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How is climate change impacting net primary production and reference evapotranspiration in the Zagros region of western Iran?

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ABSTRACT
We assessed how climate change may impact net primary production (NPP) and reference evapotranspiration (ET_0) from the Zagros region of western Iran covered extensively by oak, -*Quercus branti* Lindl. forests. The daily meteorological parameters of temperature (T), precipitation (P), relative humidity (RH), wind speed (WS), and sunshine hours were obtained from 20 meteorological stations throughout the region over a 30-year period (1988-2017). Net primary production and ET_0 were estimated by the synthetic and the FAO Penman-Monteith models, respectively. A non-dimensional relative sensitivity coefficient was used to examine the sensitivity of NPP and ET_0 to changes in the meteorological parameters. The sensitivity analyses were carried out for T, P, and WS within a possible range of ± 10%, ± 30%, and ± 10%, respectively, from the long-term mean. Except for the P with no notable trend, other meteorological parameters exhibited upward or downward trends. The mean NPP and ET_0 values were estimated to be 6.5 t ha^{-1} y^{-1} and 3.9 mm d^{-1} across the Zagros region, respectively. Net primary production was found to be more sensitive to precipitation with a sensitivity coefficient of 0.66 and less sensitive to temperature with a sensitivity coefficient of 0.40. The ET_0 sensitivity coefficients in response to T changes doubled relative to WS (0.33 against 0.63). Identifying the contributing factors in NPP and ET_0 trends is important for understanding the relative impacts of climate change and human activities in arid and semi-arid regions.

Keywords: FAO Penman-Monteith model, Sensitivity analyses, Synthetic model.
Article type: Research Article.

INTRODUCTION
Anthropogenic and climatologic changes transform the land surface in many ways that affect the fluxes of energy and trace gases between land and atmosphere. Human emissions change the chemical composition of the atmosphere, and climate change poses a fundamental threat to places, species, and people's livelihoods. Feedback loops among all these processes couple land, the atmosphere, and biogeochemical cycles of nutrients and trace gases extending the human and climate influences even further (Suni *et al.* 2015). To adequately address these changes, we must urgently prepare for the consequences of global warming. Vegetation is a major component of the global carbon cycle since it regulates carbon dioxide (CO_2) via exchange of energy and water (Zhu *et al.* 2013). Net primary production (NPP) is the rate at which vegetation in an ecosystem fixes CO_2 from the

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atmosphere (gross primary production, GPP) minus the rate at which the vegetation returns CO_2 to the atmosphere through plant respiration. In this way, NPP is linked to, and impacted by, the climatic consequences of rising concentrations in atmospheric CO_2 and other greenhouse gases (Fu *et al.* 2016). Quantifying NPP and its interactions with climate factors is therefore a necessary endeavor to improve understanding C cycling dynamics (Yang *et al.* 2017). The water loss through the exchange of CO_2 by leaf stomata during photosynthesis plus evaporation from soil and plant surfaces is evapotranspiration (ET). ET computes the water lost by a land surface, so it is thus a component of the water balance in a region. Under global environmental change, monitoring variations in NPP and ET is significant in tracking degradation in ecosystem services (FAO 2014). Global warming may induce a general acceleration or intensification of the global hydrological cycle and thus an alteration in the ET process (Wentz *et al.* 2007; Douville *et al.* 2013) and impacts to ecosystem services (Field *et al.* 2007; Jung *et al.* 2010; Davie *et al.* 2013). Yet, how vegetation is responding to the changing climate is not well understood (Li *et al.* 2016) and understanding the interactions between the carbon and water cycles has been known as one of the gaps in global change research (Ehleringer *et al.* 2000; Pereira *et al.* 2004; Jackson *et al.* 2005). Ecosystem productivity and water use (i.e., evapotranspiration, ET) are coupled at multiple scales (Chapin *et al.* 2002; Waring & Running 2007). Vegetation can respond to water stress in several ways, such as, increasing water uptake from soil (Hsiao 1973; Waring & Running 2007). Determining the functional responses of plants to water stress is still one of the most complex issues in plant stress biology (Bray 1997). In order to respond to global environmental change with sound land management practices, there must be a clear understanding of how multiple stresses affect all ecosystem processes. The rise of greenhouse gases concentrations, such as CO_2, is primarily the result of anthropogenic forcing on the climate system, and this anthropogenic increase in CO_2 can also have profound impacts on regional ecosystems, such as the Zagros forests of western Iran (Safaei *et al.* 2021). These forests are mostly dominated by stands of Brant`s oak, *Quercus brantii* Lindl. (Sagheb Talebi *et al.* 2014; Rashidi Tazhan *et al.* 2019; Karim *et al.* 2020; Bagheri *et al.* 2020; Gheibi *et al.* 2021; Attarod *et al.* 2023). Although the Zagros forests provide various ecosystem services, including water resources, soil conservation, carbon sequestration, timber, wildlife habitat, and air purification, the region has been impacted by climate change and land use changes during the past couple of decades (Heidarlou *et al.* 2019; Japelaghi *et al.* 2019; Heidarlou *et al.* 2020; Mosavi *et al.* 2020; Sharifi *et al.* 2021). Oak trees have been in decline since 2002 (Pourhashemi *et al.* 2017), and Iranian forest managers believe that one of the potential drivers of the decline of oak trees in this region is changes in meteorological parameters due to climate change in recent years (Attarod *et al.* 2016). The oak forest decline in upper watersheds of the Zagros forests resulting from climate change directly impacts downstream water users by increasing overall soil erosion (Doulabian *et al.* 2021), increasing sedimentation in reservoirs (Azari *et al.* 2021), increasing demand for irrigated agriculture (Mosavi *et al.* 2020), and increasing the need for communities to adapt to water shortage (Pakmehr *et al.* 2020; Chenani *et al*. 2021). Research has mainly emphasized the impacts of climate change on vegetation, and some research on feedback of terrestrial ecosystems to climate change has focused on their potential role as carbon sources (Field *et al.* 2007). Fewer studies, however, explored the effects of inter-annual variability of vegetation on land surface processes, such as evapotranspiration (Zhi *et al.* 2009). Quantifying the impacts of climate change and anthropogenic activities on Zagros region is an essential step for developing sustainable region ecosystem management strategies under the background of climate change and increasing anthropogenic activities occurring in the Zagros. However, it is difficult to effectively separate these two main factors (Chen *et al.* 2014). Therefore, the main questions addressed in this study were (i) how has NPP and ET in the Zagros region trended over the past 30 years in the context of global warming and (ii) was there a geographic pattern to sensitivities coefficients of ET and NPP to the expected changes climatic parameters during this period. We hypothesized that NPP would decrease and ET would increase with diminished precipitation and increased temperature during the 30-year period. Also, we hypothesized that sensitivity coefficients of NPP and ET for climatic parameters would be uniformly consistent throughout the Zagros forest region. We test these hypotheses using established models of NPP and ET measurement and long-term climate data from 20 weather stations within the Zagros forest region. The Zagros region in west of Iran is claimed to be sensitive and vulnerable to climate change and anthropogenic activities.

MATERIALS AND METHODS

Study area

The research was conducted in the Zagros region of western Iran. The Zagros region consists of the western and southern slopes of the Zagros Mountains, which run from northwest to southeast, from the Turkish border to the

Persian Gulf. Elevation ranges from 200 to 4,500 m. The mean annual precipitation varies between 250 and 800 mm. The Zagros forests primarily consist of oak species covering a vast area of the Zagros Mountains with an average length and width of 1,300 and 200 km, respectively (Fig. 1). Classified as semi-arid forests, the Zagros forests have an area of approximately six million ha and account for almost 44% of Iran's forests (Sagheb Talebi *et al.* 2014). These forests are most important with respect to water supply, soil conservation, climate change, and the socio-economical balance of the entire country. In this region, the average annual precipitation (P) varies between 400 and 800 mm, while the mean annual air temperature (T) ranges from 9 ºC to 25 ºC (Fathizadeh *et al.* 2013). Maximum rainfall historically occurs during winter and spring, from January to June. Summers are hot and dry, while winters are cool. Seven rivers that discharge 34.5 billion cubic meters of water and accounting for 40% of the total ground and surface water of the country, form in the Zagros Mountains and flow into the fertile plains in the valleys. The existence of these water resources is directly dependent upon the existence of these forests. High amount of ecosystem services, especially the abundant supply of water, has resulted in a high population density in the region. The population of the region is 9.8 million, of which 1.5 million live inside the forested areas, extensively modifying the ecosystem (Sagheb Talebi *et al.* 2014).

Meteorological data

Meteorological data recorded by 20 synoptic meteorological stations distributed across the Zagros region were selected (Fig. 1). These 20 meteorological stations were the closest synoptic stations to the Zagros forests. The range in meteorological data records is from 1988 to 2017.

Evapotranspiration and net primary production models

We used the FAO Penman-Monteith (PM) combination equation to calculate daily reference evapotranspiration (ET_0). It is the standard method proposed by the International Commission for Irrigation and Drainage (ICID) and Food and Agriculture Organization of the United Nations (FAO). The PM equation calculates daily ET_0 with the assumption that the reference crop evapotranspiration is a hypothetical crop with a uniform height of 0.12 m, a surface resistance of 70 s m^{-1} and an albedo of 0.23, closely resembling the evaporation of an extension surface of green grass actively growing and adequately watered (Allen *et al.* 1998). Daily ET_0 is calculated as:

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

where, ET_0 (mm day^{-1}) is the reference ET; R_n (MJ m^{-2} day^{-1}) is the net radiation at the crop surface; G (MJ m^{-2} day^{-1}) is the soil heat flux density; T (°C) is the mean daily air 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 air temperature; and γ (kPa $°C^{-1}$) is the psychrometric constant calculated as 0.665×10^{-3} AP; in which AP (kPa) is the atmospheric pressure. Due to the absence of solar radiation measurements in the measurement sites, the calculation procedure using sunshine duration as a primary input, as suggested by Allen *et al.* (1998) was used for computing the net radiation. G at the daily scale beneath the grass reference surface was relatively small and thus could be ignored in the PM combination equation (Goyal 2004; Maruyama *et al.* 2004). Therefore, G= 0 MJ m^{-2} day^{-1}. To calculate the wind speed at 2 m above the surface, the wind speed data were converted by the following equation recommended by FAO (Allen *et al.* 1998).

$$u_z = u_2\,[4.87/\ln(67.8z - 5.42)] \qquad \textbf{(2)}$$

where u_2 is the wind speed at 2 m above ground surface (m s^{-1}), u_z is the measured wind speed at z m above ground surface (m s^{-1}), and z is the height of measurement above ground surface (m). Annual NPP in units of t ha y^{-1} was simulated using the synthetic model (Gang *et al.* 2013). The model was based on actual evapotranspiration (AET) which was closely related to the photosynthesis of vegetation, and was established mainly on the biomass data from 125 sets of natural mature forest in China and 23 sets of natural vegetation NPP that included forest, grassland, and desert. This model integrated the interaction among many variables satisfied by Equations 3-5:

$$NPP = RDI^2 \times \frac{MAP \times (1 + RDI + RDI^2)}{(1+RDI)(1+RDI^2)} \times \exp[-\sqrt{(9.87 + 6.25\,RDI)}] \times 100 \qquad \textbf{(3)}$$

$$RDI = (0.629 + 0.237\,PER - 0.00313\,PER^2)^2 \qquad \textbf{(4)}$$

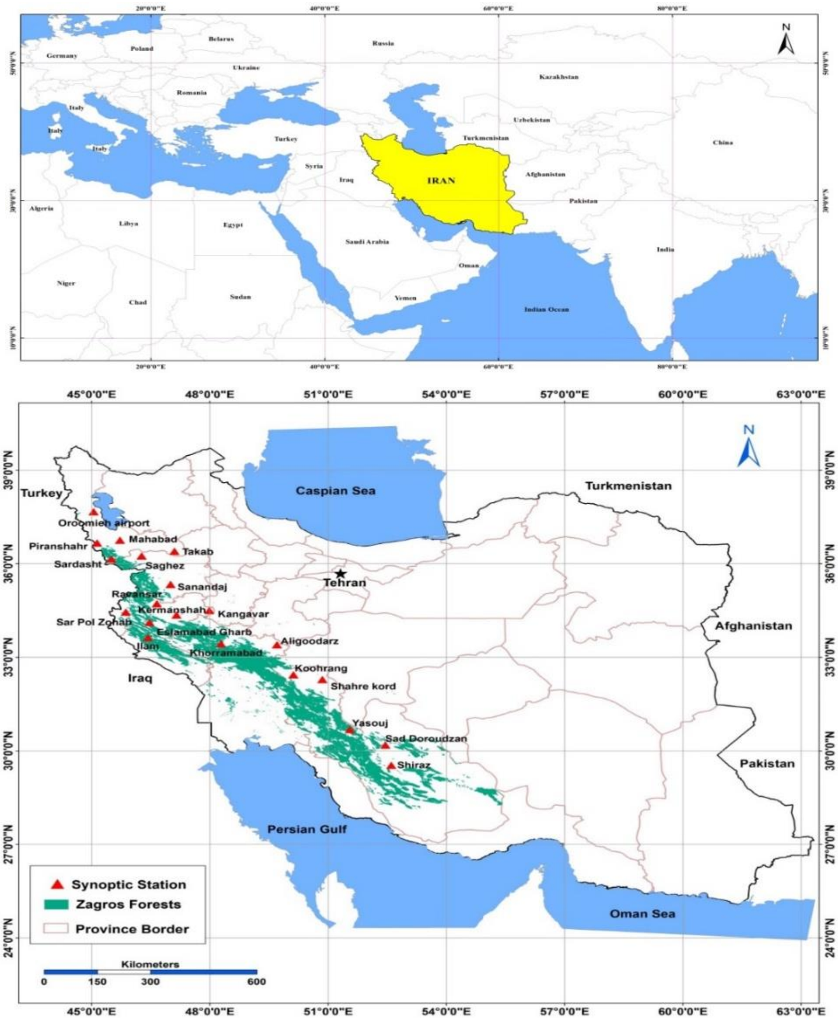

Fig. 1. Positions of the 20 selected synoptic weather stations in the Zagros region in western Iran.

$$PER = \frac{PET}{MAP} = \frac{BT \times 58.93}{MAP} \quad \textbf{(5)}$$

where MAP is mean annual precipitation (mm), RDI is the radiative dryness index which can be calculated by the rate of evapotranspiration (PER). PET is potential evapotranspiration (mm), and BT is biological temperature which is the average temperature (0~30°C) during the vegetative growth of plant.

Net primary production and reference evapotranspiration sensitivity coefficients

A practical method of presenting a sensitivity analysis is to plot relative changes of a dependent variable (here, NPP or ET_0) against relative change of an independent variable (i.e., precipitation, temperature, and wind speed) as a curve (e.g., Singh & Xu 1997; Goyal 2004; Attarod *et al.* 2015, 2018, 2020). We calculated the mean sensitivity coefficient as the slope of the relationship between the percent changes in NPP or ET_0 against the percent changes in temperature, precipitation, and wind speed (Fig. 2 as an example).

Clearly, the larger the sensitivity coefficient, the larger the effect an independent variable has on the dependent variable. Net primary production variations were examined between +30% to -30% for annual precipitation and +10% to -10% for air temperature. However, for the estimation of ET_0 sensitivity, both air temperature and wind speed were altered between +10% and -10%. Temperature, precipitation, and wind speed are the most significant driving factors that control the ET_0 and NPP.

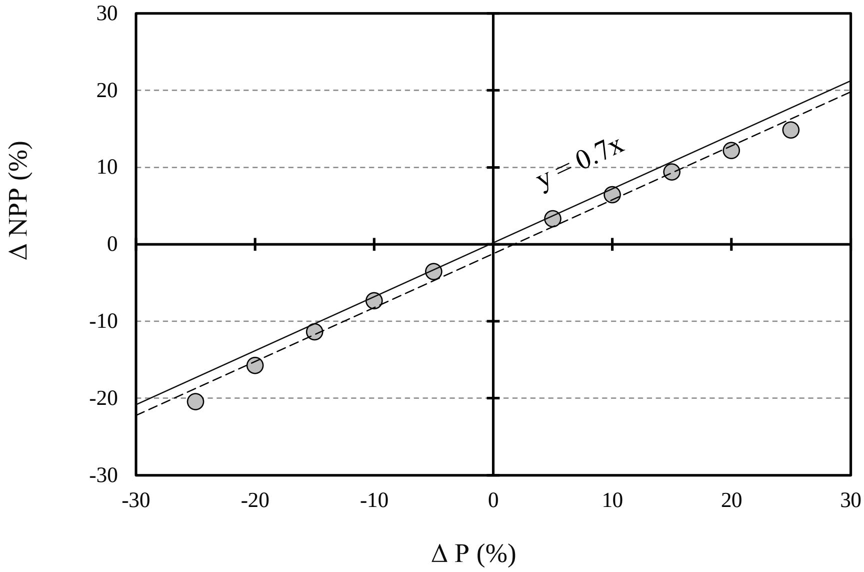

Fig. 2. An example of plotting the percent change in precipitation (ΔP) to percent change in net primary production (ΔNPP) as a regression calculated where the slope is a non-dimensional coefficient of sensitivity.

Statistical test for trend analysis

The trend analysis was performed on an annual timescale using the Mann–Kendall (MK) test. It is a non-parametric test for identifying trends in time series data (Mann 1945). The test is also highly recommended for general use by the World Meteorological Organization (Zhang *et al.* 2009). It is simple and robust and has low sensitivity to abrupt breaks due to homogeneous time series (Jaagus 2006). A positive Mann-Kendall statistic (Z_{MK}) indicated an upward trend in the time series, while a negative Z_{MK} statistic indicated a downward trend. Testing the trend was performed at the specific α significance level. When $|Z_{MK}| > Z_{(1-\propto/2)}$, the null hypothesis was rejected, and a significant trend existed in the time series. $Z_{(1-\propto/2)}$ was obtained from the standard normal distribution table (Karandish *et al.* 2016). In this study, significance levels of $\propto = 0.01$ and 0.05 were applied. The critical values of $Z_{(1-\propto/2)}$ for p-values of 0.05 and 0.01 from the standard normal table are 1.96 and 2.58, respectively.

RESULTS AND DISCUSSION

30-year values and trends of meteorological parameters

Mean annual temperature and precipitation ranged widely from 20.4 °C (Sar Pol Zohab) to 9.7 °C (Takab), and from 308 mm (Oroomieh airport) to 1335 mm (Koohrang), respectively (Table 1). Wind speed varied broadly from 1.4 m s^{-1} (Yasouj) to 3.9 m s^{-1} (Aligoodarz). Highest standard deviations were observed for annual temperature and precipitation in Kangavar (1.3 °C) and Koohrang (373.4 mm), respectively (Table 1). Our 30-year data showed that mean annual temperature, precipitation, relative humidity, wind speed, and sunshine hour are 14.3 °C, 510 mm, 47.0%, 2.2 m s^{-1}, and 8.3 h, respectively, across all measurement sites in the Zagros region. The 'de Martonne' climate classification, as described by Croitoru (2013) and calculated based on annual temperature and precipitation, demonstrated wide-ranging values from 66.5 (Koohrang, extremely humid) to 11.2 (Shiraz, semi-arid). Sixty five percent of stations (13 stations out of 20 stations in total) indicated the semi-arid climate type. Using the average I_{DM} (21.5), the climate classification categorized for the Zagros region was in the Mediterranean climate type, although there was a large variation reported (standard deviation = 12.5; Table 1).

Statistically increasing significant trends were detected for the annual air temperature in 13 out of 20 stations (Table 1). However, for wind speed, statistically significant increasing and decreasing trends were observed for 12 and 2 stations, respectively (Table 1). By combining the daily meteorological data of 20 stations located in the Zagros region, we found a significant increasing trend for temperature (Z=2.75**) and wind speed (Z=4.96***), however, precipitation did not exhibit a statistically significant trend (Z =-1.93). Moreover, relative humidity and sunshine hours represented decreasing (Z=-2.39*) and increasing (Z=2.32*) trends, respectively.

Table 1. Long-term (1988-2017) annual average and standard deviation (± SD) of meteorological parameters recorded by the synoptic meteorological stations distributed over the Zagros region, western Iran and their climate types according to the de Martonne aridity index (I_{DM}; Croitoru *et al.* 2013). I_{DM} is an 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 ($35 \leq I_{DM} \leq 55$), and Extremely humid ($I_{DM} > 55$).

Station	Elevation (m asl)	Temperature (°C)	Precipitation (mm)	Relative humidity (%)	Wind speed (m s^{-1})	Sunshine hour (h)	Values of I_{DM} (Climate type)
Aliogoodarz	2022	13.1 ± 0.7	388 ± 105	**40 ± 2	*3.9 ± 0.9	8.8 ± 0.3	16.7 (Semi-arid)
Eslam Abad Gharb	1348.8	14.2 ± 0.9	461 ±109	50 ± 3	**2.0 ± 0.6	8.4 ± 0.4	19.1 (Semi-arid)
Ilam	1337	17.0 ± 0.8	561 ± 158	40 ± 2	**2.3 ± 0.5	8.5 ± 0.3	20.8 (Mediterranean)
Kangavar	1468	**13.1 ± 1.3	391 ± 90	51 ± 2	*1.8 ± 0.4	*8.0 ± 1.1	16.9 (Semi-arid)
Kermanshah	1318.6	**15.6 ± 0.8	410 ± 95	**43 ± 3	**2.5 ± 0.3	8.0 ± 0.4	16.0 (Semi-arid)
Khorramabad	1147.8	**16.9 ± 0.9	468 ± 124	**45 ± 4	*2.0 ± 0.6	8.3 ± 0.4	17.4 (Semi-arid)
Koohrang	2285	*10.1 ± 0.9	1335 ± 373	*44 ± 3	1.5 ± 0.3	8.0 ± 0.3	66.5 (Extremely humid)
Mahabad	1351.8	**13.3 ± 0.9	398 ± 101	**51 ± 4	**2.2 ± 0.5	7.7 ± 1.2	17.1 (Semi-arid)
Oroomieh airport	1328	**11.7 ± 0.8	308 ± 95	59 ± 3	**2.0 ± 0.7	*7.9 ± 0.7	14.2 (Semi-arid)
Piranshahr	1455	**13.4 ± 1.0	652 ± 165	52 ± 4	**2.2 ± 0.5	*7.8 ± 0.4	27.9 (Semi-humid)
Ravansar	1379.9	*15.3 ± 0.7	508 ± 109	44 ± 3	**2.6 ± 0.5	8.3 ± 0.3	20.1 (Mediterranean)
Sad Doroudzan	1652	**18.5 ± 0.9	**460 ± 150	*41 ± 4	**2.3 ± 0.6	9.0 ± 0.3	16.2 (Semi-arid)
Saghez	1522.8	11.3 ± 0.9	445 ± 123	54 ± 3	2.3 ± 0.5	**8.2 ± 0.3	20.9 (Mediterranean)
Sanandaj	1373.4	**14.1 ± 0.8	**377 ± 92	**47 ± 2	*2.0 ± 0.3	**8.2 ± 0.3	15.7 (Semi-arid)
Sardasht	1670	**13.4 ± 1.2	834 ± 205	*51 ± 6	**3.3 ± 0.8	8.1 ± 0.4	35.6 (Very humid)
Sar Pol Zohab	545	20.4 ± 0.8	**413 ± 86	46 ± 2	1.8 ± 0.7	8.4 ± 0.4	13.6 (Semi-arid)
Shahre Kord	2048.9	11.7 ± 0.7	320 ± 95	*45 ± 3	**1.8 ± 0.7	8.8 ± 0.2	14.8 (Semi-arid)
Shiraz	1484	*18.9 ± 0.6	*323 ± 112	**38 ± 3	1.9 ± 0.3	9.2 ± 0.3	11.2 (Semi-arid)
Takab	1817.2	**9.7 ± 0.9	344 ± 134	54 ± 3	2.1 ± 0.4	*7.3 ± 2.0	17.4 (Semi-arid)
Yasouj	1816.3	15.0 ± 0.7	797 ± 225	44 ± 5	1.4 ± 0.4	*8.8 ± 0.3	31.8 (Humid)
Mean		14.3 ± 2.9	510 ± 243	47 ± 5	2.2 ± 0.6	8.3 ± 0.5	21.5 ± 12.2
+ Trend number (sig)		17 (13)	2 (0)	4 (1)	15 (12)	16 (7)	

- Trend number (sig)	3 (0)	18 (4)	16 (9)	5 (2)	4 (0)

*Trends statistically significant at the 95% confidence level; **Trends statistically significant at the 99% confidence level.

Twenty meteorological stations represented by different climate types in the Zagros regions were selected to determine how changes in mean meteorological variables are impacting NPP and ET_0. On the annual time scale, the data were analyzed to compute trends of temperature, precipitation, relative humidity, wind speed, and sunshine hours in the Zagros region. Thirteen out of twenty stations displayed an increasing trend for temperature; however, precipitation exhibited no notable trend at almost all stations, except for 4 stations in which there was a negative trend. More than half of the stations showed increasing trends of wind speed. Overall, 48 significant increasing and decreasing trends, out of 100 trends, i.e. five variables multiply by twenty stations, were detected when all weather data recorded at the whole meteorological stations were considered concluding that the approximately 50% of the whole meteorological parameters were affected by climate change throughout the Zagros region during the 30-year period. Other studies detected similar results related to meteorological trends in the Zagros region. For instance, Attarod *et al.* (2016) reported similar increasing/decreasing trends with fewer numbers of weather stations for the same meteorological variables in the Zagros region. Similar trends in mean meteorological variables have been reported in other places of the world. For example, increasing trends in mean temperature have been reported in southern Spain (0.16°C- 0.40°C per decade; Espadafor *et al.* 2011) and France (0.2°C- 0.41°C per decade; Chaouche *et al.* 2010). At the global scale, the temperature increase over the last century was 0.74°C (IPCC 2007). This warming climate has led to increased potential evapotranspiration and increased irrigation demands in regions with shortage of rainfall (Chattopadhyay & Hulme 1997). Ghahraman & Taghvaeian (2008) reported significant decreases in annual rainfall over the northwest of Iran using the linear regression method. These decreasing trends in precipitation and relative humidity suggest a shift towards a much drier climate, which may cause a greater atmospheric water demand and, consequently, an increase in vegetation water demand in the Zagros region (Wang *et al.* 2014).

Net primary production and evapotranspiration

Net primary production, calculated by the synthetic model, varied extensively from 4.5 t ha^{-1} y^{-1} in Takab with a semi-arid climate to 9.4 t ha^{-1} y^{-1} in Koohrang with an extremely humid climate. However, the mean NPP value (± SD) across Zagros region was estimated to be 6.5 t ha^{-1} y^{-1} (± 1.4). Generally, highest standard deviations were observed for annual NPP in the semi-arid locations of Shiraz and Sad Doroudzan (2.0 t ha^{-1} y^{-1}; Fig. 3). Maximum ET_0 was observed in Aligoodarz and Sad Doroudzan (4.7 mm d^{-1}), and minimum ET_0 was observed in Takab and Oroomieh airport (3.2 mm d^{-1}). The mean ET_0 value across the Zagros region was estimated to be 3.9 mm d^{-1} (SD = ± 0.5) and, similar to NPP, 55% of stations exhibited ET_0 to be less than the mean value (Fig. 4).

Table 2. Values of Z statistic of the Mann–Kendall test for net primary production (NPP) and reference evapotranspiration (ET_0) during from 1988 to 2017.

Station	NPP	ET_0	Station	NPP	ET_0
Aliogoodarz	-0.89	1.28	Ravansar	-0.96	-1.78
Eslam Abad Gharb	-0.78	3.39**	Sad Doroudzan	-2.92**	3.14**
Ilam	-1.68	3.35**	Saghez	-0.32	2.35*
Kangavar	-0.03	4.28**	Sanandaj	-2.32*	3.21**
Kermanshah	-1.53	5.14**	Sardasht	1.29	2.03*
Khorramabad	-0.68	2.85**	Sar Pol Zohab	-2.78**	1.32
Koohrang	-1.53	-2.43*	Shahre Kord	-0.75	4.42**
Mahabad	-0.32	5.10**	Shiraz	-2.14*	-0.18
Oroomieh airport	0.85	5.39**	Takab	-0.39	2.46*
Piranshahr	1.28	3.14**	Yasouj	-1.93	1.57

**Trends statistically significant at the 99% confidence level; *Trends statistically significant at the 95% confidence level.

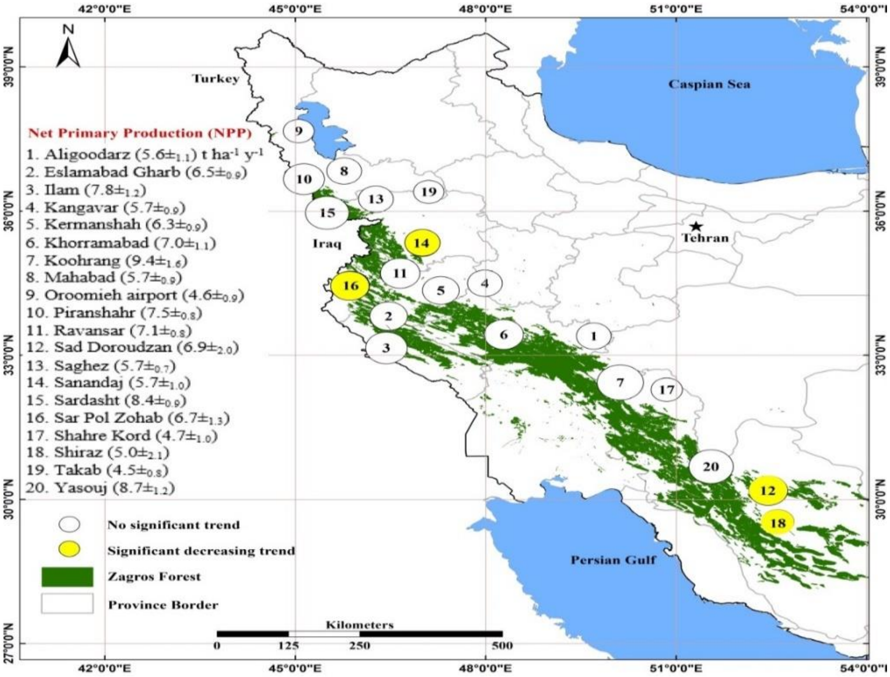

Fig. 3. Mean annual net primary production (NPP ± SD) for the meteorological stations throughout the Zagros region, west of Iran. The size of circles represents the magnitude of NPP. White and yellow circles represent the no significant and significant decreasing trends, respectively.

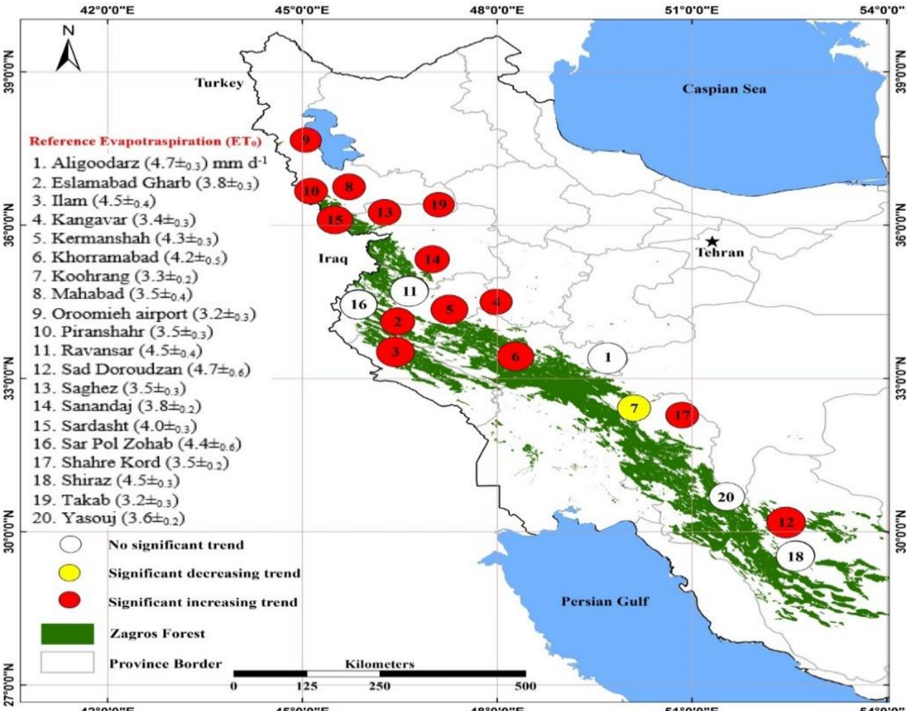

Fig. 4. Mean daily reference evapotranspiration (ET_0 ± SD) for the meteorological stations throughout the Zagros region in western Iran. The size of circles represents the magnitude of ET_0. White, yellow, and red circles represent the no significant, significant decreasing trends, and significant increasing trends, respectively.

We found that trends of NPP over a 30-year period from 1988 to 2017 were significantly decreasing at the 95% confidence level for only four stations with the semi-arid climate type (Sanandaj, Sar Pol Zohab, Shiraz, Sad Doroudzan; Table 2). Nevertheless, ET_0 from 14 stations presented significant increasing trends while only one station (Koohrang) had a significant decreasing trend at the 95% confidence level (Table 2). When the entire data of weather stations throughout the Zagros region were combined, a significant increasing trend was detected by the Mann-Kendall test for ET_0 ($Z = 4.0$***); however, NPP showed no statistically significant trend ($Z = -1.64$).

Climate change played a crucial role in influencing NPP of Zagros region. In the semi-arid climate, NPP was found to be more sensitive to precipitation rather than temperature, though NPP was positively affected by both meteorological variables. Increases in precipitation are known to have a positive influence on NPP (Lauenroth & Sala 1992; Briggs & Knapp 1995), but NPP-temperature relationship has been studied much less frequently (Ye *et al.* 2013). The positive effect of temperature on NPP is unexpected since greater temperatures minimize water availability and as a result has a negative impact on productivity (Bradford *et al.* 2006). This positive effect is difficult to explain simply as a composite effect of different ecosystems (Mohamed *et al.* 2004). However, much more research is needed to tease-out the inherent complexity of these systems. The trends of ET_0 for the majority of stations (70% of whole stations) were increasing. The increasing trend in evaporation could be the result of an increasing trend of temperature and a decreasing trend in relative humidity (Zeleňáková *et al.* 2018). Dinpashoh *et al.* (2011) pointed out that the increasing trend in annual ET_0 in the northwestern Iran looks to be the combined effect of increasing trends in monthly ET_0 values in April, May, and June.

Sensitivity of net primary production and evapotranspiration to changing climatic parameters

There were large fluctuations in sensitivity coefficients for NPP in response to changing precipitation ranging from 0.47 for Sardasht (very humid climate) to 1.09 for Shiraz (semi-arid climate; Fig. 5). The NPP sensitivity coefficients to changing precipitation were higher than the mean sensitivity coefficient value (0.66) for 40% of all stations (Fig. 5). Our analysis displayed that NPP of the humid (extremely humid, humid, semi-humid, and very humid climates) and Mediterranean climate types were less sensitive to changing precipitation compared to the semi-arid climate (Table 3). Net primary production showed varying degrees of sensitivity to changing temperature from 0.08 to 0.72. Only one station (Shiraz), located in the semi-arid climate type, presented a NPP sensitivity coefficient <0 in response to changing temperature (-0.08; Fig. 5). The semi-arid climate type had smaller NPP sensitivity coefficients in response to changing temperature (mean value: 0.32) compared to other climates (0.48; Table 3). In general, NPP in the Zagros region was found to be more sensitive to precipitation (mean ± standard deviation: 0.66 ± 0.15) relative to temperature (mean ± standard deviation: 0.40 ± 0.17; Fig. 5).

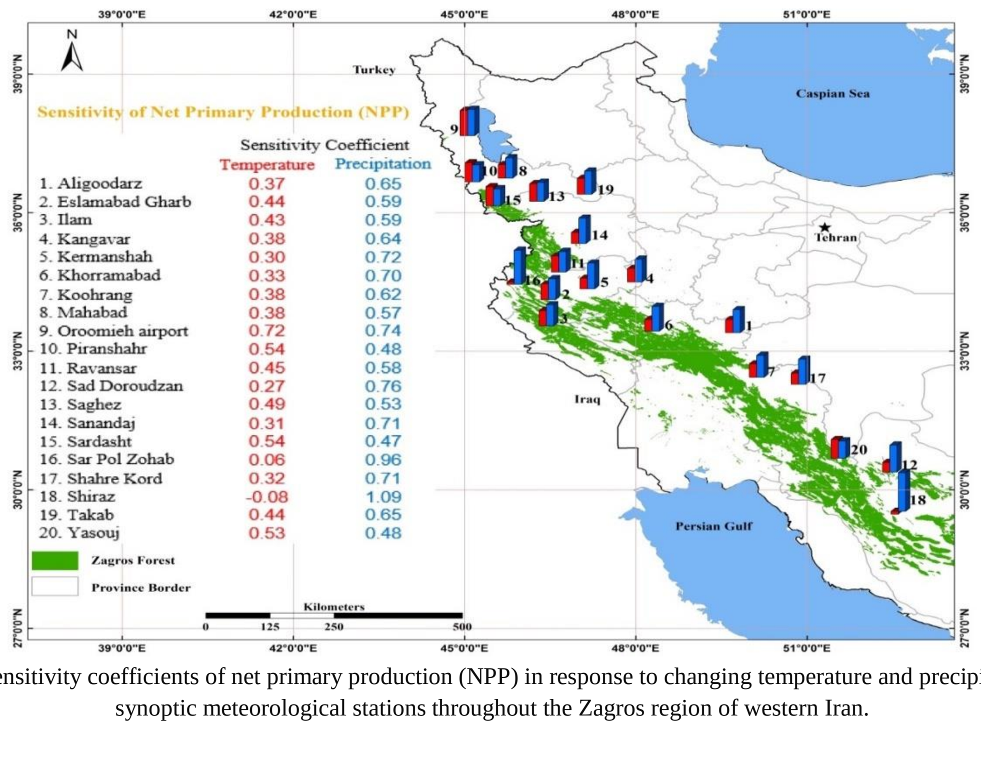

Fig. 5. Sensitivity coefficients of net primary production (NPP) in response to changing temperature and precipitation for synoptic meteorological stations throughout the Zagros region of western Iran.

In general, ET_0 was more sensitive to change in temperature (0.63) relative to wind speed (0.33) throughout the Zagros region (Fig. 6). The sensitivity coefficients of ET_0 in response to both temperature and wind speed were positive in all stations (Fig. 6). The maximum sensitivity coefficient of ET_0 in response to changing temperature was observed in Sar Pol Zohab (0.96) with the semi-arid climate. However, the maximum sensitivity coefficient was detected in Koohrang (1.48) in response to changing wind speed (Fig. 6).

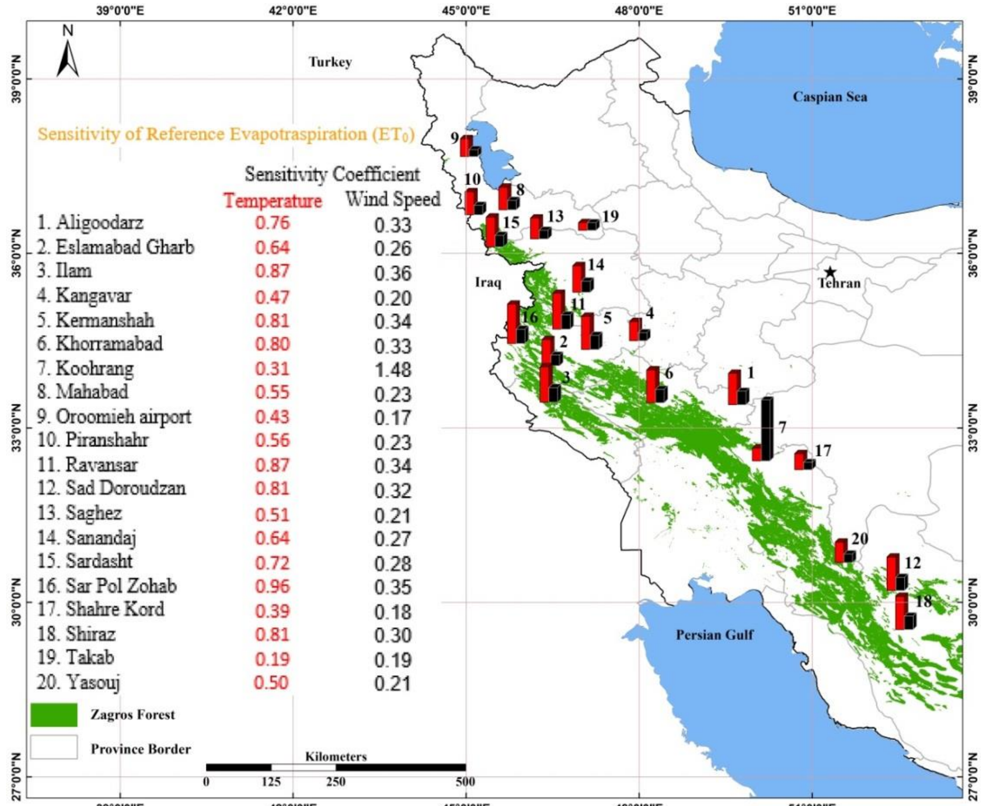

Fig. 6. Sensitivity coefficients of reference evapotranspiration (ET_0) in response to changing temperature and wind speed for the synoptic meteorological stations throughout the Zagros region of western Iran.

The ET_0 values were less sensitive to changing temperature in humid climates relative to the semi-arid and Mediterranean climates (0.52 for the humid against 0.75 for the Mediterranean and 0.63 for the semi-arid climates; Table 3). However, changing wind speed exhibited higher impact on ET from the humid climate (0.55) compared to the semi-arid (0.27), as well as to the Mediterranean climate (0.31; Table 3).

Table 3. Mean NPP (net primary production) and ET_0 (reference evapotranspiration) sensitivity coefficients to temperature (T), precipitation (P), and wind speed (WS) for diverse climate types in the Zagros region of western Iran.

Climate type	NPP (T)	NPP (P)	ET_0 (T)	ET_0 (WS)
Semi-arid	0.32	0.73	0.63	0.27
Mediterranean	0.46	0.57	0.75	0.31
Humid[1]	0.50	0.51	0.52	0.55

[1]Semi-humid, humid, very humid, and extremely humid climates are combined.

Assessing the factors that have an effect on potential evapotranspiration (PET) sensitivity to changes in different climate variables is imperative to grasp the possible consequences of climatic changes on the catchment water balance. Using a sensitivity analysis, this investigation surveyed the ramifications of baseline climate conditions on the sensitivity of ET_0 to a large range of plausible changes in temperature and wind speed and found that temperature had a greater effect for almost all the stations analysed. The results of our study were consistent with Goyal (2004), who concluded that ET_0 is most sensitive to potential changes in temperature for an arid region in India, by applying a ±20% perturbation on each of temperature, solar radiation, wind speed, and vapor pressure. Likewise, in the relatively semi-humid region of the Haihe River Basin in northern China, Tang *et al.* (2011) showed that ET_0 was most sensitive to temperature and radiation. In contrast, in the arid region of Northwest China, ET_0 was found to be the most sensitive to wind speed, followed by relative humidity, temperature, and radiation (Huo *et al.* 2013). By and large, wind speed, sunshine hours and temperature were the key factors in ET_0 change (Goyal 2004; Tanaka *et al.* 2008; Liang *et al.* 2010; Espadafor *et al.* 2011; Tabari *et al.* 2011; Tang *et al.* 2011). Climatic factors have changed incredibly within the past few decades and affected the ET_0 around the globe (IPCC 2007). For instance, during the last century (1906-2005), global air temperature has increased by 0.74 °C (IPCC 2007), and greenhouse gas emissions equals to or higher than the current exchange rates are expected to cause further warming during the current century (IPCC 2007). Loss of canopy cover from tree mortality has been reported to directly decrease transpiration and canopy interception of precipitation, leading to change in soil moisture and runoff and recharge (Fathizadeh *et al.* 2017; Anderegg *et al.* 2013). On the other hand, forest NPP is strongly influenced by site and climatic conditions, plant attributes and disturbance events (Binkley *et al.* 1997). Nevertheless, it can be concluded that oak mortality in the Zagros region, reported by several studies (Azizi *et al.* 2015; Hossenizadeh & Pourhashemi 2015; Zandebasiri *et al.* 2017; Pourhashemi & Sadeghi 2020) can have substantial indirect and secondary effects on ecophysiological and hydrological processes. However, more research is necessary to better understand the effects of Brant's oak die-back on ecohydrological processes. Research has shown that anthropogenic activities (i.e., land use and land cover change) and climate change are the two main factors that regulate terrestrial ecosystem's productivity (Esser 1987; Field 2001). However, it is currently difficult to effectively separate those (Chen *et al.* 2014). Yet, previous studies have revealed that climate-related factors are among the most important factors affecting vegetation NPP (Yang *et al.* 2017), of which temperature, precipitation, and solar radiation are the three main forces that drive vegetation growth (Richardson *et al.* 2013). Although, some studies have found opposite results. For instance, in the Tibetan Plateau region of China, Luo *et al.* (2018) found that anthropogenic activities had a negative effect on NPP variation, and it was larger than that of climate change, implying that human intervention plays a critical role in mitigating the degenerating ecosystem (Luo *et al.* 2018). Therefore, it is necessary to improve our understanding of the relative contributions of climatic factors and anthropogenic activities to the variation of NPP and ET_0 in the Zagros region. Further studies are needed to effectively isolate the effects of climatic factors and anthropogenic activities through removing the climate influence to identify the human-induced vegetation variation. Impacts of climate change on NPP and water cycle are complex and have great importance, but have been difficult to evaluate. It is, therefore, necessary to take both positive and negative impacts into account so that the uncertainties in addressing the influence of climate change on these parameters could be reduced.

CONCLUSION

NPP and ET are important indicators of ecosystem production potential and ecosystem services which are heavily affected by climate change, Climate change impacts on NPP and ET_0 have not been conclusively determined. Using a 30-year (1988-2017) period of meteorological data, we explored how changes in the meteorological variables (i.e., temperature, precipitation, relative humidity, wind speed, and sunshine hours) are impacting NPP and ET_0 in the Zagros region of western Iran. The studied meteorological parameters were affected by climate change since about 50% of their trends were significantly decreasing or increasing. Precipitation was an exception with no notable trend at almost all stations. Based on the synthetic model and results from semi-arid regions of Zagros, NPP was found to be more sensitive to precipitation and less sensitive to temperature. The mean ET_0 (estimated by the FAO Penman–Monteith equation) trends showed positive trends for most stations which could be the result of an increasing trend in temperature and a decreasing trend in relative humidity. Tree mortality in the Zagros region is assumed to be highly connected with changes in meteorological parameters. The results of this study combined with the further investigations on Zagros tree die-back can help managers to make appropriate decisions.

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