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Drought Severity and Trends in a Mediterranean Oak Forest

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Abstract: Drought is a significant natural hazard with widespread socioeconomic and environmental impacts. This study investigated the long-term drought characteristics in a Mediterranean oak forest ecosystem using the Standardized Precipitation Evapotranspiration Index (SPEI) at various time scales and seasons. The analysis was based on a long-term time series dataset obtained from a meteorological station located at the University Forest of Taxiarchis in Greece. The dataset encompassed a substantial time span of 47 years of continuous monitoring, from 1974 to 2020. To accomplish the goals of the current research, the SPEI was calculated for 3, 6, 12, and 24-month periods, and drought events were identified. The Mann-Kendall (M-K) test was used to analyze the trends in drought severity and evaluate the trends significance. The results showed that shorter time scales (SPEI3 and SPEI6) were more efficient for identifying short-term droughts, while longer time scales (SPEI12 and SPEI24) were better for identifying less frequent but longer-lasting drought episodes. The analysis consistently revealed positive trends across all seasons and time scales, indicating an overall transition towards wetter conditions. Nearly all the data series for SPEI12 and SPEI24 exhibited statistically significant upward trends (wetter conditions) at a 95% confidence level. However, more intense events were detected during the recent decade using the seasonal analysis. Additionally, as the time scale expanded, the magnitude of these trends increased. The findings contributed to a better understanding of drought dynamics in Mediterranean oak forests and provided valuable information for forest management and climate change adaptation planning.

Keywords: drought; SPEI; trend analysis; Mann-Kendall; forest meteorological station

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1. Introduction

Drought is a meteorological phenomenon identified as a relatively prolonged dry period in the natural climate cycle at a given location, resulting in water shortages [1]. It is listed among the most severe weather-related natural hazards that affect the greatest number of people worldwide [2]. Drought differs from other natural hazards (floods, wildfires, earthquakes, etc.) in various respects. It is a slow-onset hazard, which is only noticed once societies and the environment begin to experience its impacts [3,4]. Moreover, their impacts are non-structural and extend over a large geographical region [5].

The occurrence of droughts affects humans and nature alike. Based on their characteristics (i.e., duration, intensity, and frequency) they can lead to severe socioeconomic and environmental impacts [6,7]. Specifically, the negative effects of drought have been reported to impact human health [8], energy [9], food security [10], water resources [11], wildfires [12], livestock grazing [13], and forest growth [14]. Therefore, the World Meteorological Organization (WMO) classified drought according to the affected domain as meteorological, agricultural, hydrological, and socioeconomic [15].

The variability of climatic parameters, such as precipitation and evapotranspiration, on multiple time scales responds strongly to drought conditions [16]. The climate regime in the Mediterranean region, characterized by a prolonged dry period and an uneven distribution of precipitation, favors the development of drought events [17]. Additionally, the Mediterranean basin is expected to face increased challenges due to climate change as warming will possibly be greater than the global mean [18,19]. This is also highlighted by the latest assessment report from the Intergovernmental Panel on Climate Change (IPCC) [20], which anticipates warmer and dryer climates until the end of the 21st century. Hence, the drought magnitude and severity will intensify under future climate projections [21]. Droughts cause approximately EUR 9 billion in damage per year in the European Union and the United Kingdom, and this figure is expected to increase by one-third by the end of the century [22]. Therefore, continuous monitoring is required to inform strategies and minimize adverse impacts on the economy, society, and environment in the upcoming years.

Currently, there are two main approaches for drought monitoring, either based on meteorological or vegetation indices (VIs) [23]. Numerous meteorological indices have been developed to quantify drought, considering precipitation and evapotranspiration as the major inputs. The most widely applied indices are the Palmer Drought Severity Index (PDSI) [24], Standardized Precipitation Index (SPI) [25], Standardized Precipitation Evapotranspiration Index (SPEI) [26], and Reconnaissance Drought Index (RDI) [27]. These indices are commonly computed using data from ground-based meteorological stations. However, in recent studies, reanalyses and satellite-based climatic variables have been used for large-scale drought assessment [28–30]. The lack of a dense network of meteorological stations with a long-term time series of observations and the coarse resolution of gridded climatic datasets are the primary drawbacks of these approaches. On the other hand, spectral VIs have played an increasingly important role in monitoring drought conditions worldwide [31,32]. The advantages of VIs over meteorological drought indices include a greater spatial coverage, finer resolution, and more frequent revisiting cycles. The Normalized Difference Vegetation Index (NDVI) [33], Enhanced Vegetation Index (EVI) [34], and Vegetation Condition Index [35] are the most extensively used vegetation greenness indices for monitoring vegetation health and drought conditions by quantifying the photosynthetic activity and canopy structure alterations. Furthermore, water-related VIs, such as the Normalized Different Water Index (NDWI) [36] and the Land Surface Water Index (LSWI) [37], are efficient indicators for leaf water content. To this end, they have been recognized as being more sensitive for identifying drought conditions than greenness-based indicators [38,39]. The European Drought Observatory (EDO) currently employs the SPI, NDWI, and fraction of absorbed photosynthetically active radiation (fAPAR) for operational drought monitoring across Europe [40]. However, to date, there have been uncertainties surrounding the estimation of drought dynamics based on satellite products. The more accurate method is the analysis of long-term data from ground-based meteorological stations.

Understanding how forest ecosystems respond to drought may provide essential information regarding their adjustability in a certain environment and the implementation of targeted climate change adaptation plans. Therefore, drought monitoring and assessment should be integrated into forest management plans and forest strategy development. Occurrences of drought in forest ecosystems can induce forest mortality [41], losses in tree growth [42], reduced net primary production [43], and even changes to the biological diversity of vegetation communities [44]. Moreover, it is highly associated with the likelihood of wildfire occurrences [12,45] that lead to environmental degradation. To the best of the author's knowledge, few studies exist that investigate drought and aridity characteristics and the possible trends based on long-term time series from mountainous meteorological stations [46–50]. Nevertheless, an analysis of tree-ring chronologies demonstrated increased drought-related effects on mountainous forest ecosystems [14,51,52].

The main objective of this study was to investigate the drought characteristics in a typical Mediterranean oak ecosystem over the last half century (1974–2020). In particular, the SPEI index, incorporating both the effects of precipitation and water demand (evapotranspiration), was employed to quantify the severity of drought across various time scales, and the trend detection was performed using the non-parametric Mann-Kendall test, considering both annual and seasonal variations.

2. Materials and Methods

2.1. Study Area

The study area was the University Forest of Taxiarchis, which is located on the southern and southwestern slopes of Mount Cholomontas in Chalkidiki (Northern Greece) (Figure 1). It was a coppice oak forest (*Quercus frainetto Ten.*) that covered an area of approximately 5800 ha and extends from 40°23′ E to 40°28′ E and 23°28′ N to 23°34′ N. The terrain was complex with elevations ranging from 320 to 1165 m a.s.l. Additionally, part of the study area belonged to the Natura 2000 network, and specifically included a site of community importance (SCI) with the code GR1270001, known as "*Oros Cholomontas*". The forest was granted to the Aristotle University of Thessaloniki and is managed by the University Forests Administration and Management Fund (UFAMF).

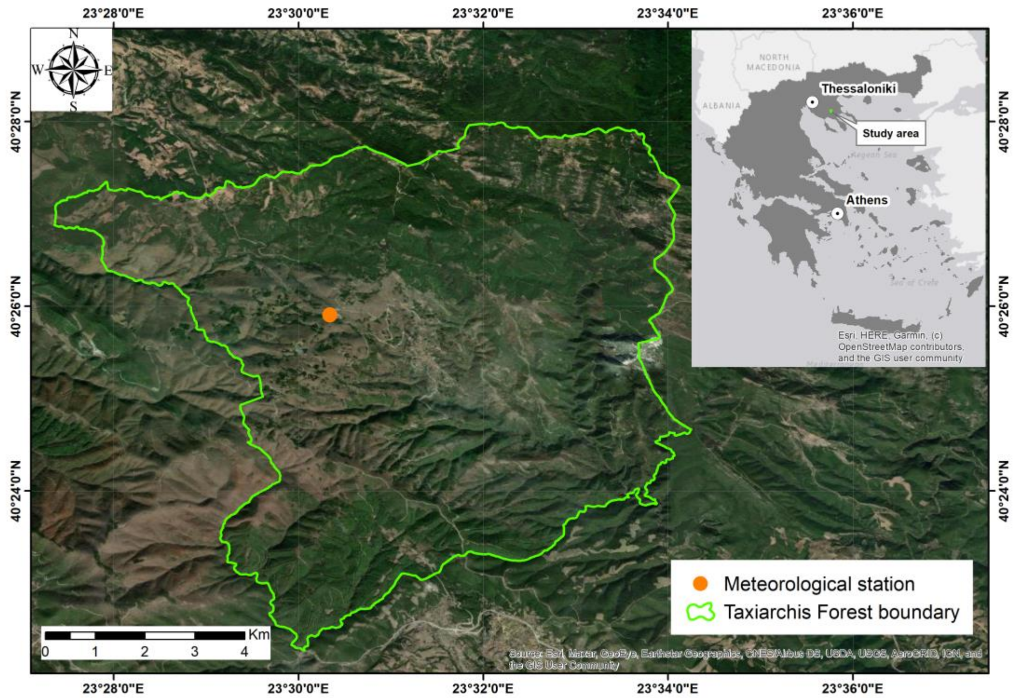

Figure 1. Location map of the Taxiarchis University Forest.

The dominant native forest species were Hungarian oak (*Quercus frainetto*) and Beech (*Fagus moesiaca*), and a portion of the forest was covered by maquis. Additionally, pine species such as Black pine (*Pinus nigra*), Maritime pine (*Pinus maritima*), Calabrian pine (*Pinus brutia*), and Aleppo pine (*Pinus halepensis*) were artificially established after reforestation.

In the study area, a manual meteorological station was installed (860 m a.s.l.) in 1974 and has been operated by the UFAMF. The station was equipped with a thermo-hygrograph, dry and wet bulb thermometers, thermometers of minimum and maximum temperatures, and a rain gauge. The recorded parameters for the daily time steps were the minimum and maximum air temperature (°C), relative humidity (%), and precipitation (mm). The station's data are available at the following link: https://uniforest.auth.gr/wp-content/uploads/2022/01/meteorologika-dedomena-taxiarchi-1974-2020.pdf (accessed on 25 June 2022). The time series were complete, without missing values, and the instruments and observing practices were common and remained consistent throughout the study period (1974–2020). According to Köppen's climate classification scheme [53], the study area was classified as a *Cfb* (temperate oceanic) climate type, generally featuring cool summers and mild winters, with a relatively narrow annual temperature range and few temperature extremes. In the long-term data recorded from 1974–2020 at the meteorological station of Taxiarchis, the average annual precipitation was 808.3 mm and the average mean annual air temperature was 11.5 °C. The hottest month of the year was July (21.7 °C), while January was the coldest (2.0 °C). Unlike most Mediterranean sites, the precipitation at the site was almost evenly distributed between the seasons (242.9 mm in winter, 206.7 mm in autumn, 196.4 mm in spring, and 162.3 mm in summer), where August (the driest month of the year) presented relatively high rainfall amounts (42.1 mm on average). This result was rather unexpected for the Mediterranean region pluviothermic diagram (Figure 2), where the dry period was absent. Such a regime suggested that the local vegetation species were generally not exposed to dry conditions and that they grew at relatively lower stress thermal conditions in the specific site with an enhanced water availability. Considering that the *Quercus frainetto* was the dominant species in the site and that its growth was highly associated with the soil water availability [54], it was expected that this forest would be highly affected by water-related stress, and thus meteorological drought episodes.

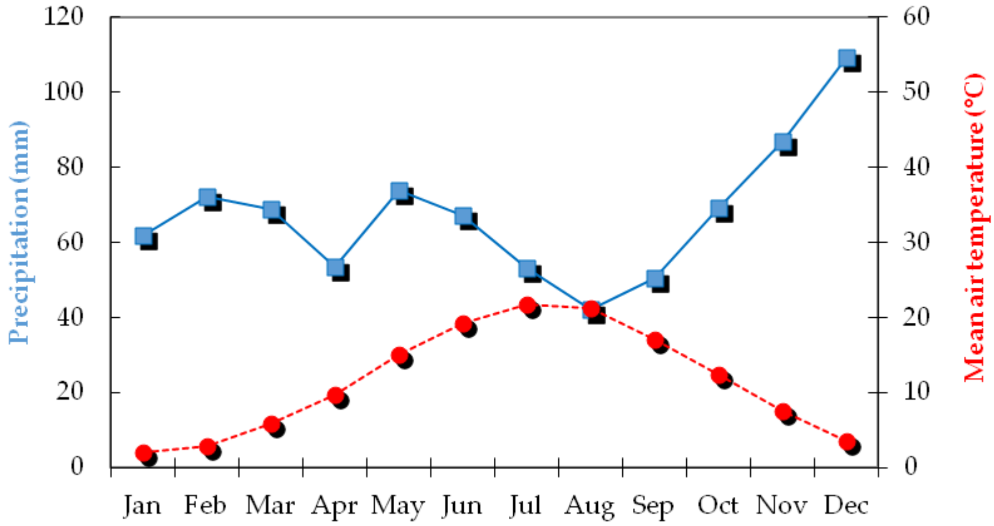

Figure 2. Pluviothermic diagram based on the climate data derived from the Taxiarchis meteorological station for the period 1974–2020.

2.2. The Standardized Precipitation Evapotranspiration (SPEI) Drought Index

The Standardized Precipitation Evapotranspiration Drought Index (SPEI) is a multi-scalar index based on a long-term series of common meteorological data and an extension of the widely used Standardized Precipitation Index (SPI). To create estimates, it uses monthly data as the difference between the precipitation P and the potential evapotranspiration (PET) to reflect the water balance in a region. These monthly values are then summarized on different time intervals and fitted against a log-logistic probability distribution, as described in Jiang et al. (2020) [55]. In this work, PET was estimated using Thornthwaite's (1948) model [56].

The index can be calculated at various time scales, ranging from one to 48 months. In our study, we focused on the 3, 6, 12, and 24-month time scales (SPEI3, SPEI6, SPEI12, and SPEI24) for the period 1974–2020. In this work, the seasonal drought assessment was performed by analyzing the 3-month SPEI for winter (December to February), spring (March to May), summer (June to August), and autumn (September to November). In addition, the 6-month SPEI of the wet semester of the hydrological year (October to March) and the relatively dry season (April to September) were also assessed, along with the 12-month SPEI of the calendar (January to December) and hydrological (October to September) year.

A detailed description of the SPEI calculation is presented in the previous studies [26]. In this work, it was performed using the open-source R package SPEI (https://cran.r-project.org/web/packages/SPEI/) (accessed on 25 June 2022). The investigation of the historical drought conditions was often enhanced by considering the length of the drought period [57]. A drought event was identified as a period characterized by continuously negative SPEI values, which concluded when the SPEI transitioned to positive values [58]. The drought categories based on the SPEI values can be found in Table 1.

Table 1. Drought classification based on the SPEI values.

Categories	SPEI Values
Extreme drought	<−2.00
Severe drought	−1.99 to −1.50
Moderate drought	−1.49 to −1.00
Near normal	−0.99 to 0.99
Moderately wet	1.00 to 1.49
Severely wet	1.50 to 1.99
Extremely wet	>2.00

According to McKee et al. [25], a measure to calculate the accumulated drought magnitude (*DM*) can be defined as follows.

$$DM = \sum_{j=1}^{x} SPEI_{ij} \tag{1}$$

where j starts with the first month of a drought and increases until the drought ends (x) for any of the i time intervals. The *DM*, measured in months, will be numerically equivalent to the drought duration if every month during the drought has an *SPEI* value of −1.0 [57]. To estimate the average intensity of each drought category, the average drought magnitude (ADM) was calculated by dividing the total *DM* by the number of drought events [57].

2.3. Trend Analysis of Droughts

The non-parametric Mann-Kendall (M-K) test was utilized to analyze the drought tendency. This test is commonly employed for trend analysis in climatological time series and is particularly suitable for data that are not normally distributed, have extreme values, and contain missing observations, which are often encountered in environmental time series [59].

Following the approach proposed by Sneyers [60], the M-K test was conducted to investigate both the annual and seasonal trends and to detect the turning point, using the data series of the SPEI values at multiple time scales. A detailed description of this method can be found in Myronidis et al. [11] and Stefanidis and Alexandridis [48].

The sequential approach of the Mann-Kendall test, which involved applying the test to all the series from the first term to the ith term (and vice versa), was also employed for a progressive analysis of the data. When there was no trend present, the graphical representation of both the direct (u_t) and backward (u_t') series using this method resulted in overlapping curves. However, in the cases where a significant trend was observed (at a 5% significance level, $|u_t| > 1.96$), the intersection of the curves provided an approximate indication of its occurrence time [60].

3. Results and Discussion

The SPEI values presented high fluctuations, indicating the index's high sensitivity to detect drought in all the time scales. The annual SPEI along with the respective values for precipitation and PET are indicatively presented in Figure 3.

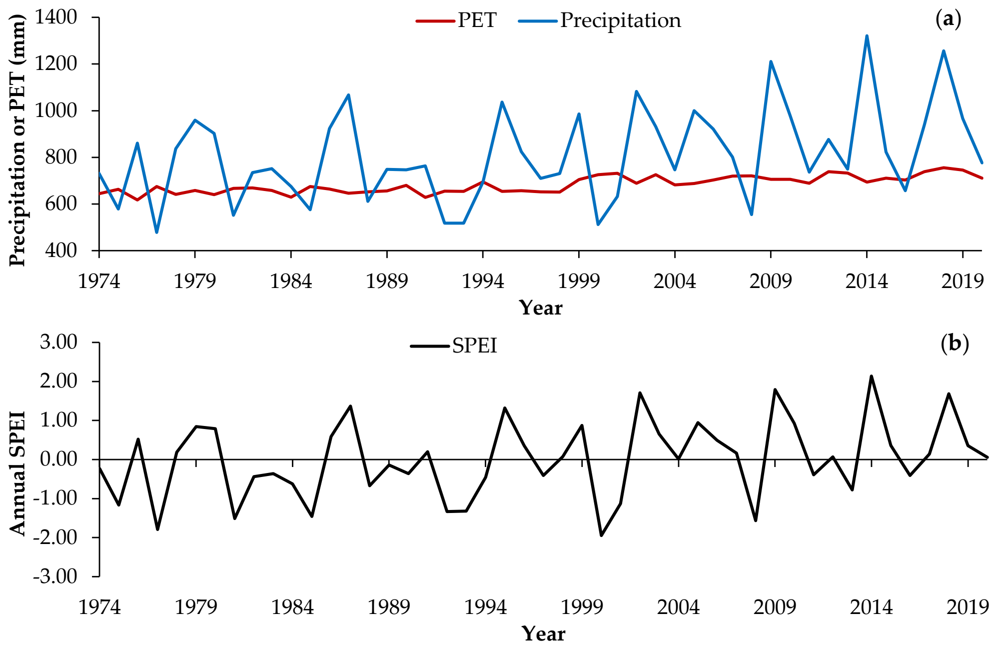

Figure 3. Annual values of (**a**) the SPEI, (**b**) precipitation, and potential evapotranspiration (PET) in the Taxiarchis University Forest for the time period 1974–2020.

The aggregated SPEI values were computed for each month throughout the year using the monthly precipitation data from a ground-based forest meteorological station, considering four different time scales (3, 6, 12, and 24 months). The temporal variations of these indices are illustrated in Figure 4 and show that the SPEI reacted differently according to the time scale.

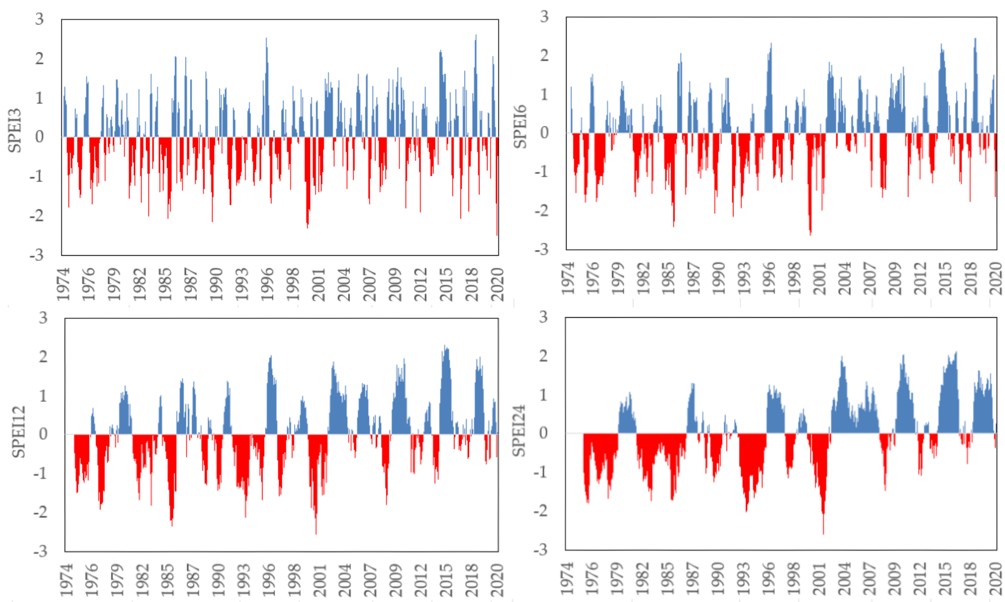

Figure 4. Temporal variation of the SPEI values at multiple time scales during 1974–2020.

At shorter time scales (SPEI3 and SPI6), there was an increase in the frequency of drought events, accompanied by a decrease in their duration. This implied that these shorter time scales exhibited recurrent climatological phenomena for drought. In contrast, longer time scales (SPEI12 and SPEI24) experienced less frequent drought episodes, but with longer durations. These patterns were also found in other regions, both in Greece [11,12] and internationally [57]. In particular, SPEI3 and SPEI6 exhibited more rapid responses to changes in the dry and wet conditions and they were more sensitive for detecting short term droughts compared to longer timesteps. On the other hand, SPEI12 and SPEI24 provided a distinct delineation of drought episodes and clearly separated the dry and wet spells. Table 2 summarizes the identified drought episodes and their main characteristics for the four SPEIs.

Table 2. Drought episodes and their main characteristics (in months) over the 1974–2020 period.

Drought Index	Drought Characteristics	Moderate Drought	Severe Drought	Extreme Drought	Total
SPEI3	Number of episodes	44	16	6	66
	Mean duration	1.5	1.4	1.3	1.4
	Relative frequency (%)	7.8	2.8	1.1	11.7
SPEI6	Number of episodes	36	16	4	56
	Mean duration	1.9	1.4	2	1.8
	Relative frequency (%)	6.4	2.9	0.7	10
SPEI12	Number of episodes	30	17	3	50
	Mean duration	2	1.5	2.7	2.1
	Relative frequency (%)	5.4	3.1	0.5	9
SPEI24	Number of episodes	26	13	3	42
	Mean duration	2.5	1.9	2.3	2.2
	Relative frequency (%)	4.8	2.4	0.6	7.8

The results indicated that there was a decrease in the total dry month from 66 (SPEI3) to 42 (SPEI24), while their mean duration increased from 1.4 (SPEI3) to 2.2 (SPEI24) months. Additionally, the relative frequencies of the total drought decreased from 11.7% (SPEI3) to 7.8% (SPEI24). Analytically, the drought characteristics for each drought category and SPEI time scale are also presented in Table 2.

The analysis of the SPEI3 values revealed that a seven-month period from March to September 2000 experienced the longest duration of drought, with an average drought magnitude of −1.8. Notably, the most extreme drought months during the entire reference period were June and July 2000, as well as November 2020, with corresponding SPEI3 values of −2.3, −2.2, and −2.5, respectively. In terms of the SPEI6 index, it highlighted an even lengthier drought period lasting for 11 months, starting from March 1997 and extending until January 1978, with an average drought magnitude of −1.3. Moreover, the months of July, August, and September 2000 exhibited remarkably extreme drought values of −2.5, −2.6, and −2.5, respectively. Moving forward to the analysis of the SPEI12 values, a prolonged drought persisted for 17 months, from August 1992 to December 1993, with an average drought value of −1.4. Furthermore, another lengthy drought period (12 months) occurred from February 1985 to January 1986, with a higher average drought magnitude equal to −1.8. The study period unveiled notable peaks in the SPEI12 values, showcasing the highest recorded values in June (−2.2) and August 1985 (−2.4), as well as in March 2001 (−2.6). These months exhibited the more extreme drought conditions, evident from the significant negative values of the SPEI index. Expanding the analysis to the SPEI24 index, two areas of prolonged drought periods were observed. The first drought period lasted 23 months, spanning from February 1993 to December 1994, while the second persisted for 17 months, from February 2001 to June 2002. Noteworthily, the second drought period exhibited a greater intensity, with an average drought magnitude of −1.7, compared to −1.5 in the first period. At this time scale of the SPEI, it was evident that January, February, and March 2002 were the months with the most extreme drought values, registering values of −2.2, −2.6, and −2.1, respectively.

Subsequently, the accumulated drought magnitude (DM) was estimated, and its temporal and seasonal distribution are presented in Figure 5. The findings provided clear evidence of a significant reduction in the DM, particularly for longer time scales (SPEI12, SPEI24) since the year 2003. However, it was worth noting that mild drought phenomena in the winter and autumn periods have become more common in recent years, primarily for short-term time scales (SPEI3, SPEI6). Nevertheless, by increasing the time scale, there was a decrease in the frequency of drought episodes, accompanied by an increase in their severity as depicted by the average drought magnitude.

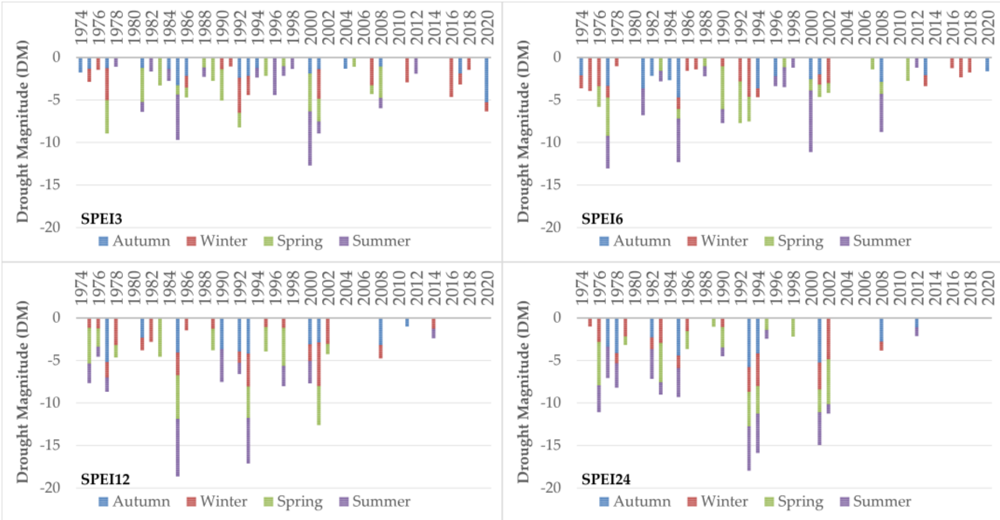

Figure 5. The accumulated drought magnitude (DM) across multiple SPEI time scales.

The specific 3-, 6- and 12-month SPEIs of the different seasons and annual time scales were important for the drought assessment, considering their relation to the phenological stages of the plants. By the seasonal assessment, spring was the season with more frequent occurrences of drought events (Figure 6). During the 47-year study period from 1974 to 2020, 11 drought spring episodes were detected, including nine moderates in the years 1977, 1981,1985, 1986, 1988, 1995, 1997, 2000, 2005, and 2008 and two extremes in 1983 and 2000. For the years 1985 and 1986, consecutive spring droughts occurred with moderate intensities. From the above distribution of the drought episodes, it was evident that spring droughts occurred more frequently during the decade 1981–1990. Specifically, in this decade, five spring droughts were recorded (four moderate and one extreme). However, the most extreme spring drought, with a 3-month SPEI value of −2.2, occurred in 2000. No spring droughts were recorded during the recent decade.

Winter droughts appeared to be more frequent during the recent decade (2011–2020), according to the values of the 3-month (December to February) SPEI depicted in Figure 6a. A total of three moderate drought episodes were recorded for the years 2011, 2016, and 2020 during the period from 2011–2020 out of the nine detected for the entire study period. Moderate droughts were recorded for the years 1977, 1990, 1992, 2001, 2011, 2016, and 2020. However, in 1993 and 2007, extreme winter droughts were detected with similar SPEI values (−1.7). In the years 1992 and 1993, consecutive winter droughts occurred and a moderate drought in 1992 was followed by a severe drought in 1993.

A total of eight summer droughts were identified, four of which were distributed in the decade 1991–2000. In the recent decade, only one moderate intense event was recorded (Figure 6c). More specifically, most of the summer drought events were moderate and detected in the years 1978, 1994, 1996, 1998, and 2001. However, severe drought events occurred in 1985, 2000, and 2012.The summer severe drought of 2000 was notable, which was followed by a moderate summer drought in 2001. It worth mentioning that in the period from 1994 to 2000, summer drought episodes occurred in the region every second year.

The distribution of the 3-month SPEI for autumn (September to November), as presented in Figure 6d, was rather interesting. The total number of eight autumn drought episodes were recorded, which was the same as the summer. The events primarily occurred during the decade 1981–1990, when three moderate droughts were identified in the years 1981, 1984, and 1986. During the recent decade, only one episode was recorded in the year

2020, which was the only extreme autumn drought episode in the total study period and presented the highest negative SPEI value (−2.5) compared to all the other seasons. The remaining five autumn droughts were moderate and were detected in the years 1975, 1992, 2001, 2008, and 2013. Autumn droughts are important for the maquis vegetation at the site and for determining the characteristics of the flowering stages that generally occur in October and November [61]. A drought episode associated with an increased temperature and limited water availability can potentially postpone the beginning of the flowering stage in specific maquis species.

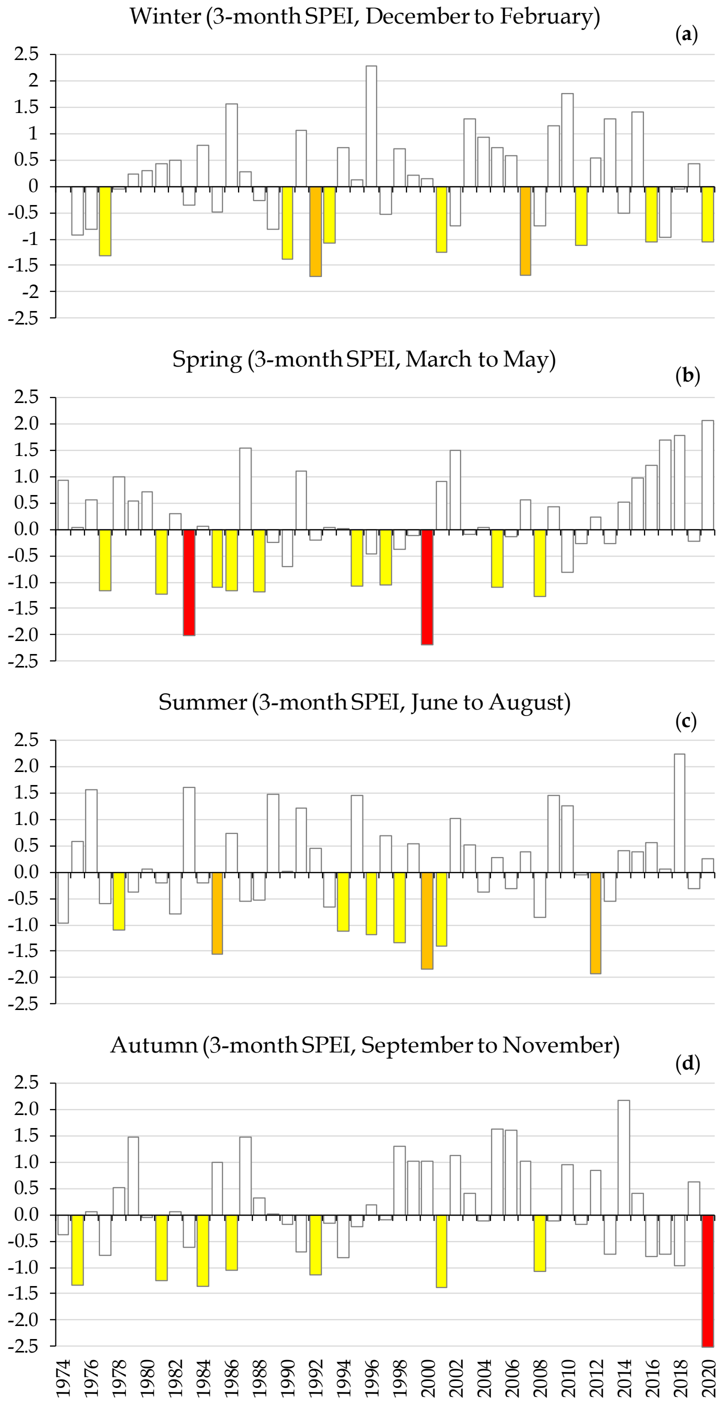

Figure 6. Seasonal SPEI values from the Taxiarchis forest site in (**a**) winter (December to February; 3-month SPEI), (**b**) spring (March to May; 3-month SPEI), (**c**) summer (June to August; 3-month SPEI), and (**d**) autumn (September to November; 3-month SPEI).

In total, six drought episodes were detected in the region during the wet semester of the year, according to the 6-month SPEI values of the period from October to March. Extremely dry conditions persisted in the years 1990 and 1992 and an extreme drought in 1992 was followed by a severe drought the next year (1993), as shown in Figure 7a.

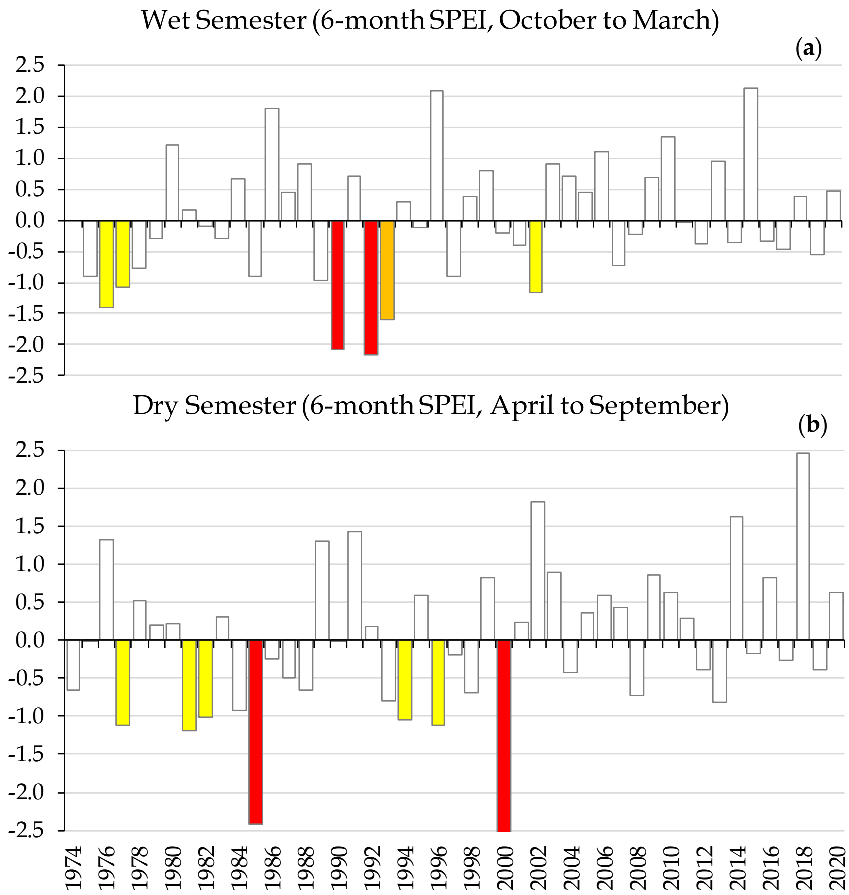

Figure 7. Seasonal SPEI values from the Taxiarchis forest site during (**a**) the wet semester (October to March; 6-month SPEI) and (**b**) the dry semester of the year (April to September; 6-month SPEI).

During the drier semester of the year (April to September), extremely dry conditions occurred in the years 1985 and 2000. Namely, an extreme dry semester drought in 2000 was the strongest of the total period, presenting an extremely low 6-month SPEI value (−2.6). In the years 1981 and 1982, two consecutive drought episodes occurred with moderate intensities, whereas single moderate droughts were detected in the years 1994 and 1996 (Figure 7b). The analysis of the wet semester held particular importance for the forest ecosystem since it was directly linked to the growing season of the major forest species (*Quercus frainetto*), which expands from April to October in the Taxiarchis forest site.

On an annual time scale (12-month SPEI), an analysis was performed for both the calendar and hydrological years. During the calendar year, nine drought episodes were recorded. Four were found to be severe and were identified for the years 1977, 1981, 2000, and 2008. The remaining five were characterized as moderate and occurred in the years 1975, 1985, 1992, 1993, and 2001 (Figure 8a). On the contrary, regarding the values of the 12-month SPEI during the hydrological years of the same period, six drought episodes were detected. One of them was extreme (1985), two were severe (1993, 2000), and tree were moderate (1977, 1990, and 1992) (Figure 8b). The years when the number of droughts detected were almost the same between the annual and hydrological year analyses, while the magnitude of the drought differed, suggested that the hydrological year 12-month time scale was more sensitive for relating agricultural drought. This was important considering the hydrological year relationship with the plant growth and development stages.

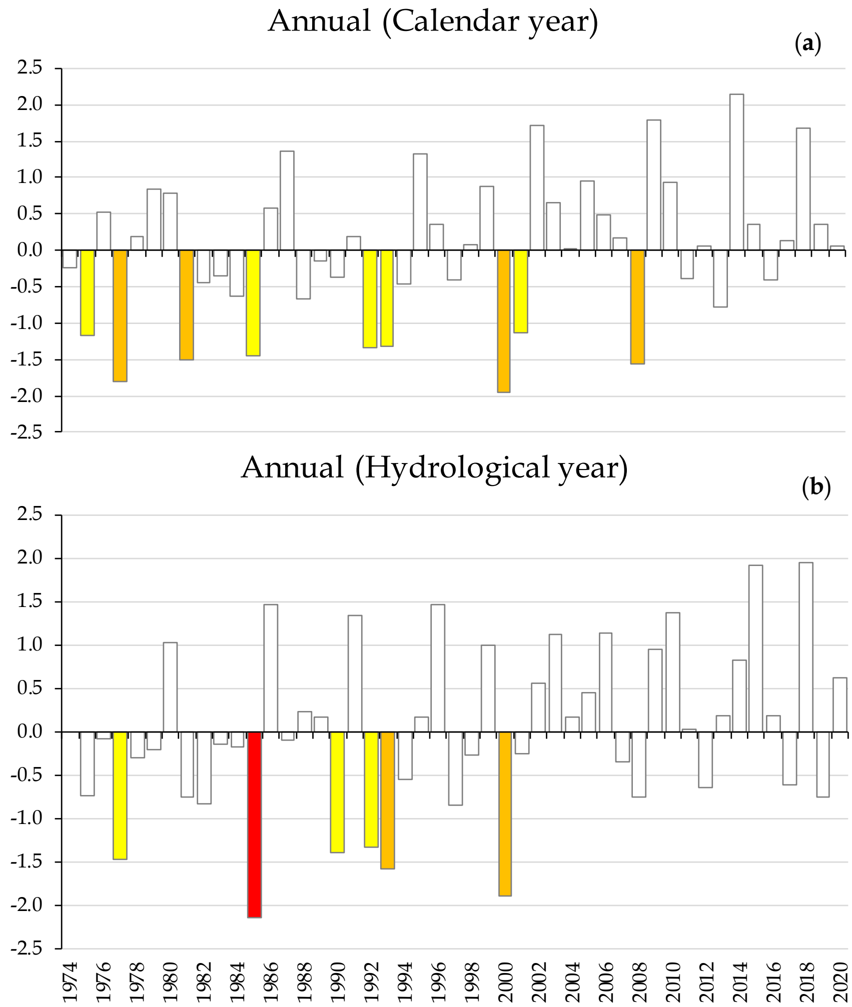

Figure 8. Annual SPEI values from the Taxiarchis forest site during (**a**) the calendar year (January to December; 12-month SPEI) and (**b**) the hydrological year (October to September; 12-month SPEI).

Proutsos et al. [62] analyzed the PET and effective precipitation changes in the mountainous forest ecosystem of Metsovo (N. Greece) for the period 1960–2000 and identified positive effective rainfall trends on an annual basis. Seasonally, the precipitation trends were found to significantly increase in winter and remain unchanged in summer, whereas strong positive PET trends were identified in summer. In the urban environment of Heraklion (Crete-S. Greece), Proutsos et al. identified a significant decrease in several drought indices for the dry semester of the year [63] and analyzed the data of the period from 1955–2022, suggesting that stronger and more frequent droughts would be expected to affect urban green sites in the future. Additionally, the investigation of the precipitation trends in the Nestos River basin (N. Greece) showed a high spatial variability and were suggested to increase in the mountainous areas of the basin and decrease in the coastal zone [64]. For the same region and for the period from 1955–2018, the drought assessment indicated that more frequent and severe drought events were recorded during the recent years, underlining that more favorable conditions persisted in the mountainous areas. Based on the SPI, the authors detected the most severe droughts in the hydrological years of 1977–1978, 1984–1985, 1988–1989, 1998–1999, and 1999–2000. They also identified significant decreasing SPI trends for the coastal part of the basin [65]. Additionally, in the urban and peri-urban forests of Attica (C. Greece), major changes to more arid conditions with limited water availability for vegetation were detected for recent years, and these changes occurred more rapidly and severely in urban areas compared to the peri-urban forests [66]. In another case study, Myronidis and Theofanous [67] highlighted an intensification of drought conditions, while warmer conditions with less precipitation prevailed in the tourist region of the South Aegean (Greece).

The average annual and seasonal SPEI values were subjected to the M-K trend test for different time scales to identify abrupt changes in the drought conditions (at a 95% significance level) within the forest ecosystem from 1974 to 2020. The analysis revealed consistent positive trends across all the seasons and time scales, indicating a transition to wetter conditions. Notably, for the annual period, the upward trends were statistically significant for all the time scales except for the 3-month SPEI. The graphical representations of the M–K test for the average annual SPEI time series is presented in Figure 9. The depicted series u(t) and u′(t) identified the onset of significant abrupt changes in 2002 for SPEI12 and SPEI24, as well as in 2001 for SPEI6.

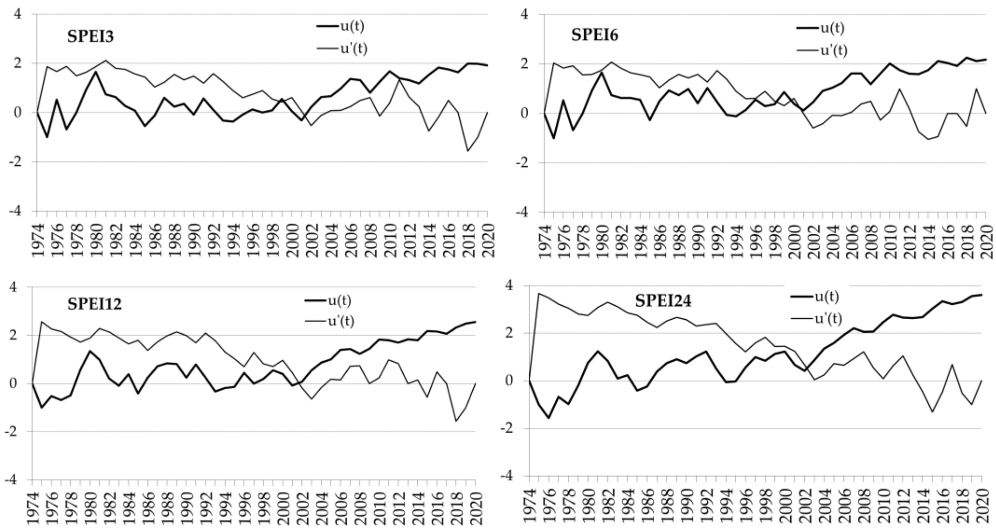

Figure 9. Graphical representation of the M-K trend test for the annual SPEI values over the period from 1974–2000.

Table 3 presents a concise summary of the outcomes derived from conducting the M-K (Mann-Kendall) test on the different seasons and time scales. The gray cells in Table 3 indicate the statistically significant trends, and the corresponding times of the occurred specific changes are reported inside the parentheses.

Table 3. Results of the M-K test (statistic ut) on an annual and seasonal basis during the period from 1974–2020.

	Annual	Autumn	Winter	Spring	Summer
SPEI3	1.9	1.7	1.2	1.9	0.9
SPEI6	2.1 (01)	1.4	1.9	1.7	1.4
SPEI12	2.5 (02)	1.8	2.9 (97)	2.3 (03)	2.3 (00)
SPEI24	3.5 (02)	2.5 (01)	3.7 (02)	3.2 (02)	3.8 (03)

The 3-month SPEI indices displayed non-significant positive trends both seasonally and annually. Similarly, for SPEI6, non-significant trends were observed in all the seasons, with the exception of the annual analysis, where a statistically significant increasing trend was identified. Nevertheless, statistically significant upwards trends (with a confidence level of 95%) were observed in almost all the data series for SPEI12 and SPEI24, with an increasing magnitude of the trends as the time scale expanded. The results also identified the turning point for the drought tendencies around 2000.

Although the most recent report by the IPCC [20] predicted drier conditions in the Mediterranean basin for the near future, an analysis of the SPEI values over a long climatic period revealed a transition towards wetter years. It was also noteworthy that previous investigations highlighted the significance of declining trends in precipitation across various regions in Greece during past decades, particularly during the latter half of the 20th century [68–70]. This was mainly due to the fact that these studies primarily considered lowland meteorological areas, where the precipitation characteristics differed from mountainous forest areas. While these studies analyzed the time series up to the year 2000, our analysis revealed a significant shift towards wetter conditions after this year. This was also confirmed by a recent study considering long-term precipitation trends in Greece using reanalysis products, highlighting increases in precipitation after the early 1990s [71]. Furthermore, a previous study analyzing the data from the same station reported increasing trends in precipitation and negligible changes in PET, which supported the observed trends in the SPEI index [48].

The results of this study aligned with the recent research conducted in Greece, which emphasized the occurrence of several wet periods during the first two decades of the 21st century. These wet periods were particularly prominent when analyzed over longer time scales, providing a clearer understanding of their patterns [72]. Unlike the aforementioned study, our research focused on a forest ecosystem and incorporated the crucial variable of temperature through evapotranspiration in the calculation of drought by employing the more advanced SPEI index instead of relying solely on the simple SPI. The studies regarding long-term drought conditions based on ground meteorological stations were limited due to the lack of continuous long-term records with quality data. To that end, the relationship of the SPEI values with satellite indices should be examined over forest sites and could be a target for future research. Another important task for future studies should be the analysis of long-term drought dynamics from ground-based stations in different forest-type ecosystems and its comparison with gridded SPEI products.

4. Conclusions

The present study aimed to analyze the drought characteristics in a Mediterranean oak forest ecosystem using the SPEI index at various time scales and seasons. The study employed an assessment based on a comprehensive dataset of ground in-situ meteorological data for almost half century (spanning from 1974 to 2020) obtained from a meteorological station located in the University Forest of Taxiarchis in Greece.

The results of this study revealed valuable insights into the drought dynamics, confirming that at shorter time scales (SPEI3 and SPEI6) the SPEI was more sensitive and more efficient for identifying more frequent short-length drought events, while longer time scales (SPEI12 and SPEI24) were more effective at detecting longer-lasting drought episodes. Moreover, through seasonal and temporal analyses of the multiscale SPEI values, different time periods of drought occurrences and varying magnitudes of these episodes were identified. The analyses consistently showed positive trends across all the seasons and time scales, indicating a transition towards wetter conditions. Notably, nearly all the data series for SPEI12 and SPEI24 exhibited statistically significant upward trends at a 95% confidence level. Moreover, as the time scale expanded, the magnitude of these trends increased.

The seasonal and annual analyses based on the 3-month SPEI values for each season and the 6-month SPEIs for the wetter and drier periods of the year, which were also associated with the main forest phenological stages, revealed that the most sensitive season was spring, which presented a higher frequency of episodes. Winter droughts were also relatively frequent; however, their frequency only increased during the recent decade compared to the previous decades. During the recent decade, only one autumn drought event was recorded in 2020, which was the strongest of the total 47-year study period with a maximum negative SPEI value (−2.5). In addition, the strongest extreme drought (SPEI = −2.6) at the drier semester of the year (6-month SPEI period when the water requirements for plants reach their maximum) was detected in the year 2000.

These findings contributed to a better understanding of drought patterns in forest ecosystems and have implications for forest management and climate change adaptation planning. The observed trends towards wetter conditions suggested that the study area may experience improved water availability in the future. However, the positive trends of the SPEI values (wetter conditions) was also associated with generally less frequent drought episodes during the last years (at least in seasonal scales, with the exception of spring droughts). In many cases, the fewer events that occurred nowadays were more intense compared to the past. This information can guide forest management strategies, such as promoting reforestation or adjusting species composition, to better adapt to changing climatic conditions by applying the appropriate silvicultural treatments. Furthermore, the climate variability showed a temporal and seasonal interchange between the dry and wet periods. Therefore, water saving measures should be scheduled to exploit water excess and confront water scarcity accordingly. Lastly, it highlighted the importance of continued monitoring and assessment of drought dynamics to mitigate potential adverse impacts on the economy, society, and environment.

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