



Research Article

Tree Growth Responses to Climatic Factors: Lessons from Semi-Arid Zagros Oak Forests, Western Iran

Elham Motaharfard¹, Ali Mahdavi^{2*}, Reza Akhavan³, Asghar Falah⁴, Reza Omidipour⁵, and Stockton Maxwell⁶

¹Ph.D. student of Forest Sciences, Dept. of Forest Sciences, Faculty of Agriculture and Natural Resources, Ilam University, I. R. Iran

²Prof., Dept. of Forest Sciences, Faculty of Agriculture and Natural Resources, Ilam University, I. R. Iran

³Associate Prof., Research Institute of Forests and Rangelands, Agricultural Research Education and Extension Organization (AREEO), Tehran, Iran

⁴Prof., Sari Agriculture Sciences and Natural Resource University, Mazandaran, I. R. Iran

⁵Assistant Prof., Dept. of Rangeland and Watershed Management, Faculty of Agriculture, Ilam University, I. R. Iran

⁶Prof., Dept. of Geospatial Science, Radford University, P.O. Box 6938, Radford, VA 24142, United States

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Abstract

The Zagros forest ecosystem, the largest forested region in Iran, is dominated by *Quercus* species and characterized by a semi-arid Mediterranean climate. Over the past two decades, increasing temperatures and evapotranspiration have imposed significant stress even on the drought-tolerant *Quercus* species. In this study, we investigated the climate-growth relationships of *Quercus brantii* Lindl., a dominant tree species in the western Iranian forest ecosystem. We collected 29 cross-sections from *Q. brantii* at the Melehpanjab and Pashmin sites for dendrochronological analysis. Generalized additive models (GAMs) were employed to identify radial growth responses and non-linear relationships and to monthly climatic variables, including precipitation and temperature, over the past 18 years (2005-2022). The model explained 66.7% of the variation in ring width. Our findings highlight the sensitivity of *Q. brantii* to climatic variability, with key drivers of growth being precipitation from October to May (Prc_{Oct_May}), precipitation from October to March (Prc_{Oct_Mar}), temperature from October to December ($Temp_{Oct_Sep}$), and potential evapotranspiration (PET) during spring and summer. Radial growth increased following moist periods (e.g., 2005–2007) but declined during dry periods (e.g., 2007–2010). *Q. brantii* exhibited a positive response to water availability prior to the growing season, and precipitation - year interactions were significant during moist periods. However, radial growth showed a negative response to elevated temperatures (particularly when average annual temperature exceeded above 22.5°C) and limited summer precipitation, which acted as a critical growth constraint. Tree growth was enhanced by PET during spring (April and May), while low soil moisture in June (linear trend) and July (non-linear trend) restricted growth. In conclusion, moisture availability emerged as the most critical factor influencing the growth of Zagros oak forests, with precipitation acting as the key constraint. Additionally, the application of GAMs provides valuable insights into estimating optimal precipitation and temperature conditions for *Q. brantii* in this region.

Keywords: Dendrochronology, Zagros forests, Tree-ring, Generalized additive model.

1. Introduction

The Zagros Mountain Range (ZMR) in western Iran harbors one of the most extensive forest ecosystems in the Middle East, covering approximately 5 million hectares and accounting for 44% of Iran's forests (Talebi et al., 2006). These forests are dominated by *Quercus* species,

particularly *Quercus brantii* Lindl., which plays a critical role in maintaining ecological stability, supporting biodiversity, and providing essential ecosystem services such as soil conservation, water regulation, and carbon sequestration (Fattahi, 1994; Valavi et al., 2018). However, the Zagros forests are increasingly threatened by climate change and anthropogenic pressures,

including overgrazing, deforestation, and land-use changes (Ghazanfari et al., 2004; Henareh Khalyani et al., 2012).

Over the past two decades, Iran has experienced significant climatic changes, with rising temperatures and declining precipitation leading to more frequent and severe droughts (Madani, 2014; Zarenistanak et al., 2014). Mean temperatures are projected to increase by 2.6°C by the end of the 21st century (NCCOI, 2014), exacerbating water stress and threatening the resilience of drought-tolerant species such as *Q. brantii*. These climatic shifts have already impacted forest productivity and growth, particularly in semi-arid regions such as the ZMR (Karim et al., 2019).

Despite its ecological and socio-economic importance, the Zagros forest ecosystem remains understudied, particularly in terms of its response to climate change. Previous dendroclimatological studies in the region have primarily focused on reconstructing past climate conditions (e.g., Arsalani et al., 2014; Azizi et al., 2013; Zarean et al., 2014), with limited attention to the recent impacts of climatic variability on tree growth. Moreover, while *Q. brantii* has been identified as a key species for dendrochronological studies due to its distinct annual rings and broad distribution (Arsalani et al., 2018a; 2018b), the species' growth-climate relationships under varying local conditions remain poorly understood (Safari et al. 2022).

This study aims to address these gaps by investigating the radial growth response of *Q. brantii* to climatic drivers in the southern Zagros forests of Iran. Specifically, we seek to: (i) assess the impact of monthly climate variables, including precipitation and temperature, on tree growth; and (ii) identify the most limiting climatic factors affecting the species' radial growth. To achieve these objectives, we applied Generalized Additive Models (GAMs), a flexible statistical approach that allows for non-linear relationships between predictors and response variables (Hastie & Tibshirani, 1990; Wood, 2017).

Using GAMs, this study significantly advances our understanding of the growth-climate relationships of *Q. brantii*. Unlike traditional linear models, GAMs allow for the exploration of non-linear relationships and interactions between climatic variables and tree growth, providing a more nuanced

understanding of species responses to environmental changes (Pedersen et al., 2018; Wood, 2017). This approach is particularly valuable in semi-arid regions like the Zagros Mountains, where tree growth is often influenced by complex and nonlinear climatic drivers. By applying GAMs at the tree level, this study not only enhances our understanding of *Q. brantii* dynamics but also sets a methodological precedent for future dendroclimatological research in similar ecosystems.

By providing new insights into the growth-climate relationships of *Q. brantii*, this study contributes to a better understanding of the species' resilience to climate change and informs conservation strategies for the Zagros forest ecosystem.

2. Materials and Methods

2.1. Research Sites

The study area is located in the ZMR of Ilam Province, Iran (Figure 1). It is characterized by an arid to semi-arid climate, with February being the coldest month (mean temperature: 0.4°C) and August the warmest (mean temperature: 38°C). The mean annual precipitation is 578 mm (Ahmadi et al., 2014; Ahmadi & Azizzadeh, 2020). In recent years, *Q. brantii* decline has been observed across large parts of the forests in Ilam Province (Moradi et al. 2021).

Due to the high wood density and decay often found in older *Q. brantii* trees in the Zagros forests (Arsalani, 2012), obtaining solid samples using traditional increment borers can be particularly challenging. To address this issue, we focused on areas of wind-thrown trees using reports from the Ilam Province Natural Resources and Watershed Management Office. Two study sites, Melehpanjab (M) and Pashmin (P), were selected for sampling due to their accessibility and suitability for cross-section collection using a saw (Table 1).

The two study sites exhibit distinct environmental characteristics that likely influence the growth dynamics of *Q. brantii*. Based on meteorological data from the nearest weather stations, the P site is generally warmer and drier than the M site. For instance, mean annual temperatures at the P site are approximately 1–2°C higher than those at the M site, while annual precipitation is 10–15% lower. These climatic differences are reflected

in the soil properties, with the P site having clay loam soils that retain less moisture compared to the loam soils of the M site. Additionally, the P site is characterized by more pronounced rocky outcrops and lower canopy cover, which may further exacerbate water stress during the dry summer months (Table 2). In contrast, the M site benefits from

slightly cooler temperatures and higher precipitation, creating more favorable conditions for tree growth. These site-specific differences provide a valuable opportunity to examine how *Q. brantii* responds to varying climatic and edaphic conditions within the same region.

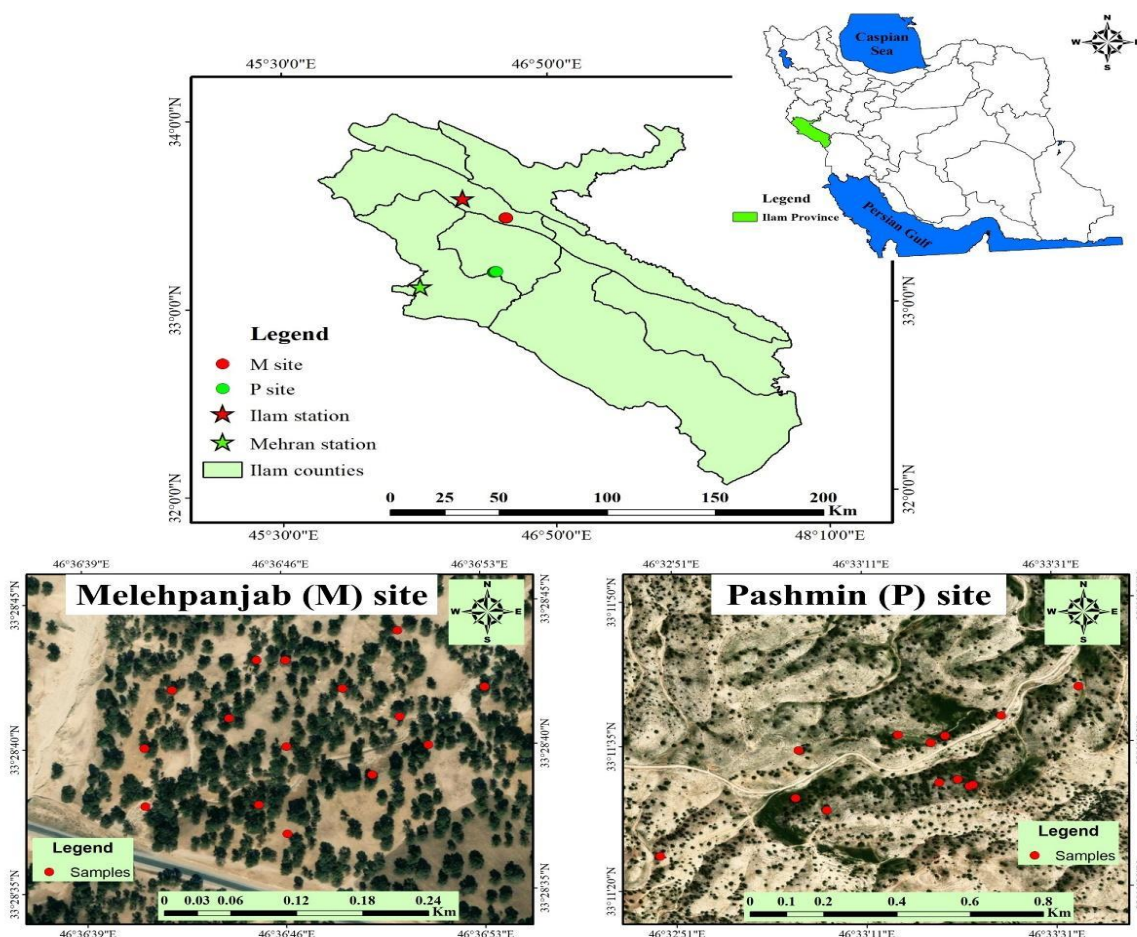


Figure 1. Location of studied areas in Ilam Province, Western Iran

Table 1. Summary characteristics of Melehanpanjab (M) and Pashmin (P) sites

Sites	Longitude	Latitude	Altitude (m a.s.l.)	DBH (cm)	H (m)	Hc (m)	No. tree
M	46o 36' 50.10" E	33o 28' 44.05" N	1450	32.36 ± 1.90	5.63 ± 0.11	1.9 ± 0.60	15
P	46o 31' 34.62" E	33o 12' 03.85" N	1480	41.71 ± 7.88	4.07 ± 0.20	1.3 ± 0.88	14

Notes: DBH—Diameter at breast height; Hc— Height to the crown base; H—Height; No. tree—number of sampled tree. Values correspond to means ± standard error.

Table 2. Summary of soil properties of Melehanpanjab (M) and Pashmin (P) sites

Sites	pH (ds/m)	SOM (%)	N (%)	K (ppm)	P (ppm)	Sand (%)	Clay (%)	Silt (%)
M	7.27 ± 0.01	4.84 ± 0.37	0.28 ± 0.02	17.15 ± 1.84	9.46 ± 0.57	45.93 ± 2.5	23 ± 1.14	31.06 ± 1.95
P	7.33 ± 0.01	5.34 ± 0.5	0.31 ± 0.02	40.7 ± 5.2	9.41 ± 0.46	38.03 ± 4	31.03 ± 2.94	30.92 ± 2.18

Notes: SOM—soil organic matter; N—nitrogen; K—potassium. Values correspond to means \pm standard error and obtained based on soil samples analysis in each site.

2.2. Data Collection and Preparation

2.2.1. Tree-Ring Data

Sampling was conducted in April 2023. Stem cross-sections were collected at breast height (1.3 m) using a chainsaw. At each site, a minimum of 14 trees was sampled. For each tree, diameter at breast height (DBH), total height, and height to crown base were measured. The cross-sections were air-dried and subsequently polished using sandpaper of varying roughness (P80, P220, P350, and P1000) to enhance tree-ring visibility for analysis (Speer 2010). High-resolution images of each cross-section were captured using a Canon EOS R5 camera (<https://global.canon>).

Tree-ring widths were measured using Motic Images Plus software (version 1.2) with an accuracy of 0.001 mm. To ensure

robustness, two radii per tree were measured. Dendrochronological data were crossdated and analyzed using the dplR package (Bunn, 2008, 2010) in R (R Core Team, 2024). After verifying measurement accuracy and crossdating, the raw series were detrended and standardized to remove non-climatic trends associated with tree age. To achieve this, several standardization methods were tested to ensure the selection of an appropriate approach. Ultimately, a cubic smoothing spline with a 50% frequency-response cutoff set to 67% of the length of each series was applied. Due to the limited availability of instrumental climate data, the analysis period was restricted to 2005–2022. Dendrochronological statistics for ring-width measurements at both sites are summarized in Table 3.

Table 3. Characteristics of tree rings in Melehpanjab (M) and Pashmin (P) sites

Sites	No. Series	Mean RW	SD RW	In.series.cor	Ar1	SNR	ESP	Ms	GLK	Gini	Time span
M	30	1.8	0.98	0.35	0.63	7.8	0.88	0.32	0.66	0.67	1951-2022
P	28	1.51	0.65	0.58	0.56	6.35	0.86	0.31	0.89	0.68	1945-2022

Notes: No Series—number of tree-ring series; Mean RW—mean ring width in mm; SD RW—standard deviation from ring width in mm; In.series.cor—The mean interseries correlation; Ar1—first order autocorrelation; SNR—signal-to-noise ratio; EPS—expressed population signal; GLK—gleichflugigkeit coefficient; MS—mean sensitivity; Gini—gini coefficient.

2.2.2. Climate Data and Trend Analysis

Local climate data are more accurate than interpolated gridded data for assessing growth-climate relationships in the Zagros forests, particularly in Ilam Province (Najafi-Harsini et al. 2022). Therefore, monthly temperature and precipitation data for Ilam Province were obtained from the Islamic Republic of Iran Meteorological Organization (IRIMO, <https://www.irimo.ir/>, accessed November 2022). For each study site, data from the closest meteorological stations were used: The Ilam Meteorological Station (IMS) and the Mehran Meteorological Station (MMS) (see Table 4 for details).

Based on the growth period of Zagros forests (April to September; Arsalani, 2012), precipitation patterns, and the physiological year (previous October to current September), several climate variables were calculated:

1. Total precipitation from the previous October to the current May (Prc_{Oct_May}),
2. Total precipitation during the pre-growing season (Prc_{Oct_Mar} : October to March of the previous year),
3. Total precipitation during the growing season (Prc_{Apr_Sep} : April to September of the current year), and
4. Mean monthly temperature from previous October to current September ($Temp_{Oct_Sep}$).

Potential evapotranspiration (PET) for each month was calculated using the Thornthwaite method (Thornthwaite 1948), and seasonal PET values for spring and summer seasons were derived.

To identify and plot trends in precipitation and temperature, R scripts provided by Tang (2020) were applied. Finally, monthly and annual trends were analyzed and visualized to highlight temporal changes.

Table 4. Summary characteristics of the meteorological stations, the Ilam Meteorological Station (IMS) and the Mehran Meteorological Station (MMS)

Met. station	Longitude	Latitude	Altitude (m a.s.l.)	Distance to site (km)	Temp _{MA} (°C)	Prc _{MA} (mm)	Time span
IMS	46° 24' 50.13" E	33° 37' 23.34" N	1337	24.52	17.06	550.21	Apr 1986-Dec 2022
MMS	46° 10' 31.06" E	33° 06' 53.04" N	150	35.61	25.91	194.22	Jul 2005-Dec 2022

Notes: Met. station—meteorological station; Temp_{MA}— mean annual temperature; Prc_{MA}— mean annual precipitation. Apr-Dec—April to December; Jul-Dec—July to December.

2.2.3. Determining the Growth-Climate Responses with Generalized Additive Models

GAMs were initially developed by Hastie & Tibshirani (1990) to combine the properties of generalized linear models with smoothing techniques (Vospernik et al., 2023). This statistical approach is particularly advantageous for modeling nonlinear relationships between predictor and response variables, offering flexibility in regression analysis (Pedersen et al., 2018).

To analyze growth-climate responses, we utilized the *mgcv* package in R, which provides tools for fitting GAMs (Wood, 2017). GAMs were constructed to estimate smooth functional relationships between radial growth and climatic factors. A Tweedie distribution was applied to link these relationships (Vospernik et al., 2023; Gadermaier et al., 2024). The

models were fitted using multiple threads (*nthreads* = 4), and the default value for *k* (basis dimension) was set to 10, except when accounting for random effects and smooth factors, where *k* = 8 was used.

A tensor-product smooth term was incorporated to model interactions between year, temperature, and precipitation. To optimize model performance, a shrinkage function (*select* = TRUE) was applied to remove terms that did not significantly improve the model (Marra & Wood, 2011). The models were fitted using the restricted maximum likelihood (REML) algorithm. Visualization of the estimated curves and model outputs was performed using the *gratia* package in R (Simpson, 2023). The following GAM structure was used (Equation 1):

$$RG + s(\text{year}) + s(\text{Prc}_{\text{Oct_May}}) + s(\text{Prc}_{\text{Oct_Mar}}) + s(\text{Prc}_{\text{Apr_Sep}}) + s(\text{Temp}_{\text{Oct_Sep}}) + s(\text{year}, \text{Prc}_{\text{Oct_May}}) + s(\text{PET}_{\text{Apr}}) + s(\text{PET}_{\text{May}}) + s(\text{PET}_{\text{Jun}}) + s(\text{PET}_{\text{Jul}}) + s(\text{PET}_{\text{Aug}}) + s(\text{PET}_{\text{sep}}) + \text{tree_id} + \text{year. tree_id} + \epsilon \quad (1)$$

where:

- **RG** represents the mean radial growth of trees,
- **s()** denotes the smooth function applied to the variables: year, precipitation, temperature, and potential evapotranspiration (PET) for April to September,
- **tree_id** was included as a random effect to account for individual tree variability,
- **year. tree_id** represents the smooth interaction term between year and tree_id, and
- **ε** is the random error term.

3. Results

3.1. Climate Trends

Analysis of climate trends indicates that precipitation occurs from October to May at IMS and from November to May at MMS (Figures 2a-b and 3a-b). Mean monthly precipitation is negligible (less than 1 mm/month) from June to September at IMS and from June to October at MMS (Figures. 2b and 3f). In recent years, mean monthly temperatures have exhibited an upward trend. Specifically, the annual mean temperature at MMS showed a significant increase between

2005 and 2010, while a different trend was observed at IMS (Figures. 2c and 3g).

Despite a temporary decrease in temperature at IMS, annual precipitation at both stations has shown a declining trend, coinciding with a severe drought period in Ilam province from 2007 to 2010. Following 2010, the annual mean temperature continued rising at both stations. Monthly climate trend analysis further revealed that mean temperatures have increased consistently across all months in recent years for both stations.

3.2. Growth Patterns

Figure 4a illustrates detrended radial growth chronologies of *Q. brantii* the seven-decade span from 1951 to 2022 for the two study sites (M and P).

Significant differences in radial growth patterns were observed between the two sites. At the M site, a declining trend in radial growth was evident from 2005 to 2009, while the P site exhibited a similar but delayed decline, beginning in 2007 (Figure 4b). Notably, the narrowest tree rings and the lowest radial growth rates were recorded in 2012 and 2022 at both sites. During these years, the average radial growth was 0.63 mm and 0.48 mm at the M site and 0.45 mm and 0.54 mm at the P site, respectively.

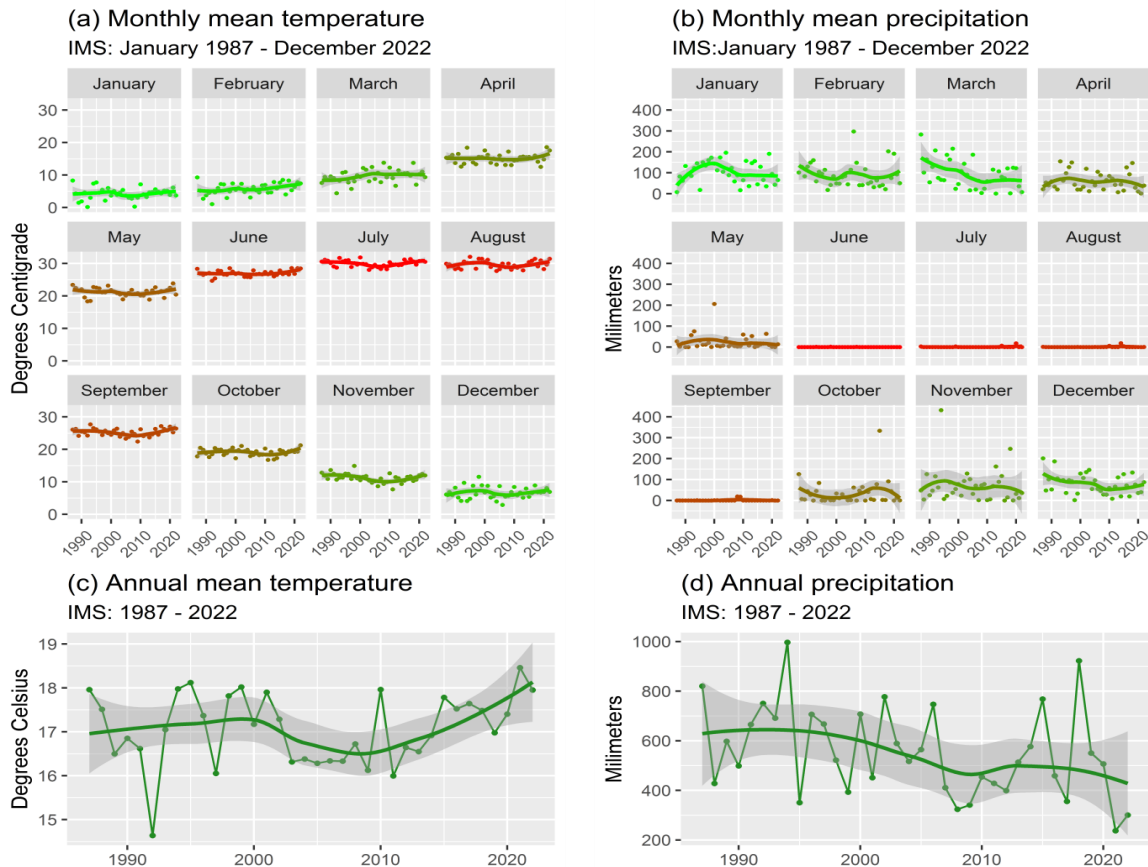


Figure 2. Annual and monthly climate trends of precipitation (right) and temperature (left) at the Ilam Meteorological Station (IMS)

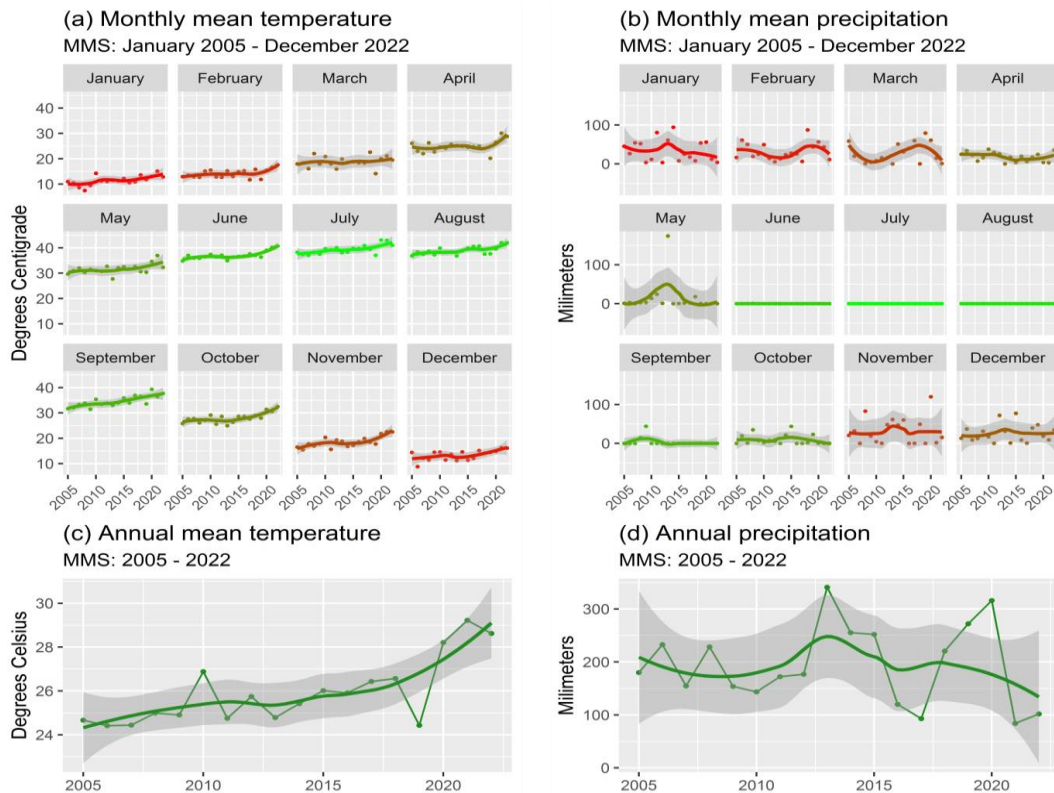


Figure 3. Annual and monthly climate trends of precipitation (right) and temperature (left) at the Mehran Meteorological Station (MMS)

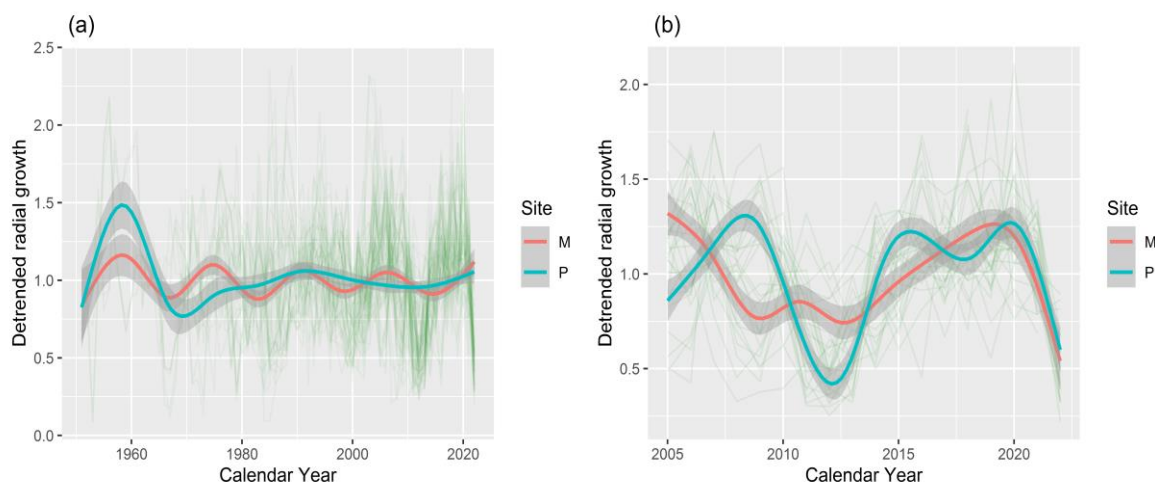


Figure 4. Detrended radial growth chronologies (GAM spline line) from 1951 to 2022 (a) and 2005 to 2022 (b) in Mlelepanjab (M) and Pashmin (P) sites

3.3. Model Structure

The modeling process began with the inclusion of calendar year as a fixed effect and tree_id as a random effect, which together explained 35.8% of the variance (adjusted $R^2 = 0.358$). With the addition of other covariates, such as temperature and precipitation, the variance explained increased to 66.7%, and the adjusted R^2 improved to 0.606 (Table 5).

Diagnostic plots were used to validate the final generalized additive model (Figure 5). The relationship between the residuals and the

linear predictor confirmed that the Tweedie distribution with $P = 1.4$ was appropriate for the data.

3.5. Effect of Year

The GAM outputs revealed that the calendar year had a significant and non-linear effect on tree growth, reflecting regional climate trends (Figure 6). The growth trend of *Q. brantii* from 2005 to 2022 exhibited variability, with a notable decline observed following a dry period from 2007 to 2010.

Table 5. Parametric coefficients and Generalized Additive Model (GAM) outputs

Variable	edf	p-value	Significance levels
S(year)	6.293e+00	< 2e-16	***
S(PrcOct_May)	2.567e+00	< 2e-16	***
S(Prc Oct_Mar)	7.305e-01	0.000340	***
S(PrcApr_Sep)	1.212e-06	0.735198	-
S(TempOct_Sep)	1.580e+00	1.38e-05	***
ti(year,PrcOct_May)	3.639e+00	5.00e-06	***
S(PETApr)	9.075e-01	< 2e-16	***
S(PETMay)	4.081e+00	< 2e-16	***
S(PETJun)	7.757e-01	0.000679	***
S(PETJul)	2.184e+00	< 2e-16	***
S(PETAug)	1.559e+00	0.000499	***
S(PETSep)	4.230e+00	< 2e-16	***
S(year,Tree_id)	3.212e+01	1.55e-05	***
S(tree_id)	6.152e-06	0.781719	-
Adj. R2 = 0.606	Deviance explained = 66.7%	REML = 7.6077	Scale est. = 0.047367
Intercept	Estimate = -0.05656	Std. Error = 0.01211	Pr(> t) = 3.95e-06

Notes: edf— Estimated degree of freedom, Sig.levels—Significance levels: (-)—non-significant; (***)— $P < 0.001$; ti()—tensor product interaction; Std. Error—Standard Error; Scale est— Scale Estimate.

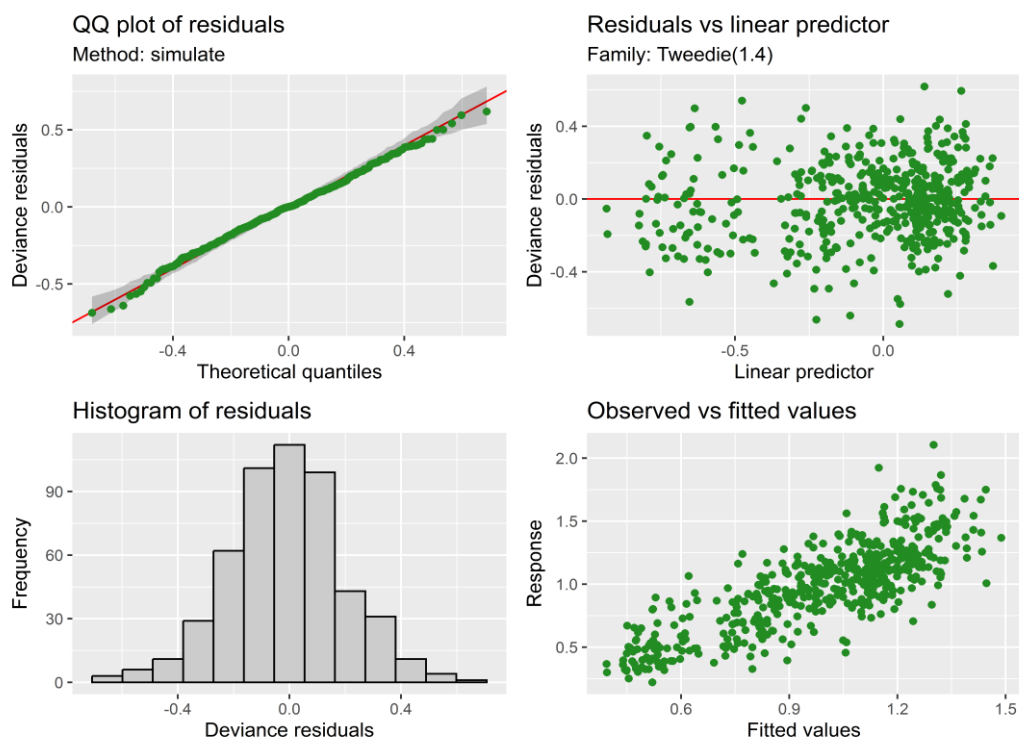


Figure 5. Diagnostic plots for final Generalized Additive Model (GAM) model evaluation defined by the appraise () function. The QQ-plot (upper left) and the histogram (lower left) of the residuals (observed value - fitted value) are used to whether the residuals follow a normal distribution. The plots of residuals against linear predictor values (upper right) and of observed versus fitted values (lower right) used to whether the fitted values match well with response variables.

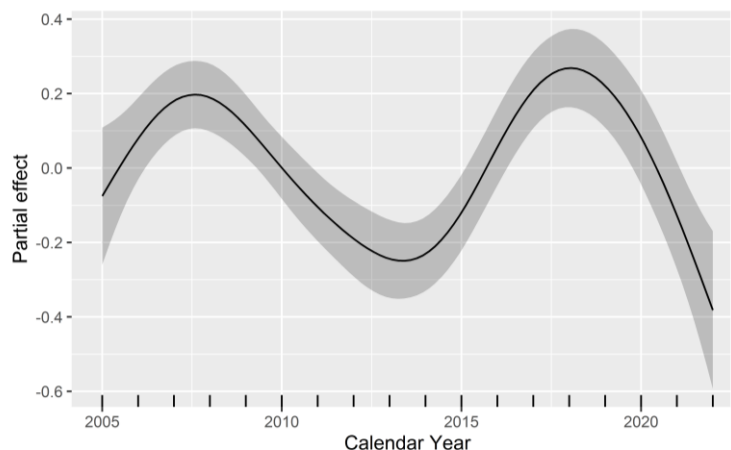


Figure 6. Partial effect of calendar year on tree ring width. The shaded area represents the 95% confidence interval of effect

3.6. Growth–Climate Relationships

The GAMs revealed that tree growth was significantly influenced by precipitation during the study period (2005–2022). Precipitation exhibited a non-linear effect on growth, with *Q. brantii* growth increasing in response to precipitation from October to May (Prc_{Oct_May}) up to a peak of 625 mm, after which growth declined (Figure 7a). Precipitation during the pre-growing season (Prc_{Oct_Mar}) and the

growing season (Prc_{Apr_Sep}) also positively influenced growth (Figure 7b), although the effect of growing-season precipitation was not statistically significant (Figure 7c).

Notably, the interaction between year and precipitation indicated that precipitation levels before and after the drought period (2007–2010) had the most pronounced impact on tree growth (Figure 7d).

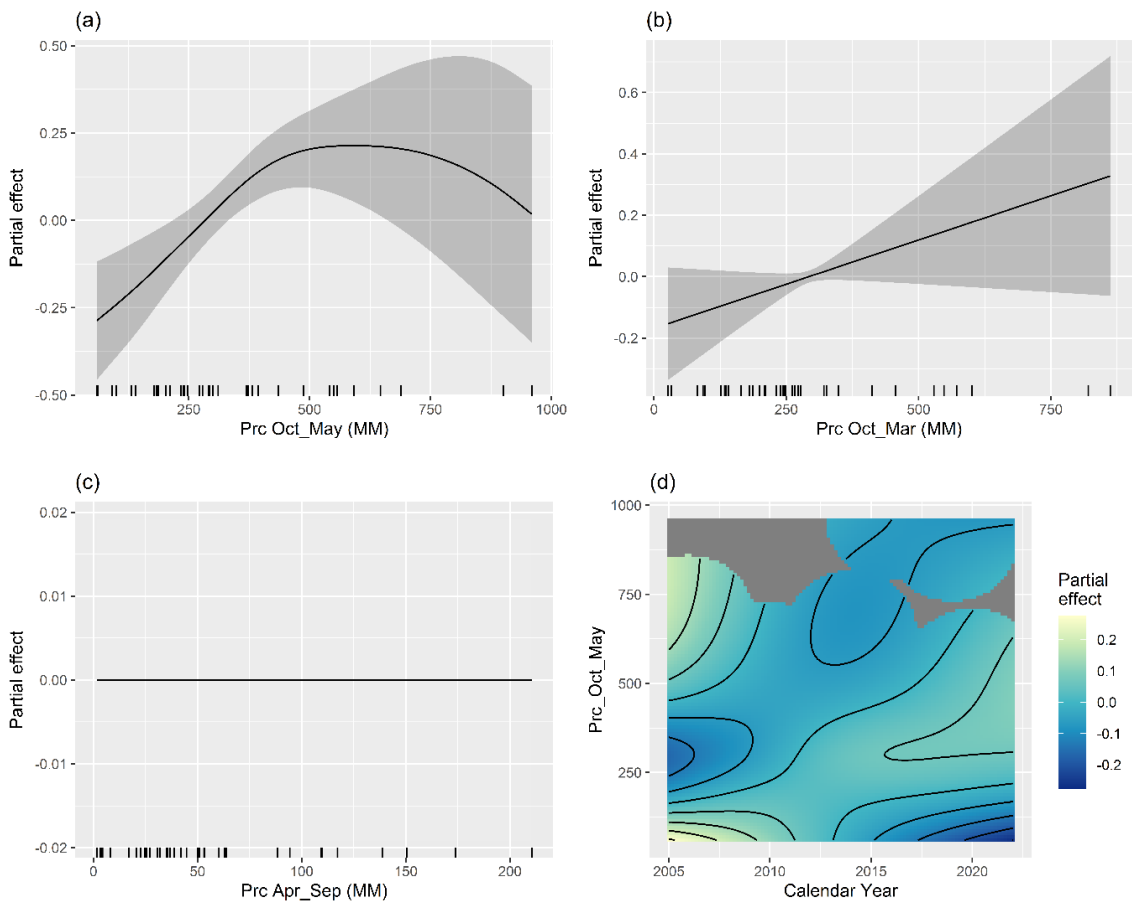


Figure 7. Partial effect of precipitation interaction between year and precipitation on tree ring width. The shaded area represents the 95% confidence interval of effect

The growth of *Q. brantii* exhibited a non-linear response to temperature from the previous October to the current September. Growth increased with rising temperatures,

peaking at 22.5°C, after which further increase in temperature negatively affected tree growth (Figure 8).

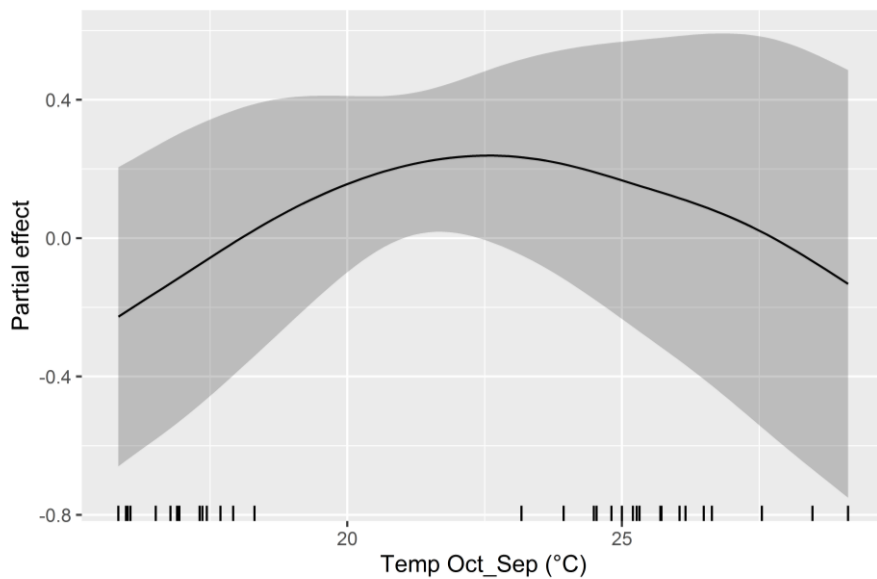


Figure 8. Partial effect of temperature in previous and current year on tree ring width. The shaded area represents the 95% confidence interval of effect

The radial growth response of *Q. brantii* to PET varied significantly between the spring and summer seasons. During spring, PET showed a positive and significant relationship with radial growth, whereas in summer, tree growth responded negatively to increasing evapotranspiration. Specifically, radial growth

increased non-linearly with PET in April (Figure 9a) and linearly in May (Figure 9b). In contrast, tree growth declined significantly with rising PET in June (linear trend; Figure 9c) and July (non-linear trend; Figure 9d). The influence of PET in August and September on tree growth displayed a more variable trend (Figure 7).

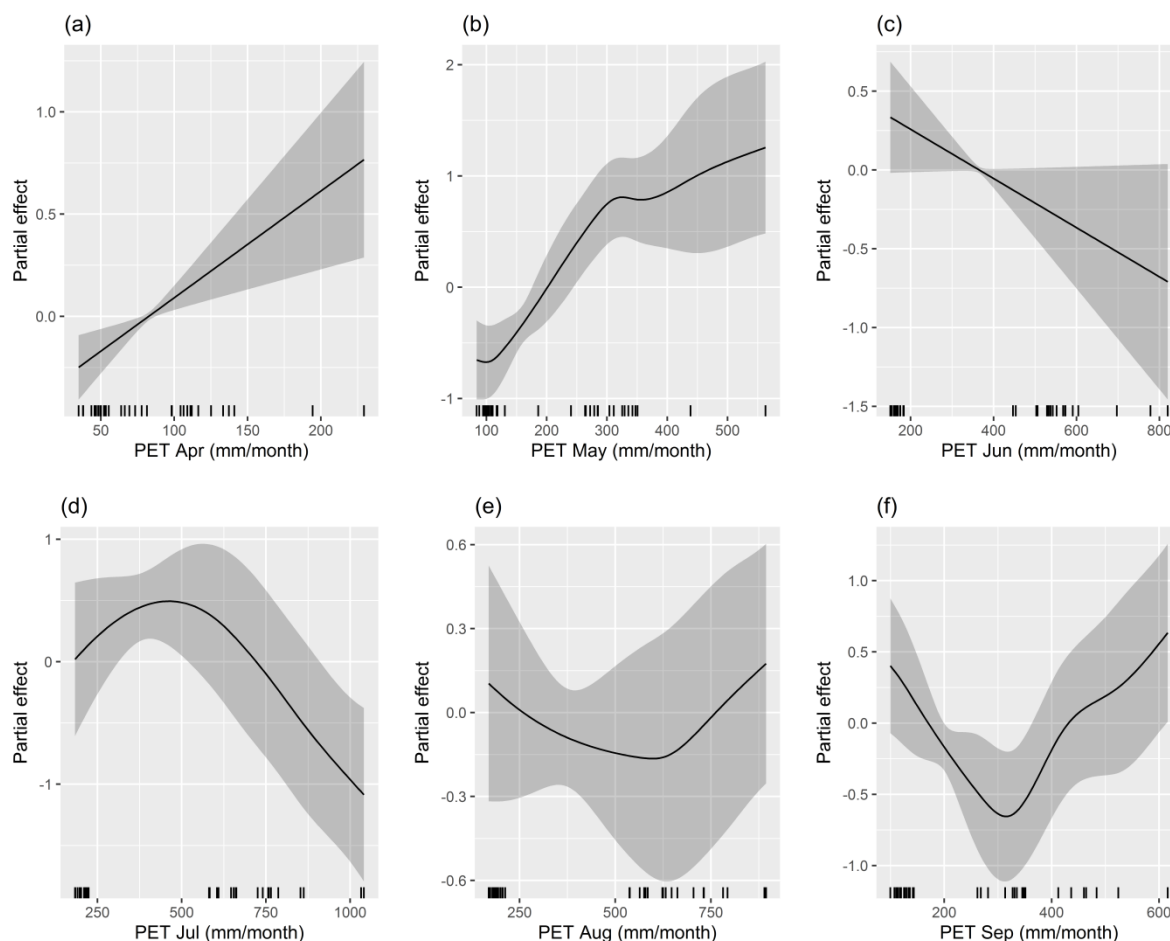


Figure 9. Partial effect of evapotranspiration (PET) for spring and summer seasons during the growing season on tree ring width. The shaded area represents the 95% confidence interval

4. Discussion

In this study, we analyzed the growth response of *Q. brantii* to climatic drivers using GAMs in the southern Zagros forests of western Iran. The final model explained 66.7% of the variation in ring width, which is consistent with previous studies (e.g., Azizi et al., 2013) and exceeds some model estimates for semi-arid regions like the central Zagros forests.

As previously described, the P site is generally warmer and drier compared to M site, which likely contributed to the observed differences in radial growth between the two sites. For instance, the M site showed a

declining trend in radial growth from 2005 to 2009, while the P site exhibited a similar but lagged decline, beginning in 2007 (Figure 4b). These patterns highlight the importance of site-specific climatic and edaphic conditions in shaping the growth dynamics of *Q. brantii*.

Why site-specific differences were not modeled separately?

While the initial analysis highlighted differences in growth patterns between the two sites, we chose not to model growth-climate relationships separately for each site for several reasons. First, our primary objective was to identify the overarching climatic drivers

affecting *Q. brantii* growth across the southern Zagros region, rather than focusing on site-specific responses. By combining data from both sites, we were able to enhance the statistical power of our analysis and capture a broader range of climatic variability. Second, the limited sample size at each site ($n = 14$ trees per site) would have reduced the robustness of site-specific models, particularly given the complexity of GAMs and the need to account for multiple climatic variables.

However, we acknowledge that site-specific differences in climate and soil conditions may influence tree growth, as evidenced by the divergent growth trends observed in Figure 4. To address this, we included site as a random effect in our GAMs, which allowed us to account for variability between sites while focusing on the overall growth-climate relationships. This approach is supported by previous studies that have successfully used mixed-effects models to analyze tree growth across environmentally heterogeneous regions (e.g., Zang et al., 2014; Vospernik et al., 2023).

Reconciling site differences in the analysis

In the early part of the Results section, we emphasized the differences in growth patterns between the two sites to provide context for the observed variability in *Q. brantii* growth. However, in subsequent analyses, we focused on the common climatic drivers affecting growth across both sites, as our goal was to identify generalizable patterns rather than site-specific responses. This approach is consistent with the broader objective of the study, which was to understand the growth-climate relationships of *Q. brantii* at a regional scale. Future studies with larger sample sizes and more extensive climatic data could explore site-specific responses in greater detail, providing valuable insights into the local adaptation of *Q. brantii* to varying environmental conditions.

Temporal growth patterns and climatic variability

The GAM model confirmed the temporal responsiveness of *Q. brantii* to climatic drivers, although the analysis was limited to the period 2005–2022 due to limitations in local climate data availability. We observed an increased growth trend between 2006 and 2007, followed by a decline from 2008 to 2015. These patterns

align with regional climatic events, such as the severe drought of 2008, which was associated with rising temperatures and reduced precipitation (Arsalani et al., 2022). Since 2000, precipitation in the ZMR has decreased by 6% compared to previous decades (Attarod et al., 2023), further emphasizing the impact of climatic variability on tree growth.

Climate-growth relationships

Consistent with previous studies (e.g., Arsalani et al., 2018b), our results indicate that precipitation and temperature are the primary climatic factors influencing the radial growth of *Q. brantii*. Growth responded positively to precipitation, particularly during the pre-growing season (October–March), and negatively to temperatures exceeding 22.5°C. This pattern aligns with findings from other studies in the Zagros forests (Azizi et al., 2013; Zarean et al., 2014; Arsalani et al., 2018b; Najafi-Harsini et al., 2022) and from other semi-arid regions such as Pakistan (Iqbal et al. 2020), China (Jing et al. 2022), and the Mediterranean basin (Camarero et al., 2023). Approximately 80% of annual precipitation in the ZMR occurs during autumn and winter, replenishing soil moisture critical for early-season growth (Lebourgeois et al., 2004; Arsalani et al., 2018b; Yuan et al., 2019; Safari et al., 2022; Najafi-Harsini et al., 2022; Campelo et al., 2022). Late-season precipitation may also support carbohydrate production and storage, further enhancing radial growth (Arsalani et al., 2022).

The negative effects of high temperatures are likely tied to increased respiration rates and reduction in net carbon storage (Huang et al. 2018). Similarly, Oladi et al. (2017) found that while moderate warming may initially stimulate radial growth in beech trees, exceeding optimal temperature thresholds leads to declines. High summer temperatures also adversely affect latewood formation in *Q. brantii* (Arsalani et al., 2018a).

Potential evapotranspiration (PET) and seasonal variability

Our findings indicate that the response of *Q. brantii* to potential PET varies significantly between spring and summer. During spring (April and May), PET was positively associated with radial growth, suggesting that moderate PET under favorable moisture

conditions supports tree productivity. In contrast, during the summer months, particularly June, July, and August, high PET had a negative effect on growth, except in September where the trend was less pronounced. Elevated PET during summer, primarily driven by high temperatures and low soil moisture, increases water loss and limits growth (Arsalani et al., 2014; Santos-Malengue et al., 2023). Under such conditions, reduced soil water availability constrains CO₂ assimilation and photosynthetic activity, ultimately leading to narrower growth rings (Gonçalves et al., 2021).

Limitations and future directions

Despite the robustness of our findings, it is important to acknowledge certain limitations. First, the relatively small sample size of trees ($n = 29$) was a consequence of both legal restrictions on sampling live trees and the technical challenges associated with extracting cores from dense and often decayed wood of older *Q. brantii* individuals. Although this limitation may constrain the generalizability of our results, the application of advanced statistical techniques (e.g., GAMs) and the alignment of our findings with those of previous studies help to strengthen the reliability of our conclusions.

Second, the analysis was limited by the relatively short time span of available climate data (2005–2022), due to incomplete local records. Nevertheless, this period encompasses critical climatic events, such as episodes of severe droughts and anomalously wet years, which allowed us to assess the sensitivity of *Q. brantii* to climatic variability. Future research should aim to extend the temporal scale of analysis using dendroclimatic reconstructions or satellite-derived climate products.

To build on the findings of this study, future research should aim to increase sample size by including additional sites across the Zagros region. Integrating local meteorological data with long-term reconstructions or satellite-derived datasets could also enhance the temporal depth of growth-climate analysis. Additionally, investigating the combined effects of climatic and non-climatic factors

(e.g., human activities, soil properties) on tree growth would provide a more comprehensive understanding of the drivers influencing *Q. brantii* growth dynamics in this ecologically sensitive region.

5. Conclusions

This study employed GAMs to explore the relationship between the radial growth of *Q. brantii* and climatic variables in the Zagros forests. The results reveal that the growth of this species is strongly influenced by climatic fluctuations, particularly by autumn and winter precipitation, which supports early-season growth. Conversely, elevated temperatures—especially during the warmer months—negatively impact growth, underscoring the species' sensitivity to heat and drought stress. These findings highlight the importance of managing water resources and mitigating the pressures of climate change in the Zagros forests.

The practical implications of these findings support the development of sustainable management strategies for the Zagros forests. Approaches such as improving soil water storage through rainwater harvesting, reducing human pressures like overgrazing and deforestation, and using drought-resistant species in afforestation programs can enhance the resilience of these ecosystems to climate change. Additionally, long-term monitoring of tree growth and climatic changes will facilitate the development of predictive growth models and more effective management planning. These efforts are essential not only for sustaining forest health but also for ensuring the preservation of their critical ecosystem services these woodlands provide, such as soil stabilization and carbon sequestration.

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پاسخ رشد درختان به عوامل اقلیمی: درس‌هایی از جنگل‌های نیمه‌خشک بلوط زاگرس، غرب ایران

الهام مطهر فرد^۱، علی مهدوی^{۲*}، رضا اخوان^۳، اصغر فلاح^۴، رضا امید پور^۵ و استاکتون مکسول^۶

^۱دانشجوی دکتری، گروه علوم جنگل، دانشکده کشاورزی، دانشگاه ایلام، ایلام، ایران

آستاذ، گروه علوم جنگل، دانشکده کشاورزی، دانشگاه ایلام، ایلام، ایران

^۲دانشیار بخش تحقیقات جنگل، مؤسسه تحقیقات جنگل‌ها و مراتع کشور، سازمان تحقیقات، آموزش و ترویج کشاورزی، تهران، ایران

^۴آستاذ، گروه جنگلداری، دانشکده منابع طبیعی، دانشگاه علوم کشاورزی و منابع طبیعی ساری، مازندران، ایران

^۵استادیار، گروه مرتع و آبخیزداری، دانشکده کشاورزی، دانشگاه ایلام، ایلام، ایران

آستاذ، دپارتمان علوم مکانی، دانشگاه ردفورد، ویرجینیا، آمریکا

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چکیده

بوم‌سازگان جنگلی زاگرس، بزرگترین ناحیه جنگلی ایران، بوسیله گونه‌های بلوط (*Quercus*) غالب بوده و با اقلیم نیمه خشک مدیترانه ای مشخص می‌شود. در طول دو دهه گذشته، افزایش دما و تبخیر- تعرق، فشارهای قابل توجهی را حتی روی گونه‌های بلوط که بردبار به خشکی هستند، تحمیل کرده است. در این مطالعه، روابط رشد- اقلیم بلوط ایرانی *Quercus brantii* Lind. که گونه غالب بوم‌سازگان جنگلی غرب ایران است را مورد بررسی قرار گرفت. برای تحلیل‌های گاه‌شناسی، ۲۹ مقطع عرضی از درختان بلوط *Q. brantii* در دو رویشگاه مله‌پنجاب و پشمین جمع‌آوری شد. مدل‌های جمعی تعمیم یافته (GAMs) برای شناسایی روابط غیرخطی و پاسخ‌های رشد درخت به متغیرهای اقلیمی ماهانه شامل دما، بارندگی در ۱۸ سال گذشته (۲۰۰۵-۲۰۲۲ میلادی) استفاده شد. مدل ۶۶/۷ درصد تغییرات پهنای حلقه‌های سالانه را توضیح داد. یافته‌های ما حساسیت *Q. brantii* به تغییرات اقلیمی را نشان می‌دهد، با این نکته که عوامل کلیدی محرک رشد شامل بارندگی از اکتبر سال قبل تا می سال جاری (PTC_{Oct-May})، بارندگی از اکتبر سال قبل تا مارس سال جاری (PTC_{Oct-Mar})، دما از اکتبر سال قبل تا دسامبر سال جاری (Temp_{Oct-Sep}) و تبخیر و تعرق پتانسیل (PET) در طول بهار و تابستان بودند. رشد شعاعی پس از دوره‌های مرطوب (مانند ۲۰۰۵-۲۰۰۷ میلادی) افزایش یافت ولی در طول دوره‌های خشک (مانند ۲۰۰۷-۲۰۱۰ میلادی) کاهش رشد شعاعی اتفاق افتاد. *Q. brantii* پاسخ مثبتی به دسترسی به آب قبل از فصل رشد نشان داد، و تعامل بین بارندگی و سال رویش در طول دوره‌های مرطوب، معنی‌دار بود. با این حال، پاسخ رشد شعاعی درخت به افزایش دما منفی بود (مخصوصاً دمای بیش از ۲۲/۵ درجه سانتی‌گراد و از اکتبر سال قبل تا سپتامبر سال جاری) و بارندگی محدود در طول تابستان به‌عنوان یک عامل محدودکننده حیاتی برای رشد درخت عمل کرد. رشد درخت بوسیله PET در فصل بهار (ماه‌های آوریل و مه) بهبود یافت، درحالی‌که، کمبود رطوبت خاک در ماه ژوئن (با روند خطی) و ماه ژوئیه (با روند غیرخطی) رشد را محدود کرد. به‌طور کلی، دسترسی به رطوبت به‌عنوان مهم‌ترین عامل تأثیرگذار بر رشد جنگل‌های بلوط زاگرس شناسایی شد، جایی که بارندگی به‌عنوان عامل محدودکننده اصلی عمل می‌کند. علاوه بر این، استفاده از GAMs بینش‌های ارزشمندی را برای تخمین شرایط بهینه بارندگی و دما برای رشد *Q. brantii* در این منطقه فراهم می‌کند.

واژه‌های کلیدی: گاه‌شناسی، جنگل‌های زاگرس، حلقه‌های سالانه، مدل جمعی تعمیم‌یافته.