DENDROBIOLOGY

2017, vol. 78, 32–39

http://dx.doi.org/10.12657/denbio.078.004

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Age-dependent response to extreme Mediterranean climate in annual rings of brant's oak (*Quercus brantii* Lindl.)

Received: 26 November 2016; Accepted: 5 May 2017

Abstract: The relationship between tree-ring growth and climate in *Quercus brantii*, a widespread and dominant tree species in Zagros-Anti-Taurus Mountains, was investigated by both age-dependent and independent approaches. A total number of 118 trees were sampled in a region where severe Mediterranean climate prevailed. An overall chronology plus three age-dependent chronologies of <80, 80 to 160 and >160 years old were constructed to study growth-climate relationships based on an integrated approach of principle component stepwise regression followed by complementary response function analysis. High age heterogeneity of overall chronology diminished its climatic signals and growth priority was significantly presented in the models. Biennial and triennial precipitation variations were highly related with annual tree ring growth of young and old oaks, respectively. However, hot growing season negatively affected all age-dependent chronology indices. By increasing tree ages the negative effects of warm autumn prior to growth decreased and late winter fall became a limiting climatic factor in old trees. Results of response function analysis also revealed that all oak trees from each age classes were sensitive to increasing April temperature. It's anticipated that, regarding the trends of late frost, this species will face with many challenges in this region and similar areas.

Keywords: annual growth, climate change, drought, dendrochronology, late frost

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Introduction

Extreme summer drought, low winter temperature and low water-holding capacity of soil are the most natural challenging factors that many perennial plants of Mediterranean regions are dealing with. Regardless of the extent of drought tolerance, annual radial growth of the trees in these regions are highly correlated with inter-annual variations in climatic factors, especially with precipitation (Campelo et al., 2007) as they can even be used to reconstruct past environmental conditions that they were already exposed (Douglass, 1919). However, in regions with dry growing season such as Mediterranean regions, it's more likely for plants to form false rings by going to the transient dormancy in summer and consequent initiating of the second period of growth in early autumn (Campelo et al., 2007).

Many studies examining the dendroclimatic relationships have been conducted in arid as well as temperate climates. Also a few studies in west Mediterranean highland zones with summer precipitation have been reported (Houerou, 2004). However, no information exists about age-dependent response of annual tree rings in east Mediterranean zones with severe drought season occurring due to negligible summer rainfalls. Some rare studies in the Middle East do not fulfill this expectation. Liphschitz et al. (1979) investigated the relationship between climatic parameters and annual rings of *Juniperus polycarpus* L., an endemic evergreen conifer present in snow covered mountains of Iran, and found that generally the chronology index of this species is highly correlated with annual precipitation but when the amount of rainfall is above 450 mm, the summer temperature becomes a limiting factor. Recently, it has been widely demonstrated that use of age-dependent models instead of traditional age independent models can conducted to better illustrate the climatic signals. Age-dependent responses of tree rings to environmental variations have been already reported in the literature (Szeicz & MacDonald, 1994; Vieira et al., 2009). Generally it is thought that older trees are more climate representative than younger ones so that the presence of young trees in dendroclimatic studies could lead to a biased mean chronology of the site (Carrer & Urbinati, 2004). Also, due to longer time span of growing season, young trees have more intra-annual radial growth fluctuations than old trees (Vieira et al., 2009).

Oaks due to their wide-spread distribution and common usage as building timber in the past have been considered widely as climate proxy in temperate regions. *Quercus brantii* (Lindl.) is the most abundant deciduous species through Zagros-Anti-Taurus Mountains in west of the Iranian plateau and its survival is considered to be strongly dependent on early spring precipitation, and is sensitive to long drought periods (Djamali et al., 2010). Despite its wide range of distribution, no dendrochronological evidence of this species is available. Therefore, this study was designed (1) to find out the most important climatic factors affecting radial growth of *Q. brantii* trees within the study region, and (2) to investigate the potential of age-dependent chronological approach in *Q. brantii* (with different cambial age classes) to better illustration of climatic variations on its radial growth.

Materials and Methods

Study area

The studied area was 600 ha of a natural forest (Bensenjan's research forest 30°42' N. Lat. and 51°35' E. Long.) with the elevation ranged from 1800 to 2300 m above the sea level. It is located in the north of Yasuj city, the center of "Kohgiluyeh and Boyer-Ahmad" province in Iran that is a part of western aspect of Zagros Mountains in the southwestern Iranian plateau (Fig. 1). The climate is extremely Mediterranean with typically dry growing season (18.3 mm precipitation from May to August) (Fig. 2) with maximum and minimum monthly mean temperature of 35°C and –2°C for July and January, respectively. Meteorological records of precipitation and temperature were obtained from Yasuj airport meteorological station (Yasuj, Iran, 1830 m above the sea level), approximately 3 km west of the studied area, from 1987 to 2009. The soil textures is mostly clay

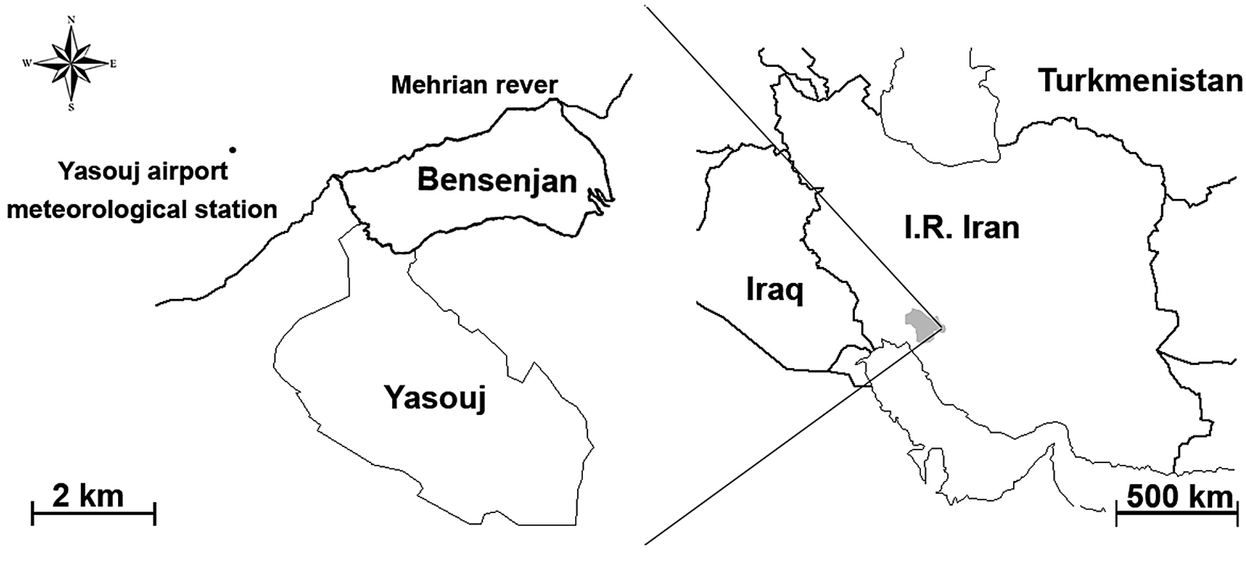

Fig. 1. Location of the studied province in Iranian plateau (gray color) and boundaries of study area (Bensenjan research forest) in north of Yasuj city (Iran). Position of meteorological station has been demonstrated by black circle. This map is derived from google map (31 July, 2012)

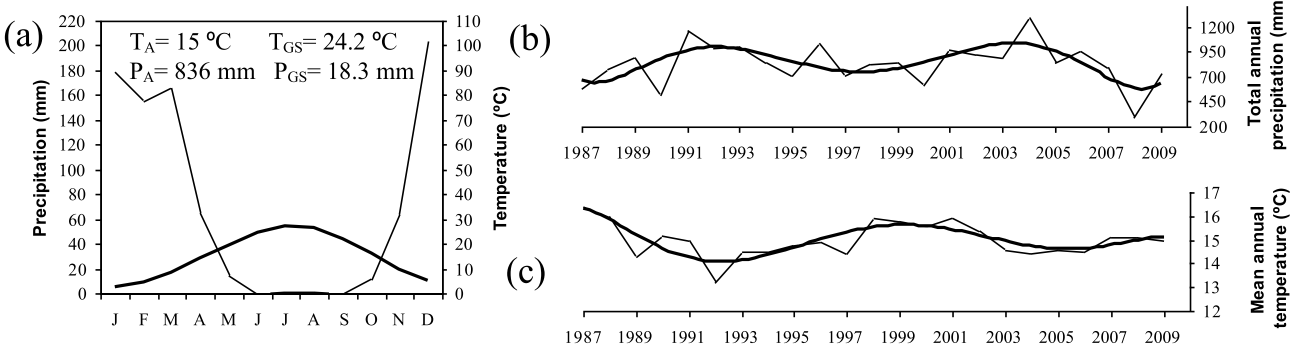

Fig. 2. Climate diagram of Yasuj (a), Iran (30°50' N. Lat. and 51°41' E. Long.) located at 1830 m asl from 1987 to 2009 is shown. T_A: annual average of day bulb temperature, P_A: annual average of precipitation, T_{GS}: average of dry bulb temperature within growing season (May to August), P_{GS}: average of precipitation within growing season. The variation of total annual precipitation (b) and total annual temperature (c) with their general 6 order polynomial trends are shown

to sandy-clay-loam and alkaline (pH=7.5, OC=1.8% and N=0.3%). *Quercus brantii* is the dominant tree species in this region covering more than 90 percent of the total forest in this region.

Sampling strategy, tree-ring preparation, and chronologies construction

During summer 2010, nineteen sites based on a 500 × 1000 m random systematic inventory grid were subjected to sampling. In each site, approximately five to six healthy trees of *Quercus brantii* with diameter of 10 to 55 cm were selected. Four cores from each tree, as far as possible, were taken at height of 75 cm. Afterwards, the cores were naturally dried at room temperature, and were surface treated by fine grades of sandpapers (from 200 to 400 grit) to polish their transverse cross sections. Then cores of each site accompanied by a scale were scanned (Epson V30, Indonesia) with the resolution of 1200 dpi and their ring widths were measured manually using ImageJ 1.43u, an image processing software (Rasband, 1997), as accurate as of 0.01 mm. Finally trees were categorized in three age classes of young (<80 years old), middle-aged (80–160 years old) and old (>160 years old) based on tree rings frequency. Totally, out of 118 sampled trees, 40, 44 and 34 were categorized as young, middle-aged and old trees, respectively. Time series of tree rings were cross dated using TSAP-Win program and evaluated using COFECHA. Then the tree ring data were detrended by fitting the cubic smoothing spline with 10 years filter length to remove both effects of tree age and seeding cycle (that is almost every 7 to 10 years) and focusing on climatic fluctuations occurring within this time frame, and residual chronologies were constructed by using ARSTAN program. Finally we constructed four chronologies consisting of whole (overall chronology), young (under 80 years), middle-age (from 80 to 160 years) and old trees (more than 160 years).

Dendroclimatic analysis

The relationship between tree-ring widths and climate from 1987 to 2009 (based on available meteorological data) was investigated in four residual chronologies (one age-independent chronology and three age-dependent chronologies) by principal components regression analysis (Hidalgo et al., 2000) followed by response function analysis (Fritts & Xiangding, 1986) using IBM SPSS Statistics 19 software (SPSS Inc., Chicago, IL, USA). According to the literature (Sheppard et al., 1989; Chaar & Colin, 1999) and local meteorological data, a time period from September (t–1) to August (t) was used to build climatic matrix as a period of onset of frost hardening, growth and final resting date. In order to achieve more reliable predictors, a small set of climatic variables, instead of all possible variable combinations, were included in PC analysis (Hidalgo et al., 2000). First of all, a matrix of climatic predictors consisting of monthly precipitations and temperatures (from previous September to current August) was constructed. Standardized climatic predictors were subjected to PCA to produce new independent climate related variables. Then two models were used in multiple regression analysis to predict residual chronologies. In the first model the out coming components together with 1, 2 and 3 years lags of correspondence standard chronology (as growth priority) were used as final predictors. In the second model, three further climatic predictors consisting of annual, biennial and triennial cumulative precipitations were introduced. Pre-selection of variables performed by considering eigenvalues ($\lambda >= 1$), and un-rotated climatic components were used as predictors of residual chronologies. Predictor variables were selected by stepwise selection approach (Criteria: Probability of F to enter <= 0.05, Probability of F to remove >= 0.10). The remaining variables and their coefficients in different age classes and single master chronology were compared. In order to perform response function analysis,

Table 1. General characteristics of sampled cores and their related residual chronologies for whole (overall), young, middle-aged and old *Quercus brantii* trees in Bensenjan forest (Iran)

General descriptive of cores	Master chronology type			
	Overall	<80	80–160	>160
Range of tree age (years)	40–430	40–79	80–160	161–430
Time span	1895–2010	1985–2010	1934–2010	1895–2010
Number of trees (cores)	118 (418)	41 (141)	44 (154)	33 (123)
Mean of raw ring width (mm)	0.564	0.990	0.478	0.530
Within tree correlation (rwt)	0.307	0.408	0.334	0.419
Between tree correlation (rbt)	0.312	0.366	0.336	0.352
Expressed population signal (EPS)	0.934	0.970	0.976	0.973
Variance in first eigenvector (%)	19.87	27.72	24.98	18.99
Residual chronology				
Standard deviation	0.071	0.284	0.515	0.032
Mean sensitivity	0.217	0.120	0.226	0.319
First order autocorrelation	0.318	0.085	0.010	0.011
Signal to noise ratio (SNR)	3.185	1.618	1.463	1.334

the standardized regression coefficients of first model (including monthly climatic data and growth priority) were multiplied by the climatic principle component to obtain a new set of regression coefficient related to original monthly data (Fritts & Xiangding, 1986). Finally these coefficients were divided by related standard error to examine their significant level by t-test.

Results

Tree-ring chronologies

Descriptive statistics of cores and residual chronologies are presented in Table 1. Total time span of master chronologies for whole, young, middle-aged and old trees were 115, 25, 76 and 115 years, respectively. All chronologies had high reliability according to Wigley et al. (1984) regarding critical value of 0.85 for expressed population signal (EPS).

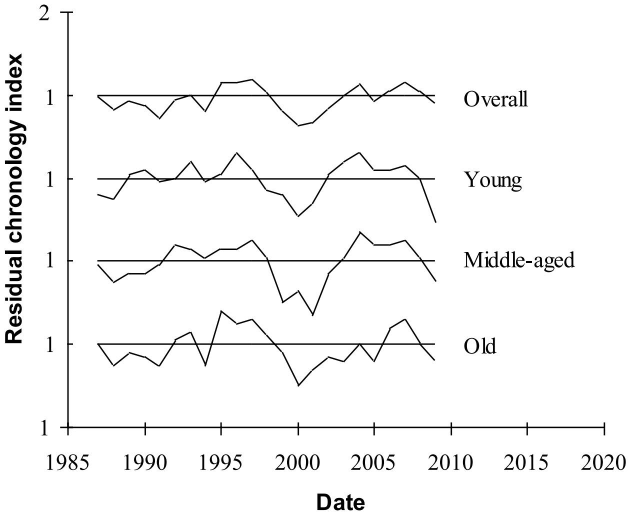

Fig. 3. Residual chronologies of whole (Overall), young (40–80 years old), middle-aged (80–160 years old) and old (160–430 years old) *Quercus brantii* trees in Bensenjan forest (Iran), in time span from 1987 to 2009

Overall master chronology had higher signal to noise ratio (SNR) than the rest of the chronologies, implying potentially more climatic information in this chronology. Whereas residual chronology index of old trees (>160 years old) revealed the highest mean sensitivity accompanied by lowest standard deviation and first order autocorrelation. The residual chronologies in time span from 1987 to 2009 are presented in Fig. 3.

Analysis of climate–growth relationship

All together 24 principle components were truncated to 7 PCs based on eigenvalue criteria ($\lambda >= 1$) (Table 2). These PCs accompanied by 1 to 3 years lags of standard chronology were included in first type of model to predict residual chronology indices of master cores. No PCs were significantly involved in regression model (1) to predict the overall master residual index in stepwise procedure and only one year lag of standard chronology with coefficient of 0.353 remained in the model with adjusted R^2 of 0.438 (Table 3). Applying age-dependent master residuals in first model, as predictand, conducted to entering climatic PCs in the model so that for residual chronology index of young trees (40 to 80 years old), PC1 and PC2 with regression coefficients of –0.023 and –0.027 were significantly included in the fit of the model with adjusted R^2 of 0.588 (Table 3). In middle-aged trees (80 to 160 years old) in addition to PC1 and PC2, one year lag of std. chronology index were contributed to fit the model, and for old trees (over 160 years old), PC1 and PC6 with regression coefficients of –0.025 and 0.023 remained in the model with adjusted R^2 of 0.468 (Table 3).

In second type of model to predict residual chronology of master chronology indices (Table 4),

Table 2. First 7 principle components of monthly climatic data from 1987 to 2009 in Yasuj (Iran)

		Components						
		1	2	3	4	5	6	7
Precipitation	September	–0.389	0.670	0.345	0.192	–0.202	–0.037	–0.079
	October	–0.331	0.607	–0.136	0.249	–0.118	0.282	0.319
	November	–0.220	0.081	0.216	–0.826	–0.239	0.145	0.048
	December	–0.446	–0.289	0.002	0.107	–0.331	–0.066	0.616
	January	–0.244	–0.664	0.237	0.373	0.280	0.249	0.164
	February	–0.149	–0.055	–0.065	0.052	–0.251	0.773	–0.087
	March	–0.156	–0.058	–0.320	0.310	–0.126	0.423	–0.569
	April	–0.563	0.189	0.494	0.219	0.030	0.330	0.156
	May	–0.341	0.217	–0.662	–0.175	0.199	0.052	0.106
	June	–0.338	0.707	0.427	–0.310	0.070	0.118	–0.007
	July	–0.204	–0.584	0.312	0.271	0.382	0.111	0.048
	August	–0.193	0.500	0.492	0.266	–0.115	–0.272	–0.333
Temperature	September	0.397	0.672	0.064	0.512	–0.013	–0.155	0.075
	October	0.469	0.015	0.597	0.313	–0.336	–0.266	0.075
	November	0.373	0.257	–0.215	0.408	0.316	0.176	0.002
	December	0.509	0.297	0.069	0.252	0.565	0.064	0.248
	January	0.294	0.066	0.416	–0.398	0.633	0.043	0.017
	February	0.099	–0.046	0.779	–0.164	0.218	0.252	–0.221
	March	0.227	–0.298	0.655	–0.148	–0.226	0.076	0.152
	April	0.826	–0.242	–0.080	–0.090	–0.097	–0.218	–0.112
	May	0.792	–0.041	0.322	0.057	–0.325	0.291	0.100
	June	0.820	–0.334	–0.063	0.129	–0.298	0.246	–0.017
	July	0.626	0.490	–0.307	–0.175	–0.155	0.228	0.187
	August	0.708	0.423	–0.086	–0.275	0.194	0.246	0.093

accumulative precipitation of current, and one and two previous growing years were considered to be assessed together with variables present in model one. The results of stepwise selection method in multiple regression analysis of overall master chronology index by second model variables were similar with first model. Use of age-dependent master chronology indices, as predictand in second model, highlighted the effect of accumulative precipitation of current and previous years. Residual chronology index of young trees was significantly predicted by presence of standardized biennial precipitation (BP_Z) with regression coefficient of 0.037 and adjusted R^2 of 0.655. Residual index of middle-aged trees were predicted by PC1 and standardized triennial precipitation (TP_Z) with regression correlation of –0.017 and 0.036, respectively (Adj. R^2, 0.751). Also, two variables of PC6 and standardized triennial precipitation (TP_Z) were

Table 3. Models type 1. Regression models to predict overall and age-dependents residual chronologies of *Quercus brantii* trees in Bensenjan forest (Iran) including climatic principle components (PCs) and three lags of std. chronology (Lag 1–3) as growth priority index in stepwise selection procedure (Criteria: Probability of F to enter <= 0.050, Probability of F to remove >= 0.100)

Master core type	Model	Adj. R^2
Overall	0.637 + 0.353 Lag1	0.438
40–80 year old	0.997 – 0.023 PC1-0.027 PC2	0.588
80–160 year old	0.588 – 0.028 PC1-0.014 PC2 + 0.411 Lag1	0.665
160–430 year old	0.992 – 0.025 PC1+ 0.023 PC6	0.468

Table 4. Models type 2. Regression models to predict overall and age-dependents residual chronologies of *Quercus brantii* trees in Bensenjan forest (Iran) including climatic principle components (PCs), standardized cumulative annual (AP_Z), biennial (BP_Z) and triennial precipitation (TP_Z), and three lags of std. chronology (Lag 1–3) as growth priority index in stepwise selection procedure (Criteria: Probability of F to enter <= 0.050, Probability of F to remove >= 0.100)

Master core type	Model	Adj. R^2
Overall	0.611 + 0.353 Lag1	0.438
40-80 year old	0.997 + 0.037 BP_Z	0.655
80-160 year old	0.998 – 0.017 PC1 + 0.036 TP_Z	0.751
160-430 year old	0.995 + 0.027 PC6 + 0.021 TP_Z	0.512

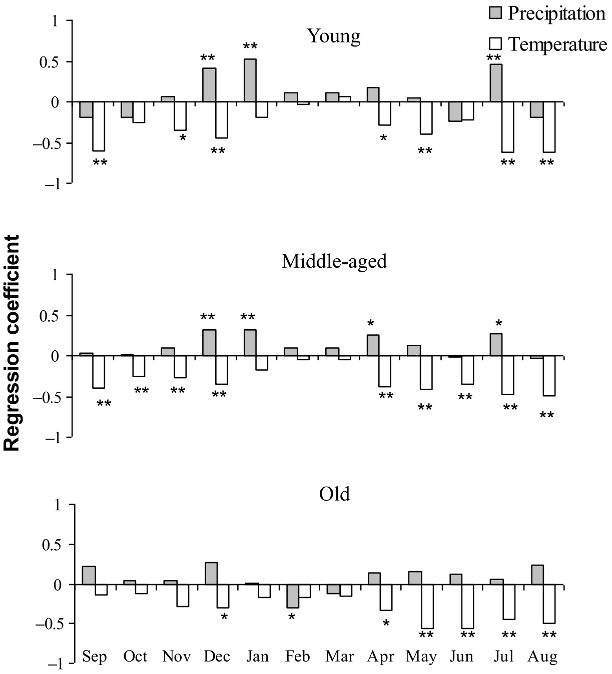

Fig. 4. Response function analysis of tree-ring width residual chronologies for *Quercus brantii* young, middle-aged and old trees and monthly climate data from September$_{(t-1)}$ to August$_{(t)}$ in time span from 1987 to 2009 (*P<0.05, **P<0.01)

entered in the model to predict the residual index of old trees. Standardized annual precipitation (AP_Z) was not independently considered in any of the regression models.

Annual ring growth of the trees mostly exhibited a negative correlation with temperature. Response function analysis (Fig. 4) demonstrated that the temperature of prior September to December had negative effect and precipitation of prior December and current January and July had positive effect on current tree-ring growth of younger trees. Also the temperature of April to August was negatively correlated with tree-ring growth of all trees with exception of the growth of young trees that was not significantly correlated with June temperature. Particularly, the precipitation of February negatively correlated with annual ring growth of old trees.

Discussion

Age of the sampled trees in study area (ranged from 40 to 430 years) represented highly heterogeneous age distribution of trees in this forest. Applying the whole cores to construct a residual master chronology resulted in a relatively long time span chronology, with a residual chronology implying high signal to noise ratio (3.18) and moderate first-order autocorrelation (0.32) (Table 1). Regardless of high signal to noise ratio of overall residual chronology, no climatic component appeared in the first model (including PCs) to predict overall residual chronology.

Unlike most of the oak species (Epron & Dreyer, 1993), *Quercus brantii* has high sensitivity of stomatal conductance to soil water deficit (Nazari, 2011). Therefore, it is expected that in Mediterranean regions with high climatic variability, a considerable amount of ring-width growth of brant's oak must be correlated to some extent to climatic variables. It seems that the main reason for weak participation of climatic variables to predict overall residual chronology of oak trees is due to incomplete elimination of unwanted noises (*i.e.* age dependent response) of the tree rings (Hughes et al., 2011). In overall master chronology, the effects of heterogeneous age distribution of trees were still present and therefore the first lag of standard chronology appeared vigorously in both models.

Age dependency of tree chronologies recently has been reported in many studies. As Vieira et al. (2009) in a study conducted in Mediterranean climate (Portugal) showed that old trees of *Pinus pinaster* were not affected by monthly temperature but by precipitation of current May and October, whereas growth of younger trees were impaired by August temperature and increased with a wet and warm May and a wet January.

In case of *Quercus brantii* the use of age-specific chronologies caused to enter climatic components in the models. So that in first model, PC1 (drought year with hot growing season) negatively impressed all age-dependent residual chronologies. With increasing age of the trees, the negative effect of PC2 (warm September with low January and July rainfall) on residual chronology decreased and gradually replaced with PC6 (winter rainfall) in old trees. On the other hand, with increasing the age of the trees, their dependency on July precipitation and also their susceptibility to drought conditions of previous year (autumn temperature) decreased. In many studies, performed in typical Mediterranean areas, high precipitation in May induced the formation of wider tree rings mostly due to formation of earlywood for longer periods (Vieira et al., 2009). By taking into consideration of altitudinal differences, it seems in more drought conditions like severe Mediterranean climate the formation of earlywood is predated and more limited than typical Mediterranean climates.

Supplementary response function analysis illustrated the new sights of climate-growth relationships of *Quercus brantii* trees. Results of response-function analysis showed that the impact of late spring frost in *Quercus brantii* trees is age asymmetric, hence increasing the average monthly temperature of April negatively affected their ring growth in all age classes. Frost damage can appear in three forms: early frost (autumn), winter frost (winter) and late frost (spring) (Chaar & Colin, 1999). In common oak species, the impact of late frost is more common than winter frost (Jones, 1959). By increasing global warming and weather instability, the risk of the late frost increased (Walter et al., 2013). Trend of the late spring frost in the studied area have been determined +5 days per decade (Rahimi, 2011). So, increasing April temperature speeds up the bud flushing process in *Quercus brantii* trees and exposes them to the probable risk of late spring frost and consequently causes ring-width growth reduction.

Precipitation of July was positively correlated to ring-width of young and middle-age trees. Timing and duration of xylogenesis of trees differ by age. Generally young trees have longer growing period than older ones due to earlier onset of cambium activity and later ending of lignification (Rossi et al., 2008). Also it's reported that small oak (*Quercus robur*) trees, due to weak stomatal control on photosynthesis, exhibited faster recovery of tree ring growth after extreme drought events (Zang et al., 2012). Therefore, it's speculated that the young and middle-age oak trees could be able to resume xylogenesis by increasing July precipitation. Temperature of September to December, prior to growth season, adversely affected ring-width growth of young and middle-age trees. This reduction probably is in relation with declining size of dormant cambium zone and or reduction of carbohydrate accumulation during hardening period (Fernández et al., 1996).

Generally, old trees of *Quercus brantii* were poorly affected by monthly precipitation during investigated time span of this study. Due to the presence of shallow root system and long growing period, smaller trees are affected more by environmental variations than older ones. Less susceptibility of ring-width growth of old trees to climatic variations was in agreement with the findings in *Pinus pinaster* (Vieira et al., 2009). It was also observed that young and middle-age trees of *Quercus brantii* benefited from prior December and current January precipitation but old trees were negatively affected by February precipitation. High winter precipitation and consequently high snow load may lead to a reduction in soil temperature at lower parts in spring. Low soil temperature in growing season diminishes root activity (Teskey et al., 1984). As older trees possess deeper root system than younger ones, they distinctly face up with low soil temperature in spring.

Conclusion

In conclusion, this study has demonstrated that, despite generally similar pattern of climatic response in different age classes, including all oak trees of different ages in the same chronology extremely diminished the climatic signals of the residual chronology as a result of age suppression. All oak trees from each age classes were sensitive to increasing April temperature that likely led to late frost susceptibility of trees. Precipitation of July was mostly beneficial for younger brant's oak individuals and old trees were not able to resume their radial increment in a wet July. Late winter precipitation suppressed radial growth of old trees by decreasing underground temperature during the initial growing season. Regarding the trends of climate changes in this region, it's expected that this species will be faced with late frost and its younger individuals will be gradually declined by global warming.

Detecting the appropriate range of tree age in *Quercus brantii* can improve use of this species in dendrochronological studies of this region. According to the results of this study, this age would be at least 160 years old. Brant oak trees with age between 160 to 450 years old, might be heterogeneous in growth pattern that interferes climatic signals after detrending and need to be further investigated.

Acknowledgments

This work is financially supported by University of Yasouj (Project Nr. 1385). We thank Sohrab Alvani-Nejad, Majid Bahrevar, and Mahmud Heidari for helping us to collect core samples from the field. We are also grateful to general director of Natural Resources and Watershed Management of Kohgiluyeh-and-Boyer-Ahmad Province to provide us the opportunity of study in Bensenjan forest.

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