Dendrochronological Potential of *Juniperus foetidissima* Willd in Central Anatolia, a Semi-arid Region of Turkey

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The dendrochronological potential of *Juniperus foetidissima*, growing in central Anatolia, was assessed. Raw, standard, and residual tree-ring chronologies were prepared for *J. foetidissima* trees in the Eskişehir region using classical dendrochronological methods for the period between 1875 and 2014. All the chronologies were statistically relevant, and the running correlation, expressed population signal, and mean sensitivity values in the residual tree-ring chronology were within the given limits. Therefore, the residual tree-ring chronologies were used to assess the climate-growth relationship. The relationships between tree-ring width growth and climate variables (mean temperature, monthly sum of precipitation) were investigated using response function analysis (moving windows correlations) in the R platform. Positive or negative relations were found between the residual tree-ring widths and the monthly precipitation and mean temperature, but with low coefficient values. The tree-ring width growth showed a significantly negative response to precipitation in August of the current year for the period in 1977-2001 and 1978-2002 and significantly positive to temperature in June of the current year for the period in 1971-1995, 1972-1996, and 1993-1996. In conclusion, despite some problems with cross-dating, *J. foetidissima* can generally be used for dendrochronological research and is suitable for developing long-term chronologies.

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INTRODUCTION

Annual rings can provide information about the ecological characteristics of trees in the areas where they grow, as well as provide reliable data for research in such fields as history, archaeology, and past climate (Panyushkina 2011). Thus, it is important to create long-term chronologies in order to transfer knowledge in these areas. In particular, long-lived tree species such as juniper have great importance. Junipers, as drought-resistant tree species of Turkey, play an important role in expanding forest cover in semi-arid Central Anatolia (Kahveci *et al*. 2018).

There is no consensus regarding the number of juniper species on Earth. Farjon (2001) described 52 species, but Adams (2014) studied junipers for many years and stated that there are 67 species. Yilmaz *et al*. (2011) stated that the genus is represented by eight species in Turkey. *Juniperus excelsa* is the most widespread juniper tree species in Turkey and also throughout the world (Douaihy *et al*. 2011). *Juniperus foetidissima* is distributed in southeast and east Europe, the Caucasus, and West and Central Asia at altitudes from 700 to 2000 m a.s.l. (Farjon 2013). *Juniperus* is listed as a priority habitat by the European

Commission (Natura 2000) and juniper cutting is prohibited in Turkey. *J. foetidissima* is distributed in a limited number of areas and it is protected in different ways in several areas throughout the world (Adams 2014).

The world has passed through a period when the economic functions of forests were prioritized and importance was attached to tree species with high economic returns (Simoncic *et al.* 2013). Few forestry studies have investigated juniper trees in Turkey, where the juniper forests are highly degraded and rehabilitation of these forests is difficult due to the semi-arid conditions; furthermore, junipers are not fast-growing tree species. The slow growth of *J. foetidissima* is considered an advantage for dendrochronological research (Sarangzai and Atta 2018).

Long-lived tree species can potentially provide long time series that reflect changes in climate conditions (Badeau *et al.* 1996). The aim of many dendrochronology researchers is to create the longest chronology possible and *J. foetidissima* is an important tree species for achieving this goal in Turkey. However, juniper wood has problems in terms of cross-dating because junipers grow under extremely dry conditions and they can have missing rings as well as false or double rings (Touchan and Hughes 1999). Therefore, juniper wood has generally been ignored by dendrochronologists. *J. foetidissima* has the same problem with a very irregular growth pattern and alternating phases of sensitivity (Sass-Klaassen *et al.* 2008), thereby leading to narrow, missing, or unclear boundaries (Wils and Eshetu 2007). These problems may be overcome by further dendrochronological research using juniper (Sarangzai *et al*. 2011).

In this context, Touchan *et al*. (2007) studied *J. excelsa* and established the longest juniper chronology (AD 1076 to 2000) for southwestern Anatolia. Esper *et al*. (2007) investigated the growth behavior of juniper trees at different elevations in Central Asia. Sass-Klassen *et al*. (2008) found that juniper tree rings contain a large-scale precipitation signal in the Ethiopian highlands. Opala *et al*. (2017) investigated the climate-growth relationship for *J. semiglobosa* Regel in the Pamir-Altay Mountains system. Emaminasab *et al*. (2020) investigated *J. foetidissima* and *J. oblonga* M.B., and found strong relationships between ring-width series and climate factors.

It is important to understand the ecology of *J. foetidissima* because it is one of the main tree species that grow in arid areas of Turkey. *J. foetidissima* is also one of the tree species that are found frequently in archaeological excavations. Thus, in the present study, the dendrochronological potential of *J. foetidissima* in Turkey was analyzed. In particular, wood characteristics and tree-ring series of *J. foetidissima* were investigated, and the relationships between tree-ring width growth and climate variables (mean temperature, monthly sum of precipitation) were calculated.

EXPERIMENTAL

Materials

The present study was conducted in two locations in Eskişehir province in Turkey around Ağaçhisar village /Alpu district and Kayı village/Mihalıççık district, which are located on the border of the Central Anatolian Region of Turkey (Fig. 1). The forests in the Central Anatolian region are steppe forests. Some such areas can be defined as relicts since the population was more widespread in the past. The populations have been reduced because the areas have been degraded by humans for thousands of years. *J. foetidissima* mainly grows in forest relicts on mountains, and the oldest trees are found in the best stands.

The sampling was conducted in suitable areas where the focus was on the occurrence of junipers in groups with relatively old juniper trees. The wood cores of all juniper trees were taken in the case of diameter at breast height (DBH) > 5 cm and recorded longitude and latitude (UTM), altitude (m), exposure (˚), slope (%), and human impact (HI) (Tab. 1).

Incremental cores were taken from damage-free living trees using a Jim-Gem 14″ increment borer of 5 mm. In total, 180 wood cores were sampled. Data were collected from sampling plots in October–November 2014 and 2015. Only 54 wood cores were suitable for processing because the other samples exhibited internal rot and spiral gain. Stem disks could be very helpful for cross-dating, but none were found in the study area.

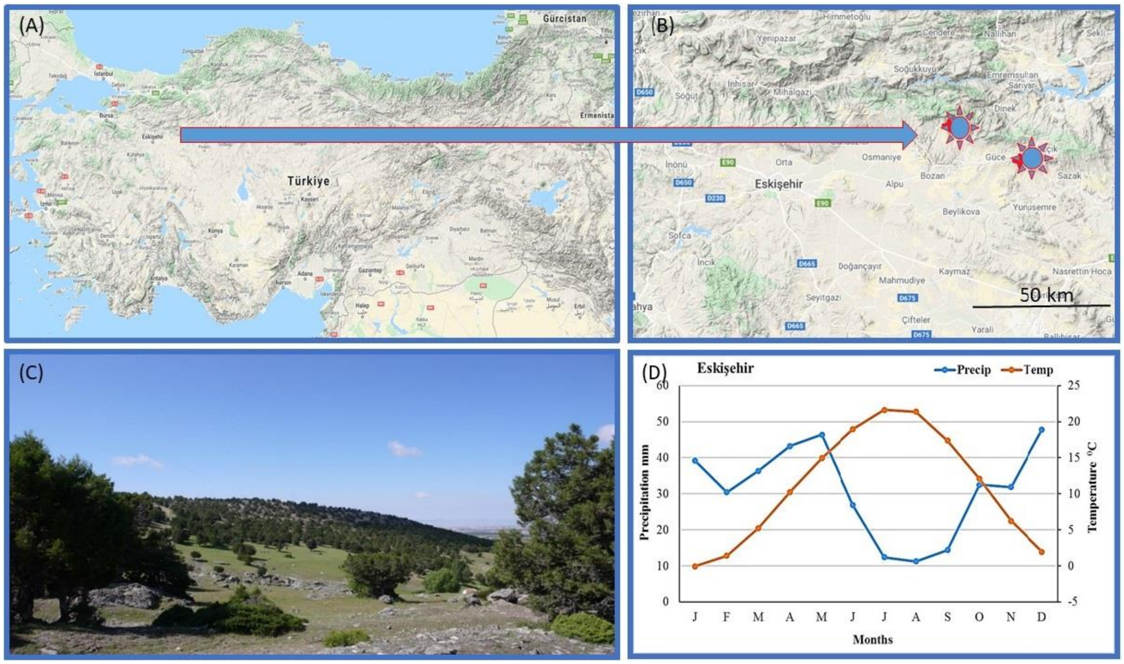

Fig. 1. (A) Study area, (B) study locations, (C) View of a *J. foetidissima* stand and (D) Climate diagram of Eskişehir

Table 1. Characteristics of Sample Site

Location	N	E	Elevation	Slope (%)	Aspect	Mean Height	Mean DBH	Total years	Tree	Wood core
Kayı/ Mihalıccık	39°54′	31°09′	1113	20	SW	7.73	47.3	1710-2014	8	8
Agaçhisar /Alpu	39°51′	31°30′	1235	50	NW	5.9	37.6	1885-2014	10	15

Methods

The 54 wood cores were scanned at 2300 dpi using an Epson scanner. After image acquisition, ring widths were measured using tracing paths interactively in the image (WinDENDRO 2006). After obtaining measurements, all cores were cross-dated visually (Stokes and Smiley 1996) and statistically using TSAP-Win software (Rinn 2010). The quality of cross-dating was checked using the COFECHA program (Holmes 1983). Several problems occurred during the cross-dating and quality control procedure. It is very common to find juniper wood without incremental rings on one side, whereas the other side may have larger than normal annual rings. Moreover, juniper trees aged more than 100 years can have missing and locally absent rings, or double rings, which make cross-dating difficult (Kahveci and Arslan 2021). Finally, 23 samples of the remaining 18 trees from both locations were used for further analyses of this study. In the older samples, the annual rings widths over 140 years old had to be excluded due to cross-dating problems (Tab.1).

The cross-dated sequences were standardized to remove age-related growth trends using ARSTAN software (Cook and Krusic 2005). First, the ring-width measurements were transformed by adaptive power transformation and standardized using a linear regression curve. The detrended series from individual tree cores were combined into chronologies using a bi-weight robust mean. To evaluate the signal strength in the site chronologies, the running correlation (rbar) and expressed population signal (EPS) were calculated. These are measures of the average correlations between the tree-ring series at each site (Speer 2010), and mean sensitivity. Raw, standard, and residual chronologies were created for the study sites for the period between 1875 and 2014.

Climate-growth relationship analysis was conducted using response function analysis (moving windows correlations) in the “treeclim” package (Zang and Biondi 2015) in the R platform (Bunn 2008, R Core Team 2012). Monthly precipitation and monthly mean temperature records from meteorological station measurements over 50 years were used for climate signal detection. Meteorological data for the research site were obtained from the General Directorate of Meteorology (GDM) for 1965 to 2015 (GDM 2020). The residual chronology was used to analyze the tree-ring growth-climate relationships.

RESULTS AND DISCUSSION

Wood Characteristics

Central Anatolia is located in the center of Turkey, where drought is the most severe in the region. Drought limits the vegetation cover, but human activity also has great impacts (Kahveci 2022). Indeed, the effects of humans may become more damaging than those of drought because plants cannot regenerate quickly due to the lack of precipitation and various responses can occur (Scarascia-Mugnozza *et al*. 2000). *J. foetidissima* forests have also been degraded due to overuse in the arid Central Anatolian region. *J. foetidissima* was found in mixed stands with *J. excelsa* and *Quercus* spp., as well as in unmixed stands at the study sites. However, *J. foetidissima* prefers a specific ecological niche (Kahveci and Arslan 2021).

Internal rot was detected in many samples. The young individuals had wider and smoother annual rings, and the annual rings narrowed as the trees became older. Many wood anomalies were observed, including irregular tree-ring widths with abrupt changes between wider rings and extremely small rings in some cases, as well as double rings, partly missing rings, and false rings in cores, especially in older trees (Fig. 2). The missing rings may occur during phases of depressed growth and double rings most often occur in wide tree rings (Saass-Klaassen *et al.* 2008).

Incompatible wood core samples from the same tree were observed very often, and thus *J. foetidissima* had partly missing rings in some cases. Early wood and late wood rings were very easy to distinguish because the late wood contained thick-walled tracheids that appeared darker than the early wood (Fig. 2).

Wood anomalies occur due to genetic, ecological, or other reasons. Studies conducted in this region have shown that junipers can produce root shoots, and some old *J. foetidissima* trees have been propagated from root shoots (Kahveci and Arslan 2021).

However, it is generally considered that conifer species do not produce root shoots, and thus they cannot readily regenerate (Bonga 2014). The ability to produce root shoots of *J. foetidissima* may be advantageous for the survival in an arid region, but shifting coppice to high forest has increased the probability of internal rot in trees (Huss and Kahveci 2011) and decreased the life expectancy of trees. Long-lived junipers may be from propagated seed, but even if they are grown from seed, internal rot due to human impacts (grazing, collecting firewood, winter fodder using and shifting cultivations) can also occur.

Fig. 2. Wood core anomalies in *J. foetidissima* samples taken from both locations. For example, in (A) very often seen corrugated annual rings in old trees. In (B) abnormal large annual ring possibly missing rings. In (C) annual rings developing in different directions. In (D) irregularly growing in different side of wood disc. In (E) significant differences in annual rings between heartwood and sapwood especially in young trees

Even if *J. foetidissima* was propagated from seed and does not have any internal rot, the most common issues that affect cross-dating are false or double rings, as well as missing rings and wedging or partly missing rings will continue (Emaminasab *et al.* 2020). Wils and Eshetu (2007) suggested that uncertainty remains regarding the periodicity of ring formation in trees that grow under extremely dry conditions. Therefore, false or double rings and missing rings may occur in juniper (Couralet *et al*. 2005). Sass-Klaassen *et al*. (2008) stated that false rings may be caused by a bimodal rainfall distribution in certain years due to the occurrence of winter rain and a strong monsoon event in any one year. By contrast, missing or partly missing rings (= wedging rings) are frequently formed during years with little rainfall (Emaminasab *et al.* 2020). Studies that focus specifically on the patterns of wood formation under changing ecological conditions may clarify the relationship between wood formation in juniper and the environmental conditions (Couralet *et al*. 2005).

Table 2. Chronology Statistics (1895-2014)

Statistical indicator	RAW	STD	RES
Core/tree	23/18	23/18	23/18
Common Period	1875-2014	1875-2014	1875-2014
Mean Sensitivity	0.198	0.186	0.202
Averaged rbar	0.293	0.218	0.274
Averaged EPS	0.832	0.834	0.861

RAW = raw chronology, STD = standard chronology, RES = residual chronology, EPS = expressed population signal, rbar = inter-series correlation.

Tree-ring Series

In total, 23 wood cores from 18 *J. foetidissima* trees were successfully cross-dated and utilized. The residual tree-ring series calculated for 18 *J. foetidissima* trees in the period from 1875 to 2014 are presented in Fig. 3. The raw tree-ring widths in *J. foetidissima* varied between 1 and 5 mm, and the mean tree-ring width was 2.23 mm. The ring widths of *J. excelsa* growing in the same area varies between 0.5 and 3.5 mm (Kahveci *et al*. 2021). The three-chronology version was of good statistical quality (Tab. 2). A previous statistical analysis using ARSTAN showed that statistically valid and usable dendrochronological chronologies could be produced (Cook *et al*. 2000). Raw, standard, and residual chronologies yield slightly different results, but efforts have been made to improve the statistical quality. In the present study, many wood cores were removed from the chronology to obtain the best results.

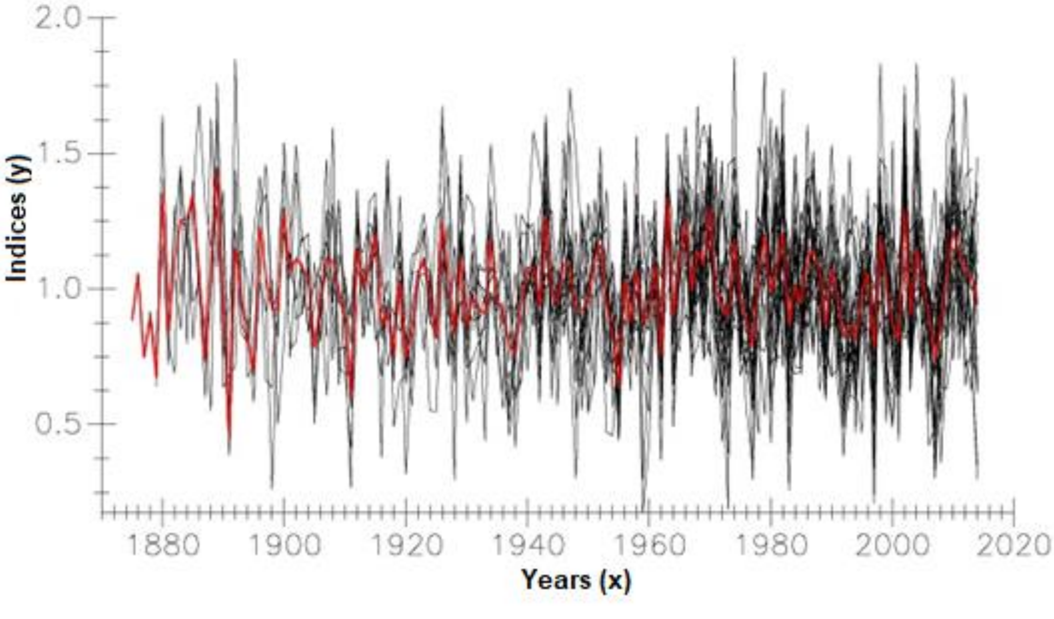

Fig. 3. Residual tree ring-width-index chronologies of *J. foetidissima* from Eskişehir with mean.

The rbar indicator was used to examine the signal strength throughout the chronology (Speer 2010) to attain an Expressed Population Signal value of 0.85 (Wilson et al. 2021). The mean rbar values for the raw and standard chronologies were 0.282 and 0.283, respectively, in the present study. The rbar value for the residual chronology was 0.323. EPS is a measure of the common variability in a chronology dependent on the sample depth (Briffa and Jones 1990). The chronology is considered reliable when the EPS value is over 0.85 (Wigley *et al*. 1984). In the present study, the mean EPS values for the raw, standard, and residual chronologies were 0.832, 0.834, and 0.861, respectively. It may be possible to increase the values by increasing the number of samples. However, Couralet *et al*. (2005) used 11 stem disks and 26 wood cores from *J. procera* and calculated the EPS value as 0.81.

Another important value is the mean sensitivity, which measures the year-to-year variability in the tree-ring width over a range from 0 to 1 (Speer 2010). Speer (2010) suggested that a mean sensitivity greater than 0.4 indicates very high sensitivity, and a mean sensitivity around 0.2 is generally accepted as indicating that a series is sufficiently sensitive for climate reconstruction. According to results obtained in the present study, the mean sensitivity values for the raw and standard chronologies were around 0.2 (0.198 and 0.186, respectively), but only the residual chronology had a value over 0.2 (0.202) (Table 2). Kahveci and Arslan (2021) found that the raw tree-ring width in *J. foetidissima* samples from Eskisehir also responded to the slope and altitude as environmental variables.

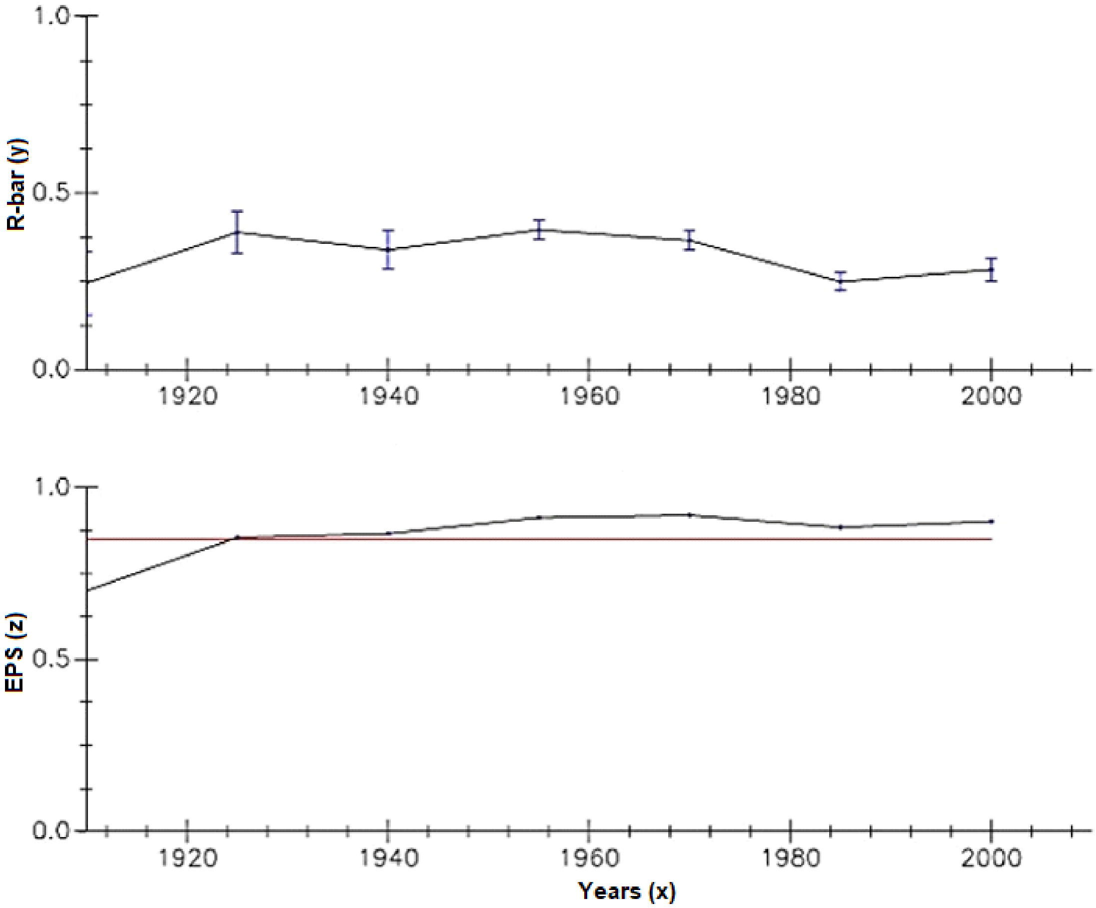

Fig. 4. Running average correlation between all series (r-bar) and expressed population signal (EPS) of the tree-ring chronology of Eskişehir between years 1875-2014

Climate-growth Relationships

The moving correlation coefficient graphs demonstrated the relationships between the climate variables and annual tree-ring width from April through to October (Fig. 5). Results showed that there are positive or negative relations between the residual tree-ring widths and the monthly precipitation, but with low coefficient values. This is also seen in tree species growing in other Central Anatolian regions. A positive correlation was found between mean annual precipitation and regional chronology of *J. excels*, also with low coefficient values in Kırıkkale (Kahveci *et al.* 2018). The coefficients of May to August precipitation were positively correlated with most of the tree-ring series, and May and June coefficients were generally significant in Anatolia (Köse *et al.* 2017). However, the tree-ring width growth response was significantly negative to precipitation in August current year for the period in 1977 to 2001 and 1978 to 2002 in this research (Fig. 5). When the annual precipitation of the research site was examined between these years, it was seen that the precipitation, which is normally over 400 mm, fell under 350 mm and precipitation was extremely low (288 and 297 mm) for these periods. However, the precipitation in August was higher when compared to other years. The reason for the negative coefficient values may be found in the genetics of *J. foetidissima*, which usually grows in arid regions with no summer rainfall.

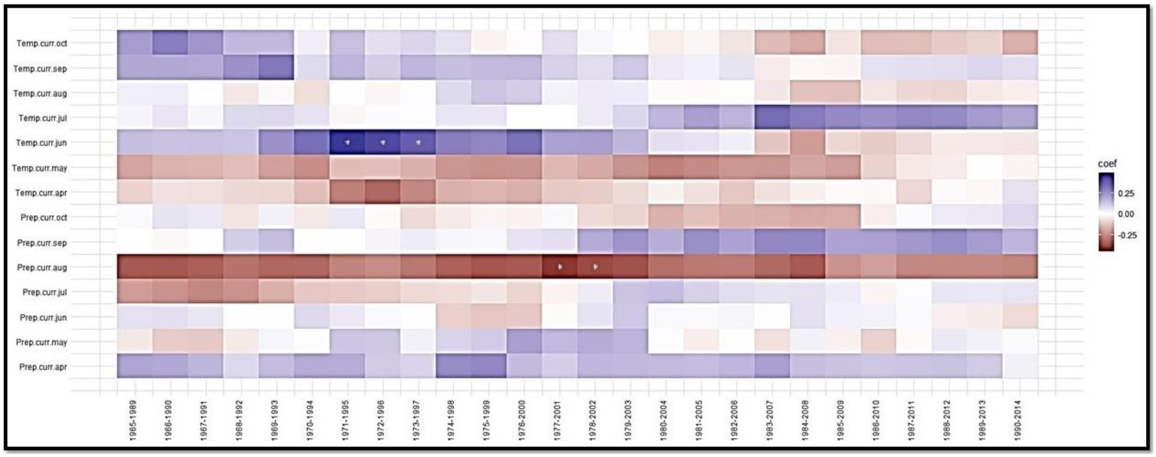

Fig. 5. Moving correlations (50-year window) between regional residual chronology and climate variables (mean temperature, monthly sum of precipitation) of Eskişehir for the period 1965–2015. Color code represents correlation coefficient. Significant ($p < 0.05$) correlations are indicated by white asterisks.

The results of the moving correlation coefficient graphs showed that there was a significant growth response to temperature in June of the current year for the period in 1971 to 1995, 1972 to 1996, and 1993 to 1996. It is not expected that the temperature strongly influences the radial growth throughout Anatolia (Touchan *et al.* 2007; Köse *et al.* 2017). The previous studies conducted in drought regions showed that precipitation was the most important limiting factor for tree-ring growth (Fonti and Babushkin 2016; Kahveci *et al*. 2018). The response in terms of growth to climatic parameters can vary depending on various factors, such as the climatic zone (boreal, temperate, or continental), growing season, type of ecosystem (steppe, tundra, or rainforest), and tree species (Nechita and Chiriloaei 2018).

Potential of *J. foetidissima* for Dendrochronological Research

Cook and Kairukstis (1990) stated that preferred species for dendrochronological research should meet the following requirements: production of distinguishable rings in most years, possession of ring features that can be dendrochronologically cross-dated, and capability of reaching sufficient age to provide the time control required for a particular investigation. Other important features include sensitivity to climate and other ecological conditions. Thus, the only unsuitable feature of *J. foetidissima* is the problem with cross-dating, which may be addressed by increasing the number of dendrochronological studies of juniper (Sarangzai and Ahmed 2011). Emmanisab (2020) also found strong relationships with climate factors and claimed that *J. foetidissima* can be used for dendro-ecological studies.

Another possibility involves finding stem disks in related regions. However, juniper trees are strongly protected in Turkey, which would make it difficult to find *J. foetidissima* stem disks. Saass-Klaassen *et al.* (2008) claimed that even if stem disk collection is not a major problem, it is still unclear whether this material is appropriate for building up long tree-ring chronologies using classical dendrochronological techniques, and thus the use of other methods was suggested, such as ^{14}C dating and $\delta^{18}O$ analyses. These methods could help to create long chronologies for *J. foetidissima*, and they also facilitate archeometric research. Indeed, the first systematic attempt at tree-ring dating at Near East archaeological sites involved collecting and analyzing tree-ring specimens from an 8th century BC tomb in Turkey (Kuniholm 1990, 1996), and *J. foetidissima* was one of the tree species found in the archaeological excavation.

CONCLUSIONS

1. *J. foetidissima* can be used to develop long chronologies, despite some difficulties with cross-dating.
2. The wood cores taken *J. foetidissima* propagated from seed may help to obtain more precise results of dendrochronological cross-dating.
3. The residual tree-ring width of *J. foetidissima* could be used to create a statistically valid tree-ring chronology and it responded to climate variability.
4. *J. foetidissima* can potentially be used to provide long series and information about past climate, environmental conditions, and historical and archaeological events.

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