JOURNAL OF FOREST SCIENCE, *64*, 2018 (3): 139–147

https://doi.org/10.17221/79/2017-JFS

Application of dendroclimatology in evaluation of climatic changes

*Mohammad Reza KHALEGHI**

Department of Watershed Management Engineering, Faculty of Natural Resources, Torbat-e-Jam Branch, Islamic Azad University, Torbat-e-Jam, Iran

**Corresponding author: drmrkhaleghi@gmail.com*

Abstract

Khaleghi M.R. (2018): Application of dendroclimatology in evaluation of climatic changes. J. For. Sci., 64: 139–147.

The present study tends to describe the survey of climatic changes in the case of the Bojnourd region of North Khorasan, Iran. Climate change due to a fragile ecosystem in semi-arid and arid regions such as Iran is one of the most challenging climatological and hydrological problems. Dendrochronology, which uses tree rings to their exact year of formation to analyse temporal and spatial patterns of processes in the physical and cultural sciences, can be used to evaluate the effects of climate change. In this study, the effects of climate change were simulated using dendrochronology (tree rings) and an artificial neural network (ANN) for the period from 1800 to 2015. The present study was executed using the *Quercus castaneifolia* C.A. Meyer. Tree-ring width, temperature, and precipitation were the input parameters for the study, and climate change parameters were the outputs. After the training process, the model was verified. The verified network and tree rings were used to simulate climatic parameter changes during the past times. The results showed that the integration of dendroclimatology and an ANN renders a high degree of accuracy and efficiency in the simulation of climate change. The results showed that in the last two centuries, the climate of the study area changed from semiarid to arid, and its annual precipitation decreased significantly.

Keywords: tree ring; autoregressive standardization; temperature; precipitation; Iran

Climate change refers to unexpected changes in the earth's climate characteristics that occur in the long-term (Goyal 2004). Further, the forest has important roles in runoff generation, soil erosion and climatic conditions (Gholzom, Gholami 2012). Increase in global temperature is the most obvious sign of this change (Babaeian et al. 2015) and therefore temperature variations are commonly used to detect and quantify possible changes in climate (Amiri, Eslamian 2010). Also, climatologic, hydrologic and hydrogeologic records are necessary for water resource planning and management. Plants grow in spring and summer seasons better than in autumn and winter. This provides the studies of climate change by annual growth rings of trees (Jafari 2010). According to previous studies, there is a relationship between precipitation, temperature, and tree rings and can, therefore, be useful for developing long-term estimates of specific hydrological variables and also in chronology studies (Cleaveland, Stahle 1989). Dendrochronology is one of the methods applied in reconstructing past environmental events. It is the science of defining past climatic and hydrologic variability from tree-ring data (Woodhouse et al. 2010; Paredes-Villanueva et al. 2015). Due to the growth-limiting effects of low precipitation and high temperatures, dendroclimatic (as one of the branches of dendrochronology) studies would be successful in part (Conkey 1979). Dendroclimatology is concerned with constructing records of past climates and climatic events by the analysis of tree growth characteristics and especially annual rings (Steinschneider et al. 2017). Reviews show that tree-ring data have been successfully applied to reconstruct hydrologic variables such as river discharge (Woodhouse, Meko 2002; Liu et al. 2010). Bogino and Jobbágy (2011) studied the relationship between climates with the growth and death of *Prosopis caldenia* Burkart in the lowlands and uplands. Moreover, their results showed that precipitation has an important role in the forest and that the optimum depth to groundwater ranges from two to eight metres. In certain areas, soil moisture declines when precipitation decreases and when depth of groundwater increases (Gholami et al. 2015; Kames et al. 2016). Therefore, trees will produce wider annual rings in wet years compared to dry years. Therefore, tree rings and vessel features are valuable proxies in the evaluation of climatic changes, but it is important to select tree species that are suitable for dendroclimatology studies. We selected *Quercus castaneifolia* C.A. Meyer (Rix, Kirkham 2009) for dendroclimatology studies in the Bojnourd region of North Khorasan, north-eastern Iran. *Q. castaneifolia* is an important species native to Iran and is a suitable selection for evaluating annual changes in climatic factors (Danek et al. 2007). *Quercus* Linnaeus is the largest genus in the family Fagaceae with approximately 300–600 species (Soepadmo 1972); it is the most common genus of Fagaceae in forests of Iran. The sensitivity of the *Quercus* species tree-ring extent to climatologic and water access changes is high. We refer to Di Filippo et al. (2010) and Gea-Izquierdo et al. (2011). To find out the climate trend in a future course, we select a climate change forecasting model using artificial neural network (ANN). In general, different studies have indicated the usefulness of the ANN to simulate the climatic factors (Maier, Dandy 2000). From these studies, it has been demonstrated that ANN models can be flexible enough to simulate the climatic factors successfully. The goal of this study is the application of dendroclimatology in the evaluation of climate change effect by combining dendroclimatology and ANN modelling to simulate the climatic factors.

MATERIAL AND METHODS

Study area

The research trees were located at 56°58'E to 57°05'E longitude and 37°23'N to 37°28'N latitude in North Khorasan province, in north-eastern Iran (Fig. 1). The study was carried out in the Bojnourd region and at the Abyari meteorological station. The Abyari station was located at an elevation of 1,600 m and was 5 km away from the study area. The annual mean precipitation and temperature were 267 mm and 13.3°C, respectively. The climate in the study area was arid; the climatic data from the Abyari meteorological station were used for comparison with the tree-ring data. The average elevation of the study area (the location of the study trees) was 1,650 m. The study trees were located in an area of similar elevation. The precipitation pattern in the study area is rainfall. The age of the study trees ranged from 180 to 250 years; we selected a period from 1800 to 2015.

Dendroclimatology studies

In order to reconstruct the climate of the past, tree rings are evaluated for their full length using statistical models. We collected 25 samples from the old trees. The longest tree-ring series covered 250 years, extending back to 1765. Two cores were extracted at breast height in the vertical directions (130 cm). We provided a suitable box for core conservation. Sanding of the cores was done until the tree-ring extent was clearly visible.

Crossdating and standardization. Crossdating can be described as the recognition of the same tree ring pattern in a species with different stands, as the actual growth date of any one ring of the pattern is the same in the different trees, and one may carry a chronology across from tree to tree (Douglass 1941). The crossdating process is done by measuring the extent of the annual tree rings. The tree-ring extents of the samples were arranged accord-

Fig. 1. Study area and the meteorological station in north-eastern Iran

ing to their cambial age (the number of rings from the centre). At first, crossdating was performed by matching tree ring patterns (wide and narrow rings) using the skeleton plot method (Douglass 1941; Stokes, Smiley 1996). Cores were visually crossdated against the established record using the signature patterns of ring width (Edmondson et al. 2014). This is a non-climatic variance when the process of its modelling, approximating and removing is known as standardization (Gholami et al. 2017a, b). The standardized tree-ring index was calculated based on Eq. 1:

$$I_{\mathrm{t}} = \frac{W_{\mathrm{t}}}{Y_t} \qquad (1)$$

where:

I_{t} – standardized tree-ring index,

W_{t} – tree-ring width (mm),

Y_t – estimated growth curve for year *t*.

We used a regression relationship and I_{t} to present a standard chronology of *Q. castaneifolia* in the Bojnourd region.

Time series analysis

After tree-ring marking, ring widths were measured to the nearest 0.01 mm with a stereomicroscope and a LINTAB$^{\mathrm{TM}}$ device (RINNTECH, Germany) with TSAP-Win$^{\mathrm{TM}}$ (Version 0.55, 2003) software. Crossdating of tree rings was carried out by using the TSAP software, which was designed as a platform for the measurement and tree-ring time series analysis. The correlation between the different indirect methods is analysed with TSAP-Win Scientific$^{\mathrm{TM}}$ a program for the measurement and analysis of tree-ring data (De Ridder et al. 2011). Non-climatic trends were removed by using the autoregressive standardization (ARSTAN 1986) program. To provide a new basis for removing non-climatic trends from tree-ring data, regional growth curves (RGCs) have been recently used (Naurzbaev et al. 2004). To obtain the RGC for the study site, the tree ring widths of all samples were averaged according to their cambial age. Moreover, the residual chronology was then used, which represented the maximum interannual climate variability. The quality of the chronologies was deemed sufficient if the expressed population signal (ESP) value of 0.88 was reached (Wigley et al. 1984). ESP was used to estimate the strength and reliability of the chronology through time (Grissino-Mayer et al. 2010). The other growth indices were coefficient of parallel variation = 0.75, ESP = 0.86, signal-to-noise ratio = 0.74 and mean sensitivity = 0.68. After determining the growth indices, for each studied tree, the time series of the tree-ring chronology was defined. Finally, a chronology related to the studied trees was defined.

Simulation of climatic parameters

In this study, a multilayer perceptron (MLP) network was applied to simulate the climatic parameters. To estimate the climatic parameters during the past centuries, it was used from a feed-forward neural network and the Levenberg-Marquardt (LM) learning algorithm. The tree-ring width and precipitation during the growth season were evaluated as inputs, and the precipitation of the growth season was adopted as the output. In the first stage, all data were normalized and divided into two classes: training data (70% of all data) and testing data (30% of all data). NeuroSolutions software (Version 5.0, 2011) was used as an ANN in the simulation. Consequently, the best network architecture for the simulation of climatic factors was found, by using a trial-and-error method that was an MLP network with a sigmoid transfer function and an LM training technique. The number of hidden neurons was changed from 1 to 10. Also, the trial-and-error method and sensitivity analysis were executed to select the appropriate input variables. Three input patterns were evaluated, and their efficiencies (*f*) were evaluated and compared, as expressed in Eqs 2–4:

$$\mathrm{AI} = f\left(W_{\mathrm{t}}\right) \qquad (2)$$

where:

AI – De Martonne aridity index,

W_{t} – tree-ring width (mm).

$$P = f\left(W_{\mathrm{t}}\right) \qquad (3)$$

where:

P – annual precipitation (mm).

$$T = f\left(W_{\mathrm{t}}\right) \qquad (4)$$

where:

T – annual mean temperature (°C).

The modelling process was started with one neuron in one hidden layer and then progress (with increasing size) until the performance of the test is satisfactory (Sy 2006). The ANN efficiency is evaluated by using the mean squared error (MSE)

Table 1. Tree-ring width – W_t (*Quercus* Linnaeus), annual precipitation (*P*), annual temperature (*T*) and the aridity index (AI)

Year	W_t (mm)	*P* (mm)	*T* (°C)	AI
1960	1.50	293	12.9	12.79
1961	2.74	312	12.2	14.05
1962	2.30	340	12.8	14.91
1963	2.36	366	12.4	16.34
1964	2.98	323	13.1	13.98
1965	2.25	368	12.6	16.28
1966	2.83	348	12.8	15.26
1967	2.61	355	12	16.14
1968	2.19	315	12.4	14.06
1969	3.20	362	13.2	15.60
1970	2.40	305	13.4	13.03
1971	2.21	323	12.8	14.17
1972	1.90	325	12.6	14.38
1973	2.28	352	13.3	15.11
1974	2.12	298	14.2	12.31
1975	2.29	312	13.7	13.16
1976	3.21	338	13.1	14.63
1977	3.40	330	13.2	14.22
1978	2.83	283	13.3	12.15
1979	3.04	346	13.2	14.91
1980	2.23	304	13.9	12.72
1981	1.94	372	12.7	16.39
1982	2.83	251	14.4	10.29
1983	1.70	143	13.3	6.14
1984	2.50	273	13.6	11.57
1985	1.20	146	12.6	6.46
1986	2.53	290	13.5	12.34
1987	2.60	273	13.4	11.67
1988	2.86	324	12.8	14.21
1989	1.99	240	13.3	10.30
1990	1.10	134	12.7	5.90
1991	3.20	325	12.9	14.19
1992	2.77	333	12.4	14.87
1993	3.21	253	12.9	11.05
1994	2.07	260	13.7	10.97
1995	1.64	194	13.1	8.40
1996	1.72	192	13.2	8.28
1997	2.28	281	13.5	11.96
1998	1.69	211	13.7	8.90
1999	2.28	291	13.5	12.38
2000	2.83	309	14.5	12.61
2001	0.88	138	12.7	6.08
2002	2.63	337	12.9	14.72
2003	2.80	373	13.6	15.81
2004	2.40	287	13.7	12.11
2005	2.30	365	14	15.21
2006	1.98	213	13.3	9.14
2007	1.87	272	13.3	11.67
2008	1.58	194	14.4	7.95
2009	2.65	301	13.3	12.92
2010	2.77	223	13.5	9.49
2011	1.85	243	14.4	9.96
2012	1.75	211	13.8	8.87
2013	1.48	198	12.9	8.65
2014	1.55	216	13.6	9.15
2015	1.69	231	13.2	9.96

and the coefficient of determination (R^2). Using a verified network for the study area for the period 1800–2015, the annual AI changes were simulated. Within the modelling process, the network input was the annual tree ring, and the network outputs were the annual AI, *P*, and *T*. Finally, to evaluate the simulation accuracy, the simulated results were compared with the recorded values.

RESULTS

Table 1 shows some of the tree-ring widths and climatic factors. Statistical analysis was carried out with the SPSS software (Version 22.0, 2016) on climatic data (including *T* and *P*). It was used from the Pearson correlation coefficients for the relationships of *P*, *T* and AI with the tree-ring chronologies. Table 2 shows the results of correlations of the tree-ring chronology with the climatic data (*P*, *T*, and AI). A significant correlation of the tree ring with *P*, *T*, and AI (Nistor 2016) was found. Also, the results showed that the tree ring was affected by *P*, *T*, and the climate classification (AI). The results from the analysis of variance indicated that tree-ring width was significantly (95% probability) related to *P* and *T*. According to results, effective factors in tree-ring width were *P* and *T*. The time series of the tree-ring chronology and the annual aridity index during the study period are presented in Fig. 2. Fig. 3 presents the time series of the tree-ring chronology and the mean tree-ring widths during the last two centuries. Also, the tree rings significantly decreased over the last 60 years. The results of an ANN simulation during the training stage for the AI simulation (R^2 = 0.9) are presented in Table 3. Based on Fig. 4, an evaluation of

Table 2. Pearson's correlation between tree rings and annual precipitation (*P*), mean annual temperature (*T*), and the aridity index (AI)

	Pearson's correlation
P	0.68
T	0.2
AI	0.67

Table 3. Results of network training for simulating the aridity index using annual tree-ring width

All runs	Best network	Training
Average of minimum MSEs	minimum MSE	0.006
Average of final MSEs	final MSE	0.04

MSE – mean squared error

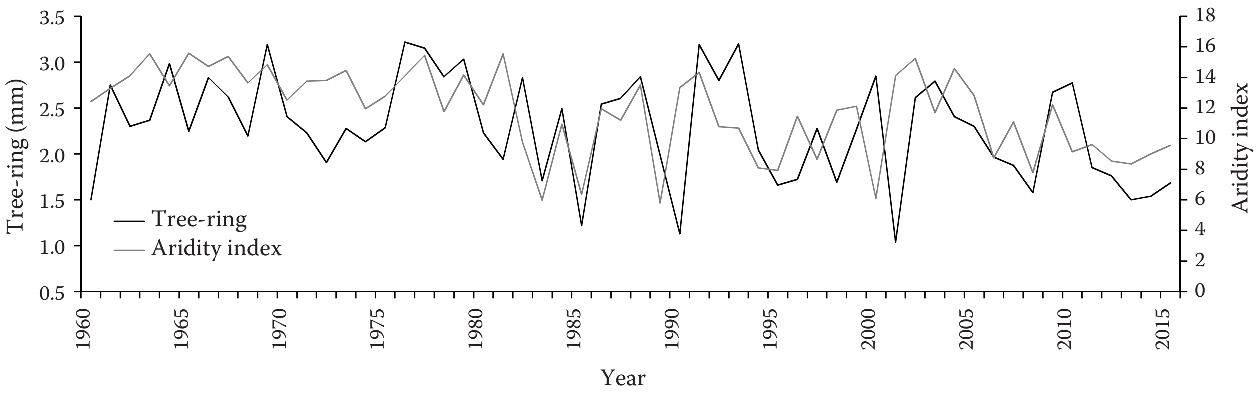

Fig. 2. Time series of the tree-ring chronology and aridity index during 1960–2015

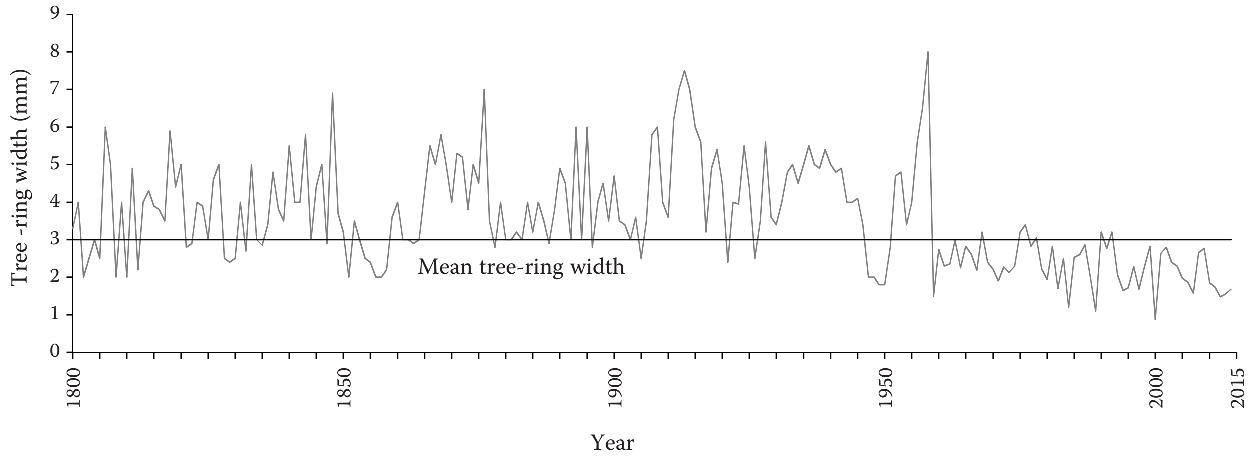

Fig. 3. Time series of the tree-ring chronology and the mean tree-ring widths in the last two centuries

the ANN efficiency in the climatic simulation during the validation (testing) stage was done by comparing the simulated and the measured aridity indices (R^2 = 0.66). Fig. 5 indicates the results of the network efficiency evaluation of the AI simulation. According to the results, the ability of an ANN in the simulation of the aridity index is at an acceptable level of accuracy. Based on these results, we found acceptable outcomes during the training stage. The optimum network structure for precipitation simulation includes an MLP with the input tree rings, a sigmoid transfer function, the LM or momentum training techniques, and one neuron. A sigmoid transfer function and the LM or momentum training techniques are some of the best selections for hydrologic modelling (Anctil, Rat 2005). After network optimization, an efficiency evaluation for the testing stage was performed via a comparison between the measured and the simulated precipitation during the growing season. Moreover, past studies confirm ANN's performance in other modelling studies (Samani et al. 2007). Fig. 6 shows the simulated AI during the last four centuries. According to the simulated De Martonne index, the climate of Bojnourd changed from semiarid to arid during the last two centu-

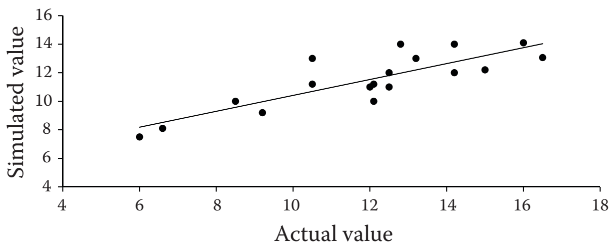

Fig. 4. Comparison between the simulated and the measured aridity index in the testing stage (R^2 = 0.7)

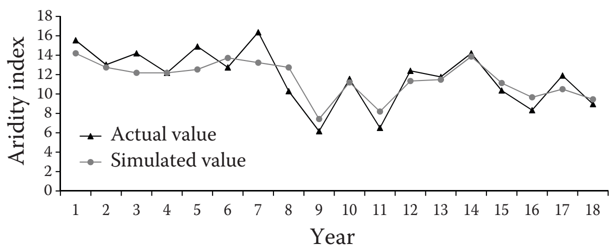

Fig. 5. Comparison between the simulated and the measured aridity index in the testing stage

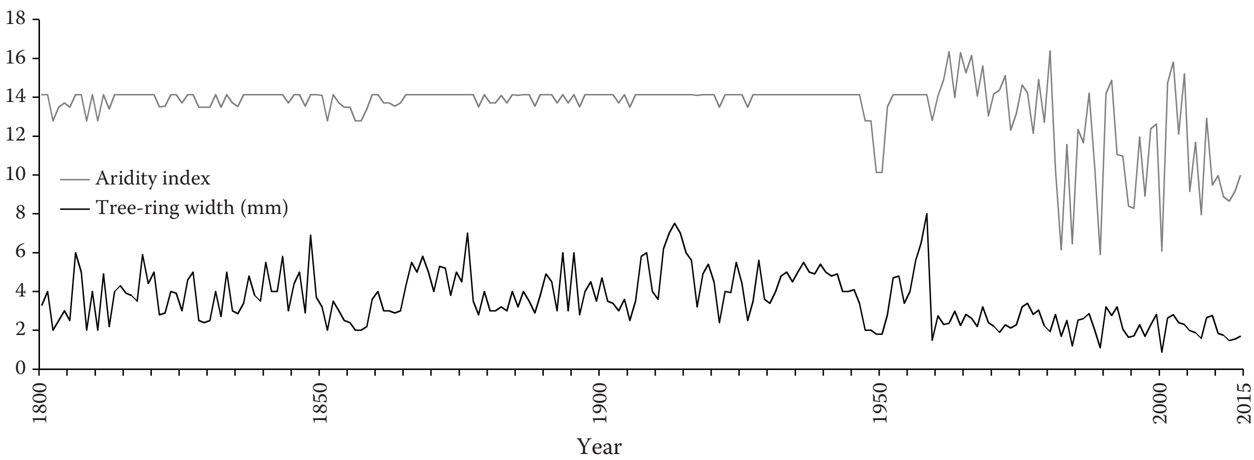

Fig. 6. The aridity index simulated by using the verified neural network and the measured tree-ring widths in the last two centuries

ries (Table 4). Fig. 7 shows the annual precipitation during the last two centuries as simulated by using dendroclimatology and an ANN. According to the results, the precipitation values in the study area decreased by about 100 mm over the last four centuries.

DISCUSSION

One of the most commonly applied methods of evaluating climatic factor changes is the evaluation of long-term records based on tree-ring analyses. To do this, the *Quercus* chronologies were developed for the Bojnourd region using different techniques, such as crossdating and standardization, and with the aid of the ARSTAN software. These chronologies were correlated with climatic factors and climate changes, and the climate changes were simulated based on the correlations. To found the variability of climate conditions due to anthropogenic effects and other effective factors, there is a need to precisely date annual tree-ring chronologies over a long period (Martinelli 2004).

Table 4. The changes in climate class, mean annual precipitation (*P*) and mean annual temperature (*T*) during the last two centuries

	P (mm)	*T* (°C)	AI	Climate classification
19th century	390	10.8*	20.4	Mediterranean
20th century	345	12.2*	15.5	semi-arid
Meteorological station (the last 55 years)	267	13.3*	12.16	arid

*This simulation has not an acceptable accuracy, AI – aridity index

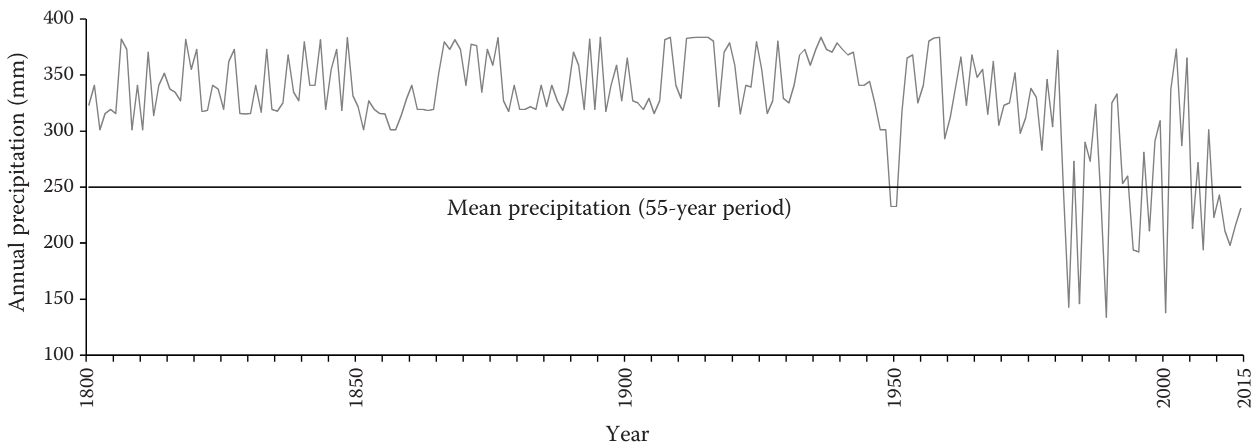

Fig 7. The simulated annual precipitation and the mean precipitation from the Bojnourd meteorological station (55-year period) in the last two centuries

Therefore, to simulate the climate changes based on large-scale chronologies dating back, dendroclimatology and an ANN were applied together. To evaluate the probable impacts of enabling/disabling tree rings, precipitation, temperature, and the aridity index, some models were developed. Based on results, a suitable input variable for ANN in climatic simulation is tree-ring width. Thus we can prove the high efficiency of the ANN and the present methodology (the integration of an ANN and dendroclimatology) in simulating climatic changes. The results showed that precipitation had a more significant relationship with tree rings than did temperature and the AI; however, using only the AI provided better results in the modelling of the climate index. Due to importance of the temperature factor under cold conditions, it is hardly likely to have been eradicated in a wetter regime (Naurzbaev et al. 2004). Based on results, the best network structure for aridity index simulation is an MLP network with a sigmoid transfer function and the LM training technique and therefore an ANN based on the LM technique is an efficient structure for climatological simulations (Nayebi et al. 2006). Also, the results of the training stage showed that the MSE and the coefficient of determination (R^2) were 0.04 and 0.9, respectively. These results proved that the use of an ANN for the simulation of climatic factors has produced good results. During the testing stage, MSE and R^2 were 0.06 and 0.7, respectively. We simulated the climatic factors for the period 1800–1960 (i.e., *P*, *T*, and AI). As shown in Fig. 7, the annual precipitation values in the study area during the last two centuries ranged from 134 to 480 mm. The annual mean temperature was from 10 to 14.5°C. This simulation can be used to define periods of drought. For example, during the last two centuries, some drought periods occurred. Based on the results, the most intense droughts occurred in 1850, 1955, 1970 and 1980 decades; the longest drought happened during 1850–1870. The reconstruction accuracy for annual temperature was lower than that for precipitation because of two main reasons: first, there was a lesser fluctuation in annual temperature in the study area; and second, the studied trees in this research grew in the highlands and in an area of low temperature. In the mid-twentieth century, particularly from 1940 to 2015, notable climatic changes occurred in the Bojnourd region. By using tree-ring chronology and the AI, we found that the climate class in the study area changed from semiarid to arid, and this trend in climatic changes continued. According to studies of Babaeian et al. (2015) in Iran, climate change continues and the change in precipitation is greater than that in temperature. Also according to many researches it has been reported from various studies that there is a diverging trend in the climate-growth relationship that started after the late twentieth century (Leal et al. 2015). We observed early climate changes in the Bojnourd region in the mid-twentieth century, during which industrialization in the study area was intensified. The climatic reconstructions (*P*, *T*, and the AI) for the period 1800–1960 showed a long-term trend toward lesser precipitation and higher aridity over the last 200 years. What is clear from the results of this study is that the precipitation in the Bojnourd region decreased in the mid-twentieth century and its climate changed from semiarid to arid during the last two centuries. Based on the above-mentioned dendroclimatology studies, an intense drought in the study area was defined. If suitable tree species were selected in suitable environmental conditions for dendroclimatology studies, capability of dendroclimatology in modelling climate change would be proved (Griggs et al. 2014). Topography, pedology, and tree physiology are the most important factors in determining the local distribution of the trees under consideration. The studied trees are located in a mountain region (with rather cold conditions), therefore the annual temperature did not change significantly during the last two centuries. The annual temperature range during the past 55 years based on secondary data was 11.9–14.5°C. This study showed that the climate in the Bojnourd region changed from semiarid to arid during the last two centuries. Therefore, in order to support decision making processes toward sustainable development, considering the knowledge of past climate changes is important and essential (Bush, Metcalfe 2012; Lopez et al. 2012). Also, these results show the instability of the climate change during the last two centuries (Babaeian et al. 2015). Further study with the use of older trees is needed to extend the tree-ring chronology further back in time, and other dendroclimatological methods, such as vessel chronology, can be applied.

Acknowledgement

The author would like to thank the Regional Water Company of North Khorasan for providing the secondary precipitation data and for helping me with the data preprocessing.

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Received for publication May 23, 2017
Accepted after corrections March 1, 2018