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Variations in Leaf Area Index of *Quercus brantii* Trees in Response to Changing Climate

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ABSTRACT

We aimed to find the meteorological parameters that affect variations in Leaf Area Index (LAI) of Persian oak (*Quercus brantii* var. *persica*) trees in the Zagros region of western Iran. Canopy developmental stage for five individual trees using a fish eye camera was monitored from August 2015 to August 2016. Meteorological parameters of Temperature (T), Precipitation (P), and Wind Speed (WS) were obtained from the nearest meteorological station during 1986-2016. FAO Penman-Monteith (PM) combination equation was employed to calculate daily reference Evapotranspiration (ET_0). The nonparametric Mann–Kendall (MK) test was used to detect significant changes in yearly meteorological parameters and ET_0. Over the study period, LAI varied from zero during the LeafLess Period (LLP), when the Woody Area Index (WAI) was 0.88, to 1.65 in Full Leaf Period (FLP). LAI showed relatively strong and significant positive linear correlations with T (R^2= 0.71), Vapor Pressure Deficit (VPD) (R^2= 0.58), and ET_0 (R^2= 0.33), such that higher LAI values were measured in warmer and drier days with higher ET_0. No statistically significant trend was detected by MK test during 1986-2016 for yearly T and VPD (MK statistic, Z_{MK}= 0.044 for T, and Z_{MK}= 0.207 for VPD). Significant relationship between leaf area index of oak trees and temperature in the Zagros region can partially confirm the connection between declining oak trees and rising temperature.

Keywords: Evapotranspiration, Meteorological parameters, Oak trees, Zagros region.

INTRODUCTION

There is consensus that global average air temperatures have increased during the 20th century, however, there is great uncertainty about the magnitude of future increases (Huntington, 2006). This warming impacts plant productivity because the warming trend is correlated to a lengthening of the growing season (Huntington, 2006). This lengthening is consistent with an overall increase in Evapotranspiration (ET) in northern temperate humid climates, because the period for active transpiration is longer and warmer (White *et al*., 1999).

The timing of phenological events is important for plant productivity and species distribution and is sensitive to changing climate variables (Chuine and Beaubien, 2001; Rathcke and Lacey, 1985). Knowledge of these relationships is crucial, not only for predicting ecosystem responses to climate change but also for understanding dynamics of forest stands. For example, in the Northern Hemisphere, there has been an increase in growing-season length (Menzel and Fabian, 1999; Parmesan and Yohe, 2003). The increase in growing season length and surface temperatures are correlated to strong phenological shifts that have been observed in the temperate to

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boreal climates of the northern hemisphere (Menzel *et al*., 2006; Menzel and Fabian, 1999; Parmesan 2006; Schwartz and Reiter, 2000). As a result, the distribution range for some species has shifted (Bertin, 2008).

At present, the concepts of climate change and global warming are considered as crucial environmental problems (Costanza and Jorgensen, 2002). One of the most important greenhouse gases that cause global warming in the world is atmospheric CO_2 (Houghton, 1997). There is a close relationship between leaf area and atmospheric CO_2 assimilation rate in trees and forest ecosystems (Kezik and Kocaçınar, 2015). Thus, leaf area and stand crown closure in forest ecosystems directly affect CO_2 assimilation rate, helping carbon sequestration in plants, while indirectly helping to reduce global warming and climate change effects (Hacisalihoğlu *et al*. 2017)

In Iran, Zagros forests, also known as oak forests, cover a huge area of the Zagros mountain ranges in the west of Iran, occupying an average length and width of 1,300 and 200 km, respectively. The Zagros forests cover 6 million hectares, contain 44% of Iran's forests area, and are mostly dominated by sparse stands of Persian oak (*Quercus brantii* var. *persica*), i.e. 3.5 million hectares out of 6 million (Sagheb Talebi *et al*., 2014).

Oak trees have been in decline since 2000, and Iranian forest managers believe the decline results from multiple factors (Attarod *et al*., 2016). Within the period of 2000-2010, meteorological parameters and climate changed in the Zagros region (Air temperature: +2.9%, Precipitation: –10.1% mm, Relative humidity: –5.5%, Wind speed: +18.7%, Reference evapotranspiration: +0.25%, and De Martonne aridity Index, I_{DM}: -10%) (Attarod *et al*., 2016). These changes may have impacted the timing of phenological events and Leaf Area Index (LAI), growing season length, as well as hydrological parameters such as ET (Wang *et al*., 2011; Murray *et al*., 1989). To our knowledge, there has been no research focused on the trend of LAI of oak trees in relation to meteorological parameters in the Zagros region. Research is needed to better understand how the LAI of oak trees will respond to changes in meteorological parameters. The objective of this paper was to find out which meteorological parameters are affecting the developmental stages of LAI of oak trees in the Zagros region.

MATERIALS AND METHODS

Site Description

The research was performed in Ilam Forest Park, 46° 24' E, 33° 37' N, 1,383 m asl (aka Chogha-Sabz Forest Park), which is located in Ilam province, Zagros region, western of Iran (Figure 1). The park area is 2,057 ha. The study site consists of sparse and scattered oak trees spaced 10-20 m away from neighboring trees. The trees originated from seeds and have an average height and diameter of 9 m and 65 cm, respectively. The understory is covered with sparse shrubs that are currently used for agroforestry activities. Tree density, including coppice trees, is approximately 40 trees per hectare.

Trees Selection

Five individual and mature oak trees with similar morphologies, i.e., tree height, Diameter at Breast Height (DBH), and Crown Projected Area (CPA), were randomly selected on a relatively flat area for phenological observations (Table 1). The canopies of these trees did not overlap with those of the adjacent trees.

Meteorological Data and ET Equation

Long-term meteorological data, from May, 4, 1986, to September, 20, 2016, recorded at Ilam Meteorological Station (46° 26' E, 33° 38' N, 1,363 m asl) were used. This is the

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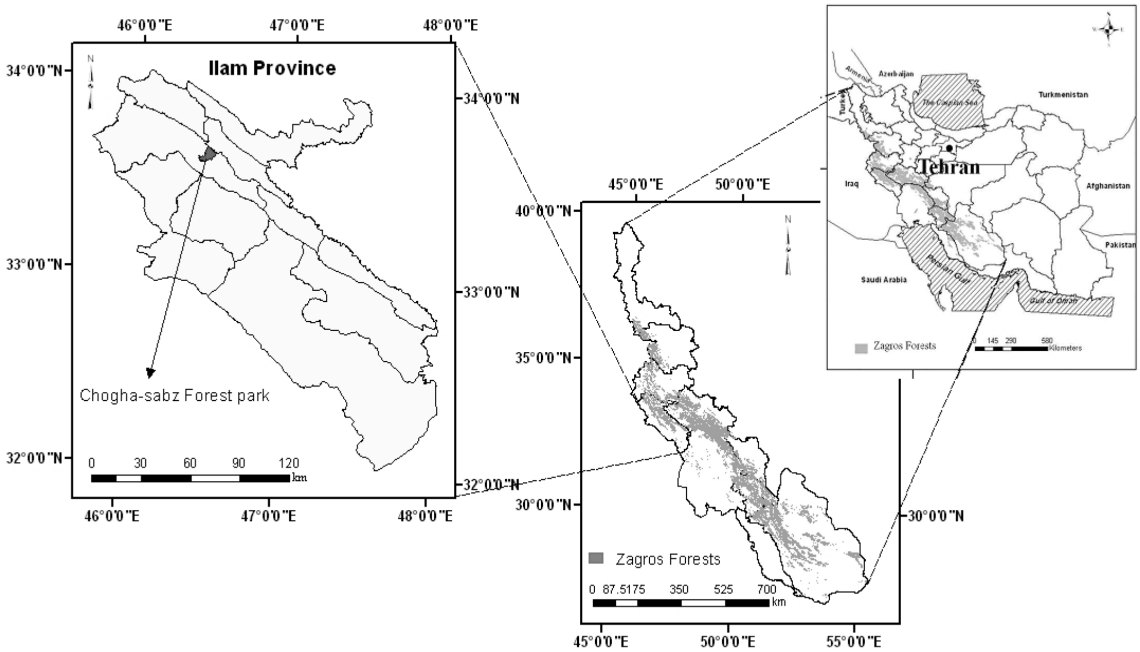

Figure 1. Location of the study site in the Zagros forests of western Iran, Ilam Province.

Table 1. Characteristics of individual Persian oak (*Quercus brantii*) trees selected for phenological observations.

Tree no	Height (m)	Diameter at Breast Height (DBH, cm)	Crown Projection Area (CPA, m^2)
1	5.2	46	42.3
2	4.7	47	38.6
3	4.5	45	53.7
4	5.6	52	55.2
5	5.2	54	60.5
Mean	5.0	49	50.0

nearest synoptic station to the study site and is approximately 600 m away from the trees. There is no significant change in elevation between the trees location and the station. Based on both Köppen climate classification and De Martonne aridity Index (I_{DM}), the region is characterized by a Mediterranean climate (I_{DM}= 22) (Croitoru *et al*., 2012). The dry period begins in April and ends in October. January is the coldest month (4.7°C; ±SD: 1.8) and July and June are the warmest months (29.2°C; ±SD: 1.0) (Figure 2), and average annual Temperature (T) is 16.9°C; ±SD: 0.7. The monthly minimum and maximum temperatures are 0.7 (January, 1992) and 31.6°C (July, 2000). Absolute daily maximum temperature is 42°C (July) and the absolute daily minimum temperature is -13.6°C (January).

Mean annual Precipitation (P) is 573 mm (±SD: 160 mm) (Figure 2), however, maximum and minimum P from 1986 to 2016 were 988 mm (1994) and 336 mm (2008), respectively. January is the wettest month (107 mm; SD: ±53) while June is the driest (0.1 mm; SD: ±0.4). Mean daily Relative Humidity (RH) is 40%, mean daily Vapor Pressure Deficit (VPD) is 1.5 kPa varied widely from 0.0 to 5.0 kPa. Monthly maximum VPD is in July (3.3 kPa) and

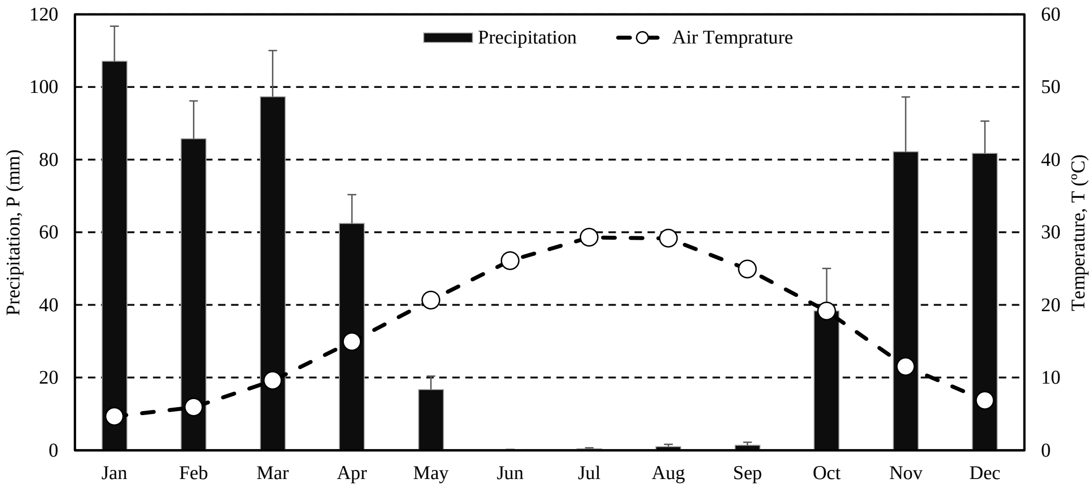

Figure 2. Monthly mean Precipitation (P) and Temperature (T) recorded during 30 years (1986-2016) at Ilam Synoptic Meteorological Station located in the Zagros region. Error bars show the Standard Error (SE) of monthly precipitation during the recorded periods.

minimum is in January (0.3 kPa). Mean daily Wind Speed (WS) is 2.3 m s^{-1} ranging from 0 to 9.9 m s^{-1}. Historically, the region has 37 frost days per year (temperatures below 0ºC) that typically occur in January and February.

Canopy developmental stages were divided into four periods: the Leaf Expansion Period (LEP); Full Leaf Period (FLP); Leaf Senescence Period (LSP); and LeafLess Period (LLP) (Fathizadeh *et al*., 2013). The distinction between the periods was regularly made by inspecting the changes in LAI of the trees in the study site (Figure 3). Canopy duration was defined at individual scale as the period between bud burst and leaf senescence dates. We investigated the correlation between LAI or canopy developmental stages and mean daily values of temperature, precipitation, wind speed, and relative humidity.

We used the FAO Penman-Monteith combination equation to calculate daily reference Evapotranspiration (ET_0). It is the standard method proposed by the International Commission for Irrigation and

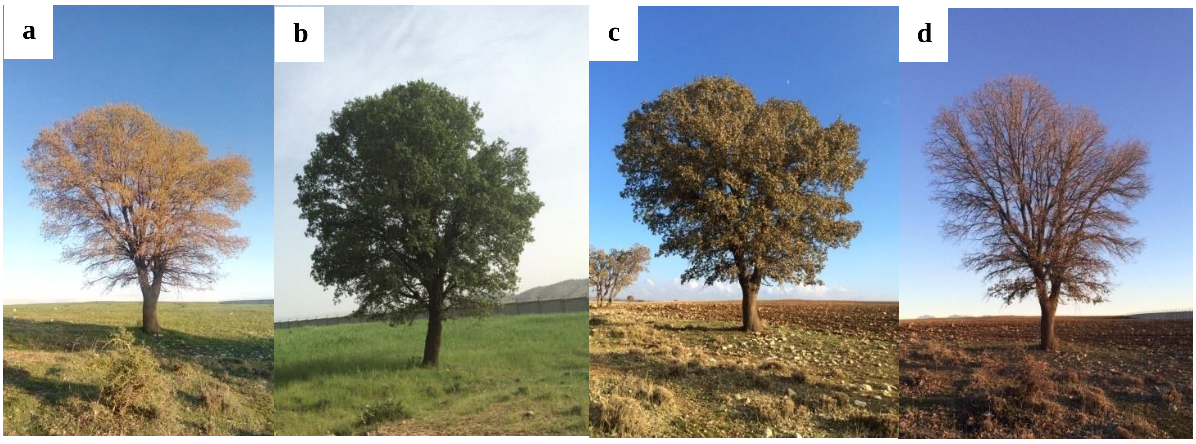

Figure 3. Developmental stages (periods) of a Persian oak (*Quercus brantii*) tree in the study site, (a) Leaf Expansion Period (LEP); (b) Full Leaf Period (FLP); (c) Leaf Senescence Period (LSP); and (d) LeafLess Period (LLP).

Drainage (ICID) and Food and Agriculture Organization of the United Nation (FAO). The FAO Penman-Monteith equation calculates daily ET_0 for a hypothetical reference crop evapotranspiration that has a height of 0.12 m, a surface resistance of 70 s m^{-1} and an albedo of 0.23. The crop is assumed to be of uniform height (e.g. green grass), is well watered and actively growing and adequately watered. The equation provided by Allen *et al.* (1998) is:

$$ET_0=\frac{0.408\Delta(R_n-G)+\gamma\frac{900}{T+273}u_2(e_s-e_a)}{\Delta+\gamma(1+0.34u_2)} \quad (1)$$

Where, ET_0 (mm d^{-1}) is the reference ET; R_n (MJ m^{-2} d^{-1}) is the net radiation at the crop surface; G (MJ m^{-2} d^{-1}) is soil heat flux density; T (°C) is the mean daily temperature at a height of 2 m; u_2 (m s^{-1}) is the wind speed at a height of 2 m; e_s (kPa) is saturation vapor pressure; e_a (kPa) is actual vapor pressure; e_s-e_a (kPa) is Vapor Pressure Deficit (VPD); Δ (kPa °C^{-1}) is the slope of vapor pressure curve at the daily mean temperature; and γ (kPa °C^{-1}) is the psychometric constant calculated as 0.665×10^{-3}AP; in which AP (kPa) is the Atmospheric Pressure. G at the daily ground heat flux is typically relatively small and thus could be ignored in FAO Penman-Monteith combination equation. Therefore, G= 0 MJ m^{-2} d^{-1} (Goyal, 2004). To calculate daily ET_0, daily mean temperature, humidity, wind speed at 2 m height, and sunshine hours were employed.

LAI Measurement

To determine LAI, digital hemispherical photographs (Canon EOS 6D with a 180° fish-eye lens: Canon EF 8-15 mm f/4L) were taken vertically from August 2015 to August 2016. Photographs were taken under uniform sky conditions (overcast weather) or near sunset or sunrise (Zhang *et al*., 2005a, b), with three days intervals (Liu *et al*., 2015). The camera was mounted on a tripod and levelled to the height of 1.3 m (Heiskanen *et al*., 2015). The photographs were analyzed using Gap Light Analyzer (GLA, Ver. 2) software for calculating LAI (Frazer *et al*., 1999). The LAI values of the 5 sampled individual trees were averaged. We used the following relation to calculate LAI:

$$LAI= VAI-WAI \quad (2)$$

Where, VAI is Vegetation Area Index measured by the camera when the trees are Full-Leafed (FLP), and WAI is Woody Area Index measured by the camera when the trees are LeafLess.

Trend Test

The linear trend of the meteorological parameters during the period 1987-2016 in the study site was evaluated by the Mann-Kendall (MK) test, which is found to be an excellent tool for trend detection and extensively used in long-term trend analysis in climatic time series (Zhang *et al*., 2004; Tabari and Hosseinzadeh Talaee, 2011; Patra *et al*., 2012; Golian *et al*., 2015; Tabari *et al*., 2015). The MK is a non-parametric test used for detecting trends in a time series (Mann, 1945) where autocorrelation is non-significant (Pingale *et al*., 2014). The Mann-Kendall statistic, Z_{MK}, are roughly normally distributed. A positive Z_{MK} value larger than 1.96 (based on normal probability table) denotes a significant increasing trend (upward trend) at the significance level of 0.05, whereas a negative Z_{MK} value lower than -1.96 shows a significant decreasing trend (downward trend).

RESULTS

Climate History and Observed Meteorology

From August 2015 to August 2016, the cumulative *P* totaled 962 mm, 67% higher than the long-term average (575 mm) (Figure 4). The higher P occurred because P

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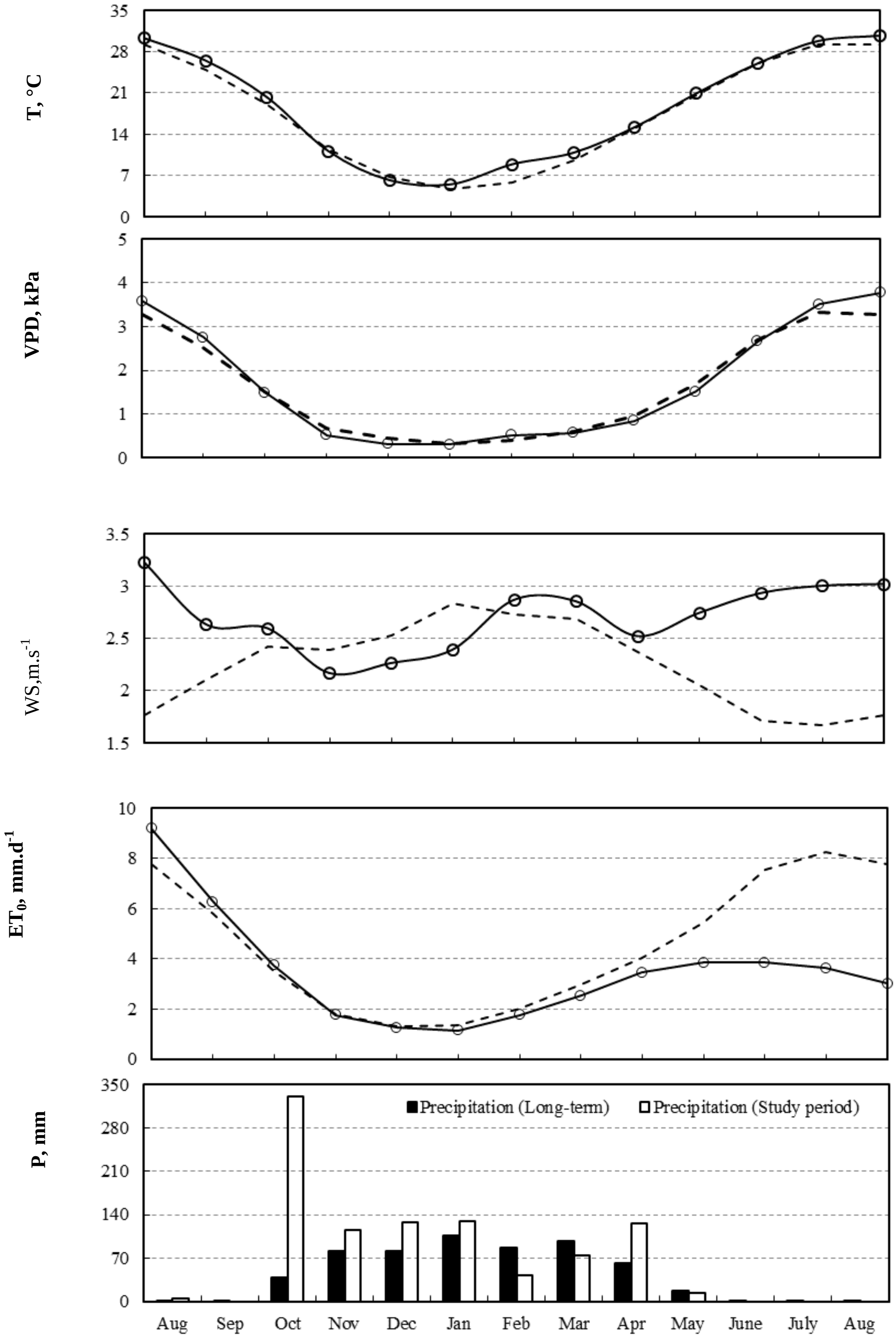

Figure 4. Monthly mean climate data for the study period (August 2015-August 2016), solid marked line, versus log-term (1986–2016), dashed line, as recorded by the nearby Meteorological Station in Ilam. From the top to bottom, Temperature (T), Vapor Pressure Deficit (VPD), Wind Speed (WS), reference Evapotranspiration (ET_0), and Precipitation (P).

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in October exceeded 300 mm, which is 8 times the long-term average.

The wettest and the driest months in the long-term records were January (107.2 mm; SD: ±53.5) and June (0.12 mm; SD: ±0.28), respectively (Figure 4). During the study period, the rainiest month was October (330.5 mm) and the driest months were June, July, August (2016), and September (0.0 mm). Compared to the 30-year mean monthly P recorded (1986-2016), the study period showed high deviation from the climate average, especially in the autumn months.

Mean annual T was 18.7°C during the study period, more than the long-term average T (17.8°C). Long-term records showed that July was the warmest month (42°C), and January was the coldest (0.7°C). However, during the study period, August (30.5°C) was the warmest and January (5.5°C) was the coldest month. Mean annual WS increased highly during the study period (21%), and a large difference was observed in summer (1.7 m s^{-1} for long-term against 3.0 m s^{-1} for the study period). VPD showed similar trends and yearly values (1.7 kPa) in the long-term and during the study period. January was the most humid month in both periods (VPD= 0.3). July is the driest month in long-term (3.3 kPa) against August (3.8 kPa) for the study period. Mean annual ET_0 was calculated as 4.6 mm per day for the long-term, against 3.5 mm per day for the study period. During the study period, the highest ET_0 was calculated for August, 2015 (9.2 mm d^{-1}) and the lowest for January (1.1 mm d^{-1}). In comparison to the long-term average, ET_0 was lower during April, May, June, July, and August, 2016 (3.5 vs 7.3 mm d^{-1}).

Seasonal Variations in LAI

Over the study period from August 2015 to 2016, mean LAI for the five trees increased to 1.65 in FLP, from May 2016 to August 2016, roughly the same value was measured during August 2015 to November 2015 (Table 2 and Figure 5).

Mid November was the starting point for decreasing *LAI*, i.e., *LSP*, and the trees were leafless from mid-January to mid-March. Expansion of leaves commenced in mid-March and the trees were fully leafed in mid-May.

Correlations between LAI and Meteorological Parameters and ET

LAI showed relatively strong and significant positive linear correlations with monthly T (n=13; r = 0.84; α=0.01), VPD (n= 13; r= 0.76; α= 0.01), and ET_0 (n= 13; r= 0.58; α= 0.05) such that higher LAI values were measured in warmer and drier days with higher ET_0 (Figure 6). There were no significant correlations between LAI and WS, and P. During the FLP, mean daily T_a, VPD and ET_0 were 26.5°C, 2.7 kPa, and 5.0 mm, respectively. However, these values corresponded to7.8°C, 0.5 kPa, and 1.7 mm, respectively, during the LLP. WS did not change much during the FLP and LLP (roughly 2.7 m s^{-1}) such that no correlation was detected with LAI.

Trend test

We examined long-term trends in yearly T and VPD recorded by Ilam Meteorological Station using Mann-Kendall test. There was a trend toward increasing T from 1987 to 2015, however, the change was not statistically significant (MK statistic, Z_{MK}= 0.044 for T, and Z_{MK}= 0.207 for VPD). The data also suggested that, after 2010, relative to the previous period (1987-2010), mean yearly T, VPD, and ET_0 changed roughly by +2.0, -1, and +8.3%, respectively.

DISCUSSION

We monitored the trend of LAI of oak trees during a typical year when annual trends of T and VPD were similar to those of

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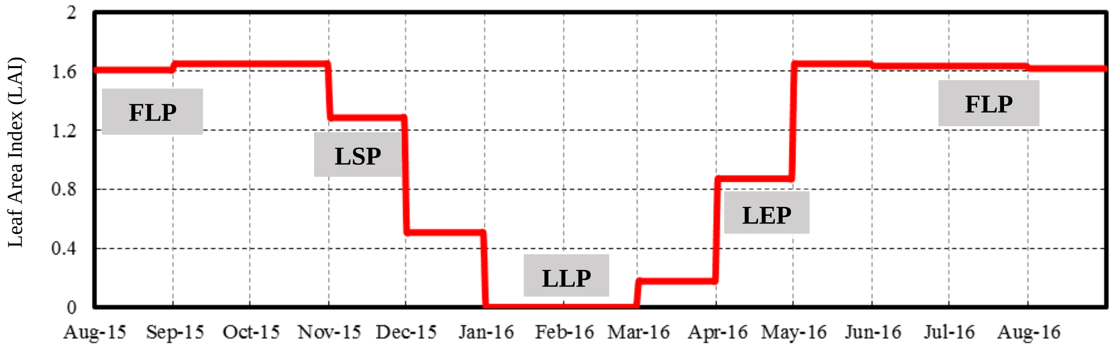

Figure 5. Trends of Leaf Area Index (LAI) (red line) for individual Persian oak (*Quercus brantii*) trees in the Zagros forests of western Iran during August 2015- August 2016. FLP, LSP, LLP, and LEP refer to Full Leaf Period, Leaf Senescence Period, LeafLess Period, and Leaf Expansion Period, respectively. LLP equals Woody Area Index (WAI).

Table 2. Leaf Area Index (LAI) values of Persian oak trees (*Quercus brantii*) at different growing stages measured in one year from August, 2015 to August, 2016.

Tree no	LEP[a]	FLP	LSP	LLP[b]
1	0.12	1.39	1.22	0.87
2	0.16	1.70	1.58	0.91
3	0.10	1.62	1.46	0.95
4	0.06	1.76	1.65	0.85
5	0.11	1.79	1.70	0.82
Mean	0.11	1.65	1.52	0.88

[a] Symbols are defined under Figure 3, and [b] Refers to Woody Area Index (WAI).

the long-term (Figure 4). We also observed the trends of meteorological parameters simultaneously to find out which meteorological parameters influence the yearly variation in LAI. Our measurements showed that T and VPD were the most important factors controlling yearly variations in LAI of oak trees in the Zagros forests (Figure 6). However, the best correlation was observed between LAI and T (Figure 6). The oak trees were fully-leafed (LAI= 1.6) approximately 180 days per year ranging from May to October when T and VPD were about 26 °C and 2.6 kPa, respectively. The trees were leafless in December, January, February, and March, once the LAI was near zero (T was 7.5°C and VPD was 0.43 kPa, on average) (Figure 5). April (LAI= 0.9; T= 15.2°C; VPD= 0.85 kPa) was the transition month (LEP) from LLP to FLP and November (LAI= 1.3; T= 11.1°C; VPD= 0.52 kPa) was the shifting month (LSP) from FLP to LLP. The strong correlations between T and LAI demonstrated that the declines in LAI were mainly controlled by T conditions at the end and beginning of the growing season, hence T is a major determinant of the large year-to-year variations in the oak trees canopy duration in Zagros forests of western Iran. Atmospheric temperature is probably the most widely used indicator of climatic changes both on global and regional scales (Goyal, 2004). According to the fourth assessment report of the IPCC (2013), global temperature has increased by 0.3 to 0.6°C since the late 19th century and by 0.2 to 0.3°C over the past forty years. Attarod *et al*. (2016) also reported that T has risen by 0.6°C during the period 2000-2010 in the Zagros region. Although we identified no statistically significant change in T and VPD during the period 1987-2016, a 0.3°C

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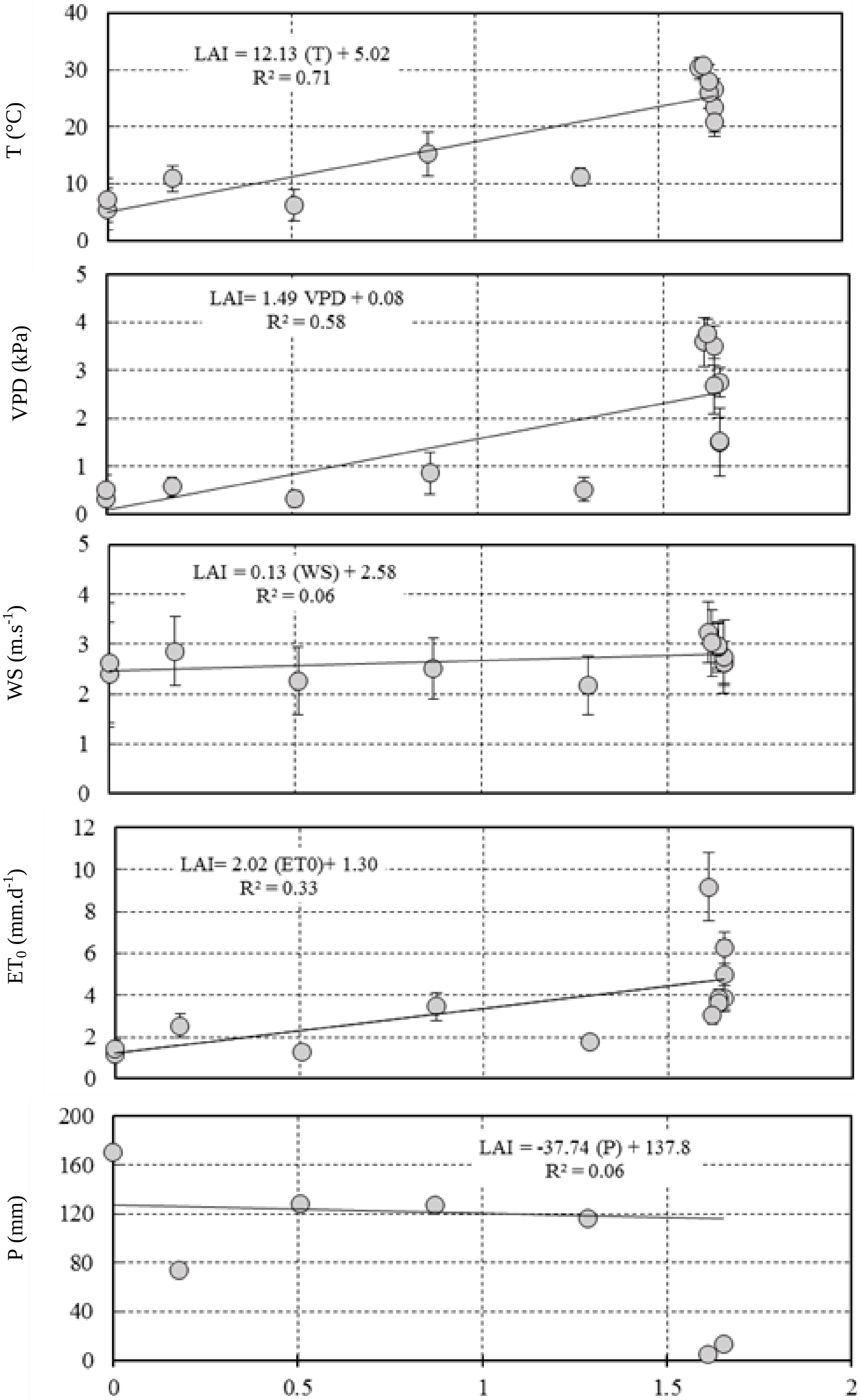

Figure 6. Relationships between Leaf Area Index (LAI) (horizontal axis) and meteorological parameters for the study period (August 2015-August 2016). Symbols on *Y*-axis are defined previously. Bars are standard error of mean.

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increase in T and minor change in VPD after 2010 were detected in the study site suggesting a possible increase in the length of growing season in the Zagros forests. Increasing growing-season length is a logical response to warmer spring and fall T in temperate regions where the growing season is confined to the period when T remains above freezing (Huntington, 2006). Advances in the timing of many plant phenological events in the Northern Hemisphere (Menzel and Fabian, 1999; Schwartz and Reiter, 2000; Parmesan and Yohe, 2003) strongly point to increases in growing-season length. Under changing temperature induced by global warming, leaf-out and leaf-fall of oak trees in the Zagros forests are early and delayed. It is also important to mention that the decline in tree transpiration is typically inconsistent with the timing of leaf-fall (Yoshifuji *et al*., 2006). It means that, at the end of the growing season, decline in transpiration definitely coincides with decreasing T, however, LAI declining starts with a delay. The lack of transpiration during the canopy duration means that the tree leaves are not active in photosynthesis and latent heat exchange; however, this period may be effective in maintaining the albedo and roughness of the vegetated surfaces (Yoshifuji *et al*., 2006). An important result of the difference between the period of leaf physiological processes and physical presence of leaves is that the net annual carbon exchange of ecosystems will not be correlated with the canopy duration but with the carbon uptake period (White and Nemani, 2003). Although radiant energy in spring and fall is relatively small in the Zagros forests compared with tropical forests, this implies that the Zagros forests are also sensitive to change in growing season length in terms of carbon and hydrological cycling.

The oak trees in the Zagros forests have been in decline since 2000 and one of the major hypotheses in decline of the oak trees in Iran is variations in meteorological parameters in recent years (Attarod *et al*., 2016). Oak trees will unquestionably experience reduction in the available water because of increased evaporative loss due to the change in growing season length since the length of the growing season has increased substantially, proposing that ET has been affected (Huntington, 2006). This preliminary research revealed a significant relationship between canopy duration of oak trees in the Zagros forests and T. The results of this research can usefully be applied for explaining the oak decline phenomenon to be partly related to climate change and, in particular, rise in T.

CONCLUSIONS

Maximum leaf area index value was recorded as 1.6, when oak trees were fully-leafed approximately 180 days per year during May-October and temperature was about 26°C with vapor pressure deficit of 2.6 kPa. Leaf area index of oak trees grown in the Zagros forests of western Iran showed significant correlations with air temperature and vapor pressure deficit. We concluded that air temperature is the most effective meteorological parameter controlling the leaf burst and shedding phenomena. Any change in annual temperature related to changing climate can have profound effects on the beginning and ending leaf developmental stages of oak trees in the Zagros forest, west of Iran.

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تغییر پذیری شاخص سطح برگ درختان بلوط ایرانی نسبت به تغییرات اقلیمی

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چکیده

هدف تحقیق حاضر یافتن مهمترین متغیرهای اقلیمی تاثیرگذار بر تغییرات شاخص سطح برگ درختان بلوط ایرانی (*Quercus brantii* var. *persica*) در ناحیه رویشی زاگرس در غرب ایران بود. بدین منظور، تغییرات سالانه تاج پوشش تک درختان بلوط ایرانی به وسیله دوربین چشم ماهی در طول یک‌سال از تابستان ۱۳۹۴ تا تابستان ۱۳۹۵ اندازه‌گیری شد. پارامترهای اقلیمی دما، بارش و سرعت باد از نزدیکترین ایستگاه هواشناسی، ثبت شده در طی سال‌های ۱۳۶۵ تا ۱۳۹۵، بدست آمدند. معادله ترکیبی پنمن مانتیث جهت محاسبه تبخیر تعرق مبنای روزانه (ET_0) و آزمون غیر پارامتری من کندال جهت آزمون معنی‌داری روند پارامترهای اقلیمی و تبخیر تعرق مبنا مورد استفاده قرار گرفتند. در طی دوره مطالعه، شاخص سطح برگ از صفر در دوره بدون برگ (با شاخص سطح چوب ۰/۸۸) تا ۱/۶۵ در دوره برگ‌دار تغییر کرد. شاخص سطح برگ همبستگی قوی و خطی با دما (R^2=۰/۷۱)، نقصان فشار بخار (R^2=۰/۵۸) و تبخیر تعرق مبنا (R^2=۰/۳۳) نشان داد به طوری‌که شاخص سطح برگ بیشتر، در روزهای گرم‌تر، خشک‌تر و با تبخیر تعرق مبنای بیشتر مشاهده شد. آزمون من کندال تغییرات درازمدت دما (Z_{MK}=۰/۰۴۴) و نقصان فشار بخار (Z_{MK}=۰/۲۰۷) را در فاصله سال‌های ۹۵-۱۳۶۵ معنی دار نشان نداد. بالارفتن دمای هوا ناشی از پدیده تغییر اقلیم یکی از فرضیات خشکیدگی درختان بلوط ایرانی در ناحیه رویشی زاگرس است و نتایج تحقیق حاضر نیز ارتباط بین شاخص سطح برگ درختان بلوط ایرانی و دما را تصدیق کرد.

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