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Do extreme climate events impact oak decline phenomenon in the Zagros Region, Western Iran?

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ABSTRACT

Assessments of forest vulnerability to climate change often emphasize average meteorological conditions, overlooking the role of extreme events in shaping forest dynamics. This study quantifies the influence of climate extremes on the decline of Zagros forests in western Iran. Using RClimDex, we analyzed minimum and maximum temperatures and precipitation records from 19 synoptic stations over 33 years (1987–2019). Stations were grouped into three climate types, semi-dry, Mediterranean, and very humid, and divided into two temporal phases: pre-decline (1987-2000) and post-decline (2001-2019). Trends in 14 extreme climate indices, including temperature extremes, precipitation intensity, spell durations, growing season length, and annual wet-day totals, were evaluated for each region and period. Of 266 trends analyzed, 21% were statistically significant in both pre- and post-decline phases. In the very humid region, the proportion of significant trends fell from 28.5% to 21.4% after the decline, while in the semi-dry region, significance remained stable (~19%). The Mediterranean region showed a slight increase from 19.5% to 23%. Over the full study period, 52.2% of trends were significant, with the highest proportion (69%) in the very humid region, followed by semi-dry (48.8%) and Mediterranean (50%). These results highlight marked spatial and temporal variability in extreme climate events, underscoring their importance in accelerating forest decline. This work provides a quantitative basis for incorporating extreme climate indices into adaptive forest management and climate resilience strategies.

Keywords: Climate extremes, Forest decline, RClimDex, Trend analysis.
Article type: Research Article.

INTRODUCTION

Greenhouse gas (GHG) emissions have steadily increased in recent decades, contributing to global climate change (Valdez-Cepeda *et al.* 2003). As a result, the global mean surface temperature has increased by approximately 0.07 °C per decade since the late 19th century (NOAA, 2023) and extreme weather events have become more common. Climate extremes are defined as meteorological phenomena that exceed thresholds near the high or low ends of the observed range (Lavell *et al.* 2012). These events include heatwaves, droughts, storms, swells, cold fronts, and hurricanes (Marengo *et al*. 2009). Although extreme events are rare, even small shifts in their frequency and intensity can have more profound effects than similar changes in mean values (Reichstein *et al.* 2013). While climate extremes generally have negative impacts on forests, some studies have noted temporary and limited positive effects such as increased forest dynamics and growth, improved water-use efficiency, and extended growing seasons, though these are often accompanied by disruptions to ecosystem dynamics and biodiversity

(Lloyd & Bunn 2007). Organisms and populations typically exhibit physiological and developmental responses to environmental stress (Shuli Niu *et al.* 2014). However, ecosystem responses to extreme events are complex, influenced by the event's intensity, the ecosystem's inherent vulnerability and resilience, and prevailing environmental conditions. Many ecosystems are vulnerable to these disturbances, ultimately suffering degradation (Herrero & Zamora 2014). Numerous studies have reported increases in tree mortality and dieback due to drought and/or high temperatures, including in southern Europe, boreal forests of western North America, and temperate forests (van Mantgem *et al.* 2009). Mediterranean and semi-Mediterranean forests in European countries have also been affected by climate change, potentially contributing to oak (*Quercus petraea*) dieback (Thomas & Büttner 1998). Similar patterns of oak (*Quercus* spp.) dieback have been observed in the Zagros forests of western Iran during the 2000-2002 period, resulting in the loss of approximately 1.5 million hectares of forest over the past two decades (Pourhashemi *et al.* 2017). This decline has been attributed to multiple biotic and abiotic factors including drought, overgrazing, low canopy cover, tree age, rain-fed agriculture underneath trees, oak charcoal disease, pests, and dust storms. These factors disrupt forest functioning, reducing resilience to stress (Attarod *et al.* 2023). Under persistent disturbance, oak trees shift from storing starches in their roots to consuming them for metabolic survival. If the disturbance continues, trees initially attempt to recover but ultimately decline once resources are exhausted (Bréda & Badeau 2008). Previous research has mainly focused on changes in mean climatic values and has not adequately addressed the role of extreme events in oak forest decline in this region. Attarod *et al.* (2023) studied precipitation trends across 20 stations in three climate types (semi-dry, Mediterranean, and very humid) in the Zagros region and found only 10% of stations showed a statistically significant decreasing trend in precipitation. Moreover, comparisons of mean annual precipitation before (1988-2000) and after (2000-2019) the onset of oak decline showed no statistically significant differences. Similarly, Attarod et al. (2021) found no significant trends in annual, monthly, or seasonal precipitation before and after decline periods. However, earlier studies reported correlations between oak decline and changes in temperature, precipitation, and wind speed (Attarod *et al.* 2023). Given the projected increase in the frequency and intensity of extreme events, it is essential to explore their potential role in the degradation of the Zagros forests. This study investigates how extreme climate events may have contributed to oak decline and compares the frequency and intensity of these events before and after emergence of oak decline.

MATERIALS AND METHODS

Study area

This research was conducted in the oak forests of western Iran. The Zagros forests, covering approximately 6 million hectares, constitute 44% of Iran's forested area (Sagheb-Talebi *et al.* 2014). Stretching from the northwest to the southwest of the country (Sagheb-Talebi *et al.* 2014), these forests are known for their biodiversity, including the Persian squirrel (*Sciurus anomalus*) and are dominated by species such as *Quercus* spp., mainly the Brant`s oak (*Q. brantii*), *Pistacia* spp., *Crataegus* spp., and *Pyrus* spp. (Sagheb-Talebi *et al.* 2014). The mean annual precipitation in the Zagros region is 447 mm, and the mean annual temperature is 14.5 °C, based on data recorded from 16 synoptic weather stations between 1988 and 2022 (Attarod *et al.* 2025). Historically, 80% of the annual rainfall occurs during winter and spring (Attarod *et al.* 2023).

Meteorological data

We analyzed daily meteorological data, including precipitation and maximum and minimum temperatures, obtained from the Islamic Republic of Iran Meteorological Organization (IRIMO). The data were collected from 19 synoptic weather stations across the Zagros region (Fig. 1; Table 1) and covered two periods, before the oak decline (1987-2000) and after the decline (2001-2019). These weather stations are well-distributed across the Zagros region, representing three distinct climate types, semi-dry (mean annual precipitation: 390 mm), Mediterranean (506 mm), and very humid (916 mm; Table 1). This classification is based on the de Martonne aridity index (I_{DM}) value (Croitoru *et al.* 2013) and calculated using annual temperature and precipitation. Index values ranged from 10 to 19.9 for the semi-dry climate type and from 20 to 23.9 for the Mediterranean type. We combined both humid and very humid climate types into one category labeled as "very humid," where the I_{DM} value exceeds 28 (Attarod *et al.* 2023). To ensure accurate regional analysis, we specifically selected stations with long-term time series and minimal missing data (less than 2%; Table 1; Fig. 1).

Methodology

We employed the RClimDex software package, developed by the Climate Research Branch of the Meteorological Service of Canada for the Expert Team on Climate Change Detection and Indices (ETCCDI). Extreme events were calculated using this software, written in the R programming language. For more information and access to the software, see http://cccma.seos.uvic.ca/ETCCDI (Zhang, 2005).

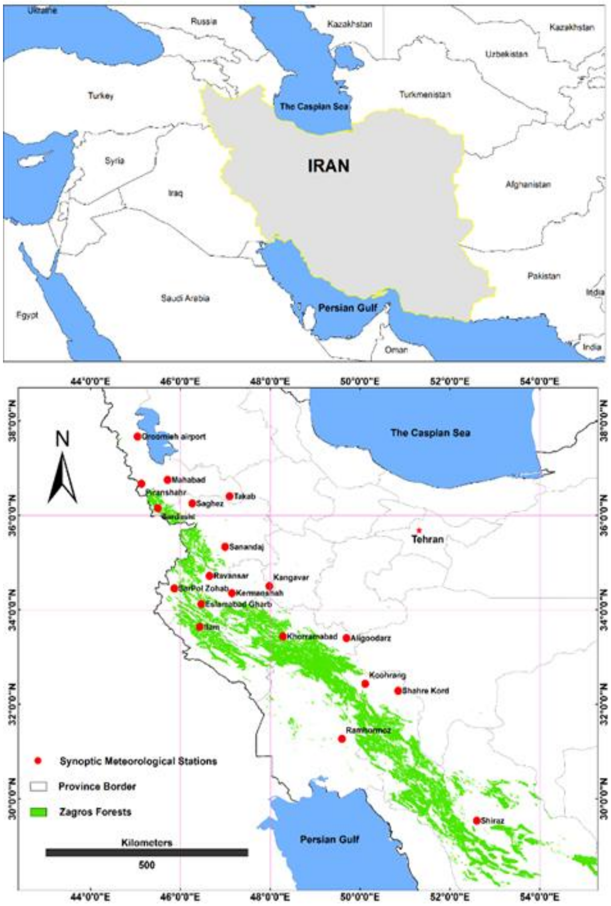

Fig. 1. Locations of the synoptic meteorological stations in the Zagros region in Western Iran.

Table 1. Characteristics of the synoptic meteorological stations located in the Zagros region of Iran. I_{DM} is the aridity index calculated by the annual precipitation (P) and mean annual temperature (T), $I_{DM} = P/(T+10)$. Arid ($I_{DM} < 10$), Semi-arid ($10 \leq I_{DM} \leq 20$), Mediterranean ($20 \leq I_{DM} < 24$), Semi-humid ($24 \leq I_{DM} < 28$), Humid ($28 \leq I_{DM} < 35$), Very humid ($35 \leq I_{DM} \leq 55$), extremely humid ($I_{DM} > 55$).

Area	Station	Elevation (m)	Latitude (N)	Longitude (E)	Missing data (%)	I_{DM} value
Mediterranean	Eslamabad Gharb	1348.8	34º 07'	46º 28'	0.5	20.1
	Ilam	1337	33º 38'	46º 26'	0	21.6
	Ravansar	1379.7	34º 43'	46º 39'	0	20.8
	Saghez	1522.8	36º 15'	46º 16'	0	20.8
Semi-Dry	Aligoodarz	2022	33º 24'	49º 42'	0	17.3
	Kangavar	1468	34º 30'	47º 59'	0	17.4
	Kermanshah	1318.6	34º 21'	47º 09'	0	16.7
	Khorramabad	1147.8	33º 26'	48º 17'	0	18.1
	Mahabad	1351.8	36º 45'	45º 43'	0	17.3
	Oroomieh airport	1328	37º 40'	45º 03'	0	14.1
	Ramhormoz	150.5	31º 16'	49º 36'	0	17.5
	Sanandaj	1373.4	35º 20'	47º 00'	0	15.9

	Sar Pol Zohab	545	34º 27'	45º 52'	0	14.3
	Shahre Kord	2048.9	32º 17'	50º 51'	0.2	14.8
	Shiraz	1484	29º 32'	52º 36'	0	11.2
	Takab	1817.2	36º 24'	47º 06'	0	16.3
Very Humid	Koohrang	2285	32º 26'	50º 07'	0.2	68
	Sardasht	1670	36º 09'	45º 30'	1.2	36
	Piranshahr	1455	36º 40'	45º 08'	0.1	29.4

Data quality control

Meteorological data can be affected by various factors such as manual keying errors, station location, land-use changes, instrument adjustments, and observational issues (Aguilar *et al.* 2003). These factors can result in unreasonable values including a) negative daily precipitation values, b) daily maximum temperatures lower than the daily minimum temperature, and c) outliers which are values that deviate significantly by more than four times the standard deviation from the mean of the daily values. To ensure data reliability, we conducted quality control on the meteorological data from all stations using the RClimDex package (Zhang, 2005).

Indices

For the investigation of extreme events, the ETCCDI recommended a total of 27 indices, consisting of 16 temperature and 11 precipitation indices (Table 2). These indices are categorized into five groups as follows:

1) Percentile-based indices: represent the amount of precipitation exceeding the 95th percentile (R95p) and 99th percentile (R99p), as well as the coldest and warmest deciles for the maximum and minimum temperatures.

2) Absolute indices: capture the maximum or minimum values within a specific season or year.

3) Threshold indices: measure the number of days when a temperature or precipitation value exceeds or falls below a predetermined threshold.

4) Duration indices: define periods characterized by extreme warmth, cold, wetness, or dryness, and includes growing season length and periods of mildness.

5) Other indices: indices that don’t fit into the above categories but can significantly impact society due to their changes.

By applying these indices, we were able to value the occurrence and characteristics of extreme events (Alexander, 2006).

Trend analysis

We employed non-parametric methods to investigate significant trends in the climatological time series. Specifically, two non-parametric methods, the Mann-Kendall test and the Sen's slope estimator, were used to detect trends in the meteorological variables. These methods are commonly used to assess the significance of trends in hydro-meteorological time series. They possess robustness against the influence of outliers and do not require the assumption of an underlying probability distribution for the data series (Sen, 1968). Throughout the article, the statistical significance of identified trends was assessed at $\alpha = 0.05$ level. The null hypothesis was rejected when the absolute value of the Mann-Kendall statistic (Z) exceeded the critical value, or when the p-value was less than the specified significance level ($\alpha = 0.01$ or $\alpha = 0.05$). Should the null hypothesis be rejected, the trend's direction shifts positive and negative Z values indicate an upward trend and a downward trend, respectively (Ademe *et al.* 2020). In total, 266 time series (19 weather stations×14 indices) were detected, each index for before and after emergence of decline.

Table 2. List of 27 ETCCDI core indices. Red color indices are those investigated in this article.

	Percentile-based indices	
ID	**Definitions**	**Unit**
TN10p	Cold nights (Percentage of days when TN < 10th percentile)	%
TN90p	Warm nights (Percentage of days when TN > 90th percentile)	%
TX10p	Cold days (Percentage of days when TX < 10th percentile)	%

TX90p	Warm days (Percentage of days when TX > 90th percentile)	%
R95p	Very wet days (annual total PRCP when RR > 95th percentile)	mm
R99p	Extremely wet days (annual total PRCP when RR > 99th percentile)	mm

Absolute indices

ID	Definitions	Unit
TXx	Annual maximum value of daily maximum temperature	℃
TNx	Annual maximum value of daily minimum temperature	℃
TXn	Annual minimum value of daily maximum temperature	℃
TNn	Annual minimum value of daily minimum temperature	℃
RX1day	Monthly maximum 1-day precipitation amount	mm
RX5day	Monthly maximum 5-day precipitation amount	mm

Threshold indices

ID	Definitions	Unit
FD0	Frost days (annual count when TN (daily minimum) <℃)	days
ID0	Ice days (annual count when TX (daily maximum) <℃)	days
SU25	Summer days (annual count when TX (daily maximum) > 25℃)	days
TR20	Tropical nights (annual count when TN (daily minimum) > 20℃)	days
R10	Annual number of heavy precipitation days > 10 mm	days
R20	Annual number of very heavy precipitation days > 20 mm	days

Duration indices

ID	Definitions	Unit
CSDI	Cold spell duration indicator (annual count of days with at least 6 consecutive days when TN > 10th percentile)	days
WSDI	Warm spell duration indicator (annual count of days with at least 6 consecutive days when TX > 90th percentile)	days
GSL	Growing season length (annual (Jan.1 –Dec. 31 in NH, July 1 – June 30 in SH) count between first span of at least 6 days with daily mean temperature (TG) > 5℃ and first span after 1 July (1 Jan. in SH) of 6 days with TG < 5℃)	days
CDD	Consecutive dry days (maximum number of consecutive days with RR < 1 mm)	days
CWD	Consecutive wet days (Maximum number of consecutive days with RR>=1mm)	days

Other indices

ID	Definitions	Unit
PRCPTOT	Annual total wet day precipitation (RR ≥ 1 mm)	mm
DTR	Diurnal temperature range (Monthly mean difference between TX and TN)	℃
SDII	Simple daily intensity index (annual total precipitation divided by the number of Wet days (defined as PRCP ≥ 1.0 mm) in the year	mm

RESULTS AND DISCUSSION

Percentile-based indices

In the semi-dry climate type, there has been a rise in the number of stations displaying a significant trend for both cold days (TX10p, 25%) and warm days (TX90p, 42%), after starting oak decline (Table 3). However, in the very humid climate, there was a significant decrease of 34% in the number of stations that reported cold nights (TN10p) and warm nights (TN90p) following the oak decline. After the emergence of the decline, TX10p increased by 67% the very humid climate (Table 3). The Mediterranean climate type has exhibited significant changes in the percentage of stations showing an increasing trend for TN10p, TX10p, and TX90p following oak decline. After the emergence of the phenomenon of oak trees decline, TN10p significantly increased to 75% of the stations in the Mediterranean climate type, compared to 25% before the decline. Additionally, the two indices of TX10p and TX90p experienced increases of 75% and 25% the Mediterranean climate type, respectively (Table 3).

Table 3. The percentage of weather stations with significant annual trends for percentile-based indices (cold/warm days/nights) before and after the phenomenon of oak decline in the semi-dry, very humid, and the Mediterranean climate types of the Zagros region (↑ = increasing trend, ↓ = decreasing trend).

Climate type	**TN10p (Cold nights)**		**TN90p (Warm nights)**		**TX10p (Cold days)**		**TX90p (Warm days)**	
	Before	**After**	**Before**	**After**	**Before**	**After**	**Before**	**After**
Semi-dry	↓42	↓42	↑33	↑33	↓17	↓42	↑25	↑67
Mediterranean	↓25	↓75	↑50	↑50	0	↓75	↑25	↑50
Very humid	↓67	↓33	↑67	↑33	0	↓67	↑67	↑67

Our analysis revealed that changes in percentile-based indices in the Mediterranean and semi-dry climate types were similar. After the decline, both Mediterranean and semi-dry climates exhibited an increase in TX90p and TN90p indices, with an average rise of two percent and there was an average decrease of three percent in the occurrence of TX10p and TN10p. In the very humid climate type, only two parameters, TN90p and TX90p, showed a slight change of one percent (Fig. 2).

Threshold indices

Within the Mediterranean climate, we observed a 75% reduction in the percentage of stations displaying a significant trend in the R20 index after the start of oak decline. In contrast, the semi-dry and very humid climates experienced a more moderate decrease of 34%. Remarkably, the ID0 index exhibited an 8% decrease in the semi-dry climate and a large decrease (34%) in the very humid climate among stations with a significant trend (Table 4). A significant increase of 9% in the SU25 index for the semi-dry and 33% for very humid climate were detected (Table 4). Additionally, the FD0 index experienced a noteworthy reduction of 17% in the semi-arid climate type following the decline (Table 4).

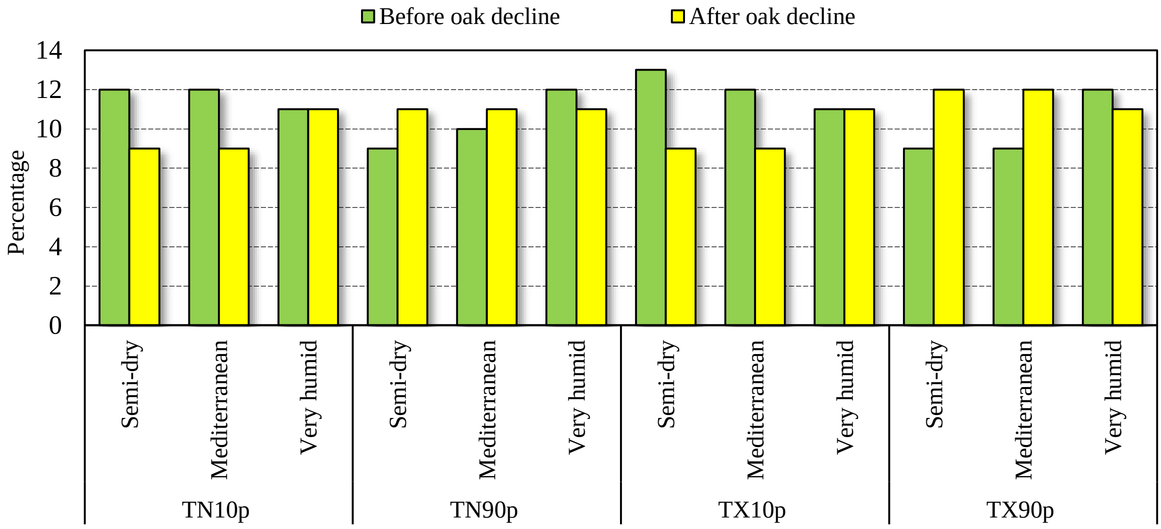

Fig. 2. Changes in percentile-based indices: TN10p (Cold nights) - TN90p (Warm nights) - TX10p (Cold days) - TX90p (Warm days), before and after the oak decline phenomenon in the semi-dry, Mediterranean, and very humid climate types of the Zagros region.

Table 4. The percentage of stations with significant annual trends for threshold indices before and after the phenomenon of oak decline in the semi-dry, very humid, and Mediterranean climate types of the Zagros. (↑ = increasing trend, ↓ = decreasing trend).

Climate type	R20 (Heavy precipitation days)		ID0 (Ice days)		SU25 (Summer days)		FD0 (Frost days)	
	Before	After	Before	After	Before	After	Before	After
Semi-dry	↑67	↑33	↓8	0	↑8	↑17	↓17	0
Mediterranean	↑75	0	0	0	0	0	0	0
Very humid	↑67	↑33	↓67	↓33	0	↑33	0	0

The R20 index exhibited considerable changes in different climates. In the Mediterranean climate, it decreased by 5 days, whereas in the very humid and semi-dry climates, it showed an increase of 5 and 14 days, respectively (Fig. 3). Furthermore, the ID0 index displayed a consistent decrease in all three climate types after the oak decline compared to before. The most significant change was observed in the very humid climate where it decreased by 12 days. In contrast, the SU25 index increased by approximately 10 days after the oak decline in all climate types (Fig. 3).

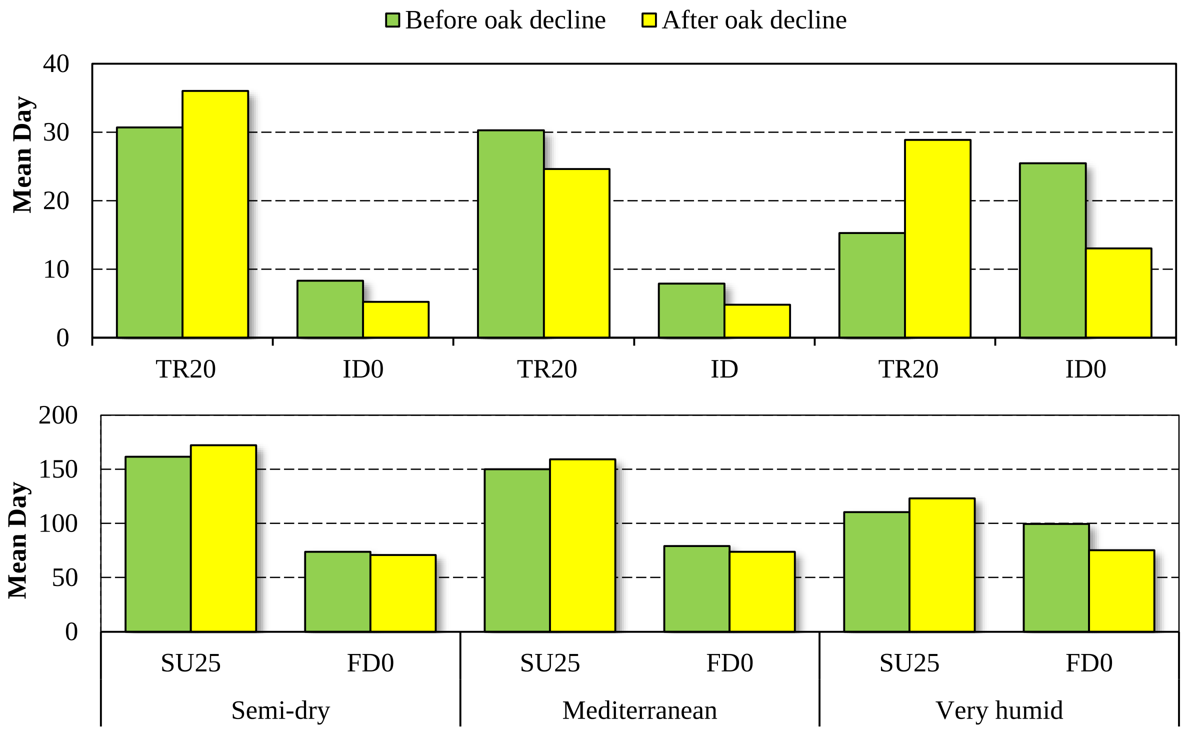

Fig. 3. Changes in threshold indices: TR20 (Heavy precipitation days), ID0 (Ice days), SU25 (Summer days), and FD0 (Frost days) before and after the phenomenon of oak trees decline in the semi-dry, very humid, and Mediterranean climate types of the Zagros.

Duration indices

Prior to the oak decline phenomenon in the Mediterranean climate type, only 25% of stations indicated a significant trend CWD, but the number significantly increased to 50% after the initiation of oak decline (Table 5). Before the decline, the Mediterranean climate type exhibited the highest occurrence of statistically significant trends in the CSDI, with 25% of stations showing such trends. In contrast, only 8% of stations in the semi-dry climate type demonstrated the same trend (Table 5). It is important to highlight that statistically significant trends in CSDI were nearly absent after the onset of oak decline (Table 5). Before the decline, humid and Mediterranean climates had the highest percentages of statistically significant trends in WSDI (specifically 33% and 25%, respectively) (Table 5). After the start of oak decline, these trends dropped to zero. In contrast, semi-dry climates trends WSDI increased from 8% to 17%. The number of stations exhibiting significant trends in CDD post oak decline increased 8% only in the semi-dry climate (Table 5). Before the decline, 8% of stations in the semi-dry climates and a remarkable 33% in the very humid climates exhibited significant trends in the GSL index. However, the landscape following the decline presented a different scenario, as with the number of stations showing significant trends in GSL decreasing across semi-dry and very humid climate types (Table 5).

Table 5. The percentage of stations with significant annual trends for duration indices before and after the phenomenon of oak trees decline in the semi-dry, very humid, and Mediterranean climate types of the Zagros. (↑ = increasing trend, ↓ = decreasing trend)

Climate type	**CWD (Consecutive wet days)**		**CSDI (Cold spell duration indicator)**		**WSDI (Warm spell duration indicator)**		**CDD (Consecutive dry days)**		**GSL (Growing season length)**	
	Before	**After**	**Before**	**After**	**Before**	**After**	**Before**	**After**	**Before**	**After**
Semi-dry	↓8	↑8	↓8	0	↑8	↑17	0	↓8	↑8	0
Mediterranean	↓25	↑50	↓25	0	↑25	0	↓25	↓25	0	0
Very humid	0	0	0	0	↑33	0	0	0	↑33	0

While the CWD, CSDI indices remained largely stable following the phenomenon of oak trees decline, semi-dry and Mediterranean climates experienced significant changes (Fig.4). The CDD and GSL indices showed no significant changes in the three climates (Fig. 4).

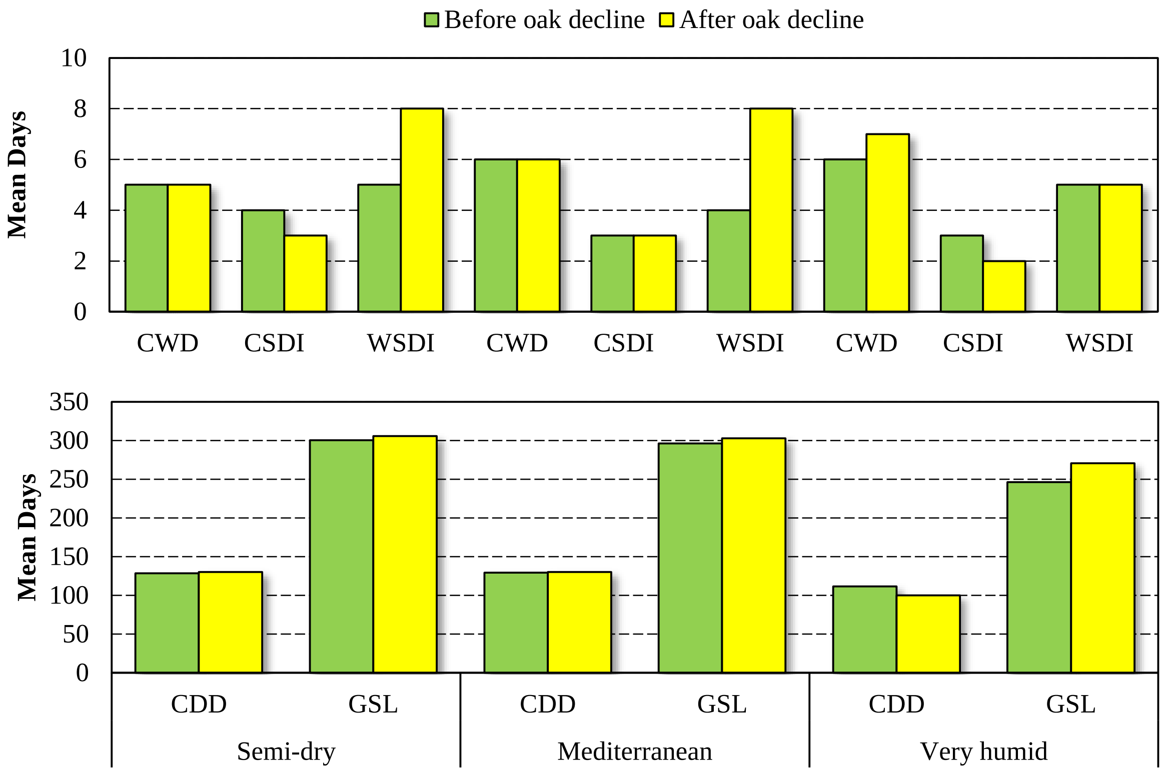

Fig. 4. Changes in duration indices: CWD (Consecutive wet days)- CSDI (Cold spell duration indicator)- WSDI (Warm spell duration indicator)- CDD (Consecutive dry days)- GSL (Growing season length), before and after the phenomenon of oak decline in the semi-dry, very humid, and Mediterranean climate types of the Zagros

Other indices

In the semi-dry climate type, the proportion of stations exhibiting a notable trend in PRCPTOT decreased by only 9%. However, the analysis of the PRCPTOT trend within the Mediterranean and very humid climate types revealed that none of the stations displayed a significant trend before and after the decline period (Table 6).

Table 6. The percentage of stations with significant annual trends in annual total wet day precipitation (PRCPTOT) before and after the phenomenon of oak decline, in the semi-dry, very humid, and Mediterranean climate types of the Zagros. (↑ = increasing trend, ↓ = decreasing trend).

Climate type	**PRCPTOT (Annual total wet day precipitation)**	
	Before	**After**
Semi-dry	↓17	↑8
Mediterranean	0	0
Very humid	0	0

PRCPTOT showed a decrease in precipitation in both the semi-dry (406 mm *vs.* 372 mm) and Mediterranean (528 mm *vs.* 487 mm) climate types following the decline (Fig. 5). This decline is associated with an average reduction of 34 mm in the semi-dry climate type and 41 mm in the Mediterranean climate type (Fig. 5).

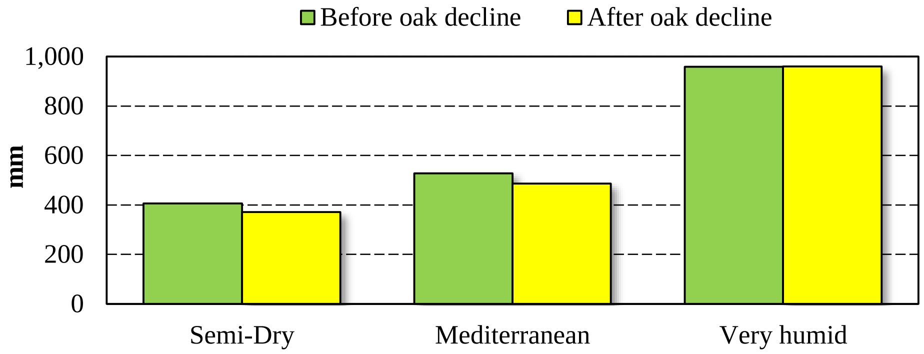

Fig. 5. Changes in annual total wet day precipitation (PRCPTOT) index before and after the phenomenon of oak trees decline (2000) in the semi-dry, very humid and Mediterranean climate types of the Zagros region, Western Iran

Extreme indices for the period of 1987-2019

The statistical significance and direction of trends for the percentile-based indices were examined over the period 1987-2019. In all climate types, both TX90p and TX10p showed significant trends in 100% of stations, with warm days exhibiting positive trends and cold days showing negative trends across all stations (Table 7). The TN90p index generally exhibited significant positive trends across all climate types, except for the Mediterranean, where 25% of stations showed negative trends (Table 7). Similarly, TN10p showed predominantly negative trends, with 8% and 25% of stations in the semi-dry and Mediterranean climates, respectively (Table 7).

Table 7. The percentage of stations with significant positive and negative annual trends for percentile-based indices, over the whole period spanning from 1987 to 2019 in the semi-dry, very humid, and the Mediterranean climate types of the Zagros.

Climate type	**TN10p (Cold nights)**		**TN90p (Warm nights)**		**TX10p (Cold days)**		**TX90p (Warm days)**	
	Positive	**Negative**	**Positive**	**Negative**	**Positive**	**Negative**	**Positive**	**Negative**
Semi-dry	8	75	75	0	0	100	100	0
Mediterranean	25	75	75	25	0	100	100	0
Very humid	0	67	100	0	0	100	100	0

The significance of trends for threshold indices was also analyzed for the full study period (1987-2019). The R20 index exhibited significant positive trends at the majority of stations, except for the semi-dry and Mediterranean climate types, where 8% and 25% of stations, respectively, demonstrated significant negative trends (Table 8). In contrast, the ID0 index revealed significant negative trends across all climate types (Table 8). The SU25 index showed statistically significant positive trends at most stations across all three regions (Table 8). The FD0 index exhibited a significant positive trend solely in the semi-dry climate type, while significant negative changes were observed in the other climate types except Mediterranean (Table 8).

Table 8. The percentage of stations with significant positive and negative annual trends for threshold indices, over the whole period spanning from 1987 to 2019 in the semi -dry, very humid, and Mediterranean climate types of the Zagros.

Climate type	**R20 (Heavy precipitation days)**		**ID0 (Ice days)**		**SU25 (Summer days)**		**FD0 (Frost days)**	
	Positive	**Negative**	**Positive**	**Negative**	**Positive**	**Negative**	**Positive**	**Negative**
Semi-dry	42	8	0	25	67	0	17	33
Mediterranean	25	25	0	50	75	0	0	0
Very humid	67	0	0	100	100	0	0	100

A significant negative trend in CWD was observed at 17% of the stations within the semi-dry climate type. In contrast, CSDI exhibited significant trends at most stations across all three types of climate, except for the semi-dry climate type, where only 8% of the stations showed significant positive trends. The WSDI index demonstrated a statistically significant positive trend across all regions. Furthermore, the CDD and GSL indices exhibited significant positive trends in the semi-dry and very humid climate types, respectively (Table 9).

Table 9. The percentage of stations with significant positive and negative annual trends for duration indices, over the whole period spanning from 1987 to 2019 in the semi-dry, very humid, and Mediterranean climate types of the Zagros.

Climate type	**CWD (Consecutive wet days)**		**CSDI (Cold spell duration indicator)**		**WSDI (Warm spell duration indicator)**		**CDD (Consecutive dry days)**		**GSL (Growing season length)**	
	Positive	**Negative**	**Positive**	**Negative**	**Positive**	**Negative**	**Positive**	**Negative**	**Positive**	**Negative**
Semi-dry	0	17	8	34	50	0	8	0	0	0
Mediterranean	0	0	0	50	50	0	0	0	0	0
Very Humid	0	0	0	67	100	0	0	0	67	0

PRCPTOT trends were generally weak and inconsistent across climate types during 1987-2019, with 17% and 25% of stations in the semi-dry and Mediterranean climate types, respectively, showing significant negative trends. No significant trends were observed in the very humid climate type (Table 10).

Table 10. The percentage of stations with significant positive and negative annual trends in annual total wet day precipitation (PRCPTOT) over the whole period spanning from 1987 to 2019, in the semi-dry, very humid, and Mediterranean climate types of the Zagros.

Climate type	**PRCPTOT (Annual total wet day precipitation)**	
	Positive	**Negative**
Semi-dry	0	17
Mediterranean	0	25
Very humid	0	0

Temperature indices

Climate change, driven by the rising concentration of greenhouse gases, is expected to disrupt many sectors of society, with agriculture and forestry being especially vulnerable. Unlike manufacturing or retail industries, which can adapt more easily, ecosystems such as forests are highly sensitive to climatic shifts (Parry, 2000). Forests may face altered species composition, reduced productivity, and heightened vulnerability to hazards like wildfires. One of the most critical concerns is the rise in temperature extremes, which can have long-term effects on forest health. For example, low temperatures can damage trees that are sensitive to early spring frosts or late autumn cold spells, adversely impacting their growth and survival (Heide, 1985). The Zagros forests in Iran offer a striking case of how climate change is already affecting forest ecosystems. As temperatures rise, several studies have highlighted significant impacts on the habitat of Persian oak, the dominant species in these forests. Safaei et al. (2021) modeled the future distribution of *Q. brantii* and predicted notable habitat shifts under climate change scenarios. Similarly, Valavi et al. (2019) forecasted a contraction in suitable habitats, pushing them toward higher altitudes .Our study investigated how extreme climate events may contribute to oak forest decline by focusing on shifts in climate indices such as cold and warm events, ice and frost days, and their durations. These indices have shown significant changes since 2000 across various climate types in the region, including semi-dry, very humid, and Mediterranean zones. In general, the region has become warmer. Specifically, nighttime temperatures have increased. Hence, the results provide valuable insight into how climate extremes are driving ecological stress in the Zagros forest. Changes in the frequency of warm and cold days and nights can significantly impact tree physiology. For instance, bud dormancy, a critical process in a tree's growth cycle, depends on chilling temperatures and long nights in autumn. These cold conditions are essential for triggering budburst in spring (Cannell & Smith 1983). Internal growth signals and photoperiod interact with chilling requirements, and even shortened nights can partially compensate for insufficient chilling, especially in mild winters (Cannell & Smith 1983). In the semi-arid Zagros Mountains, such cold conditions appear vital for oak tree health. Interestingly, fluctuating temperatures might be more effective in breaking the rest phase than constant cold, as our results suggest (Fishman *et al.* 1987). Warmer temperatures following a chill period may cause earlier budburst, but this also increases the risk of frost damage (Cannell & Smith 1986). While elevated temperatures may initially enhance growth, they can ultimately raise water demand and reduce resilience. In semi-dry and Mediterranean climates, this leads to heightened water stress, which impairs growth and reproduction (Olszyk *et al.* 1998). Although short-term growth may increase, excessive water demand can eventually weaken trees. This pattern is evident in the Zagros region, where warming has already imposed considerable stress on oak forests. Warmer autumns and winters prevent the development of adequate frost hardiness, leaving trees vulnerable to cold damage (Sakai & Larcher 2012). In the Zagros, this trend correlates with a decline in frost days and increased frost damage (Rahimi 2011). Frost-injured trees are also more prone to pests and diseases (Leinonen *et al.* 1995). Shorter growing seasons further restrict carbon storage and photosynthesis, which are essential for survival. Combined with increased temperatures and reduced precipitation, these stressors significantly challenge forest health. The situation is even worse in silvopastoral systems, where limited ground cover and soil erosion intensify water scarcity, further suppressing tree growth (Safari *et al.* 2022). The results clearly show a consistent reduction in cold days (TX10p) and cold nights (TN10p) across all climate types, especially after 2000. For instance, in the semi-dry climate, 25% of stations showed a significant increase in TX10p, while 42% showed an increase in TX90p. In very humid climates, cold nights (TN10p) decreased significantly at 34% of stations, while warm nights (TN90p) showed a slight increase. In Mediterranean climates, the trends were even more pronounced, with increases in TN10p (from 25% to 75%), TX10p (to 75%), and TX90p (to 25%). These findings support the general observation that nights are warming faster than days, which is consistent with global climate trends.

Precipitation indices

Forests in western Iran are particularly vulnerable due to shifting summer precipitation patterns (Homayounfar *et al.* 2024), which no longer support current forest cover and are exacerbated by growing wildfire risks (Maracchi *et al.* 2005). Climate change is expected to compound these challenges, triggering unpredictable changes in seasonal temperature, storms, precipitation, and extreme events (Michener *et al.* 1997). Several studies have emphasized the influence of precipitation shifts in the Zagros. For example, Safari *et al.* (2022) found that tree growth in the Central Zagros Mountains is strongly influenced by regional climate, especially precipitation and drought. Their findings revealed a consistent limitation in tree growth during the growing season due to declining rainfall in recent decades, a clear indicator of climate change. Similarly, Balling Jr *et al.* (2016) reported increasing trends in seven extreme precipitation indices across western Iran from 1951 to 2007. This study examined extreme precipitation indices across different Zagros climate types and revealed significant alterations in rainfall patterns. In particular, there are fewer large storm events and a reduction in the number of days with precipitation. These changes have major implications for understanding the region's climate dynamics and ecological resilience. In semi-arid zones like the central Zagros, tree growth is highly dependent on rainfall, particularly in early spring (April), when higher temperatures, cambial activity, and leaf sprouting escalate water demands (Habibi 2016). However, heavy rainfall can be harmful. Intense precipitation over short periods may cause flash floods and soil erosion, washing away nutrient-rich topsoil and damaging roots, ultimately stunting growth and increasing mortality (Rahimi, 2011). Similarly, prolonged flooding saturates the soil, depriving roots of oxygen, leading to root rot and increased vulnerability to pests and diseases. Excess moisture also promotes outbreaks of oak moths and pathogens like Phytophthora spp., threatening forest health (Bentz *et al.* 2010). The results confirm a general decline in the frequency of large storms and wet days (R20), especially in Mediterranean climates (decrease of 5 days). In contrast, semi-dry and very humid climates showed an increase in R20 (5 and 14 days, respectively), indicating a shift toward more concentrated, and intense rainfall events. Similarly, the number of ice days (ID0) decreased in all climate types, with the most significant drop in very humid climates (12 fewer days). These changes reflect a broader pattern of warming and drying, consistent with the global trend of climate change. Moreover, the total annual precipitation (PRCPTOT) declined in both semi-dry (34 mm) and Mediterranean (41 mm) climates, which, combined with rising temperatures, has likely intensified drought conditions and reduced water availability for oak trees. This supports the findings of Safari *et al.* (2022) regarding the limiting effect of declining rainfall on tree growth in the region.

CONCLUSION

The Zagros oak forests of western Iran have undergone significant decline due to the rising frequency and intensity of extreme climate events, particularly since 2000. Our analysis of 33 years of climate data across semi-arid, Mediterranean, and very humid regions revealed notable changes in extreme temperature and precipitation indices. These included increased warm days and nights, fewer frost days, and altered rainfall patterns. These shifts have exceeded the physiological thresholds of oak trees, intensifying water stress, disrupting dormancy cycles, and increasing susceptibility to pests and disease. Although some studies suggest minor benefits of climate change, such as a longer growing season, the overall impact on the Zagros forests has been negative. The reduction in cold extremes has compromised frost hardiness, while both droughts and intense rainfall have stressed trees in multiple ways. When combined with human-driven pressures like overgrazing and deforestation, these climatic changes have accelerated forest degradation. Our findings underscore the urgent need for adaptive forest management strategies. Efforts should focus on enhancing forest resilience through sustainable land use, reforestation with drought- and pest-resistant species, and improved water management. Future research should continue to explore long-term interactions between climate and forest ecosystems to better forecast and mitigate the impacts of ongoing climate change.

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REFERENCES

Ademe, D, Zaitchik, BF, Tesfaye, K, Simane, B, Alemayehu, G & Adgo, E 2020, Climate trends and variability at adaptation scale: Patterns and perceptions in an agricultural region of the Ethiopian Highlands. *Weather and Climate Extremes,* 29: 100263, https://doi.org/10.1016/j.wace.2020.100263.

Aguilar, E, Auer, I, Brunet, M, Peterson, TC & Wieringa, J 2003, Guidelines on climate metadata and homogenization. *World Meteorological Organization,* 1186(Oct.), 53.

Alexander, LV, Zhang, X, Peterson, TC, Caesar, J, Gleason, B, Klein Tank, AMG, Haylock, M, Collins, D, Trewin, B, Rahimzadeh, F & Tagipour, A 2006, Global observed changes in daily climate extremes of temperature and precipitation. *Journal of Geophysical Research: Atmospheres*, 111(D5), https://doi.org/10.1029/2005JD006290.

Attarod, P, Zhu, H, Beiranvand, S, Pypker, TG, Bayramzadeh, V, Mariv, HS & Karimi, K 2025, Past and future climate change in the Zagros region of western Iran. *Anthropocene*: 50*:* 100475, https://doi.org/10.1016/j.ancene.2025.100475.

Attarod, P, Beiranvand, S, Asgari, M, Fanaei, N & Hashemzadeh, M 2021, The effects of rainfall fluctuations on declining Zagros forests in Ilam and Lorestan provinces. *Iranian Journal of Forest,* 13(2): 141–154, https://doi.org/10.22034/ijf.2021.136938.

Attarod, P, Beiranvand, S, Pypker, TG, Bayramzadeh, V, Helali, J, Mashayekhi, Z, Fathi, J & Soofi Mariv, H 2023, Are precipitation characteristics and patterns impacting oak tree decline in the Zagros region of western Iran? *Caspian Journal of Environmental Sciences*, 21(4): 753–765, https://doi.org/10.22124/cjes.2023.7122.

Balling Jr, RC, Kiany, MSK & Roy, SS 2016, Anthropogenic signals in Iranian extreme temperature indices. *Atmospheric Research*, 169: 96–101, https://doi.org/10.1016/j.atmosres.2015.09.030.

Bentz, BJ, Régnière, J, Fettig, CJ, Hansen, EM, Hayes, JL, Hicke, JA, Kelsey, RG, Negrón, JF & Seybold, SJ 2010, Climate change and bark beetles of the western United States and Canada: direct and indirect effects. *BioScience*, 60(8): 602–613, https://doi.org/10.1525/bio.2010.60.8.6.

Bréda, N & Badeau, V 2008, Forest tree responses to extreme drought and some biotic events: Towards a selection according to hazard tolerance? *Comptes Rendus. Geoscience,* 340(9–10): 651–662, https://doi.org/10.1016/j.crte.2008.08.003.

Cannell, MGR & Smith, RI 1983, Thermal time, chill days and prediction of budburst in *Picea sitchensis*. *Journal of Applied Ecology,* 20: 951–963, https://doi.org/10.2307/2403139.

Cannell, MGR & Smith, RI 1986, Climatic warming, spring budburst and frost damage on trees. *Journal of Applied Ecology,* 177–191, https://doi.org/10.2307/2403090.

Croitoru, AE, Piticar, A, Imbroane, AM & Burada, DC 2013, Spatiotemporal distribution of aridity indices based on temperature and precipitation in the extra-Carpathian regions of Romania. *Theoretical and Applied Climatology,* 112(3): 597–607, https://doi.org/10.1007/s00704-012-0755-2.

Fishman, S, Erez, A & Couvillon, GA 1987, The temperature dependence of dormancy breaking in plants: Mathematical analysis of a two-step model involving a cooperative transition. *Journal of Theoretical Biology,* 124(4): 473–483, https://doi.org/10.1016/S0022-5193(87)80221-7.

Habibi, M 2016, Investigating the impact of climate changes on qualitative and quantitative growth of oak trees (case study: central Zagros). *Open Journal of Ecology*, 6(6): 358–366, http://dx.doi.org/10.4236/oje.2016.66034.

Heide, OM 1985, Physiological aspects of climatic adaptation in plants with special reference to high-latitude environments. Plant Production in the North, pp. 1–22.

Herrero, A & Zamora, R 2014, Plant responses to extreme climatic events: a field test of resilience capacity at the southern range edge. *PLoS ONE*, 9(1): e87842, https://doi.org/10.1371/journal.pone.0087842.

Homayounfar, S, Zolfaghari, R, Cavender-Bares, J & Fayyaz, P 2024, Autumn cold acclimation and freezing tolerance of three oak species in semi-Mediterranean Zagros forests. *Forest Systems*, 33(2): e06–e06, https://doi.org/10.5424/fs/2024332-20865.

Lavell, A, Oppenheimer, M, Diop, C, Hess, J, Lempert, R, Li, J & Myeong, S 2012, Managing the risks of extreme events and disasters to advance climate change adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC), 3: 25–64.

Leinonen, I, Repo, T, Hänninen, H & Burr, KE 1995, A second-order dynamic model for the frost hardiness of trees. *Annals of Botany*, 76(1), 89–95, https://doi.org/10.1006/anbo.1995.1082.

Lloyd, AH & Bunn, AG 2007, Responses of the circumpolar boreal forest to 20th century climate variability. *Environmental Research Letters,* 2(4), 045013, http://dx.doi.org/10.1088/1748-9326/2/4/045013.

Maracchi, G, Sirotenko, O & Bindi, M 2005, Impacts of present and future climate variability on agriculture and forestry in the temperate regions: Europe. *Climatic Change*, 70(1), 117–135.

Marengo, JA, Jones, R, Alves, LM & Valverde, MC 2009, Future change of temperature and precipitation extremes in South America as derived from the PRECIS regional climate modeling system. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, 29(15): 2241–2255, https://doi.org/10.1002/joc.1863.

Michener, WK, Blood, ER, Bildstein, KL, Brinson, MM & Gardner, LR 1997, Climate change, hurricanes and tropical storms, and rising sea level in coastal wetlands. *Ecological applications*, 7(3): 770–801, https://doi.org/10.1890/1051-0761(1997)007[0770:CCHATS]2.0.CO;2.

Niu, S, Luo, Y, Li, D, Cao, S, Xia, J, Li, J & Smith, MD 2014, Plant growth and mortality under climatic extremes: an overview. *Environmental and Experimental Botany*, 98, 13–19, https://d1wqtxts1xzle7.cloudfront.net/43557238/dx.doi.org/10.1016/j.envexpbot.2013.10.004.

NOAA National Centers for Environmental Information 2023, Global surface temperature anomalies and trends. National Oceanic and Atmospheric Administration. https://www.ncei.noaa.gov/.

Olszyk, D, Wise, C, VanEss, E, Apple, M & Tingey, D 1998, Phenology and growth of shoots, needles, and buds of Douglas-fir seedlings with elevated CO2 and/or temperature. *Canadian Journal of Botany*, 76(12): 1991–2001, https://doi.org/10.1139/b98-169.

Parry, ML (Ed) 2000, Assessment of potential effects and adaptations for climate change in Europe: The Europe ACACIA project. Jackson Environment Institute, University of East Anglia.

Pourhashemi, M, Jahanbazi Goujani, H, Hoseinzadeh, J, Bordbar, SK, Iranmanesh, Y & Khodakarami, Y 2017, The history of oak decline in Zagros forests. *Journal of Iran Nature,* 2(1), 30–37, https://doi.org/10.22092/irn.2017.109535.

Rahimi, M 2011, Trends in frost days, late and early frost dates, and the frost-free season over Iran during 1951–2005. In WCRP Open Science Conference: Climate Research in Service to Society, Colorado, USA.

Reichstein, M, Bahn, M, Ciais, P, Frank, D, Mahecha, MD, Seneviratne, SI, Zscheis chler, J, Beer, C, Buchmann, N, Frank, DC, Papale, D, Rammig, A, Smith, P, Thonicke, K, van der Velde, M, Vicca, S, Walz, A & Wattenbach, M 2013, Climate extremes and the carbon cycle. *Nature* 500(7462): 287–295, https://doi.org/10.1038/nature12350.

Safaei, M, Rezayan, H, Firouzabadi, PZ & Sadidi, J 2021, Optimization of species distribution models using a genetic algorithm for simulating climate change effects on Zagros forests in Iran. *Ecological Informatics,* 63: 101288, https://doi.org/10.1016/j.ecoinf.2021.101288.

Safari, E, Moradi, H, Seim, A, Yousefpour, R, Mirzakhani, M, Tegel, W & Kahle, HP 2022, Regional drought conditions control *Quercus brantii* Lindl growth within contrasting forest stands in the central Zagros Mountains, Iran. *Forests*, 13(4): 495, https://doi.org/10.3390/f13040495.

Sagheb Talebi, K, Sajedi, T & Pourhashemi, M 2014, Forests of Iran: A Treasure from the Past, a Hope for the Future. *Springer Netherlands*, 15325.

Sakai, A & Larcher, W 2012, Frost survival of plants*:* Responses and adaptation to freezing stress (Vol. 62). Springer Science & Business Media.

Sen, PK 1968, Estimates of the regression coefficient based on Kendall’s Tau. *Journal of the American Statistical Association,* 63(324): 1379–1389.

Thomas, FM & Büttner, G 1998, Nutrient relations in healthy and damaged stands of mature oaks on clayey soils: Two case studies in northwestern Germany. *Forest Ecology and Management,* 108(3), 301–319.

Valavi, R, Shafizadeh-Moghadam, H, Matkan, A, Shakiba, A, Mirbagheri, B & Kia, SH 2019, Modelling climate change effects on Zagros forests in Iran using individual and ensemble forecasting approaches. *Theoretical and Applied Climatology,* 137(1): 1015–1025, https://doi.org/10.1007/s00704-018-2625-z.

Valdez-Cepeda, RD, Hernández-Ramírez, D, Mendoza, B, Valdés-Galicia, J & Maravilla, D 2003, Fractality of monthly extreme minimum temperature. *Fractals*, 11(02): 137–144, https://doi.org/10.1142/S0218348X0300163X.

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(5913): 521–524, https://doi.org/10.1126/science.1165000.

Zhang, X, Aguilar, E, Sensoy, S, Melkonyan, H, Tagiyeva, U, Ahmed, N & Wallis, T 2005, Trends in Middle East climate extreme indices from 1950 to 2003. *Journal of Geophysical Research: Atmospheres*, 110(D22), https://doi.org/10.1029/2005JD006181.