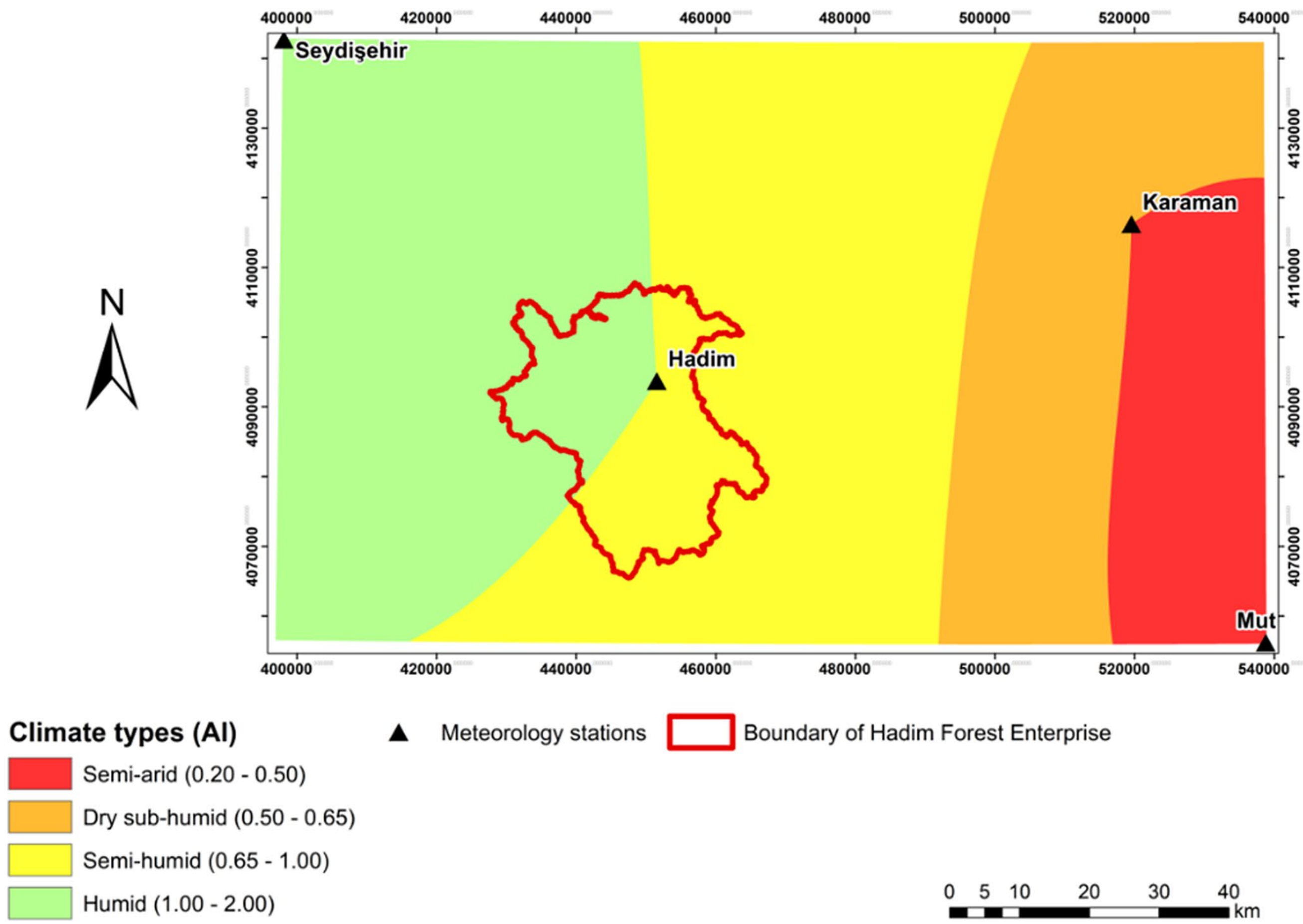

Fig. 2 Spatial distribution of the climate types over the study area and its surrounding region

trends in the series. Here, the climatological values were the dependent variable and time was the independent variable. The statistical significance of each estimated β coefficient (i.e., slope) was tested using the Student's t-test with $(n-2)$ degrees of freedom. Using a two-tailed test of the Student's t-distribution, "the null hypothesis of the absence of any linear trend in the climatic time-series" was rejected based on the large t-test values (Türkeş and Sümer 2004).

Temporal drought analyses

Before going through the analysis, it is essential to present a summary of drought definitions here. Drought is generally a complex natural hazard that influences natural and human systems, including forest ecosystems, agriculture, water resources and society in various ways (Türkeş 2017; Turkes 2020a). Some of these impacts are mainly related to long-term and geographically coherent hydrological droughts; on the other hand, some are associated with agricultural droughts (Türkeş et al. 2020). According to the IPCC (2018), drought is a period of abnormally dry weather long enough to cause a serious hydrological imbalance. Because drought is a relative term, any discussion regarding the amount of precipitation deficit should refer to the precipitation-related activity under discussion. For instance, a shortage of precipitation during the growing season impinges on agricultural crop production or a forest ecosystem function in general. This is defined as an agricultural drought. A shortage of precipitation during the runoff and percolation period has negative implications primarily on water supplies, which is defined as a hydrological drought (IPCC 2018). On the other hand, changes in soil moisture and groundwater are also influenced by increases in actual evapotranspiration amounts (e.g., changes in basic climatologic soil-moisture balance) in addition to reductions in precipitation amounts and/or changes in precipitation regime in a climatic region or in agricultural or water basin. A relatively short period (from a few weeks to a few months) with an abnormal precipitation deficit in a geographical region or a water catchment is defined as a meteorological drought (Türkeş 2017).

We performed temporal drought analysis using both the AI, which was already explained above and the

Standardized Precipitation-Evapotranspiration Index (SPEI). The purpose of this analysis was to present whether long-term agricultural or hydrological drought conditions occur with respect to changes in water balance and potential evapotranspiration in the study area. These conditions may occur due to the combined impacts of changes in the precipitation regime, significant increases in air temperatures and decreases in relative humidity.

The multi-scalar drought index of the SPEI was developed by Vicente-Serrano et al. (2010) and Beguería et al. (2010). A prominent advantage of the SPEI over other drought indices is that it considers the effect of PET on drought severity, which its multi-scalar characteristics enable the identification of different drought types and impacts in the context of global warming.

The ready-use regional SPEI time-series over a region including the study district [(36.75, 32.25), (37.25, 32.75)] were taken from the SPEI Global Drought Monitor, which offers near real-time information about drought conditions at the global scale, with a 0.5-degree spatial resolution and a monthly time resolution (https://spei.csic.es/home.html; https://spei.csic.es/database.html). We derived 1, 12, 24, 36, and 48-month SPEI time-scales for the period of 1950 to 2020 from the SPEI Global Drought Monitor center. For calculating the PET values in these SPEI time-series, the Thornthwaite approach was used to estimate the PET as in the AI.

Results

In this section, in order to comprehensively document and scientifically discuss the impacts of climate change and forest management on the mortality pattern of Taurus fir stands in Hadim Forest Enterprise, the following factors have been investigated: (a) Detailed climate of the study area and its surroundings, (b) Observed changes and trends in long series of individual station-based climatological data, (c) Observed changes and trends in regional climatological series, (d) Observed changes and trends in the regional AI and SPEI series, (e) Changes in forest cover, (f) Areal transitions among different LULC classes, (g) Changes in the spatial structure of the landscape, (h) Changes in the stand structure, and (i) Impacts of forest management and wildfire have been investigated. Then, in the Discussion section, we have evaluated all the results and their implications in detail by synthesizing the changes in the above-mentioned factors in forest cover and the transitions, fragmentation, structural characteristics of forest stands, and finally, the possible impacts of climate and forest management on tree mortality.

Detailed climate of the study area and its surroundings

In terms of the local climate types based on the *AI*, the study area was generally characterized by a humid climate in the northwest and a semi-humid climate in the east and south (Fig. 2). This distribution pattern indicated a clear climate type gradient from a more humid in the west to a drier climate in the east. As a result, both humid and semi-humid climate conditions dominated the study area, both of which were suitable ecologically for developing a Mediterranean type coniferous forest biotope over the Hadim district and its surrounding region, particularly in the western and southern districts, as in most of the Central and Western Mediterranean sub-region of Turkey.

Based on the Köppen-Geiger climate classification system, the Mediterranean Region of Turkey, including the study area, is mainly characterized by the dry summer subtropical Mediterranean climate (Csa) (Türkeş 2013). This region is influenced by mid-to-high degree drought probability and drought risk. The probability of extremely dry conditions in Turkey indicates maximum values on the coast of the Mediterranean Region with a probability of about 0.25 (Turkes 2020). Although the annual soil-moisture deficit is not typical in the mid-latitude temperate (Group *C* climates) in general, seasonal soil-moisture deficiency—especially in summer months—is apparent in the Mediterranean (Csa and Csb) climates because of the changes in the regional and hemispheric circulation, pressure systems and air mass, producing dry conditions in the summer months (Turkes 2020).

Observed changes and trends in long series of individual station-based climatological data

The results of the statistical time-series analyses are given in Table 5. LSLR and M–K test results were almost the same regarding both nature (direction of the trend) and magnitude (p values) of observed trends (Table 5). Thus, only the M–K $u(t)$ results were evaluated. Generally, there were evident increases in air temperature, while both increasing and decreasing trends were observed in precipitation in Hadim, geographically the most representative station of the study area. The relative humidity series, on the other hand, showed strong decreasing trends for this station. Observed increased (i.e., warming) trends in the mean air temperatures and average maximum and minimum air temperatures of Hadim station were statistically significant ($p < 0.01$). Increasing trends in annual temperatures are attributable to sharp increases, especially in the summer.

Observed decreased trends in both annual and winter precipitations were significant only for winter ($p < 0.05$). As for autumn, a slightly increasing trend was seen (Table 5). No significant trends were observed in other

Table 5 Resultant test statistics of the least-squares linear regression and the M–K analysis techniques applied to the long-term series of the climatological observations recorded in Hadim (Had), Karaman (Kar) and Mut stations

	The least-squares linear regression (*t*)					The Mann-Kendal rank correlation *u* (*t*)				
	Annual	Winter	Spring	Summer	Autumn	Annual	Winter	Spring	Summer	Autumn
Had mean temp.	4.31**	0.40	0.80	7.15**	4.47**	3.88**	0.96	0.65	5.50**	3.86**
Had av. max. temp.	5.33**	0.76	1.84	6.23**	5.47**	4.37**	1.25	1.59	4.82**	4.56**
Had av. min. temp.	3.79**	1.40	1.94	5.86**	2.69**	3.86**	1.45	1.82	4.74**	2.61**
Had precipitation	− 1.58	− 2.36*	− 0.17	1.10	0.77	− 1.50	− 2.13*	− 0.28	0.79	1.29
Had rel. humidity	− 4.13**	− 4.35**	− 2.72**	− 1.77	− 2.90**	− 3.47**	− 3.85**	− 2.62**	− 1.72	− 2.51*
Kar mean temp.	2.85**	− 0.44	2.69**	6.45**	2.19*	2.75**	− 0.80	2.20*	5.20**	2.51*
Kar av. max. temp.	1.77	− 0.35	2.12*	3.95**	0.11	1.99*	− 0.50	1.99*	3.90**	0.99
Kar av. min. temp.	3.83**	− 0.63	2.62*	7.35**	3.47**	4.34**	− 0.33	3.30**	11.42**	4.12**
Kar precipitation	− 0.78	− 1.00	− 0.90	0.95	0.38	− 0.84	− 1.04	− 1.10	1.08	0.28
Kar rel. humidity	− 8.46**	− 4.81**	− 6.89**	− 3.73**	− 5.89**	− 6.01**	− 4.38**	− 5.26**	− 3.49**	− 4.37**
Mut mean temp.	3.52**	2.37*	3.26**	2.06*	4.87**	2.31*	1.65	2.06*	0.50	3.90**
Mut av. max. temp.	− 1.47	− 0.97	− 0.71	− 0.82	− 1.62	− 1.02	− 0.98	− 0.44	− 0.67	− 1.06
Mut av. min. temp.	2.98**	0.21	2.36*	2.33*	3.99**	3.05**	0.07	1.66	1.91	2.65**
Mut precipitation	− 0.68	− 1.32	0.51	0.38	0.71	− 0.79	− 1.65	0.60	0.38	0.77
Mut rel. humidity	− 2.17*	− 1.61	− 1.99	− 0.17	− 1.71	− 2.28*	− 1.49	− 1.98*	− 0.45	− 1.54

(*) The increasing (or decreasing) trend is statistically significant at the 0.05 significance level

(**) The increasing (or decreasing) trend is statistically significant at the 0.01 significance level

precipitation series. Decreased trends in relative humidity, on the other hand, were significant in all seasons except for summer ($p < 0.05$).

As for the surrounding stations, observed trends in Karaman were similar to Hadim; in general, rapid warming was evident in the air temperature time-series (Table 5). However, results from the Mut station, relatively differ from the Hadim and Karaman stations in terms of the trend and year-to-year variability because Mut has distinct microclimate characteristics within the Central Taurus Mountains. Although we used its data in the climate type and station-based time-series analysis, it was excluded from the trend analysis of the regional time-series.

Observed changes and trends in regional climatological series

Observed changes in the regional-average climatic variables for the Hadim-Karaman district are presented in Table 6. Accordingly, strong warming trends were observed in annual, summer, and autumn mean; annual, summer, and autumn average maximum; annual, spring, summer, and autumn average minimum regional temperatures. Based on the long-term graphics presented in Fig. 3, the trends were clearer just after the 1992 cold year. Since then, they changed to warmer conditions than the long-term average (Figs. 3, 4, 5).

As for precipitation totals, no significant trend was found except for winter. Annual total winter precipitation showed

Table 6 Resultant test statistics of the least-squares linear regression and the M–K analysis techniques applied to the long-term series of the climatological observations averaged for the Hadim-Karaman (Had-Kar) district

	The least-squares linear regression (*t*)					The Mann-Kendal rank correlation *u* (*t*)				
	Annual	Winter	Spring	Summer	Autumn	Annual	Winter	Spring	Summer	Autumn
Had-Kar mean temp.	3.66**	− 0.07	1.76	7.57**	3.72**	3.41**	− 0.09	1.40	5.65**	3.78**
Had-Kar av. max. temp.	3.68**	0.12	2.02*	5.31**	3.53**	3.41**	0.23	1.80	4.44**	3.39**
Had-Kar av. min. temp.	4.75**	0.95	2.85**	9.58**	3.97**	4.30**	0.84	2.69**	6.45**	3.62**
Had-Kar precipitation	− 1.48	− 2.15*	− 0.59	1.30	0.62	− 0.98	− 1.95	− 0.71	0.86	1.08
Had-Kar rel. humidity	− 6.45**	− 4.63**	− 4.53**	− 3.05**	− 4.51**	− 4.95**	− 4.15**	− 3.85**	− 3.22**	− 3.50**

(*) The increasing (or decreasing) trend is statistically significant at the 0.05 significance level

(**) The increasing (or decreasing) trend is statistically significant at the 0.01 significance level

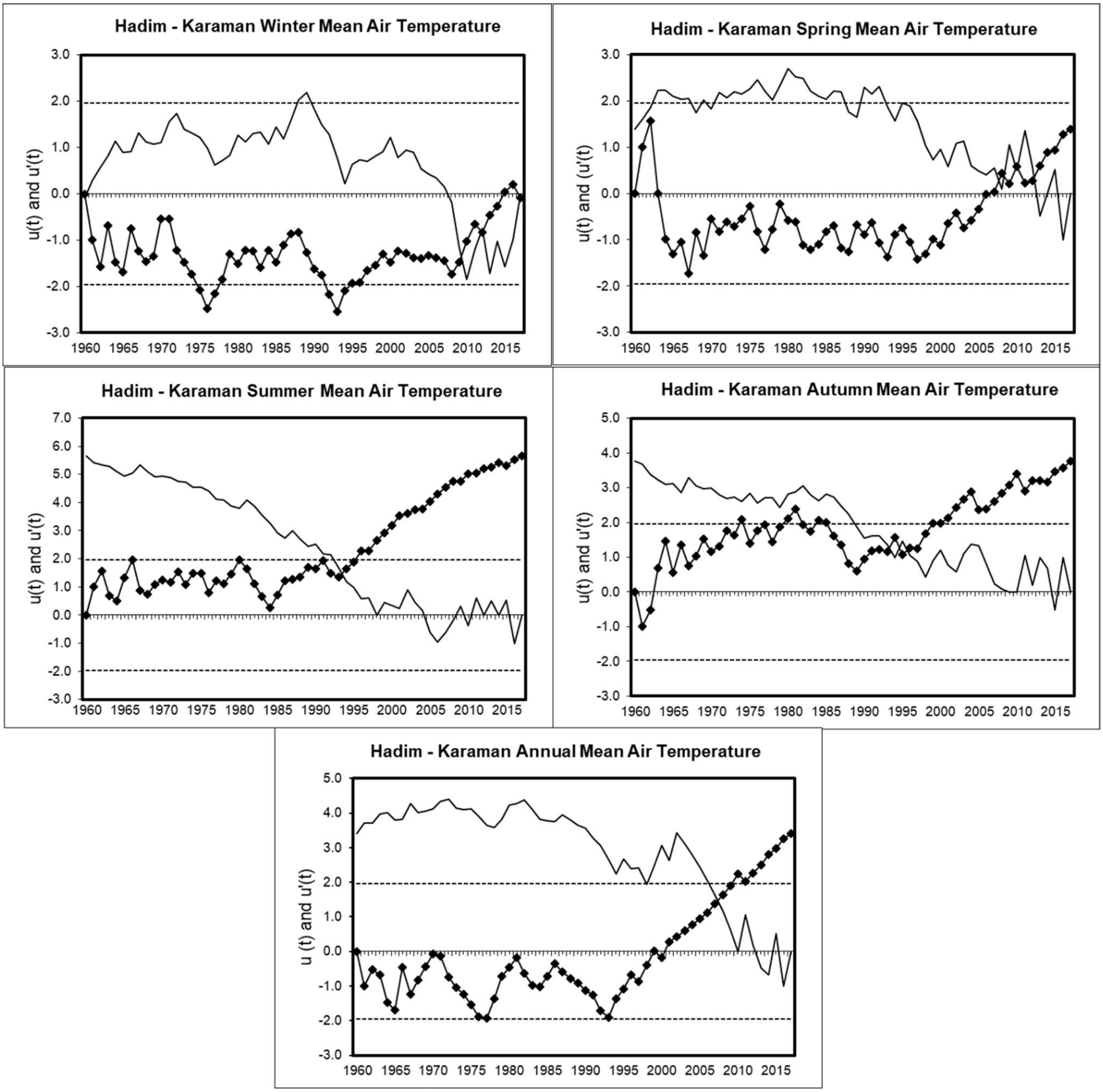

Fig. 3 Long-term trends and fluctuations in annual and seasonal mean air temperature series of the Hadim-Karaman district in Turkey from sequential values of the statistics *u(t)* (*lines*) and *u'(t)* (*filled squares*) of the M–K test, with critical value of ± 1.96 at the 0.05 level of significance (*dotted lines*) based on the two-sided normal distribution

a decreased trend almost at the 0.05 significance level. In other words, a long-term aridification process was seen in the region (Fig. 6). The decreased trend in the winter precipitation started in the early-1980s. However, it reached a new equilibrium in the 1990s and maintained near the average of recent periods. The observed decreased trend in the annual precipitation, on the other hand, started in the late-1980s but no significant arid period has been experienced since then ($p < 0.05$). For the Hadim-Karaman district, long-term trends and fluctuations for other seasons are seen in Fig. 6.

As for relative humidity, strong and significant decreased trends starting from the mid-1980s were remarkable in both annual and seasonal means ($p < 0.01$) (Fig. 7). These trends were more evident in the 1997–2017, 2005–2017, and 2009–2017 periods for the winter, spring, and summer seasons, respectively. The annual mean relative humidity, on the

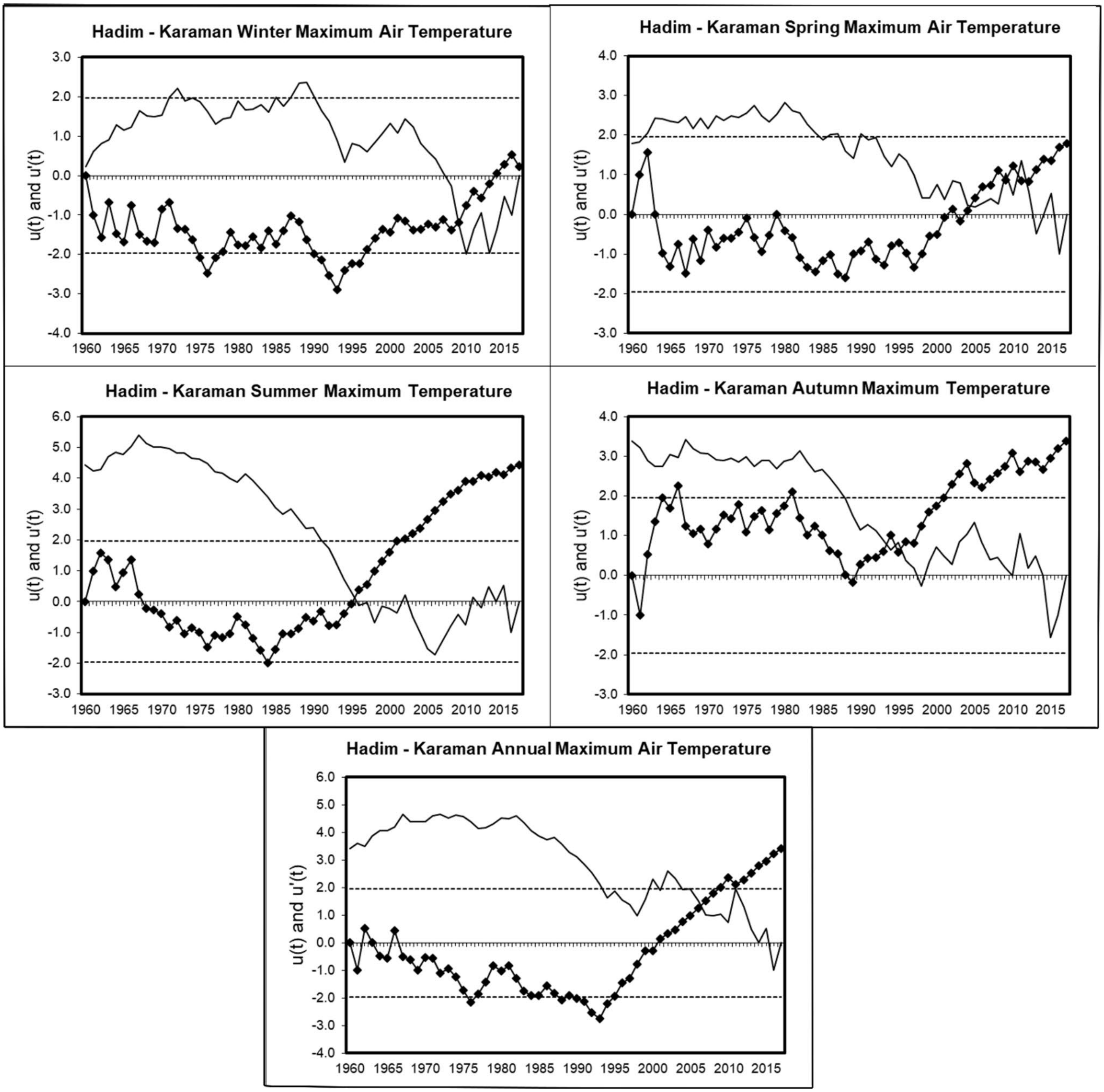

Fig. 4 Long-term trends and fluctuations in annual and seasonal average maximum air temperature series of the Hadim-Karaman district in Turkey from sequential values of the statistics *u(t)* (*lines*) and *u'(t)* (*filled squares*) of the M–K test, with critical value of ± 1.96 at the 0.05 level of significance (*dotted lines*) based on the two-sided normal distribution

other hand, showed a clear decreasing trend in proportion to the long-term average between the years 2004 and 2017.

Observed changes and trends in the regional AI and SPEI series

Figure 8 shows a significant decrease in AI during the examined period, which means increased dryness in both series of Hadim and Karaman. Due to the different baseline climate (i.e., the long-term average AI values indicating the local climate type), it was seen that there was a significant trend from humid climatic conditions mostly evident during the 1960s, 1970s, and 1980s to the dry sub-humid climatic of the 2000s and 2010s in the AI series of Hadim (Fig. 8a), whereas there was a significant change from semi-humid conditions dominated during the mid-to-late 1970s to dry sub-humid and then to semi-arid conditions occurring after the early 2000s along with the

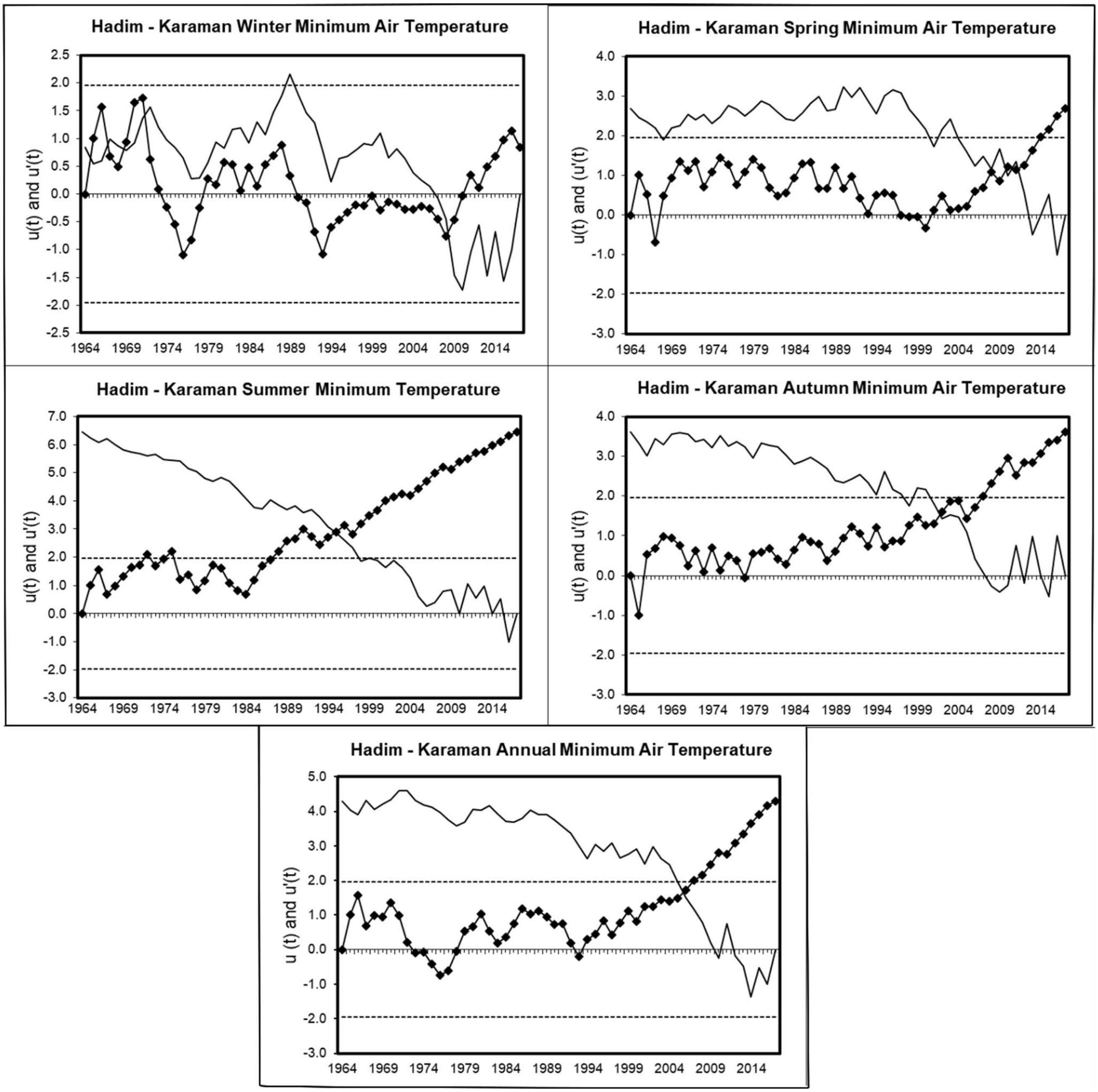

Fig. 5 Long-term trends and fluctuations in annual and seasonal average minimum air temperature series of the Hadim-Karaman district in Turkey from sequential values of the statistics *u(t)* (*lines*) and *u'(t)* (*filled squares*) of the M–K test, with critical value of ± 1.96 at the 0.05 level of significance (*dotted lines*) based on the two-sided normal distribution

severe drought events during this period in the Karaman station (Fig. 8b).

As for the long-term variations in the regional SPEI series derived from the 1, 12, 24, 36, and 48-month time-scales for a sub-region including the study district, drier than long-term average conditions have tended to increase generally since the late 1980s and the year of 1990 in the SPEI time-series for all time-scales considered in the study (Fig. 9). Accordingly, particularly in the SPEI series for the 24, 36, and 48-month time-scales, a long period from 1990 to 2020 was characterized mostly by long-term drought tendency (Figs. 9c, d, e). Due to the long-term drought tendencies (drying) seen in this period, drought conditions that were very likely prevalent in the Hadim district can be recognized as a period characterized by long-term agricultural and hydrological droughts. Furthermore, drought events developed between 2000 and 2010 were mostly characterized with SPEI values smaller than −1, and the second half

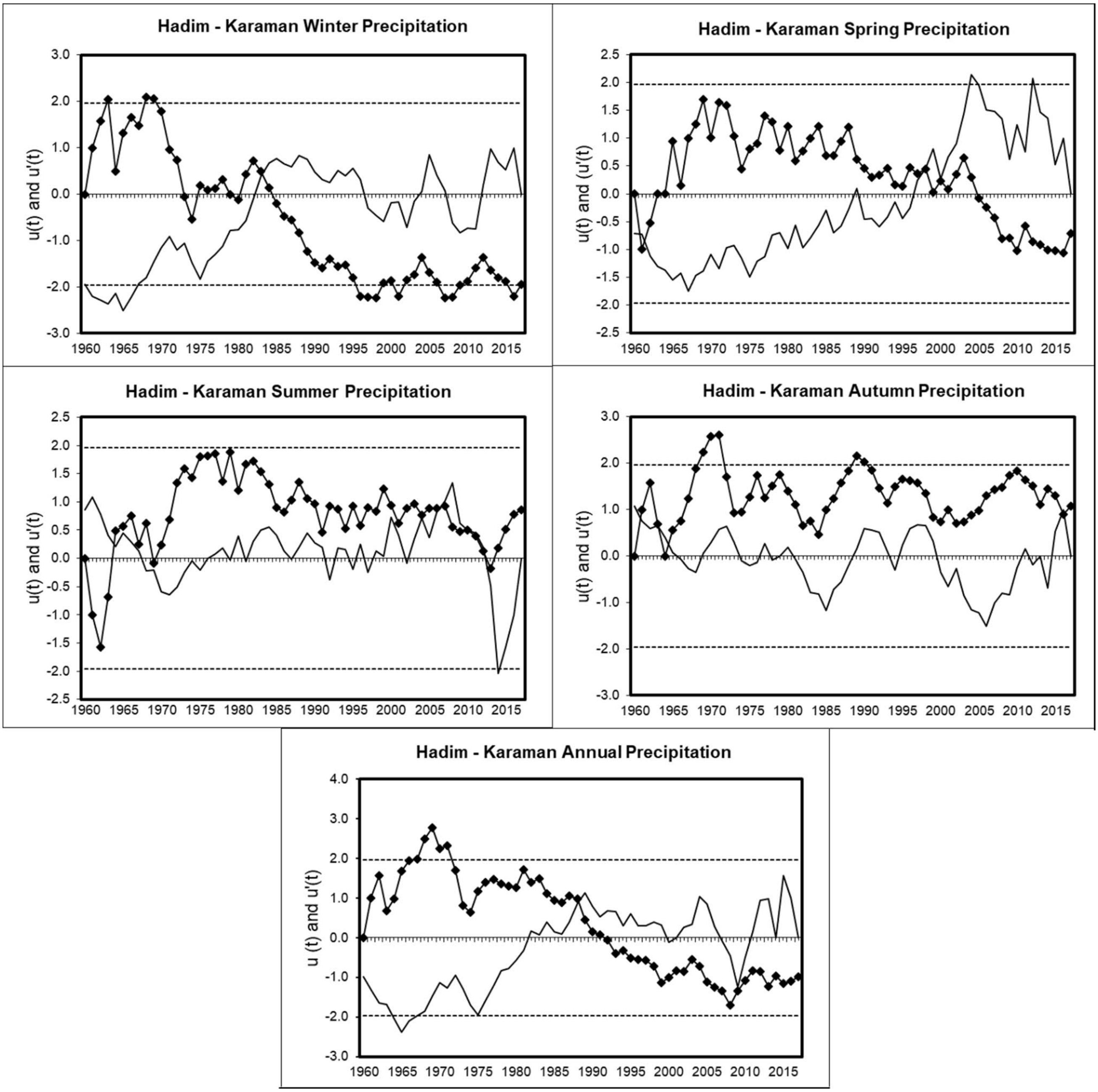

Fig. 6 Long-term trends and fluctuations in series of annual and seasonal precipitation totals of the Hadim-Karaman district in Turkey from sequential values of the statistics *u(t)* (*lines*) and *u'(t)* (*filled squares*) of the M–K test, with critical value of ± 1.96 at the 0.05 level of significance (*dotted lines*) based on the two-sided normal distribution

of the period with SPEI values smaller than −1.5 up to −2.5; these values represent moderate, and severe and very severe droughts, respectively.

Finally, it is important to underline that the Taurus fir is not a drought-tolerant tree species like other typical Mediterranean conifers, such as Calabrian pine (Bozkuş 1986; Cailleret et al. 2014). All these findings and assessments summarized above suggest that significant observed climatic changes (e.g., increased air temperatures and droughts and decreased relative humidity) and theoretically very likely declined climatological soil water balance are the two driving factors on tree mortality in Hadim's Taurus fir forests. The evidence for the intensive tree mortality is documented in the following subsections.

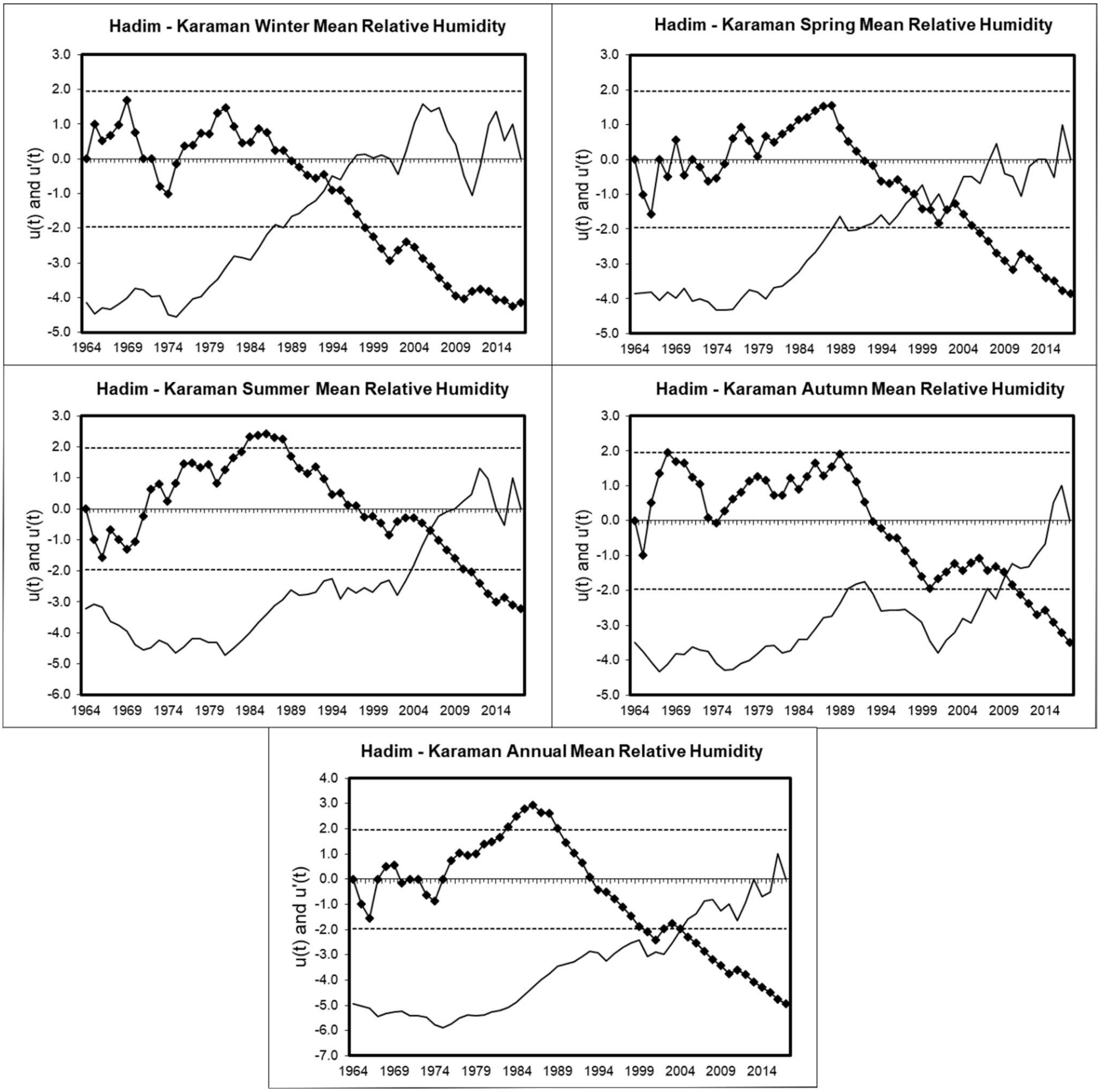

Fig. 7 Long-term trends and fluctuations in series of annual and seasonal mean relative humidity of the Hadim-Karaman district in Turkey from sequential values of the statistics *u(t)* (*lines*) and *u'(t)* (*filled squares*) of the M–K test, with critical value of ± 1.96 at the 0.05 level of significance (*dotted lines*) based on the two-sided normal distribution

Changes in forest cover

Based on the GIS analyses of temporal stand type maps, it was seen that the area coverage of pure fir stands in Hadim Forest Enterprise gradually decreased at the (LULC) class level. In contrast, the total forested lands increased with an annual forestation rate of 0.5% between 1971 and 2016 at the landscape level (Table 7). The drastic change in the fir stands was as much as − 82.3% for the 45 years resulting in a remaining area of only 542 ha in 2016. Thus, an annual forestation rate of − 3.8% was calculated for the pure fir, which could be considered as the rapid loss of area at the class level. Temporal changes in area coverages were rather complicated. The area of fir-dominated mixed stands showed a fluctuated trend among different periods (Table 7). Fir-associated mixed stands, however, started to increase after 1993. This may be attributed to the transformation from pure to mixed stands from 1993 to 2016. The spatiotemporal

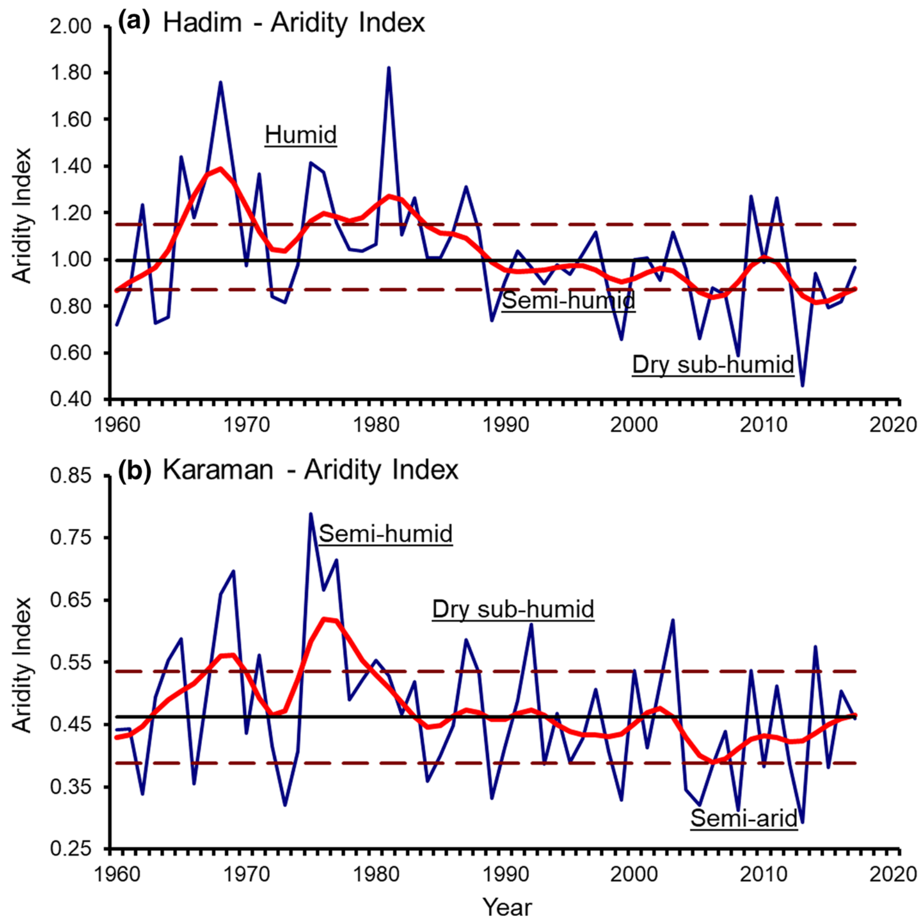

Fig. 8 Inter-annual and long-period variations in the original and smoothed series of the aridity index values of (a) Hadim, and (b) Karaman stations. (*dark lines*) shows 9-point low-pass gaussian filter; (*lines*), median value of the AI series and (*dotted lines*), lower and upper median quartiles on the time-series graphics

changes by species mix can be seen in the maps given in Fig. 10.

As for tree crown closure, the area coverages for all canopy cover classes, excluding degraded stands, showed an increasing trend from 1971 to 2016 (Table 7). The degraded stands, which had a canopy cover of less than or equal 10%, increased from 3268 to 4335 ha in the first period; then, dramatically decreased to 253 ha in the second period. Since degraded lands took up large areas in Hadim, this dramatic decrease led to an annual forestation rate of −0.8% by total canopy covers (Table 7). In fact, large areas of degraded fir stands, marked as red both in 1971 and 1993's maps, disappeared in 2016 (Fig. 11). This indicated a significant transformation from degraded fir to other LULCs.

Areal transitions among different LULC classes

After analyzing the changes in area coverages of fir forests, transitions among different forest covers and other LULC classes were documented for the overall period (1971–2016). The areal transitions among fir forests were evaluated by species mix. Accordingly, more than half of the pure fir stands (1722.2 ha) changed to stands dominated by other tree species (Table 8). The rest, transformed into mixed fir (966.6 ha) and non-forest lands (226.5 ha), such as rocky areas, agricultural lands, or other bare lands. Anatolian black pine and Lebanon cedar were two species concomitant with fir in the mixed forest stands. Only 153.9 ha of pure fir stands remained steady in the same period. Other changes among different LULCs are seen in Table 8.

The transition map in Fig. 12 represents steady-state and changed fir stands in terms of the species mix. Almost all fir forests in the northwestern parts of the study area more or less changed. In contrast, some forest blocks in the northeastern and southern parts remained steady-state (Fig. 12). These parts are generally located at the north-facing slopes. Based on the t-test results, the slope aspect was found to be a significant ecological factor affecting steady-state and changed stands ($p < 0.01$) (Table 9). Specifically, 82% of the steady-state fir forests are located on north-facing slopes. Surface slope, altitude, and growing site were other ecological factors affecting the areal transitions. The changed forest stands were mostly on steeper slopes, while the steady-state stands were on relatively flat ground ($p < 0.05$). The mean altitude of the changed stands was higher than that of the steady-state stands ($p < 0.01$). Similarly, steady-state stands had better site conditions than the changed ones ($p < 0.001$) (Table 9). A good site

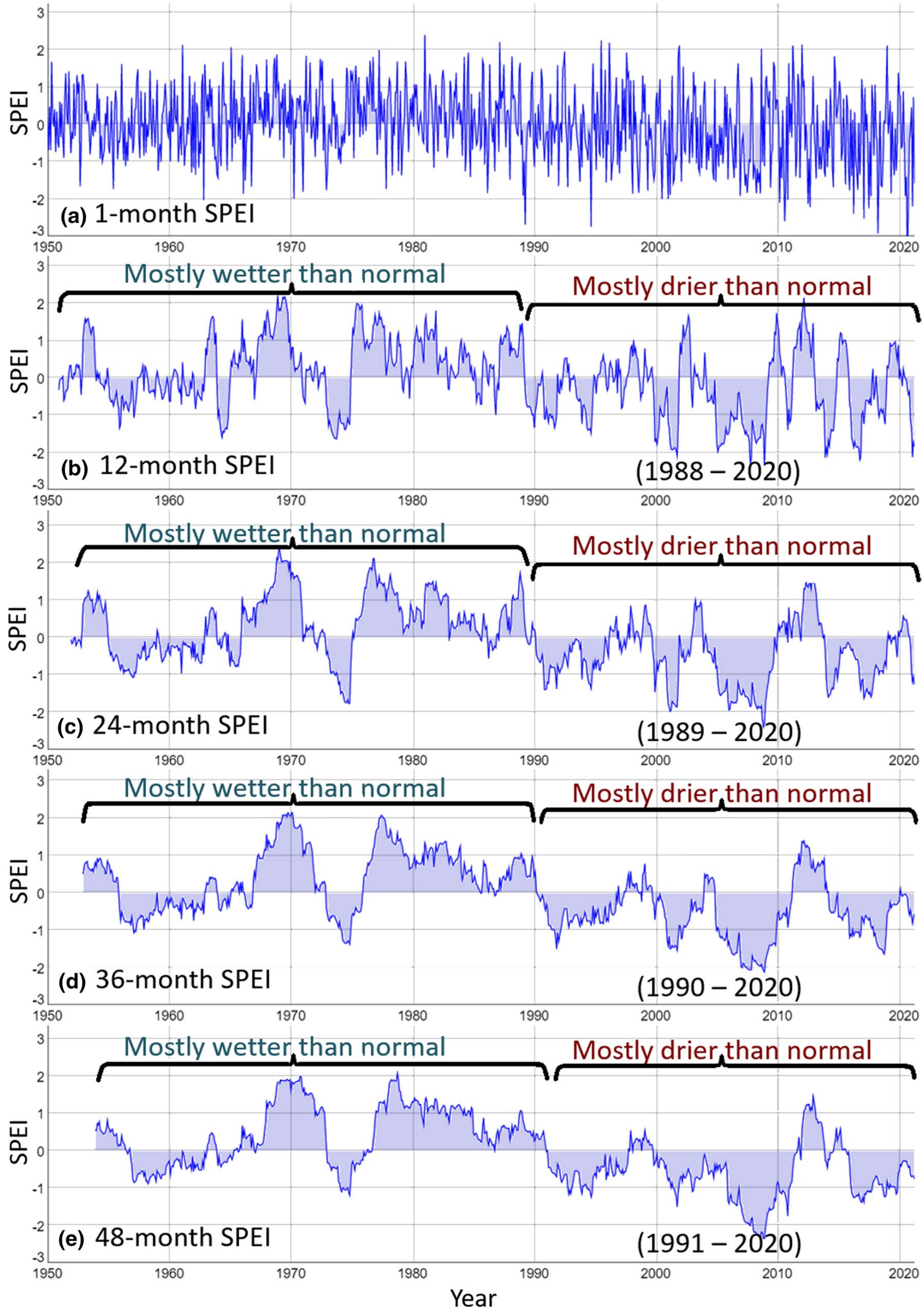

Fig. 9 Inter-annual (a, b; one to 12-month time-scales) and long-period (c, d, e; from 24 to 48-month time-scales) variations in the regional Standardized Precipitation-Evapotranspiration Index (SPEI) during the period of 1950–2020

Table 7 The change in forest cover by different planning periods

Stand parameters	LULC classes	Forest cover in different years (ha)			Periodical changes in the area (%)			Annual rate of forestation (%)***
		1971	1993	2016	1971–1993	1993–2016	1971–2016	1971–2016
Species mix*	Pure fir	3069	1266	542	−58.7	−57.2	−82.3	−3.8
	Fir-dominated mixed	1626	4337	2698	+166.7	−37.8	+65.9	+1.1
	Fir-associated mixed	768	493	2687	−35.8	+445.0	+249.9	+2.8
	Total	5463	6096	5927	+11.6	−2.8	+8.5	+0.2
Canopy cover classes**	Fully-covered fir	84	92	368	+9.5	+300.0	+338.1	+3.3
	Moderate-covered fir	553	759	688	+37.3	−9.4	+24.4	+0.5
	Loosely-covered fir	790	1680	1957	+112.7	+16.5	+147.7	+2.0
	Degraded fir	3268	4335	253	+32.6	−94.2	−92.3	−5.5
	Total	4695	6866	3266	+46.2	−52.4	−30.4	−0.8
All forested lands		27,871	31,059	34,260	+11.4	+10.3	+22.9	+0.5

(*) A forest stand is identified as *mixed* if the 2nd (associated) species exists more than 10% in total standing volume

(**) Canopy cover statistics were given only for pure fir and fir-dominated mixed stands (fir-associated mixed excluded)

(***) The negative rates refer to deforestation at the class level

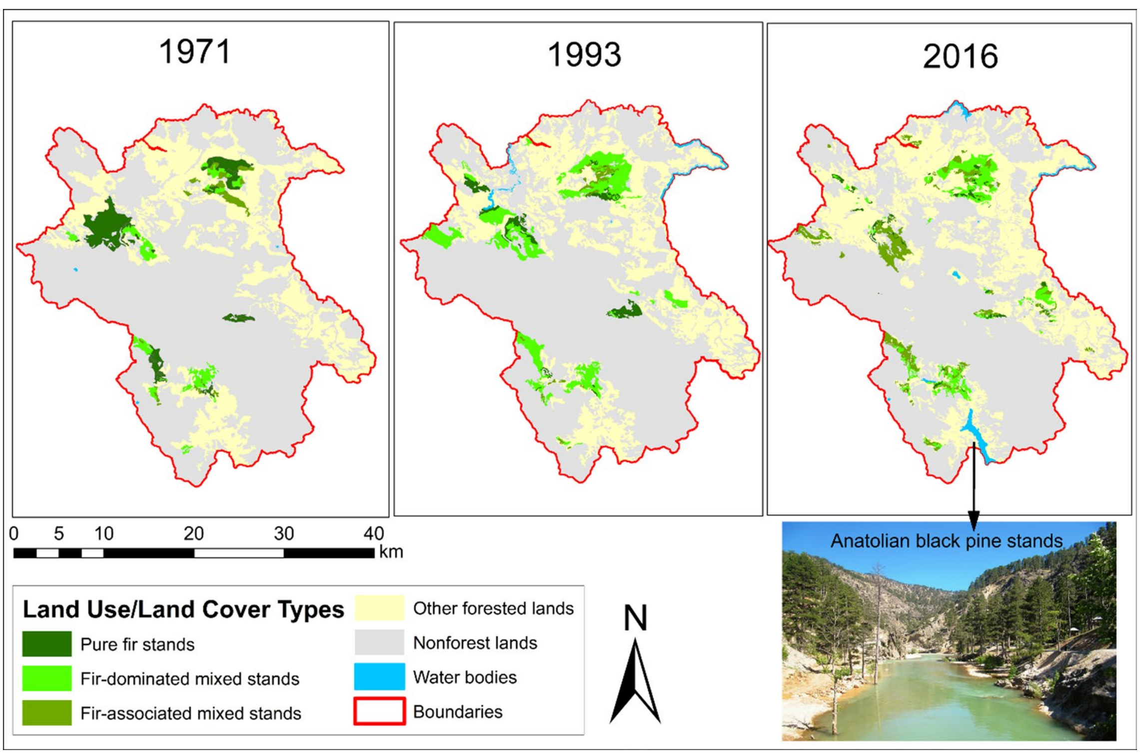

Fig. 10 Spatiotemporal changes in fir forests by the species mix parameter (Photo: Ahmet Poçanoğlu)

condition refers to a flatter land where the soil is deep and rich in nutrient content, stoniness is low and the rainfall is sufficient. Stands of trees located on good sites usually grow faster than those located on poor sites (GDF 2017; van Laar and Akça 2007).

Changes in the spatial structure

The patch metrics provided useful information when evaluated together with areal statistics. The number of patch (NP) metric increased continuously in all forest cover types,

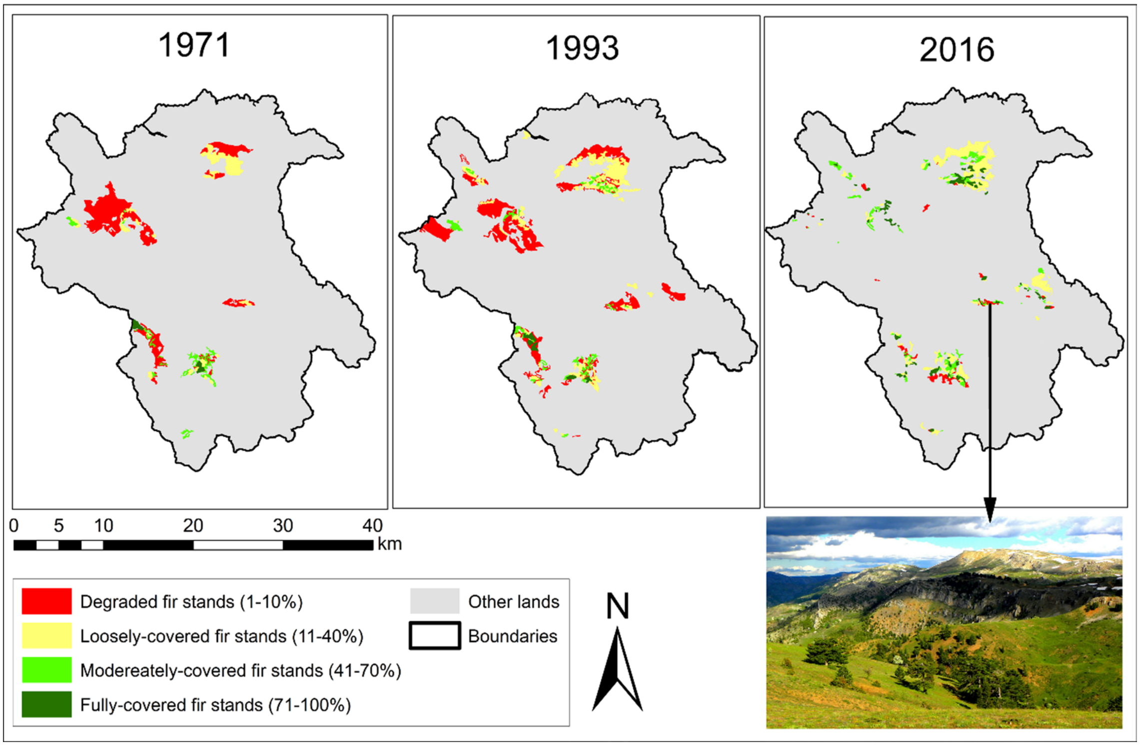

Fig. 11 Spatiotemporal changes in fir forests by the canopy cover parameter (Photo: Abdullah Ünlü)

Table 8 The transition matrix of pure and mixed fir stands between 1971 and 2016

	LULC classes	Spatiotemporal transitions of LULC classes (ha) Pure fir	Fir-domi. mixed	Fir-asso. mixed	Other forests	Non-forest lands	Water bodies	Total area in 2016 (ha)
Spatiotemporal transitions of LULC classes (ha)	Pure fir	**153.9**	623.1	343.5	1722.2	226.5	0.0	3069.2
	Fir-dominated mixed	64.9	**503.7**	709.6	255.9	92.2	0.0	1626.3
	Fir-associated mixed	31.1	314.7	**134.9**	263.0	24.7	0.0	768.4
	Other forests*	236.6	1033.5	1073.6	**17,039.1**	2785.5	239.6	22,407.9
	Non-forest lands**	55.9	223.1	424.9	9050.3	**52,514.3**	132.3	62,400.8
	Water bodies	0.0	0.0	0.0	1.6	15.5	**0.8**	17.9
Total area in 1971 (ha)		542.4	2698.1	2686.5	28,332.1	55,660.7	372.7	90,290.5

(*) *Other forests* refer to all forest stand types which do not include any fir species

(**) *Non-forest lands* refer to agriculture, grassland, settlement, and other bare lands

(***) The bold values refer to the unchanged areas for each LULC class

except for fir-associated mixed stands (Table 10). In fir-associated mixed stands, however, it slightly decreased from 21 to 17 in the first period (1971–1993); then, remarkably increased to 118 in the second period (1993–2016). As stated in the previous section, the slight decrease in the first period was attributed to its areal loss. At the landscape level, the NP showed an increasing trend, like many other classes. In other words, the forest became more fragmented during the overall period covering 1971 to 2016. However, the severest fragmentation was in the pure fir class since its annual rate of forestation was – 3.8%. Namely, pure fir forests had only 33 patches when their area coverage was 3069 ha in 1971; in 2016, however, it increased to 88, although their coverage decreased to 542 ha. This finding indicated that pure fir was one of the most susceptible classes to forest disturbances in the study area.

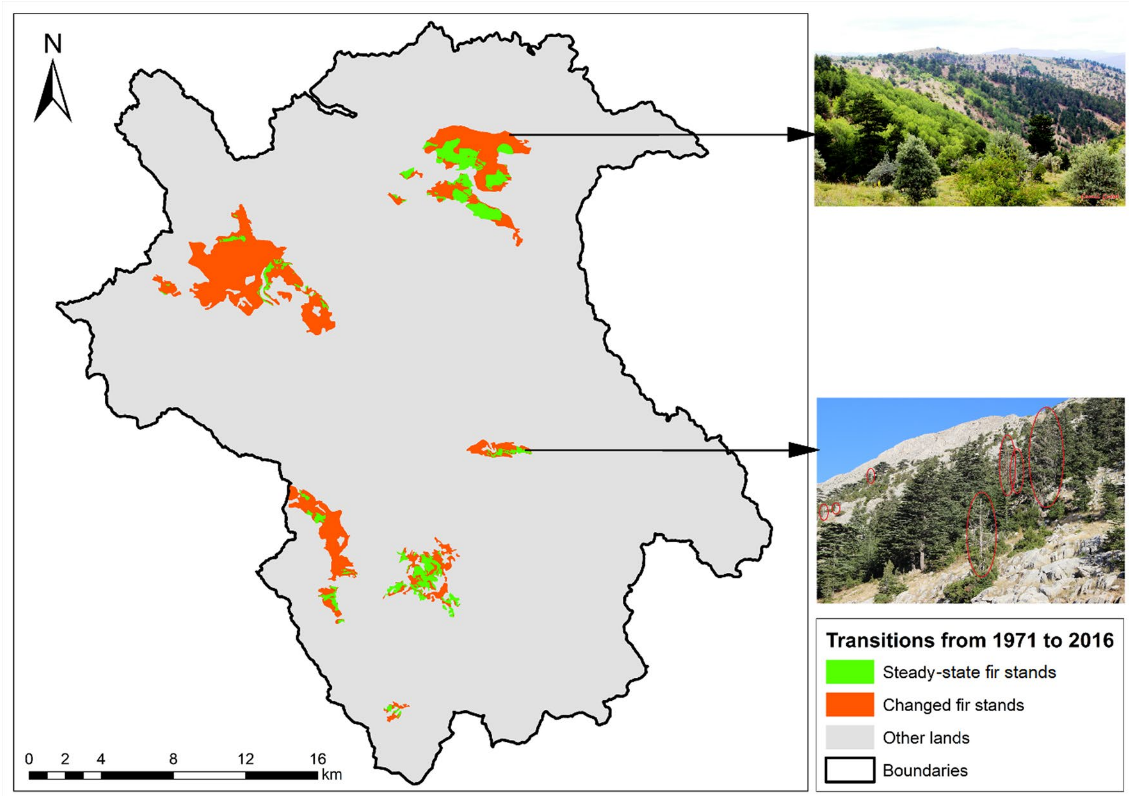

Fig. 12 The transition map of pure and mixed fir stands from 1971 to 2016. The photo on the right shows standing deadwoods circled in red (Photos: Akkın Semerci)

Table 9 Ecological factors affecting transitions between pure and mixed fir stands

Ecological factor	Categorical variable	Mean	P value (t-test)
Surface slope (%)	Steady-state fir stands	39	0.024
	Changed fir stands	43	
Growing site (bonitet class)	Steady-state fir stands	4.05	< 0.001
	Changed fir stands	4.51	
Altitude (m, asl)	Steady-state fir stands	1650	0.002
	Changed fir stands	1680	
Slope aspect	Steady-state fir stands	N/A	0.003
	Changed fir stands	N/A	

As for the mean patch size (MPS) metric, a general decreased trend was observed at the class and landscape levels (Table 10). Excluding fir-dominated mixed stands, the MPS significantly decreased for all LULC classes. Similar to the NP metric, the most remarkable decrease was in the pure fir class, whose MPS values were 93 ha in 1971, 25 ha in 1993, and only 6 ha in the last period. The trends for the largest patch size (LPS) metric, on the other hand, showed distinct features for different forest covers. It dramatically decreased from 1543 to 26 ha for the pure fir class over the 45 years, mainly due to the changes in the procedures of forest inventory mapping in Turkey. Other changes in the LPS by different forest covers are seen in Table 10. As for the mean edge length (MEL) metric, there was a decreasing trend at both the class and landscape levels (Table 10). The only exception was in the fir-associated mixed class, which led to areal transitions from pure fir stands. Indeed, this class showed remarkable improvements, based on almost all indicators. By contrast, the MEL metric for pure fir class decreased by 3450 m between 1971 and 2016.

Changes in the stand structure

In addition to the spatial changes, the structural quality of productive fir forests was examined by several stand parameters (Table 11). As for the number of trees parameter, a decreased trend was observed for pure fir cover at the stand type level. By contrast, this parameter increased in fir-dominated mixed stand types. In GSc1, for example, there were 207, 225, and 292 stems per unit area (1 ha) in 1971, 1993, and 2016, respectively. This finding indicated a slight increase in stand density of loosely-covered fir-cedar mixed stands in their thin-tree (20–35.9 cm) developmental stage. Since thin trees were abundant in the entire study area, the

Table 10 The changes in patch metrics by different planning periods

LULC classes	Number of patch (#)			Mean patch size (ha)			Largest patch size (ha)			Mean edge length (m)		
	1971	1993	2016	1971	1993	2016	1971	1993	2016	1971	1993	2016
Pure fir	33	51	88	93	25	6	1543	157	26	4952	3252	1502
Fir-domi. mixed*	48	120	175	34	36	15	268	486	211	3736	3662	2357
Fir-asso. mixed*	21	17	118	37	29	23	77	190	696	2799	3872	2952
All fir forests	102	188	381	54	32	16	1543	486	696	4024	3570	2344
All forestlands	330	588	1882	84	53	18	1543	1621	917	5811	4630	2525

(*) A forest stand is identified as mixed if the 2nd (associated) species exists more than 10% in total standing volume

Table 11 The changes in stand structure by different planning periods

Stand mix	Stand type codes*	Age class in 2016**	Number of trees (# ha^{-1})			Standing volume (m^3 ha^{-1})			Volume increment (m^3 ha^{-1})			Standing deadwood volume (m^3 ha^{-1})***		
			1971	1993	2016	1971	1993	2016	1971	1993	2016	1971	1993	2016
Pure fir stands	Gb3	III	–	–	611	–	–	44	–	–	1.6	–	–	0
	Gbc1	–	380	184	–	103	48	–	1.3	0.9	–	0	0	–
	Gbc2	–	503	494	–	66	79	–	1.7	1.9	–	0	1.1	–
	Gc3	IV	–	–	620	–	–	88	–	–	2.3	–	–	0.7
	Gcd1	–	305	246	–	55	158	–	1.2	2.2	–	0.2	4.7	–
	Gcd2	V	375	300	340	87	153	88	1.7	2.3	1.7	0	1.1	1.9
	Gd2	V	–	–	292	–	–	168	–	–	2.3	–	–	1.1
	Gd3	V	–	–	513	–	–	264	–	–	3.7	–	–	4.6
	Average		390	307	475	78	110	130	1.5	1.8	2.3	–	–	–
											Total	0.2	6.9	8.3
Fir-dominated mixed stands	GArbc1	III	278	171	184	27	17	17	0.8	0.5	0.5	0	2.6	1.2
	GArcd1	III	191	225	246	65	73	107	1.6	1.3	1.6	0	0	0
	GÇkc1	–	226	–	–	33	–	–	0.9	–	–	0	–	–
	GÇkc2	IV	–	–	462	–	–	96	–	–	2.2	–	–	9.1
	GÇkcd1	V	262	232	354	124	174	121	1.9	2.1	2.1	0	2.3	4.5
	GÇkd1	V	–	–	246	–	–	147	–	–	2.0	–	–	0.3
	GÇkd2	V	–	–	549	–	–	235	–	–	3.6	–	–	14.1
	GMnb1	III	–	–	293	–	–	19	–	–	0.7	–	–	2.7
	GSc1	V	207	225	292	78	124	103	1.4	1.7	2.1	0.5	5.4	0.3
	GSc2	V	285	380	342	104	140	110	1.8	2.2	2.0	0.9	1.9	2.6
	GSc3	V	–	–	827	–	–	123	–	–	3.4	–	–	5.3
	GScd2	VI	–	–	342	–	–	110	–	–	2.0	–	–	2.6
	GScd3	VI	582	572	534	175	251	222	3.2	3.8	3.4	5.8	24.6	4.3
	GSd1	VII	–	–	292	–	–	133	–	–	2.1	–	–	0.3
	GSd2	VII	–	–	381	–	–	287	–	–	8.6	–	–	0.4
	Average		290	301	381	87	130	131	1.7	1.9	2.6	–	–	–
											Total	7.2	36.8	47.7
All fir stands	Average		326	302	406	83	122	131	1.6	1.9	2.1	–	–	–
										Grand total		7.4	43.7	56.0

(*)The stand type codes are identified in Table 2

(**)I. Age class: 0–20 yrs; 21–40 yrs: II. Age class; 41–60 yrs: III. Age class; …

(***)Standing deadwood volumes in the mixed stands were given only for Taurus fir trees (the deadwood of associated species was excluded) average of this parameter increased from 326 to 406 stems per unit area for all fir stands in the overall period (Table 11).

Regarding standing volume, fluctuations were observed in pure and mixed fir stands. The average volumes moderately increased during the first period (1971–1993). However, in the second period (1993–2016), they remained almost stable at 120–130 $m^3\ ha^{-1}$, although fir forests developed into the advanced age classes (Table 11). This can be attributed to intensive tree mortality, and harvesting operations in regeneration sites of some mature stands as scheduled by the old management plan (GDF 1993). Regarding the volume increment parameter, slightly increased trends were observed in the averages from 1971 to 2016 (Table 11). As for mixed fir stands, on the other hand, volume increments were higher than those of pure stands.

The changes in deadwood volumes were also analyzed for fir species based on temporal FMP data. As seen in Table 11, there were no or a few deadwood in fir forests in 1971, except for the stand type GScd3. In 1993, deadwood volume reached nearly 25 $m^3\ ha^{-1}$ for the GScd3, a mature mixed stand near its rotation age. In this period, deadwood volumes substantially increased almost in all stand types. In 2016, total deadwood increased further in pure and mixed stands of fir. Taking all stands together, the total amount of deadwood volume continuously increased from 7.4 $m^3\ ha^{-1}$ to 56 $m^3\ ha^{-1}$ in Hadim Forest Enterprise at the landscape level (Table 11).

Since deadwood volume was a useful indicator for monitoring tree mortality, its spatial changes between 1971 and 2016 were further analyzed based on temporal stand type maps (Fig. 13). Accordingly, the map of the first period (1971–1993) represented a healthy and vigorous forest across the entire landscape. Relatively high deadwood volumes were observed only in the southern parts of Hadim. These parts are located at the lowlands with an altitude of ~ 1200–1300 m asl. This orographic vegetation belt also forms the lowest distribution of Taurus fir in Turkey (Bozkuş 1986; Akkemik 2000; Kavgaci et al. 2010). In the following periods, deadwood volumes substantially increased to around 10 $m^3\ ha^{-1}$ in the same parts (Fig. 13). Moreover, fir forests in the northern parts have possibly become more susceptible to disturbances, too. As a result, significantly high deadwood volumes were observed in most fir forests across the study area in 2016. It is possible to see a large amount of deadwood even in the upper forest zone, around 2000 m. This phenomenon is thought to be caused by the increased drought and water deficit in the region.

The impacts of forest management and wildfire

To differentiate the roles of natural mortality, salvage logging, and commercial logging in evaluating mortality processes, we first documented fir regeneration sites from the FMPs. Accordingly, 132.7 ha of mature fir stands (both

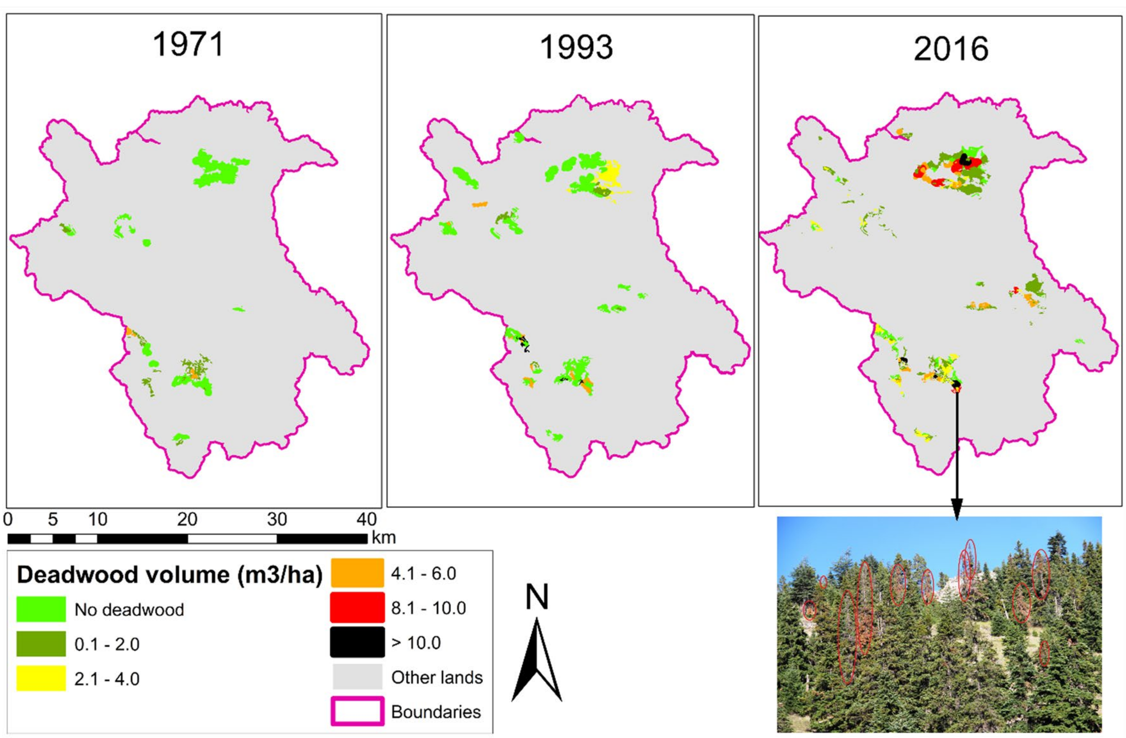

Fig. 13 Spatiotemporal changes of standing deadwood in productive fir forests. Standing deadwoods are circled in red (Photo: Akkın Semerci)

pure and mixed) were regenerated between 1971 and 2016. It was observed that the same species composition generally remained in these regenerated sites. Only 12.3 ha of these sites were converted to other tree species, particularly Anatolian black pine. As a result of commercial logging operations, approximately ten thousand m^3 fir (roundwood and firewood) was removed from the forest during a 45-year period.

Aside from commercial logging, high deadwood volumes in Hadim's fir forests have motivated forest practitioners to salvage logging operations as they started to remove dead trees from the forest year by year. In Hadim Forest Enterprise, the official statistics have been kept regularly since 2007. A total of 6466 m^3 deadwood—only for Taurus fir species—were removed from the forest during the 11 years between 2007 and 2018. The total amount of extracted timber (deadwood) volume from the salvage-logged areas can be seen in Fig. 14. The total volumes of standing deadwood were also presented in the same figure by planning periods. As a result, the total amount of deadwood (both standing and extracted) increased from 906 m^3 in 1971 to 11,840 m^3 in 2016 at the landscape level (Fig. 14).

According to the official statistics, eight wildfires have occurred in Hadim Forest Enterprise since 2007. During wildfires, a total amount of 4.9 ha of forested areas were burnt. The average amount of burnt forest area was approximately 0.6 ha per wildfire. The percentage of the burnt areas was specified neither by stand types nor tree species. Thus, we had no information regarding the direct impacts of wildfire on the spatiotemporal change in fir cover. However, it was observed that the burnt areas were naturally or artificially regenerated with the same tree species following the wildfire.

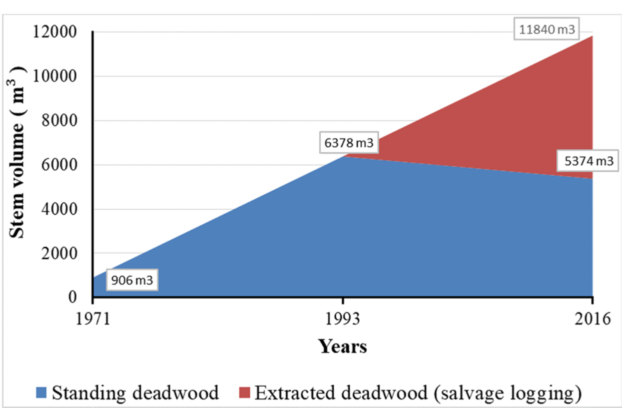

Fig. 14 Total amount of standing deadwood volumes and removals from the salvage-logged areas in Hadim (only for Taurus fir species)

Discussion

Changes in forest cover and transitions

The most remarkable areal loss was observed in the pure fir stands. From a total area of 3069 ha in 1971, they decreased to 1266 ha and 542 ha in 1993 and 2016, respectively. Fir cover decreases in Hadim with an annual forestation rate of −3.8%, although this rate is 0.5% for the entire forest ecosystem. Since fir is one of the most susceptible tree species to drought stress (Bozkuş 1986; Cailleret et al. 2014), salvage logging statistics, field observations, and meteorological data analysis suggest that climate-induced tree mortality leads mainly to rapid areal losses in fir species. Many research from Mediterranean countries reported similar findings for this tree genus. Linares (2011), for instance, stated a long-term vegetation migration in the Spanish fir, a relict tree species in Spain. Similarly, Tsopelas et al. (2004) revealed that large-scale tree mortality events in Greek fir forests were experienced in Greece after the drought year of 2000. Before these events, Linares and Camarero (2011) pointed out significant growth decline and defoliation process in silver fir species in the Spanish Pyrenees. All the researchers cited above evaluated that climate change (i.e., increases in air temperatures, decreases in precipitation, and relative humidity) was the major driving factor for the intensive tree mortality in fir forests.

The limited area for unchanged (steady-state) fir forests in Hadim was further analyzed in this study. They are often located at the north-facing slopes of Hadim Forest Enterprise. This finding can be attributed to Turkey's northern slopes being shady; thus, more humid conditions prevail on those lands. Sunny (south-facing) slopes, contrastingly suffer from extreme summer droughts that can be mortal for the Taurus fir, as stated by Akkemik (2000) and Kavgaci et al. (2010). Similarly, other ecological factors such as altitude, slope, and growing site significantly affected the temporal dynamics of changed or transformed fir forests in our case ($p < 0.05$). In his dissertation, Bozkuş (1986) studied the natural distribution of the Taurus fir in Turkey for the first time. He stated that the Taurus fir was the only shade-tolerant tree species functional in the Mediterranean forests. It prefers the northern slopes opposite to the Mediterranean Sea, with less sunshine. The species also prefers the shaded valleys and deep soil pits. The altitude was also a driving factor for the natural distribution of this species. There were almost 200–300-m altitude differences in its lower distribution range between north- and south-facing slopes (Bozkuş 1986). In another study, Cailleret et al. (2014) analyzed climate-induced mortality events in silver fir forests in southern France. The researchers reported that tree mortality and canopy damages were rarely attributable to altitude. Instead, they were related to site conditions mainly shaped by local edaphic and topographic factors. Forest soil had a massive effect on tree mortality in their study. In the present study, the mean site indices of steady-state and changed fir forests were statistically different ($p < 0.001$). Thus, our findings generally agree with Cailleret et al. (2014) and Bozkuş (1986). The differences in mean slope were also significant for the steady-state and changed forests ($p < 0.05$). Steady-state forests, located at relatively flatter sites, possibly have a deeper soil layer than those of changed forests. We predict that water deficit in forest soils—after several drought years in particular—negatively affects fir species during the long and dry summer seasons experienced in Hadim, like in many other Mediterranean forests.

Fragmentation

Based on the patch metrics calculated in GIS environment, it was seen that fragmentation both for fir stands and the entire forest periodically increased in Hadim from 1971 to 2016. However, the fragmentation in fir stands was more rapid, especially for the pure fir class, than those of other forest covers. Increased isolation of individual forest patches in the pure fir class seems to be a robust indicator of tree mortality when considered together with the long-term trends in the observed climate data. Similarly, Fosso and Karahalil (2020) analyzed the spatiotemporal change in another Mediterranean forest near Hadim between 1965 and 2010. They reported that their forest became almost three times more fragmented at the end of the 45 years. The relevant studies had significant evidence for relating this change with climate variability in the region. Linares (2011), in another comprehensive study, focused on the biogeography and evolution of all the Mediterranean firs (nine species). Like us, he reported high fragmentation degrees for fir species and concluded that the climate factors—particularly long-term dryness in the Mediterranean Basin—played a vital role in this deteriorative process. For Hadim Forest Enterprise, we may list some additional external factors, including small-scale wildfires in the region, new firebreaks created by the GDF (GDF 2016), past rehabilitation works in large degraded fir sites (Çolak et al. 2010), as well as recent constructions of the Eğiste, and Gevne dams. All of these may have contributed to the change in the landscape-scale fragmentation status of Hadim in addition to drought-induced tree mortality.

As for individual patch metrics, the MPS decreased to a significant extent almost for all LULC classes in Hadim. For the pure fir class, the mean areas of stands shrank to more than one-tenth of their former areas between 1971 and 2016. Thus, one can assess that fir forests, like many other LULCs in Hadim, lost their ecological integrity and structural quality. As a result, they gradually transformed into a more patchy state. Likewise, the LPS metric showed decreased trends, too. Deng et al. (2020) reached similar findings for China's forests. They reported that deforestation and fragmentation degrees increased in Jixi City during the 22 years between 1993 and 2015. However, the researchers attributed these negative changes to human activities such as mining, farming, and construction sites. Since Hadim Forest Enterprise is a more remote and marginal site than Jixi City, human interventions are limited in our study area. Therefore, we evaluate that increased fragmentation in Hadim during the 45-year period may be a result of intensive tree mortality caused by natural disturbances such as drought and water deficit. The study by Bozkuş (1986) partly supports our argument. In this comprehensive study, he reported that the natural range of Taurus fir in Turkey was larger in the past than today. However, it has a confined and isolated distribution now, probably due to unfavorable climatic conditions.

Nevertheless, developing remote sensing (RS) technologies and GIS mapping techniques may also affect the temporal change in some patch metrics. Until the 2000s, forest stand types were being separated with coarse delineations in Turkey because of several limitations embedded into the low-resolution based analog aerial photos and ground measurement techniques (Kadiogullari et al. 2014). Toward the millennium, however, new tools and techniques such as GIS, GPS, database management systems, and high-resolution-based RS started to be used actively in the Turkish forestry thanks to the rapid improvement in information and communication technologies. Thus, mapping professionals are now generating more detailed stand type maps based on very-high-resolution color-infrared digital imageries and precise ground data with minimal errors (Baskent and Yolasigmaz 1999). There is no need to delineate thousands of hectares of degraded forests with small openings or rocky areas as one land cover type, as it was done in the 1970s. Instead, it can be separated into as little as 0.3-ha sub-compartments in GIS environment, as recommended by the national forest management regulation and its up-to-date guideline (GDF 2008, 2017).

Structural characteristics of forest stands

After 1993, it was seen that the standing volumes in fir forests did not reach the values predicted in the growth and yield table of Taurus fir (Miraboğlu 1955) based on natural forest development. Moreover, most of the loosely- and medium-covered stands disappeared from the area between 1971 and 2016. They can be explained by tree mortality, commercial thinning and wrong harvesting techniques nationally used in large regeneration sites in that period. Indeed, they reduced the structural quality of most of Turkey's forests in the second half of the twentieth century, as stated both by Başkent et al. (2005) and Çolak et al. (2010). Fortunately, these kinds of misguided management actions have recently been abandoned. Instead, the ecosystem-based multifunctional forest management concept—coupled with close-to-nature silviculture—has been recognized in the last decades (Asan 2017; Çolak et al. 2010; GDF 2008). Within this concept, Hadim Forest Enterprise has been divided into six management units, each with different forest functions ranging from non-wood forest products (i.e., honey) production to hydrological regulation in the current FMP (GDF 2016). Hence, the management actions are specified by forest planners depending on the management objective of each unit. Accordingly, three distinct forest functions—wood production, nature conservation, and erosion control—have been assigned to the fir forests in the new management plan of Hadim covering 2016 to 2035. Except for the wood production unit, no annual allowable cut was determined for the fir management units until 2035, thanks to the ecosystem-based multifunctional forest management philosophy (GDF 2016). Therefore, it can be predicted that standing volumes of fir forests located within the management units for nature conservation and erosion control functions will increase based on the growth curve of the Taurus fir, unless biotic or abiotic disturbances (e.g., insect outbreaks, wildfires) occur.

Regarding forest growth, there was a clear difference between pure and mixed fir forests in Hadim Forest Enterprise. This is not surprising because the positive difference in the mixed forests is possibly related to the faster growth rates of the associated tree species (i.e., Anatolian black pine) than fir. Additionally, drought and water shortage in the region may negatively affect the growth rates of fir species more than other species. In this respect, Linares and Camarero (2011)'s study reflected similar implications for silver fir species in Spain, whose forests are also sensitive to the negative impacts of climate change.

Deadwood is a useful indicator for assessing biodiversity and understanding tree mortality dynamics in a forest ecosystem. In general, a limited amount of deadwood volume (5–10 stems ha^{-1} or 3–5 m^3 ha^{-1}) is desired by forest planners in managed forests to conserve wildlife, and micro-habitats (GDF 2017; Karahalil et al. 2017). However, deadwood volumes as much as 24.6 m^3 ha^{-1} (9.8% of total standing volume) like in our case, are extremely high even for an unmanaged forest. A recent study in the same region was conducted by Karahalil et al. (2017). They calculated a mean standing deadwood volume of 0.5 m^3 ha^{-1} based on field measurements in Köprülü Canyon National Park. Researchers suggested that 2–3% of the total standing volume was optimal for deadwood, particularly in forests managed under protection functions such as nature conservation. Therefore, high deadwood volumes in Hadim also reflect high mortality levels for fir forests since forest stands dominated by other tree species have no or few deadwood.

A continuously increasing trend was observed in the total amounts of standing deadwood volume in pure and mixed fir stands. The amount of 7.4 m^3 ha^{-1} deadwood in 1971 increased to 56.0 m^3 ha^{-1} in 2016. Our field observations show that the increasing trend is likely to continue unless serious precautions are taken. This kind of drastic change is risky for the sustainability of Taurus fir forests in Turkey. Consequently, extensive salvage logging operations were started in Hadim Forest Enterprise in 2007. Since then, thousands of cubic meters of dead trees have been extracted from the fir forests, and these operations continue. One of the possible impacts of salvage logging may be on forest growth. After the logging operations, the growth rates of remaining trees are expected to increase due to reduced intra- or inter-species competition for resources such as light, water, and soil (Bettinger et al. 2009). Therefore, no significant increment loss was observed in fir stands for the last period (Table 11).

The possible impacts of climate and forest management on tree mortality

Given the long-term trends in observed climate data, it was seen that warmer conditions and an aridification process were prevailing in both Hadim and its surroundings. Starting with 1993, in particular, the warming trend was more apparent. This was coherent with the areal loss, and fragmentation processes increased in the same planning period (1993–2016). The changing point in the climate series in 1992 can be explained by the radiative forcing effect of the 1991 Mount Pinatubo eruption, as suggested by Tayanç et al. (2009) and Erlat and Türkeş (2019). According to the researchers, the climate of Turkey—particularly in the Mediterranean and Central Anatolia regions—was greatly affected by this volcanic eruption. In contrast, weak or opposite impacts were recorded for the Black Sea and Marmara regions of the country. Since Hadim Forest Enterprise is located in a transition zone between the Mediterranean and Central Anatolia region, we evaluate that the first half of the 1990s was critical for the onset of intensive tree mortality events in Taurus fir species.

Taurus fir is a drought-sensitive tree species in Mediterranean forest ecosystems (Bozkuş 1986; Cailleret et al. 2014). Based on the evaluations of the long-term temporal climatic variations along with considerable drought conditions we have seen so far, the cumulative effect arising from the adverse environmental and ecological-physiological conditions created by the significantly increasing drier and warmer climatic conditions and the associated physical and biological changes may have exceeded the adaptive capacity of Taurus fir trees in the Hadim district. Thus, it can be suggested that the disturbance regime of the forest ecosystem reached a critical threshold during the long period, generally starting after the year 1990 (Figs. 8–9). Furthermore, this negative effect on forest and agricultural systems is likely to continue in many other regions or sub-regions and districts of Turkey (Türkeş 2020a and 2020b).

In this context, in addition to the major climatic changes observed in most of Turkey, including the Central Mediterranean sub-region and the study district (i.a., Erlat and Türkeş 2013, 2016, 2017; Türkeş et al. 2009; Özcan et al. 2018; Türkeş and Erlat 2018; Türkeş 2020b; Erlat et al. 2021), adverse impacts of the observed significant climatic changes and droughts discussed above which increased in the 1990s or 2000s depends on the climatic elements may have been responsible, in addition to other likely factors, for tree mortality events and degradation in the Taurus fir ecosystem in the Hadim Forest Enterprise.

In terms of forest management, fir forests were generally set aside for conservation in Hadim's forest function maps since they were located on steep slopes. Therefore, no substantial intervention was scheduled for fir forests between 1971 and 2016 (GDF 1971, 1993, 2016). Silvicultural interventions such as commercial thinning, final felling, and regeneration concentrated on Anatolian black pine stands. A limited amount of fir stands (132.7 ha) was naturally regenerated with the same tree species over the 45-year period. An even more limited amount of these sites (12.3 ha) were converted to different species, which are economically more important. Lebanon cedar and Anatolian black pine are two economically important tree species in the Mediterranean region of Turkey (Janssen et al. 2018). The timber of Lebanon cedar, in particular, is preferred in shipbuilding, furniture, and construction industries. In this regard, Bozkuş (1986) stated that commercial thinning activities in managed mixed stands focused on cedar and black pine species, with remaining fir trees untouched in that region. In the mixed stands of fir, he observed many cedar and pine stumps on the forest floor during his intensive field surveys in the natural distribution range of Taurus fir in Turkey. Despite this, the negative change in the area of pure fir stands was calculated as thousands of hectares in the present study (Table 7). Thus, it can be said that the impact of planned management actions on the areal loss and degradation of Taurus fir forests is limited in Hadim. However, it is also a fact that Taurus fir was not a priority in the past afforestation projects carried out in this region (Çolak et al. 2010). If the Turkish General Directorate of Afforestation was to carry out extensive projects in suitable areas with this species, the negative changes in fir forests could be reduced slightly.

On the other hand, the total amount of standing and extracted deadwood show a considerable increase in tree mortality events in the fir forests of Hadim (Fig. 14). There is approximately 13 times more deadwood in the forest today than in 1971. About half of them are extracted from the forest by salvage logging operations (Fig. 14). Here, it should be noted that the salvage logging operations are not the reason; rather, they are inevitable consequences of tree mortality or poor forest management. Despite these operations, the total standing deadwood volume is continuously increasing in the study area (Table 11).

In fact, annual salvage logging records could be used more effectively for monitoring annual tree mortality. Moreover, the nature and magnitude of the relationship between year-to-year variability in time-series of these records and annual variability in the climatological time-series could be examined using appropriate statistics, such as Pearson's correlation coefficient *r*. Thus, sound assessments could be made on possible climatological causes and/or drivers of annual variability and long-term trends in deadwood removals. Unfortunately, there are several drawbacks embedded in official statistics. In Turkey, salvage logging records have been regularly kept for many forest enterprises since 1997. For Hadim Forest Enterprise, however, they first started to be kept in 2007. Therefore, we could not date back fir deadwood records to the early-1990s. Thus, no comparison was made among deadwood removals, FMP data from the past periods (1971–1993), and long-term climate series (1960–2018).

Finally, wildfires might be considered another possible contributor to deforestation, forest fragmentation, and/or degradation in a typical Mediterranean landscape. However, official statistics indicated that they are negligible in Hadim Forest Enterprise. Only eight wildfires have occurred since 2007 in Hadim. There have been times when wildfires did not occur for several years. The average burnt area was less than 1 ha per wildfire. Compared with the average burnt area of Turkey (i.e., 17 ha), this amount is acceptable for a Mediterranean forest (GDF 2014). Thus, it would be undermining to assert that wildfires shape Hadim's landscape considerably. Consequently, we evaluate that the contribution of climate change to mortality processes is much more than the forest management actions realized in the Hadim Forest Enterprise.

Conclusion

In this study, tree mortality pattern in fir forests was thoroughly analyzed for a typical Mediterranean forest landscape, Hadim Forest Enterprise. It was clearly seen that pure fir was the most affected LULC class in Hadim Forest Enterprise over the 45-year period. The area coverage of pure fir forests was 3069 ha in 1971, whereas it was only 542 ha in 2016. More than half of them (~ 1722 ha) transformed into either forest stands dominated by other tree species (Anatolian black pine and Lebanon cedar) or mixed stands of fir. Moreover, the areal transition from pure fir stands to non-forest lands was almost 227 ha, showing a forest cover loss with an annual rate of − 3.8% for this class. In comparison with fir forests, an annual forestation rate of 0.5% was recorded for the entire forestland in Hadim, suggesting that tree mortality was selective mainly for Taurus fir. Regarding spatial structure, both fir stands and the whole forest landscape became more isolated and patchy. However, fragmentation in fir stands was much faster than those of other LULC classes. Stand structures of fir forests, on the other hand, did not considerably change from 1971 to 2016, except for the standing deadwood. Drought-induced deadwood volumes remarkably increased both in pure and in mixed fir stands. A total of 6466 m^3 fir deadwood has been removed from the salvage-logged areas since 2007. As global warming is expected to continue, deadwood removals from Hadim Forest Enterprise will seem to increase soon unless adequate measures are taken.

We also tried to differentiate the impacts of forest management actions and climate on Taurus fir species. In Hadim, fir stands were mainly managed under conservation-oriented forest functions. Planned silvicultural interventions on those stands were rare and quite moderate. Timber production activities generally focused on Lebanon cedar and Anatolian black pine stands due to the economic importance of their timber. Contrastingly, significant changes in the long-term climate data were evident in both Hadim and its surrounding meteorological stations. In general, increasing trends were observed for annual air temperatures, while decreased trends were obvious in the relative humidity series. The increased trends were very strong, especially in the summer months after 1992. Precipitation totals, on the other hand, showed fluctuations in different periods between 1960 and 2018.

In conclusion, warmer and increased drought conditions have dominated Hadim Forest Enterprise in the last decades. The study area and its surroundings have been subject to aridification since the early-1990s. All the maps and statistical findings presented in this study suggest that the above-mentioned changes in the Hadim's forests are results of selective tree mortality induced and driven by climatic changes in the Central Mediterranean sub-region of Turkey. Given that the future impacts of climate change on forests mostly remain uncertain, the tree mortality events in the sub-region will seem to continue in the twenty-first century. Nevertheless, forest dynamics could be controlled with the help of smart management actions, such as promoting resilience by doing mechanical thinning in fully-covered stands, stocking seed banks, assisted migration, and augmenting the population of Taurus fir species. However, such actions should be scheduled by adaptive FMPs, which require the abandonment of traditional management strategies. Because traditional forest management planning is generally based on the assumption that the future will be similar to the past.

Acknowledgments Some of the preliminary findings of this study were presented, and its abstract was published at the *International Ecology 2018 Symposium*, held on 19-23 June 2018 in Kastamonu, Turkey. Additional works, further data analyses, and significant improvements were made in the current paper. The authors thank Ayten Özdemir and İsmet Yener for data provision. The authors would also like to thank Hayati Zengin, Gökçe Yörükoğlu, and the anonymous reviewers for their detailed comments and valuable suggestions to improve the paper.

Funding This study received no external funding.

Availability of data and material The datasets generated during the current study can be available on reasonable request.

Code availability Not applicable.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

References

Adams HD, Zeppel MJB, Anderegg WRL, Hartmann H, Landhausser SM, Tissue DT, Huxman TE, Hudson PJ, Franz TE, Allen CD et al (2017) A multi-species synthesis of physiological mechanisms in drought-induced tree mortality. Nat Ecol Evol 1:1285–1291. https://doi.org/10.1038/s41559-017-0248-x

Akkemik Ü (2000) Tree-ring chronology of Abies cilicica Carr. in the Western Mediterranean region of Turkey and its response to climate. Dendrochronologia 18:73–81

Allen CD, Macalady AK, Chenchouni H, Bachelet D, McDowell N, Vennetier M, Kitzberger T, Rigling A, Breshears DD, Hogg EH, Gonzalez P, Fensham R, Zhangm Z, Castro J, Demidova N, Lim J-H, Allard G, Running SV, Semerci A, Cobb N (2010) A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. For Ecol Manag 259:660–684. https://doi.org/10.1016/j.foreco.2009.09.001

Asan Ü (2017) Forest management (planning systems). İstanbul University, İstanbul (**in Turkish**)

Aussenac G (2002) Ecology and ecophysiology of circum-Mediterranean firs in the context of climate change. Ann for Sci 59(8):823–832. https://doi.org/10.1051/forest:2002080

Aytar F, Hızal E (2012) An endemic pest of Taurus fir, Abies cilicica (Antoine et Kotschy) Carrière; Pityokteines marketae Knížek, (Coleoptera: Curculionidae, Scolytinae). Turk Entomol Derg-TU 36(2):277–285 (**in Turkish**)

Baskent EZ, Yolasigmaz HA (1999) Forest landscape management revisited. Environ Manage 24(4):437–448. https://doi.org/10.1007/s002679900245

Başkent EZ, Köse S, Keleş S (2005) The forest management planning system of Turkey: constructive criticism towards the sustainable management of forest ecosystems. Int for Rev 7(3):208–217. https://doi.org/10.1505/ifor.2005.7.3.208

Beguería S, Vicente-Serrano SM, Angulo M (2010) A multi-scalar global drought data set: the SPEIbase: A new gridded product for the analysis of drought variability and impacts. Bull Am Meteor Soc 91:1351–1354

Bettinger P, Boston K, Siry JP, Grebner DL (2009) Forest management and planning. Academic Press, Burlington MA

Bolte A, Ammer C, Löf M, Madsen P, Nabuurs GJ, Schall P, Spathelf P, Rock J (2009) Adaptive forest management in central Europe: Climate change impacts, strategies and integrative concept. Scand J for Res 24(6):473–482. https://doi.org/10.1080/02827580903418224

Bozkuş HF (1986) The natural distribution and silvicultural characteristics of Abies cilicica Carr. In: Turkey. Dissertation, İstanbul University

Breshears DD, Myers OB, Meyer CW, Barnes FJ, Zou CB, Allen CD, McDowell NG, Pockman WT (2009) Tree die-off in response to global-change-type drought: mortality insights from a decade of plant water potential measurements. Front Ecol Environ 7:185–189. https://doi.org/10.1890/080016

Brodribb TJ, McAdam SA (2013) Unique responsiveness of angiosperm stomata to elevated CO2 explained by calcium signalling. PLoS ONE 8(11):e82057. https://doi.org/10.1371/journal.pone.0082057

Brodribb TJ, McAdam SA, Jordan GJ, Martins SCV (2014) Conifer species adapt to low-rainfall climates by following one of two divergent pathways. PNAS 111(40):14489–14493. https://doi.org/10.1073/pnas.1407930111

Cailleret M, Nourtier M, Amm A, Durand-Gillmann M, Davi H (2014) Drought-induced decline and mortality of silver fir differ among three sites in Southern France. Ann for Sci 71:643–657. https://doi.org/10.1007/s13595-013-0265-0

Camarero JJ, Bigler C, Linares JC, Gil-Pelegrin E (2011) Synergistic effects of past historical logging and drought on the decline of Pyrenean silver fir forests. For Ecol Manag 262(5):759–769. https://doi.org/10.1016/j.foreco.2011.05.009

Carus S (2010) Pre-growth mortality of Abies cilicica trees and mortality models performance. J Environ Biol 31:363–368

Choat B, Brodribb TJ, Brodersen CR, Duursma RA, Lopez R, Medlyn BE (2018) Triggers of tree mortality under drought. Nature 558:531–539. https://doi.org/10.1038/s41586-018-0240-x

Collins PM, Davis BAS, Kaplan JO (2012) The mid-Holocene vegetation of the Mediterranean region and southern Europe, and comparison with the present day. J Biogeogr 39:1848–1861. https://doi.org/10.1111/j.1365-2699.2012.02738.x

Çolak AH, Kırca S, Rotherham ID, İnce A (2010) Restoration and rehabilitation of deforested and degraded forest landscapes in Turkey. Ministry of Environment and Forestry, Ankara

Deng Z, Cao J, Hu Y (2020) Spatial and temporal evolution of landscape pattern in downtown area of Jixi City, China. Eur J Remote Sens 53:104–113. https://doi.org/10.1080/22797254.2020.1713024

Doğan M, Köse N (2019) Influence of climate on radial growth of black pine on the Mountain regions of southwestern Turkey. Plants 8:276. https://doi.org/10.3390/plants8080276

Erlat E, Türkeş M (2013) Observed changes and trends in numbers of summer and tropical days, and the 2010 hot summer in Turkey. Int J Climatol 33(8):1898–1908. https://doi.org/10.1002/joc.3556

Erlat E, Türkeş M (2016) Dates of frost onset, frost end and the frost-free season in Turkey: trends, variability and links to the North Atlantic and Arctic Oscillation indices, 1950–2013. Climate Res 69:155–176. https://doi.org/10.3354/cr01397

Erlat E, Türkeş M (2017) Observed variations and trends in number of tropical nights in Turkey. Aegean Geographical Journal 26(2):95–106 (in Turkish with an English abstract, figure and table captions)

Erlat E, Türkeş M (2019) Temperature responses of Turkey's climate to the tropical volcanic eruptions over second half of the twentieth century. Theor Appl Climatol 137:2369–2379. https://doi.org/10.1007/s00704-018-2711-2

Erlat E, Türkeş M, Aydin F (2021) Observed changes and trends in heatwave characteristics in Turkey since 1950. Theoret Appl Climatol. https://doi.org/10.1007/s00704-021-03620-1

ESRI (2012) ArcGIS 10.2 for Desktop. Environmental Systems Research Institute Inc., California

FAO (1995) Forest resources assessment 1990 – Global synthesis. Food and Agriculture Organization of the United Nations, Rome

Fosso LC, Karahalil U (2020) Some important parameters to display the effects of climate change on forests: a case study in Cerle planning unit, Antalya, Turkey. Artvin Coruh University Journal of Forestry Faculty 21(1):45–58. Doi: https://doi.org/10.17474/artvinofd.527802

Gazol A, Camarero JJ, Gutierrez E, Popa I, Andreu-Hayles L, Motta R, Nola P, Ribas M, Sangüesa-Barreda G, Urbinati C, Carrer M (2015) Distinct effects of climate warming on populations of silver fir (Abies alba) across Europe. J Biogeogr 42:1150–1162. https://doi.org/10.1111/jbi.12512

GDF (1971) Historical management plans for the Hadim, Gevne, Demirlidağ, and Çiledağ forest series (1971–1990). The Turkish General Directorate of Forestry, Ankara (**in Turkish**)

GDF (1993) Forest management plan of the Hadim Forest Enterprise (1993–2012). The Turkish General Directorate of Forestry, Ankara (**in Turkish**)

GDF (2008) Forest management regulation. The Turkish General Directorate of Forestry, Ankara (**in Turkish**)

GDF (2014) Annual report for combating forest fires. The Turkish General Directorate of Forestry, Ankara (**in Turkish**)

GDF (2016) Ecosystem-based multifunctional management plan of the Hadim Forest Enterprise (2016–2035). The Turkish General Directorate of Forestry, Ankara (**in Turkish**)

GDF (2017) Ecosystem-based Multifunctional Forest Planning Guidelines (Code No: 299). The Turkish General Directorate of Forestry, Ankara (**in Turkish**)

IPCC (2018) Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. In: Masson-Delmotte VP, Zhai H-O, Pörtner D, Roberts J, Skea PR, Shukla A, Pirani W, Moufouma-Okia C, Péan R, Pidcock S, Connors JBR, Matthews Y, Chen X, Zhou MI, Gomis E, Lonnoy T, Maycock M, Tignor T, Waterfield T (eds.) (in press)

Janssen E, Kint V, Bontemps J-D, Özkan K, Mert A, Köse N, Icel B, Muys B (2018) Recent growth trends of black pine (Pinus nigra J.F. Arnold) in the eastern Mediterranean. For Ecol Manag 412:21–28. https://doi.org/10.1016/j.foreco.2018.01.047

Jandl R, Spathelf P, Bolte A, Prescott CE (2019) Forest adaptation to climate change – is non-management an option? Ann for Sci 76:48. https://doi.org/10.1007/s13595-019-0827-x

Kadioğullari Aİ, Sayin MA, Çelik DA, Borucu S, Çil B, Bulut S (2014) Analysing land cover changes for understanding of forest dynamics using temporal forest management plans. Environ Monit Assess 186:2089–2110. https://doi.org/10.1007/s10661-013-3520-9

Karahalil U, Başkent EZ, Sivrikaya F, Kılıç B (2017) Analyzing deadwood volume of Calabrian pine (Pinus brutia Ten.) in relation to stand and site parameters: a case study in Köprülü Canyon National Park. Environ Monit Assess 189:112. Doi: https://doi.org/10.1007/s10661-017-5828-3

Kavgaci A, Basaran S, Basaran MA (2010) Cedar forest communities in Western Antalya (Taurus Mountains, Turkey). Plant Biosyst 144:271–287. https://doi.org/10.1080/11263501003690720

Keleş H, Kara A, Yağan Ö, Dağdelen M (2012) A new distribution area of Taurus fir (Abies cilicica Carr.) in Turkey. Kastamonu University Journal of Forestry Faculty 12(3):114–120

Kharuk VI, Im ST, Petrov IA, Dvinskaya ML, Fedotova EV, Ranson KJ (2016) Fir decline and mortality in the southern Siberian Mountains. Reg Environ Change 17:803–812. https://doi.org/10.1007/s10113-016-1073-5

Linares JC (2011) Biogeography and evolution of Abies (Pinaceae) in the Mediterranean Basin: the roles of long-term climatic change and glacial refugia. J Biogeogr 38:619–630. https://doi.org/10.1111/j.1365-2699.2010.02458.x

Linares JC, Camarero JJ (2011) Growth patterns and sensitivity to climate predict silver fir decline in the Spanish Pyrenees. Eur J for Res 131:1001–1012. https://doi.org/10.1007/s10342-011-0572-7

McDowell NG, Allen CD, Kristina AT, Aukema BH, Bond-Lamberty B, Chini L, Clark JS, Dietze M, Grossiord C, Hanbury-Brown A, Hurtt GC, Jackson RB, Johnson DJ, Kueppers L, Lichstein JW, Ogle K, Poulter B, Pugh TAM, Seidl R, Turner MG, Uriarte M, Walker AP, Xu C (2020) Pervasive shifts in forest dynamics in a changing world. Science 368(6494). Doi: https://doi.org/10.1126/science.aaz9463

McGarigal K, Cushman SA, Neel MC, Ene E (2002) FRAGSTATS: Spatial pattern analysis program for categorical maps. Computer software program produced by the authors at the University of Massachusetts. https://www.umass.edu/landeco/research/fragstats/fragstats.html. Accessed 25 March 2021

Miraboğlu M (1955) Shape and volume research on firs. The Turkish General Directorate of Forestry Press, No. 188/5, Ankara (**in Turkish**)

NCC (2011) Climate change and forest: from models to application (Adaptation measures for Adana Forest Enterprise). The Nature Conservation Center (DKM), Ankara (**in Turkish**). http://www.dkm.org.tr/Dosyalar/YayinDosya_XG0Am3Mv.pdf Accessed 24 March 2020. Accessed 1 May 2021

Özcan O, Musaoğlu N, Türkeş M (2018) Assessing vulnerability of a forest ecosystem to climate change and variability in the western Mediterranean sub-region of Turkey. J for Res 29(3):709–725. https://doi.org/10.1007/s11676-017-0505-5

Öztürk M, Gücel S, Kücük M, Sakcali S (2010) Forest diversity, climate change and forest fires in the Mediterranean region of Turkey. J Environ Biol 31:1–9

Paudel S, Yuan F (2012) Assessing landscape changes and dynamics using patch analysis and GIS modeling. Int J Appl Earth Obs 16:66–76. https://doi.org/10.1016/j.jag.2011.12.003

Pederson N, Dyer JM, McEwan RW, Hessl AE, Mock CJ, Orwig DA, Rieder HE, Cook BI (2014) The legacy of episodic climatic events in shaping temperate, broadleaf forests. Ecol Monogr 84(4):599–620. https://doi.org/10.1890/13-1025.1

Sanchez-Salguero R, Camarero JJ, Carrer M, Gutierrez E, Alla AQ, Andreu-Hayles L, Hevia A, Koutavas A, Martinez-Sancho E, Nola P, Papadopoulos A, Pasho E, Toromani E, Carreira JA, Linares JC (2017) Climate extremes and predicted warming threaten Mediterranean Holocene firs forests refugia. Proc Natl Acad Sci USA 114(42):10142–10150. https://doi.org/10.1073/pnas.1708109114

Semerci A, Çelik O, Şanlı B, Belindir B, Gedik Ö (2004) Drought induced damages and mortalities in Pinus nigra Arn. subsp. pallasiana (Lamb.), Pinus sylvestris L. and Abies cilicica (Ant. et Kotschy.) Carr. species in semiarid central Anatolia Region of Turkey. Proceedings of scientific conference 'Impacts of the Drought and Heat in 2003 on Forests', University Freiburg, Freiburg-Breisgau, 17−19 Nov 2004

Semerci A, Şanlı BN, Şahin Ö, Çelik O, Balkız GB, Ceylan S, Argun N (2008) Examination of tree mortalities in semi-arid Central Anatolian region of Turkey during last six-year period (2002–2007). Paper presented at the International conference 'Adaptation of Forests and Forest Management to Changing Climate with Emphasis on Forest Health: A review of Science, Policies, and Practices', Umeå, 25−28 Aug 2008

Semerci A, Vatandaşlar C, Özdemir A (2018) Intensive tree mortality of Taurus fir (Abies cilicica) in Mediterranean forests of Turkey. Paper presented at the International ecology 2018 symposium, Kastamonu University, Kastamonu, 19−23 June 2018

Sneyers R (1990) On the statistical analysis of series of observations. World Meteorological Organization Technical Note 43, Geneva. https://library.wmo.int/doc_num.php?explnum_id=1065. Accessed 25 March 2021

Sterl A, Severijns C, Dijkstra H, Hazeleger W, van Oldenborgh GJ, van den Broeke M, Burgers G, van den Hurk B, van Leeuwen PJ, van Velthoven P (2008) When can we expect extremely high surface temperatures? Geophys Res Lett 35(14):L14703. https://doi.org/10.1029/2008GL034071

Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (2013) Climate change 2013: the physical science basis (Contribution of working group I to the fifth assessment report of the IPCC). Cambridge University, New York

Tayanç M, İm U, Doğruel M, Karaca M (2009) Climate change in Turkey for the last half century. Clim Change 94:483–502

Thornthwaite CW (1948) An approach toward a rational classification of climate. Geogr Rev 38:55–94

TMS (2016) Climate data from the Hadim meteorological station (1960–2015). Turkish Meteorological Service, Ankara

Tsopelas P, Angelopoulos A, Economou A, Soulioti N (2004) Mistletoe (Viscum album) in the fir forest of Mount Parnis. Greece. Forest Ecol Manag 202(1–3):59–65. https://doi.org/10.1016/j.foreco.2004.06.032

Turkes M (2020) Climate and drought in Turkey. In: Harmancioglu NB, Altinbilek D (eds) Water Resources of Turkey, World Water Resources 2. Springer, Switzerland, pp 85–125

Türkeş M, Akgündüz AS (2011) Assessment of the desertification vulnerability of the Cappadocian district (Central Anatolia, Turkey) based on aridity and climate-process system. Int J Hum Sci 8:1234–1268 (**in Turkish**)

Türkeş M, Akgündüz AS, Demirörs Z (2009) Drought periods and severity over the Konya Sub-region of the Central Anatolia Region according to the Palmer Drought Index. Aegean Geographical Journal 7:129–144 (**in Turkish**)

Türkeş M, Sümer UM, Demir İ (2002) Re-evaluation of trends and changes in mean, maximum and minimum temperatures of Turkey for the period 1929–1999. Int J Climatol 22:947–977. https://doi.org/10.1002/joc.777

Türkeş M, Sümer UM (2004) Spatial and temporal patterns of trends and variability in diurnal temperature ranges of Turkey. Theor Appl Climatol 77:195–227. https://doi.org/10.1007/s00704-003-0024-5

Türkeş M (2013) The report of preparing the Turkey's desertification map using climate data. The Turkish General Directorate of Combatting Desertification and Erosion, Ankara (**in Turkish**). https://docplayer.biz.tr/49234471-Turkiye-nin-collesme-haritasi-dokumani-hazirlanmasi-raporu.html. Accessed 25 Mar 2021

Türkeş M (2017) Drought vulnerability and risk analysis of Turkey with respect to climatic variability and socio-ecological indicators. Aegean Geographical Journal 26(2):47–70 (in Turkish with an English abstract, figure and table captions)

Türkeş M, Erlat E (2018) Variability and trends in record air temperature events of Turkey and their associations with atmospheric oscillations and anomalous circulation patterns. Int J Climatol 38:5182–5204. https://doi.org/10.1002/joc.5720

Türkeş M, Musaoğlu N, Özcan O (2018) Assessing the vulnerability of a forest ecosystem to climate change variability in the western Mediterranean sub-region of Turkey: future evaluation. J for Res 29(5):1177–1186. https://doi.org/10.1007/s11676-017-0500-x

Türkeş M (2020) Impacts of climate change on food security and agricultural production: a scientific review. Aegean Geogr J 29(1):125–149 (**in Turkish**)

Türkeş M (2020) Physical science basis of climate change II: Observed and projected climate change and variability in Turkey and in the World. Commun Phys 35(1):3–31 (**in Turkish**)

Türkeş M, Öztaş T, Tercan E, Erpul G, Karagöz A, Dengiz O, Doğan O, Şahin K, Avcıoğlu B (2020) Desertification vulnerability and risk assessment for Turkey via an analytical hierarchy process model. Land Degrad Dev 31(2):205–214. https://doi.org/10.1002/ldr.3441

UNEP (1993) World atlas of desertification. The United Nations Environment Programme (UNEP), London

van Mantgem PJ, Stephenson NL, Byrne JC, Daniels LD, Franklin JF, Fulé PZ, Harmon ME, Larson AJ, Smith JM, Taylor AH, Veblen TT (2009) Widespread increase of tree mortality rates in the western United States. Science 323:521–524. https://doi.org/10.1126/science.1165000

Wang W, English NB, Grossiord C, Gessler A, Das AJ, Stephenson NL, Baisan CH, Allen CD, McDowell NG (2020) Mortality predispositions of conifers across western USA. New Phytol. https://doi.org/10.1111/nph.16864

Williams AP, Allen CD, Macalady AK, Griffin D, Woodhouse CA, Meko DM, Swetnam TW, Rauscher SA, Seager R, Grissino-Mayer HD, Dean JS, Cook ER, Gangodagamage C, Cai M, McDowell NG (2013) Temperature as a potent driver of regional forest drought stress and tree mortality. Nat Clim Change 3(3):292–297. https://doi.org/10.1038/nclimate1693

Vicente-Serrano SM, Beguería S, López-Moreno JI (2010) A Multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index—SPEI. J Clim 23:1696–1718

Willmott CJ (1977) WATBUG: A FORTRAN IV algorithm for calculating the climatic water budget. University of Delaware, Delaware