IDŐJÁRÁS

Quarterly Journal of the Hungarian Meteorological Service
Vol. 121, No. 3, July – September, 2017, pp. 243–263

The effect of climate and soil moisture on the tree-ring pattern of Turkey oak (*Quercus cerris L.*) in Central Transdanubia, Hungary

István Péter Kovács[1] and **Szabolcs Czigány**[2*]

[1]*Department of Cartography and GIS, University of Pécs,*
Ifjúság u. 6, H-7624 Pécs, Hungary

[2]*Department of Physical- and Environmental Geography, University of Pécs,*
Ifjúság u. 6, H-7624 Pécs, Hungary

**Corresponding author E-mail: sczigany@gamma.ttk.pte.hu*

(Manuscript received in final form August 1, 2016)

Abstract—Dendrochronological studies have revealed several environmental signals of many oak species supporting the suitability of these species for climate reconstruction (*Haneca et al*. 2009). Despite the large number of studies, limited information is available on the influence of climatic condition and soil moisture on the growth characteristics of Turkey oak (*Q. cerris*). Although soil moisture is probably the most limiting factor on growth of most oak species, relevant studies in Hungary primarily focused on the effect of temperature and rainfall, and ignored the impact of soil moisture. The combined analysis of climatic factors and soil moisture would reveal the importance of the influencing factors and would point out the anatomical patterns and environmental signals of a given area. In the current study, we analyzed the dendrochronological characteristics of a grove in Western Hungary (Central Transdanubian Region), and correlated tree anatomical patterns with the mean monthly temperatures, monthly precipitation totals, and modeled soil moisture at five different depths. The grove is exposed to environmental stress due to the local soil and climatic factors. Our findings indicate that the most pronounced environmental signal stored in the oaks is the change of soil moisture that exposes a direct impact on tree growth.

Key-words: Turkey oak, soil moisture, tree-ring width, early wood width, late wood width

1. Introduction and aims

1.1. Background

One of the most notable feature of Earth's climate is its variability, which has been profoundly affecting the evolution of life, distribution, diversity, and health of trees and forest composition. The natural global warming that followed the Pleistocene glaciation is exacerbated by the increased concentration of greenhouse gases (*Smith et al*., 2014) and exerts an increasing influence on forests. According to most studies, climate of the Carpathian Basin likely becomes drier and warmer in the very near future (*Bartholy et al.,* 2008), which, besides the increasing number of extreme events, envisages the increasing frequency of droughts (*Führer et al.,* 2011a). The single known positive effect of warming climate is the increasing growth rate of the warm-loving and drought-tolerant tree species (*Somogyi,* 2007, 2008), however, this sole positive phenomena is likely unable to counterweight for all the negative effects of global warming. With the decreasing return period of drought, the occurrence of forest fire likely increases (A1B emission scenario, *Smith et al.,* 2014), while, similarly, the spreading of fungi-originated diseases speeds up, insect and pest damages intensifies, therefore, tree tissue structure alters, triggering the general deterioration of tree health conditions (*Mátyás et al.* 2010; *Klimo* and *Hager,* 2001). The habitat of less drought-tolerant species will be taken over by less productive species ((*Führer et al.,* 2011a), resulting in decreasing productivity and CO_2 uptake. In Hungary, the decreasing areal distribution of beech and sessile oak, and simultaneously, the spreading of Turkey oak is expected (*Móricz et al*., 2013). The latter species makes up 11.2 percent of the forest stands of Hungary (*Miniszteri Tájékoztató,* 2015). Nevertheless, wood quality and economical significance of Turkey oak, due to its known growth disorders (e.g., frost cracks) and imperfections, is lower than for other oak species (*Molnár et al.,* 2007). Hence, due to its spreading in the region, thorough understanding of its dendrochronological features is indispensable. Climatic preferences and reactions of common European oak species (e.g., *Quercus robur, Quercus petreae, Quercus pubescens, Quercus ilex* etc.) are well known (*Cufar et al*., 2014; *Haneca et al.,* 2009), and studies on the topic have also been conducted in Hungary (*Kern et al.,* 2009). However, due to their similar structural composition, oak species pursue different survival strategies and react for increasing drought frequency in a different manner (*Nardini* and *Tyree*, 1999). Turkey oak has a homogeneous dendrochronological character, and it is sensitive to climate changes, providing valuable climatic signals (*Nardini et al.,* 1999; *Di Filippo et al.,* 2010, *Stafasani* and *Toromani,* 2015). However, only regional data are available on the temperature and rainfall demand and drought tolerance of Turkey oak in Hungary (*Babos,* 1984; *Szabados,* 2008).

Tree-ring width (TRW) is the most commonly analyzed proxy in dendrochronological studies, which provides a general overview on tree growth. Tree-ring width fundamentally determines the anatomical features and structure of tree rings (*Gasson,* 1987; *Rao et al.,* 1997; *Leal et al.,* 2007; *Gričar et al.,* 2013), therefore, dendrochronological studies principally focus on TRW. Analyses of latewood width (LWW) and earlywood width (EWW) (*Eckstein et al.,* 1977; *Weigl et al.,* 2008), however, provide climatic signals of intra-annual resolution and enable researchers to obtain accurate paleoclimatic reconstruction of higher resolution. The aforementioned features are spatially heterogeneous, thus climatic signals are profoundly influenced by regional characteristics and settings (*Gričar et al.* 2013). Depth of groundwater table, soil moisture contents, slope, exposure, hierarchical role in ecological associations all influence growth (*Stokes* and *Smiley,* 1968), hence adequate filtering of climatic signal errors is only representative, when a sufficiently large number of specimens are sampled. In their European habitats, including Hungary, oaks most influentially react on the changes of long-term rainfall patterns. Growth of Turkey oak, depending on the water budget of the soil, is most profoundly affected by fall and winter rainfall of the preceding season and the early spring precipitation of the year of relevance (according to the authors' *former unpublished findings*). In other areas, the role of spring and summer precipitation (*Szabados,* 2008) were found to be the most influential factors, and the impact of temperature, as a limiting factor, had a lesser importance (*Haneca et al.,* 2009). Water demand of trees is primarily delivered from soils (*Fritts,* 1976), and many studies indicated that the growth of oak species is chiefly affected by mean monthly soil moisture values rather than precipitation (*Graiser*, 1951; *Auchmoody* and *Smith,* 1979). Yet, growth rate of selected species do not directly correlate with soil moisture contents (*Kwiaton* and *Wang,* 2015).

In the current study, we hypothesized, that the studied anatomical features directly indicate the plant available soil moisture totals at different depths, while only indirectly reflected the rainfall totals. Hitherto, no studies in Hungary have been conducted on the correlation between the growth characteristics of Turkey oak and the corresponding soil moisture contents. If our hypotheses are proven, implementation of the impact of various soil physical types on the growth characteristics of Turkey oak should be anticipated in the future.

Many international studies are available on the reconstruction of drought periods using tree-ring data (*Woodhouse* and *Overpeck,* 1998; *Stahle et al.,* 2000), therefore our studies may provide additional data for future analyses in this field.

To analyze the major anatomical patterns of Turkey oak, we studied a grove developed on soils of poor water availability that was formed on gravelly parent material. As groundwater table is located at greater depth than the longest roots, the association is exposed to climatic changes (group of sensitive oaks), and trees provide profound growth reactions on climatic changes.

The objective of the current study is the analysis of the anatomical patterns of the trees of the investigated site, and the comparison of anatomical patterns with local climatic and soil moisture patterns to answer the following questions: Which climatic factors are responsible for tree growth? Which climatic signals are reproducible by the analysis of the tree rings of Turkey oak? What type of correlation can be identified between the anatomical pattern of Turkey oak and the change of soil moisture?

1.2. Site description

The research site is located northwest of the city of Ajka, on the low rolling hills of the Pápa-Bakonyalja region (*Dövényi,* 2010) (*Fig. 1*). The reason for selecting the site is our preliminary knowledge and extensive studies on the geomorphology and water conditions of the site (*Babák et al.,* 2013). A second intention for site selection was the extremely slow growth rate of the Turkey oaks of the area, indicating a major drought stress, periodically exerted on the specimens of the grove. The 1000-meter thick Createaceous limestone and the overlying carbonaceous Eocene sequence of 2 to 250 meters in thickness (Szőc Limestone Formation) emerges to the surface as a horn in the vicinity of the Szék Lake (*Bohn,* 1983). These strata are overlain by younger Oligocene and Miocene gravelly sediments (Csatka Formation) (*Bihari,* 1979). By damming the Csigere Creek, the Széki Reservoir, covering an area of 68 hectars, was constructed in 1978. The experimental site is located downstream from the dam in the upper part of valley side, northeast of the town of Devecser (*Fig. 1*). Springs were revitalized here due to the replenishment of the karst water system (*Babák et al.,* 2013) from the adjacent areas. As the site is located on a ground approximately 5 to 8 meters above the springs, the trees are unaffected by spring water and capillary water rise.

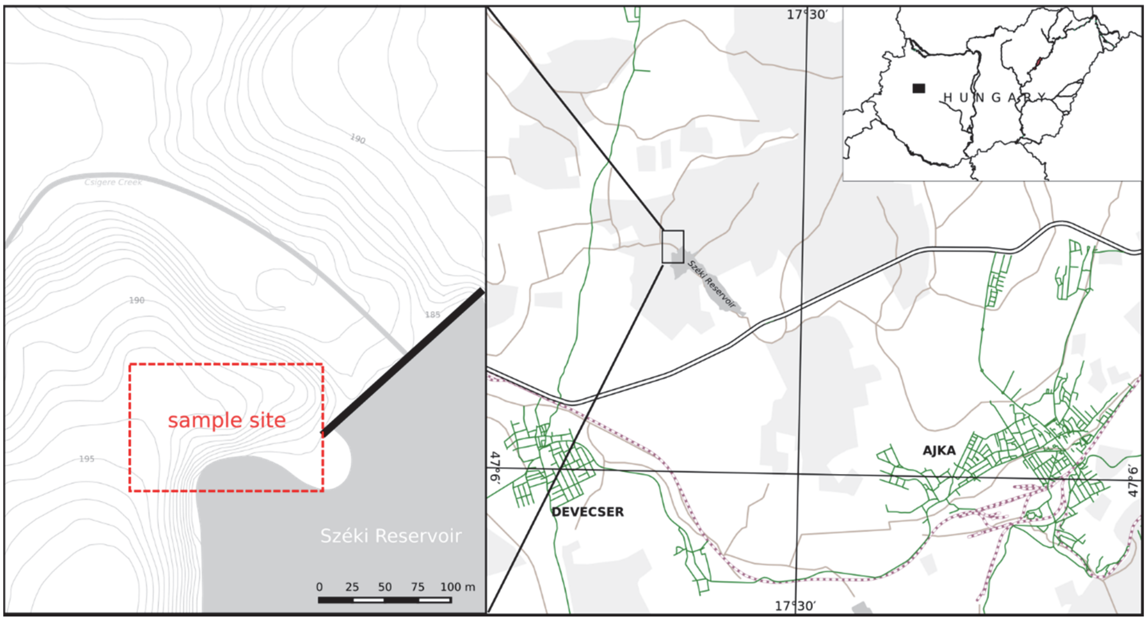

Fig. 1. Location of the study site.

The study area belongs to the Pápa-Bakonyalja forestry subregion (*Bidló et al.,* 2006). The moderately cool and moderately wet area has an annual insolation of 1,960 hours, and it is characterized with a mean annual rainfall total of 650 mm (*Dövényi,* 2010). Under the studied grove the typical genetic soil type is Leptosols (Entisols in the soil taxonomy), while the physical soil type is loam with a high concentration of coarse and gravelly fragments, characterized with unfavorable hydrologic properties and poor drainage. Topsoil thickness in the studied area ranges between 20 and 40 cm according to the AGROTOPO soil database compiled by the Research Institute for Soil Science and Agricultural Chemistry (RISSAC).

According to the studies of *Kovács et al.* (2012), the area belongs to the hornbeam-oak forest climatic zone, slowly transitioning to sessile oak – Turkey oak climate. The dominant tree species of the study area is the Turkey oak, however, along the Csigere Creek, black alder (*Alnus glutinosa*) is also commonly found. The approximate mean age of the trees of the studied grove ranges between 110 and 120 years. The average trunk diameter is around 35 cm, while the average height is about 22 meters. Turkey oak is a tree of Mediterranean origin, however, it easily adapts to the extreme temperature and soil moisture fluctuations of Hungary (*Gencsi* and *Vancsura,* 1992). Turkey oak is a ring-porous species that rarely develops missing and false rings, hence it is an ideal candidate for dendrochronological analyses (*Schweingruber,* 1993). During drought periods, taproot provides water supply for the trees, while root hairs create a homogeneous zone in the subsoil (*Führer et al.*, 2011b). The early wood vessels are relatively large, usually organized in the multiple rows. Wide rays and longitudinal parenchimas commonly characterize the xylem (*Molnár et al.*, 2007).

2. Methods

2.1. Dendrochronological methods

Sampling was done in April, 2014, during which 16 trees were sampled with random sampling (*Speer* 2011), and 31 drillings were used in our analyses. Sampling was done with a Haglöf Mora increment borer at breast height following the methods of *Jozsa* (1988). Core samples were glued to sample holders and were polished to 400 grits. The processed samples were digitalized at a resolution of 1200 dpi and were analyzed with ImageJ 1.48 software. Growth curve standardization (removal) was carried out with ARSTAN (44.h3), autocorrelation was minimized according to *Cook* (1985). Quality of the TRW, LWW, and EWW chronology, prepared for the period of 1979 to 2013, was validated with Cofecha (*Holmes,* 1983), during which mean sensitivity (MS) and expressed population signals (EPS) were considered.

Mean monthly temperatures and precipitation totals were measured at the Pápa Weather Station, located about 20 km from the study site, were downloaded from the ftp.ncdc.noaa.gov server. Data were validated and corrected with the annual precipitation data of the Hungarian Meteorological Service. Using the meteorological data, forestry aridity index (*FAI*, *Führer,* 2010; *Führer et al.,* 2011a) was calculated for the studied period.

$$FAI = 100 \cdot \frac{T_{VII-VIII}}{P_{V-VII} + P_{VII-VIII}} \, , \tag{1}$$

where $T_{VII\text{-}VIII}$ is the mean temperature of the months of July and August, $P_{V\text{-}VII}$ is the rainfall total of the months of May, June, and July, and $P_{VII\text{-}VIII}$ is the rainfall total of the months of July and August.

Linear correlations were then analyzed for all climatic, soil moisture, and anatomical datasets.

2.2. Soil moisture calculations

Using the aforementioned temperature and rainfall data, Thornthwaite potential evapotranspiration (*Thornthwaite,* 1948) was calculated according to Eq. (2):

$$E_{pot} = 16 \cdot \frac{L}{12} \cdot \frac{N}{30} \cdot \left(\frac{10 T_a}{I} \right)^{\alpha} \, , \tag{2}$$

where L is the mean length of daylight during the given month, N is the number of days in the month of relevance, T_a is the mean monthly temperature, while I is the annual heat index, the sum of the monthly heat indices i, and α was calculated according to Eq. (3):

$$\alpha = (6.75 \cdot 10^{-7} I^3) - (7.71 \cdot 10^{-5} I^2) + (1.792 \cdot 10^{-2} I) + 0,.49239 \, . \tag{3}$$

The annual heat index I was calculated as follows:

$$I = \sum \left(\frac{T_a}{5} \right)^{1.514} \, . \tag{4}$$

Using the annual evapotranspiration and precipitation data, soil moisture content was modeled for the entire 35-year period with Hydrus-1D (v.4.16.0110). The initial time step was 1 month, thus 420 time variable records were entered to the model. The maximum number of iteration was set to 100. For the hydraulic model we used the Van Genuchten-Mualem model with hysteresis, with an initial drying curve. Residual water content θ_r was adjusted to 0.0737 m^3 m^{-3}, while the saturated moisture content was set to 0.43 m^3 m^{-3}. The van Genuchten parameter of α was adjusted to 0.0019, while n and the saturated hydraulic conductivity (K_s) were set to 1.31 and 9.05 mm d^{-1}, respectively. The upper boundary condition (BC) was set to atmospheric BC with surface runoff, while for the lower BC, free drainage was selected. For the time variable BCs monthly precipitation and evaporation totals were used, and interception was not considered in the calculations. As Thornthwaite's equation calculates potential evapotranspiration, we ignored transpiration through the trees, with the exception of indicating the presence of root collar in the entire modeled soil profile with a root density of 100/mm.

Based on our field experience, a homogenous loamy soil profile of 60 cm depth was used in the model. The initial volumetric moisture content was set to 0.25 m^3 m^{-3} at the surface, and it gradually increased with depth to 0.35 m^3 m^{-3} to the bottom of the profile (60 cm). Soil moisture was modeled at depths of 4, 10, 20, 30, and 58 cm. Output model data were then correlated with tree anatomical parameters.

3. Results

3.1. Climatic changes

The overall tendency of the monthly precipitation totals indicate a decreasing trend for the period 1979–2013 for the study area (*Table 1*). Precipitation decrease is more pronounced for the months of November and December, however, a noticeable drop is observable during April and the summer months, during which water availability is crucial for tree growth. Slight increase in monthly rainfall totals is observable only in February, March, May, and September. Mean monthly temperatures, with the exceptions of September and December, indicate an increasing trend. Warming is the most pronounced during the summer months. The combined rainfall and temperature data clearly indicate the increasing aridification of the climate in the study area.

The *FAI* pattern acts similarly to the temporal aridification pattern of the area (*Fig. 2*). The *FAI* time series clearly indicates the arid periods of the late 1980s and early 1990s (=D9), the early 2000s (=D20), and the post-2010 (=D21) drought periods of the area. *FAI* is sensitive to the alteration of the arid and humid periods. The mean value of the *FAI* for the entire studied period was 6.82. Noticeably, during the dry periods, the mean value sometimes is exceed by twofold, reaching an index value of more than 13 and lasts for an excessively long time. The typical value of the index ranges between 4 and 6 during the more humid periods. The highest value of the *FAI* during the study period reached 14.17, its minimum was 3.3 with a standard deviation of 2.76. The overall temporal tendency indicated an increasing trend (*Fig. 2*).

Table 1. Slope of the linear regression line of the monthly rainfall totals (Pslope) and the mean monthly temperatures (Tslope) measured at the Pápa weather station between 1979 and 2013

Y	**Pslope**	**Tslope**
1	–0.138	0.052
2	0.258	0.024
3	0.206	0.007
4	–0.284	0.060
5	0.191	0.036
6	–0.245	0.066
7	–0.115	0.062
8	–0.133	0.043
9	0.084	–0.003
10	–0.121	0.006
11	–1.076	0.076
12	–0.593	–0.011
winter	–0.254	0.018
spring	0.112	0.034
summer	–0.493	0.057
autumn	–1.114	0.026

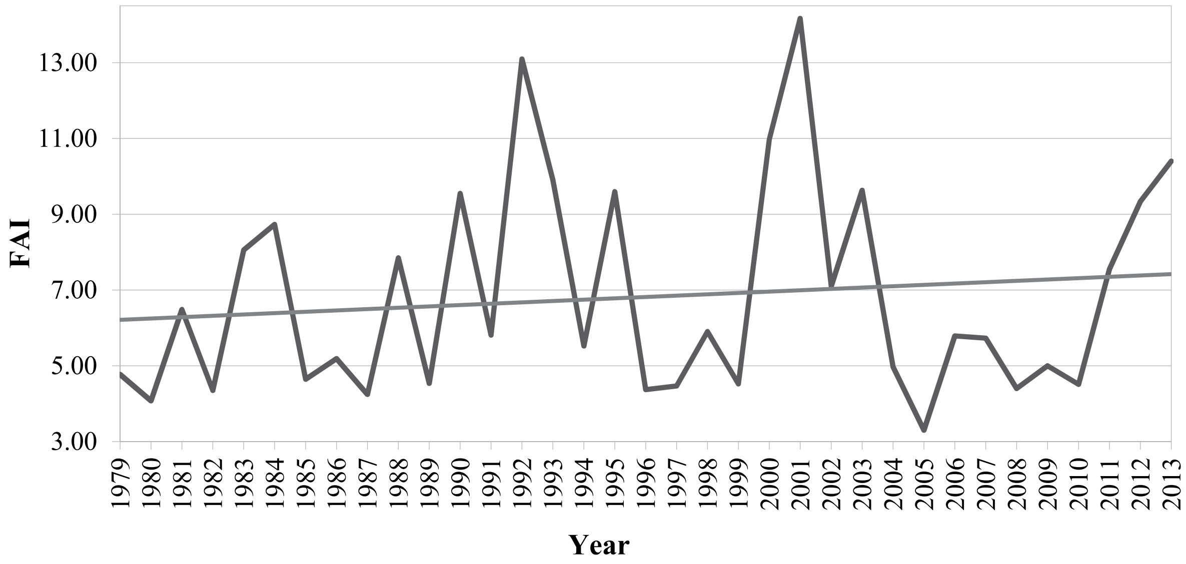

Fig. 2. Time series of the *FAI* values, based on the meteorological data of the Pápa weather station.

3.2. *Soil moisture (SM) variability over the study period*

The average soil moisture positively correlates with the month of the active vegetative period, and shows a relatively high correlation with January and February, however, we found no correlation with December. The highest correlation between *SM* and growth was found for spring and summer, especially for May and June, the months of the most intense LW formation.

As it was expected, the largest modeled soil moisture fluctuations and standard deviations were observed at a depth of 4 cm (*Fig. 3*). As shallow topsoil plays a very limited role in the physiological activity of large trees and is profoundly affected by drying up or rapid replenishment (*Echeverría et al.,* 2001; *Hegedüs et al.,* 2015), we ignored this modeled soil moisture data in our analyses. The amplitude and deviation of the *SM* data decreased with increasing depth, ranging between 0.27 and 0.33 $m^3 m^{-3}$ below the depth of 20 cm. The periodical (monthly) *SM* fluctuations, generated by rainfall and evaporation variability, were hardly detectable below 20 cm. The modeled *SM* extremes (maxima and minima) at greater depths were shifted by up to a year compared to the values detected at a depth of 4 cm. However, unlike the climatic data, no long-term linear trend is observable for the temporal changes of *SM* data (*Table 2*).

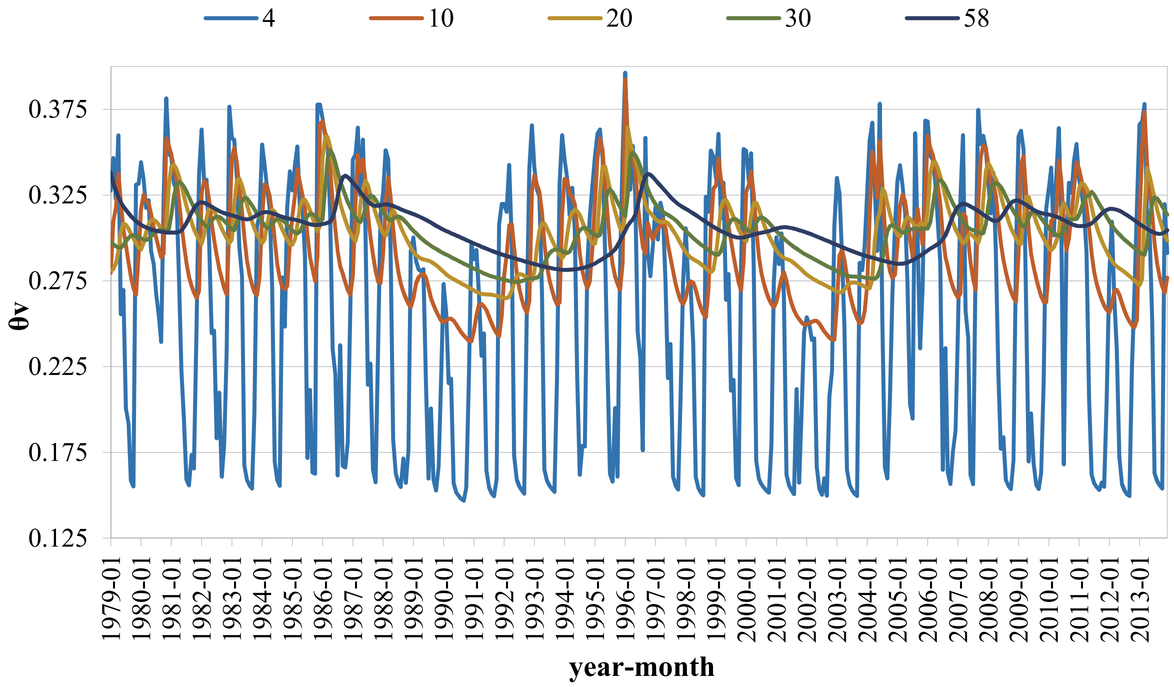

Fig. 3. Modeled volumetric soil moisture contents for the period 1979–2013 for five different depths (depths are shown in cm in the legend).

Table 2. Slope of the linear regression line of the soil moisture data at the five modeled depths between 1979 and 2013

Depth (cm)	Slope
4	–0.00039
10	–0.00021
20	–0.00009
30	–0.00002
58	–0.00018

3.3. Anatomical patterns of the studied trees

The oldest studied Turkey oaks of the experimental site reach an age of 110–120 years. During sampling, all trees were healthy, however, almost all trees were affected by frost cracks. Additionally, a considerable amount of methane has accumulated on the border of the hardwood and the sapwood, which was released in all cases during coring. Among the studied anatomical features, the earlywood and latewood form the tree-ring. Over the studied period, the tree growth and the increase of the EWW, LWW, and TRW were extremely low, compared to habitats of better water conditions (*Table 3*). Commonly, only a row of EW vessels was formed over the beginning of the growth season, therefore the EWW corresponds with the transversal width of the vessels. The deviation of the EWW was the lowest, and according to its size, this anatomical feature is the least influential (on average in 38%) in the structure of the tree ring. The only exception is the arid period during the early 2000s (from 2002 to 2004), when the width of the EW slightly exceeded that of the LW (*Fig. 4*). LW, on average, influences the TRW in 62%, and its width, similarly to the EWW is extremely low. A very strong linear correlation exists between the EWW and LWW with a coefficient of 0.998 closely correlating with the TRW.

Table 3. Statistical data of the studied anatomical features (MIN = minimum, MAX = maximum, AVERAGE = mean, STDEV = standard deviation)

	EWW	LWW	TRW
MIN	0.304	0.329	0.677
MAX	0.493	1.135	1.585
AVERAGE	0.415	0.717	1.132
STDEV	0.042	0.209	0.243

Fig. 4. Non-standardized EWW, LWW, and TRW chronology of the studied trees.

3.4. Correlation between the anatomical patterns and the climatic and SM data

At a probability level of $p = 5\%$ we only showed and analyzed correlations where correlations exceeded $r = 0.33$. The similar temporal behavior of EWW, LWW, and TRW showed a strong correlation with the measured climatic and modeled *SM* time series. The growth of the studied oaks was fundamentally influenced by monthly rainfall totals, while it was almost independent from mean monthly temperatures. Rainfall during fall of the preceding year, especially for September, showed a strong correlation with all anatomical patterns. Winter precipitation only showed correlation with the EW. Spring precipitation had a lower correlation with the anatomical patterns than the fall precipitation of the preceding year. Mean June temperatures exert a strong negative effect on growth rate. Despite the abundant literature on the importance of May precipitation (e.g., *Haneca et al.* 2009; *Gričar et al.,* 2013) on plant growth, correlations with the anatomical patterns found in the current study just fell below the threshold $r = 0.33$.

For the depth of 10 cm (*SM10*) the *SM* from January to August influenced growth rate of the studied grove, with a highest correlation with the spring months. Correlation was also found between the winter months and *SM10*, however, this is likely influenced by the moisture conditions of January and February (*Table 4*). Among the soil moisture values for a depth of 20 cm (*SM20*), the spring, summer and fall *SM* values influenced the growth rate positively. For the depth of 20 cm (*SM20*), the months from May to October impacted most intensely the growth rate of the trees. *SM30* positively correlated with the months from May to October, and if entire seasons are considered, with summer and fall. For the SM values modeled for a depth of 58 cm, no correlation was found with the anatomical patterns. In accordance with the aforementioned time shift, the highest correlation was found for growth rate with winter *SM4*, spring *SM10*, summer and fall *SM20,* and fall *SM30* data. The average soil moisture for the entire profile positively correlated with the entire studied period (from January to October), including the months of January and February. Nevertheless, we found no correlation between the *SM* of the antecedent year and the anatomical patterns. Correlation coefficients between the *FAI* and the anatomical parameters ranged between 0.45 and 0.49.

4. Discussion

The aridification trend in Hungary has been widely published by many authors (e.g., *Mátyás et al.,* 2010; *Kovács et al.,* 2012), and it is supported by the linear correlation trends of the rainfall and temperature data observed in Pápa between 1979 and 2013. The aridification tendency is in accordance with the long-term changes of *FAI* that was already documented by *Führer* (2010) and *Führer et al.,* (2011a). *FAI* values are derived from the climatic data of the most intensely warming and aridifying months. The mean *FAI* value of 6.82 for the entire studied period positions the area into the zone of the forest climate that is characterized by sessile oak and Turkey oak. This finding is in a good correspondence with the findings of *Kovács et al.* (2012), although it is found in the upper portion of this forest climate zone (*FAI* = 6.001–7.250). It is also notable, that the *FAI* many times exceeded the lower boundary of the forest steppe climate that lacks climate-indicator tree species, or, in extreme cases, is characterized by the complete absence of trees (*Führer,* 2010). Trees of the studied grove were capable to tolerate these relatively short, maximum 4-year periods, as *FAI* is only interpreted as the climatic average of decadal periods. The changes of *FAI* values are clearly reflected in the LWW, EWW, and TRW values. Such arid periods are likely undesired for tree growth, as, besides rainfall, no additional water source (e.g., spring water) is available for their physiological functioning (*Somogyi,* 2007, 2008). Aridification may result in gradual decrease in growth rate or health disorders and deterioration (*Csóka et al.*, 2009).

Table 4. Linear correlations between soil moisture and anatomical parameters, monthly rainfall totals, and mean monthly temperatures

	Precipitation			**Temperature**			**Soil moistured**												
							10 cm			**20 cm**			**30 cm**			**average**			
	eww	lww	**trw**	**eww**	**lww**	**trw**	**eww**	**lww**	**trw**	**eww**	**lww**	**trw**	**eww**	**lww**	**trw**	**eww**	**lww**	**trw**	
p9	0.441	0.427	0.428																p9
p10																			p10
p11																			p11
p12																			p12
1							0.462	0.445	0.459							0.369	0.361	0.376	1
2							0.551	0.536	0.565							0.431	0.420	0.440	2
3							0.506	0.497	0.525	0.454	0.442	0.450				0.466	0.457	0.477	3
4							0.501	0.488	0.520	0.529	0.519	0.533				0.489	0.478	0.500	4
5	0.301	0.300	0.313				0.535	0.523	0.560	0.531	0.519	0.538	0.385	0.378	0.385	0.518	0.509	0.532	5
6				−0.367	−0.373	−0.377	0.436	0.424	0.464	0.533	0.522	0.545	0.446	0.439	0.447	0.502	0.492	0.520	6
7							0.445	0.433	0.472	0.502	0.490	0.518	0.481	0.474	0.484	0.490	0.479	0.507	7
8							0.437	0.428	0.466	0.491	0.480	0.509	0.496	0.488	0.502	0.478	0.469	0.497	8
9										0.493	0.482	0.512	0.495	0.487	0.504	0.438	0.431	0.455	9
10										0.481	0.471	0.500	0.491	0.482	0.502	0.393	0.386	0.410	10
psummer																			psummer
pautumn	0.384	0.370	0.403																pautumn
winter	0.331						0.455	0.439	0.456							0.368	0.361	0.376	winter
spring	0.380	0.375	0.396				0.526	0.515	0.548	0.513	0.501	0.515				0.493	0.484	0.505	spring
summer							0.445	0.434	0.474	0.513	0.501	0.528	0.476	0.469	0.479	0.491	0.481	0.509	summer
autumn										0.472	0.462	0.490	0.492	0.483	0.502	0.397	0.392	0.417	autumn

Apparently, no direct correlation was found between surface climate and soil moisture data as *SM* is shifted in time compared to surface climatic patterns, with a simultaneous attenuation of extreme values. At greater depths, *SM* changes occur with significant lag (e.g., *Mahmood* and *Hubbard,* 2007; *Venkatesh et al.,* 2011), explained by the complex buffering and balancing capacity of soils. This process may prove favorable for trees, as they may take up water from both the shallower and deeper soil profiles. As the drying up of the deeper soil horizons is delayed, it may supply water for trees during the dry periods, while water is taken up from the shallow subsurface horizons over the rainy periods. This quasi-idealistic approach is shaded by the large spatial and temporal heterogeneity of *SM*. Additionally, different tree species take up water from various depths, i.e., their rhizosphere intrudes to different depths (*Montagnoli et al.,* 2012). Species-specific analyses of rhizosphere depths have been carried out for a limited number of tree species and solely under artificial conditions (*Grossiord et al.,* 2014). For Hungary, *Führer et al.* (2011b) provided detailed information on the general properties, of the rhizosphere and water demand of adult Turkey oaks. The rate of water uptake depends on the root density of the rhizosphere, physical soil properties and water potential (*Nobel,* 1991; *Bréda et al.* 1995). Additionally, due to the phenomena of hydraulic lift, *SM* may be transported from the moist lower soil horizons to the upper and drier soil horizons via the non-suberised radicles, whose Casparian strips are not formed yet (C*aldwell et al.,* 1998; *Jackson et al.,* 2000; *Zapater et al.,* 2011).

Because of the elevated age of the studied trees, their juvenile growth anomalies are commonly excluded from the analyses (*Norgler,* 1981). The early-season frosts may form the so-called frost cracks (*Butin* and *Shigo,* 1981) that directly do not affect tree health, but rather influence wood and timber quality. Presumably, methane-producing bacteria enter into the wood through these cracks. Nonetheless, the source of the methane generation is still subject of debates, some authors explain the process with the anoxic decomposition of the tree interior (*Covey et al.,* 2012), while others believe that methane is taken up via the roots from the soil (*Fender et al.,* 2013). During sampling, no sign of interior rot was found in the studied trees, therefore, in the absence of saturated moisture contents and organic matter, no methane generation is likely in the studied oaks. Complete understanding of the process is preferred, as the presence of methane, having 29 times higher forcing on climate than CO_2, and its subsequent emittance into the atmosphere intensifies the global greenhouse effect (*Rice et al.,* 2010). Consequently, due to their enlarged ecological amplitude, methane emission of Turkey oak may contribute to the increased greenhouse gas emission in the future.

The reduced growth rate of oaks with increasing age, which was removed from the analyzed samples, is not a climatic signal but rather a species-specific genetic nature. Tree growth was extremely slow over the study period, even compared to other test sites of higher water availability for the same period (from 1979 to 2013) indicated by lower-than-average TRW, EWW, and LWW values (according to the authors' *former unpublished findings*). In extreme cases (*Fig 4*, D20), the width of the EW exceeded that of the LW, indicating extremely arid conditions. Due to the effect of extreme weather patterns, other diseases and pests may further diminish growth rate, however, these biotic factors, due to insufficient data accessibility, are unavailable for direct modeling and encoded in tree structure in a combined manner with climatic markers. The extremely close correlation among the EWW, LWW, and TRW corresponds with the findings of *Gasson* (1987), *Rao et al.* (1997), and *Leal et al.* (2007), according to which, TRW fundamentally determines the anatomical structure of oaks. The authors' *former unpublished findings* disproved these results for oaks that were provided with excess water due to the adjacent springs. EWW and LWW are formed over different times of the growth period (*Schweingruber,* 1993), therefore, the TRW stores different environmental signals as the sum of the EWW and LWW.

In the current study, we found close correlations among EWW, LWW, and TRW, indicating a very similar temporal pattern. This similarity encumbers their correlation with the environmental variables, and the explanation of the anatomical parameters and relation to physiological activities, thus decreasing their temporal resolution.

Many authors have already indicated the primary role of rainfall, and the secondary role of temperature on oak growth (*Haneca et al.,* 2009). Fall precipitation, and especially rainfall totals of the previous September positively correlates with EWW, and this correlation was inherited to the TRW. Exclusively for the EWW, correlation was found with the winter precipitation totals. Formation of the EW vessels at certain areas may occur at the end of the growth season, or in the case of embolism, at the beginning of the growth period, or may be renewed by prior to bud burst (*Lembourgeois et al.*, 2004). It is widely known that even prior to bud burst and the photosynthetically active period, ring-pore trees develop their EW vessels (*Wareing,* 1951; *Aloni,* 1995), therefore, carbohydrates, essential for cell-formation, are allocated from the preserves of the preceding year. In case of oak species, fall is the primary period for the development and storage of sugar and starch (*Lacointe,* 2000, *Barbaroux* and *Bréda,* 2002). *Aloni* (1991) further corroborates this fact, as he pointed out that auxin, essential for activation of the cambium, accumulates during the growth period of the previous year. Therefore, compounds and hormones, vital for cell development, are readily available before bud burst. Accordingly, the width of EW is primarily influenced by the climatic conditions and water budget of the previous fall and winter (*Orcel et al.,* 1992; *Santini et al.,* 1994; *Nola,* 1996). Additionally, vessel lumen area also impacts EW width, while lumen area changes as a function of available moisture. Moreover, commonly close correlation exists between the lumen area of the vessels of EW and LW (*Nola,* 1996; *Tardif,* 1996; *Lembourgeois et al.*, 2004). According to *Lembourgeois et al.* (2004), plant available and uptaken moisture is utilized for the mobilization of carbohydrates. *Sass-Klaassen* et al. (2011) claims the complete lack of EW formation of *Q. robur* before bud burst, although these findings have not been verified for neither *Q. robur* nor *Q. cerris* by other studies. Our findings are clearly interpretable based on the aforementioned results, although, to identify the exact period of EW formation, multi-year sampling and monitoring is inevitable.

Due to the occasional two-stepped EW formation, signals contained by the EWW may differ in time. Due to the close correlations among the EWW, LWW, and TRW, explanation of this temporal difference is challenging. Nonetheless, all three parameters bear strong, climatic signals of the previous year. Seemingly, due to the environmental stress, trees prepare themselves for the next growth season, and may store and allocate a sufficient amount of carbohydrate for the growth of the subsequent year (*Bréda* and *Granier,* 1996). This process is likely positively influenced by the water supply of the moderately aridifying months. The low correlation with May precipitation is associated with LW development, since EW formation is terminated by this time. Oddly, neither negative, nor positive correlations were observed between the precipitation totals of the driest summer months and anatomical parameters, but it is explainable by the complexity of tree growth, as physiology far exceeds simple correlations (*Anning et al.,* 2013).

Due to the aridification of the area, moisture availability in the soils is highly variable in time. In areas of favorable water availability, *SM* shortage affects water availability in a delayed manner, and soil water potential should approach the permanent wilting point to exert a significant physiological effect on plants to generate distinct signals in the TRW (*Fritts,* 1952).

According to *Meyer* (2002), *SM* plays an important role in the germination of seedlings, and its impact is clearly observable in adult white oaks (*Quercus alba*). With the formation of EW, tree-ring generation is complete in 38% before the bud burst, indicating only a slight difference from *Quercus petreae*, where 43% was measured by *Bréda* and *Granier* (1996) and more than 30% by *Hinckley* and *Lasoie* (1981). Therefore, in theory, the impact of *SM* of the previous growth season on EW and TRW is 38%. During transpiration, plant available water of the capillary pores is taken up (*Nemani* and *Running,* 1989) that principally influences the leaf, and to a lesser degree, the TRW development (*Bréda* and *Granier,* 1996), but overall it supports the entire biomass of the tree (*Legg et al.,* 1979). The triggering factor of transpiration is canopy that develops simultaneously with the LW, therefore, the post-bud-burst (late spring and early summer) *SM* correlations may also be interpreted for LW. Based on our findings, it is obvious, that with increasing time, *SM* located at greater depths is taken up by the trees. In accordance with the conclusions of *Chen et al.* (2008), with decreasing moisture income in the topsoil, SM shortage and water uptake extends to greater depths over elongated dry spells. During late spring and summer, roots transport water, necessary for LW development and maintenance of physiological activities from greater depths. However, no significant correlation was found with *SM58*, which is explained by the time-shift of *SM* with increasing depth. Yet, mean *SM* of the entire profile does not provide sufficient information on the better understanding of the anatomical patterns of the studied trees, as *SM* correlations at different depth are blurred this way. Correlations between *SM* and anatomical patterns are further refined by *Riedacker* (1976), according to whom, root growth is positively influenced by available *SM*, nutrients, but negatively affected by low soil temperatures. At adequate soil temperatures, root growth remain continuous over the fall months, therefore correlation with fall *SM* is possible.

5. Conclusion

According to our results, the study area has become increasingly dry over the studied period from 1979 to 2013, and the sessile oak-Turkey oak forest climate gradually changes to forest steppe climate. Climatic signals of the D9, D20, and D21, typical for forested grasslands, were persistently dominant. However, the desiccation of soils was undetectable in the model, likely due to the replenishment of soils from the excess moisture of the cooling and more humid months. The excess moisture of the months with increased precipitations and the slightly warming mean temperatures (e.g., March and September) counteract for the water shortage of the intensively aridifying months (e.g., January, April, June, July, August, and November). Moving to greater depths in the modeled soil, a pronounced delay was observable in terms of the impact of *SM* with a simultaneous decrease in *SM* amplitudes. Furthermore, D20 and D21 influenced all anatomical features and *SM* in all depths and correlated with weather data and *FAI*.

Due to the poor soil conditions and climatic aridification, the studied trees have developed sensitivity to environmental changes, hence they bear pronounced climatic signals. Nonetheless, anatomical features, due to their almost identical patterns, hold similar signals that make the interpretation of the observed correlations more challenging.

According to our model-based results, *SM* influences anatomical patterns most significantly among all the studied meteorological and pedological factors. Modeled *SM* impact was clearly detectable to a depth of 30 cm, while poor correlation was found with *SM58*, which is likely explained by the time-delay of SM at greater depths.

The direct impact of rainfall on growth was less pronounced during the growth season than in the preceding September. In contrary to former results, we found a poor correlation between May precipitation totals and growth rate. With the exception of June, correlation between mean monthly temperatures and growth rate were less than $r = 0.33$, therefore, they are not shown in Table 3. Mean June temperature adversely influenced growth rate with $r = -0.367$, -0.373, and -0.377 for EWW, LWW, and TRW, respectively.

Acknowledgements: The current research was partly funded by the Campus Hungary Higher Education Long Term Mobility Program (TAMOP-4.2.2B/2-11/1,B2/4H/12187). The present scientific contribution is dedicated to the 650th anniversary of the foundation of the University of Pécs, Hungary.

References

Aloni, R., 1991: Wood formation in deciduous hardwood trees. In (Ed.: Raghavendera, A.S.) Physiology of Trees. JohnWiley & Sons, New York, 175–197.

Aloni, R., 1995. The induction of vascular tissues by auxin and cytokinin. In (Ed.: Davis, P.J.) Plant Hormones. Kluwer Academic Publishers, Dordrecht, 531–546.

Anning, A.K., Rubino, D.L., Sutherland, E.K., and *McCarthy, B.C.,* 2013: Dendrochronological analysis of white oak growth patterns across a topographic moisture gradient in southern Ohio. *Dendrochronologia 31*, 120–128.

Auchmoody, L.R. and *Smith, H.C.,* 1979: Oak soil-site relationships in northwestern West Virginia. U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station.

Babák, K., Kiss, I., Kopecskó, Z., Kovács, I.P., and *Schweitzer, F.,* 2013: Regeneration process of the karst water springs in Transdanubian mountains, Hungary. *Hung. Geo. Bull. 62*, 247–265.

Babos, K., 1984: A csertölgy és néhány más fafaj évgyűrűszélessége és az éves csapadék összefüggés-vizsgálata. *Bot. Közlem. 71*, 123–132. (in Hungarian)

Barbaroux, C. and *Bréda, N.*, 2002: Contrasting distribution and seasonal dynamics of carbohydrate reserves in stem wood of adult ring- porous sessile oak and diffuse-porous beech trees. *Tree Physiol. 22*, 1201–1210.

Bartholy, J., Pongrácz, R., Torma, Cs., Pieczka, I., Kardos, P., and *Hunyady, A.,* 2008: Analysis of regional climate change modeling experiments for the Carpathian basin. *Int. J. Glob. Warming 1*, 238–252.

Bidló, A., Berki, A., Király, G., Koloszár, J., Mátyás, C., and *Víg, P.,* 2006: *Magyarország erdészeti tájai.* [Forest regions of Hungary.] Állami Erdészeti Szolgálat, Budapest (in Hungarian)

Bihari, D., 1979: Devecser. A Bakony hegység földtani térképe, 20 000-es sorozat. Magyar Állami Földtani intézet, Budapest (in Hungarian)

Bohn, P., (ed) 1983: Magyarország mélyfúrási alapadatai. II. Közép-Dunántúl, 1851–1973. Magyar Állami Földtani Intézet, Budapest (in Hungarian)

Bréda, N. and *Granier, A.,* 1996: Intra- and interannual variations of transpiration, leaf area index and radial growth of a sessile oak stand (*Quercus petraea*). *Ann. Sci. For. 53*, 521–536.

Bréda, N., Granier, A., and *Aussenac, G., 1995:* Effects of thinning on soil and tree water relations, transpiration and growth in an oak forest *(Quercus petraea (Matt.) Liebl.). Tree Physiology 15,* 295–306.

Butin, H. and *Shigo, A.L.,* 1981: Radial shakes and "frost cracks" in living oak trees. Northeast For. Exp. Stn., Broomall, Pa.

Caldwell, M.M., Dawson, T.E., and *Richards, J.H.*, 1998: Hydraulic lift: consequences of water efflux from the roots of plants. *Oecologia 113*, 151–161.

Chen, X., Rubin, Y., Ma, S., and *Baldocchi, D.,* 2008: Observations and stochastic modeling of soil moisture control on evapotranspiration in a Californian oak savanna. *Water Resour. Res. 44*, 1–13.

Cook, E.R., 1985: A time series approach to tree-ring standardization. Dissertation, University of Arizona.

Covey, K.R., Wood, S.A., Warren, R.J., Lee, X., and *Bradford, M.A.,* 2012: Elevated methane concentrations in trees of an upland forest. *Geophys. Res. Lett. 39,* L15705.

Cufar, K., Grabner, M., Morgós, A., del Castillo, E.M., Merela, M., and *de Luis, M.,* 2014: Common climatic signals affecting oak tree-ring growth in SE Central Europe. *Trees 28*, 1267–1277.

Csóka, Gy., Koltay, A., Hirka, A., and *Janik, G.*, 2009: Az aszályosság hatása kocsánytalan tölgyesek és bükkösök egészségi állapotára. *„Klíma-21" Füzetek 57*, 64–73. (in Hungarian)

Di Filippo, A., Alessandrini, A., Biondi, F., Blasi, S., Portoghesi, L., and *Piovensan, G.* 2010: Climate change and oak growth decline: Dendroecology and stand productivity of Turkey oak (*Quercus cerris* L.) old stored coppice in Central Italy. *Ann. For. Sci. 67*, 706–706.

Dövényi, Z. (ed.) 2010: Magyarország kistájainak katasztere. MTA FKI, Budapest. (in Hungarian)

Echeverría, T., Ibarra, P., and *Martínez, J.* 2001: Soil moisture in oak-wood and pine-wood of the Mancayo (Iberian Range, Spain) *Cuadernos de Investigación Geográfica 27*, 17–26.

Eckstein, D., Frisse, E., and *Quiehl, F.,* 1977: Holzanatomische Untersuchungen zum Nachweis anthropogener Einflüsse auf die Umweltbedingungen einer Rotbuche. *Angew. Bot. 51*, 47–56. (in Deutsch)

Fender, A-C., Gansert, D., Jungkunst, H. F., Fiedler, S., Beyer, F., Schützenmeister, K., Thiele, B., Valtanen, K., Polle, A., and *Leuschner, C.* 2013: Root-induced tree species effects on the source/sink strength for greenhouse gases (CH_4, N_2O and CO_2) of a temperate deciduous forest soil. *Soil Biol. Biochem. 57*, 587–597.

Fritts, H.C., 1952: Radial Growth of Beech and Soil Moisture in a Central Ohio Forest during the Growing Season of 1952. *Ohio J. Sci. 56*, 17–28.

Fritts, H.C., 1976: Tree rings and climate. Academic Press, London

Führer, E., 2010: A fák növekedése és a klíma. *„KLÍMA-21" Füzetek 61*, 98–107. (in Hungarian)

Führer, E., Horváth, L., Jagodics, A., Machon, A., and *Szabados, I.,* 2011a: Application of a new aridity index in Hungarian forestry practice. *Időjárás 115*, 205–216.

Führer, E., Czupy, Gy., Kocsisné-Antal, J., and *Jagodics, A.* 2011b*:* Gyökérvizsgálatok bükkös, gyertyános–kocsányos tölgyes és cseres faállományban. *Agrokémia és Talajtan 60*, 103–118. (in Hungarian)

Graiser, R.N., 1951: Relation Between Topography, Soil Characteristics, and the Site index of White Oak in Southeastern Ohio. US Department of Agriculture, Forest Service, *Technical Paper 121*, 12 pp.

Gasson, P., 1987: Some implications of anatomical variations in the wood of pedunculate oak (*Quercus robur* L.). including comparisons with common beech (*Fagus sylvatica* L.). *IAWA J. 8*, 149–166.

Gencsi, L., Vancsura, R., 1992: Dendrológia. Erdészeti növénytan II. Mezőgazda Kiadó, Budapest, 260–267.

Gričar, J., de Luis, M., Hafner, P., and *Levanič, T.,* 2013: Anatomical characteristics and hydrologic signals in tree-rings of oaks (*Quercus robur* L.). *Trees 27*, 1669–1680.

Grossiord, C., Gessler, A., Granier, A., Berger, S., Bréchet, C., Hentschel, R., Hommel, R., Scherer-Lorenzen, M., and *Bonal, D.* 2014: Impact of interspecific interactions on the soil water uptake depth in a young temperate mixed species plantation. *J.f Hydrol. 519*, 3511–3519.

Haneca, K., Čufar, K., and *Beeckman, H.,* 2009: Oaks, tree-rings and wooden cultural heritage: a review of the main characteristics and applications of oak dendrochronology in Europe. *J. Archaeol. Sci. 36*, 1–11.

Hegedüs, P., Czigány, S., Pirkhoffer, E., Balatonyi, E., and *Hickey, R.,* 2015: Analysis of spatial variability of near-surface soil moisture to increase rainfall-runoff modelling accuracy in SW Hungary. *Open Geosci*. *7*, 126–139.

Hinckley, T.M. and *Lassoie, J.P*., 1981: Radial growth in conifers and deciduous trees: a comparison. *Mitt. Forstlichen Bundesversuchsanstalt* (Vienna) *142*, 17–56.

Holmes, R.L., 1983: Computer-assisted quality control in tree-ring dating and measurement. *Tree-Ring Bull. 43*, 69–75.

Jackson, R.B., Sperry, J.S., and *Dawson, T.E.,* 2000: Root water uptake and transport: using physiological processes in global predictions. *Trends Plant Sci. 5*, 482–488.

Jozsa, L.A., 1988: Increment core sampling techniques for high quality cores. Forintek Canada Corporation, Vancouver.

Kern, Z., Grynaeus, A., and *Morgós, A.,* 2009: Reconstructed precipitation for southern Bakony Mountains (Transdanubia, Hungary) back to AD 1746 based on ring widths of oak trees. *Időjárás 113*, 299–314.

Kwiaton, M. and *Wang, J.R*., 2015: Radial Growth Responses of Four Deciduous Species to Climate Variables in Central Ontario, Canada. *Am. J. Plant Sci. 6*, 2234-2248.

Klimo, E. and *Hager, H.,* 2001: Executive summary. In: (Eds.: *Klimo E, Hager H.*) The floodplain forests in Europe: current situation and perspectives. Brill, Leiden, pp vii–xi.

Kovács, G., Illés, G., Mészáros, D., Szabó, O., Vigh, A., and *Heil, B.,* 2012: A termőhelyi tényezők és a faállományviszonyok kapcsolatának jelenlegi és jövőbeli alakulása a noszlopi erdőtömbben I. *Erdészettud. Közl. 2*, 47–60. (in Hungarian)

Lacointe, A., 2000: Carbon allocation among tree organs: a review of basic processes and representation in functional-structural tree models. *Ann. For. Sci. 57*, 521–533.

Leal, S., Sousa, V.B., and *Pereira, H.,* 2007: Radial variation of vessel size and distribution in cork oak wood (*Quercus suber* L.). *Wood. Sci. Technol. 41*, 339-350.

Legg, B.J., Day, W., Lawlor, D.W., and *Parkinson, K.J.,* 1979: The effects of drought on barley growth: models and measurements showing the relative importance of leaf area and photosynthetic rate. *J. Agric. Sci. 92*, 706–716.

Lembourgeois, F., Cousseau, G., and *Ducos, Y.,* 2004: Climate-tree-growth relationships of *Quercus petraea* Mill. stand in the Forest of Bercé ("Futaie des Clos", Sarthe, France). *Ann. For. Sci. 61*, 1-12.

Mahmood, R. and *Hubbard, K.G.,* 2007: Relationship between soil moisture of near surface and multiple depths of the root zone under heterogeneous land uses and varying hydro climatic condition. *Hydrological Proc. 21*, 3449–3462.

Mátyás, Cs., Führer, E., Berki, I., Csóka, G., Drüszler, Á., Lakatos, F., Móricz, N., Razstovits, E., Somogyi, Z., Veperdi, G., Vig, P. and, *Gálos, B.,* 2010: Erdők a szárazsági határon. *Klíma-21. Füzetek 61*, 84–97. (in Hungarian)

Meyer, V.C., 2002: Soil Moisture Availability as a Factor Affecting Valley Oak (Quercus lobata Neé) Seedling Establishment and Survival in a Riparian Habitat, Cosumnes River Preserve, Sacramento County, California. *USDA Forest Service Gen. Tech. Rep.* PSW-GTR-184, 551–564.

Miniszteri tájékoztató, 2015: Magyarország erdőállományának 2014. évi helyzetéről, állapotáról. www.kormany.hu/download/1/27/80000/tajekoztato_erdoallomany_2014.pdf#!DocumentBrowse. Accessed 2 February 2016. (in Hungarian)

Molnár, S., Peszlen, I., and *Paukó, A.,* 2007: Faanatómia. Szaktudás Kiadó Ház, Budapest. (in Hungarian)

Montagnoli, A., Terzaghi, M., Di Iorio, A., Scippa, G.S., and *Chiatante, D.,* 2012: Fine-root morphological and growth traits in a Turkey-oak stand in relation to seasonal changes in soil moisture in the Southern Apennines, Italy. *Ecol. Res. 27*, 1015–1025.

Móricz, N., Rasztovits, E., Gálos, B., Berki, I., Eredics, A., and *Loibl, W.,* 2013: Modelling the potential distribution of three climate zonal tree species for present and future climate in Hungary. *Acta Silv. Lign. Hung. 9*, 85–96.

Nardini, A., Lo Gullo, M.A., and *Salleo, S.,* 1999: Competitive strategies for water availability in two Mediterranean *Quercus* species. *Plant Cell Environ. 22*, 109–116.

Nardini, A. and *Tyree, M.T.,* 1999: Root and shoot hydraulic conductance seven *Quercus* species. *Ann. For. Sci.* 56, 371–377.

Nemani, R.R.. and *Running, S.W.,* 1989: Testing a theoretical climate-soil-leaf area hydrologic equilibrium of forests using satellite data and ecosystem simulation. *Agric. For. Meteorol. 44*, 245–260.

Nobel, P.S., 1991. Phvsicochemical and environmental plant physiology. San Diego: Academic Press. Inc.

Nola, P., 1996: Climatic signal in earlywood and latewood of deciduous oaks from northern Italy. In (Eds.: *Dean, J.S., Meko, D.M., Swetnam, T.W.*), Tree Rings, Environment and Humanity, Radiocarbon. 249–258.

Norgler, P., 1981: Auskeilende und fehlende Jahrringe in absterbenden Tannen (*Abies alba* Mill.). *Allgemeine Forstzeitung 28*, 709–711. (in Deutsch)

Orcel, A., Orcel, C., Favre, A., Mohnhaupt, M., and *Hurni, J.P.*, 1992: Dendroclimatic model constructed with oakwoods of the Swiss Piémont Jurassien. In (Eds.: *Bartholin, T.S., Berglund, E., Eckstein, D., Schweingruber, F.H., Eggertsson, O.*) Tree Rings and Environment, Proceedings of the International Symposium, Ystad, South Sweden, 3–9 September, 1990, Lund University, Department of Quaternary Geology, Lund. 247–253.

Rao, R.V., Denne, M.P., and *Aebischer, D.P.,* 1997: Latewood density in relation to wood fibre diameter, wall thickness, and fibre and vessel percentages in *Quercus robur* L. *IAWA J 18*, 127-138.

Rice, A.L., Butenhoff, C.L., Shearer, M.J., Teama, D., Rosenstiel, T.N., and *Khalil, M.A.K.*, 2010: Emissions of anaerobically produced methane by trees. *Geophys. Res. Lett. 37*, L03807.

Riedacker, A., 1976: Rythmes de croissance et de régénération des racines des végétaux ligneux, *Ann. Sci. For. 33*, 109–138.

Santini, A., Bottacci, A., and *Gellini, R.*, 1994: Preliminary dendroecological survey on pedunculate oak (*Quercus robur* L.) stands in Tuscany (Italy). *Ann. Sci. For. 51*, 1–10.

Sass-Klaassen, U., Sabajo, C.R., and *den Ouden, J.*, 2011: Vessel formation in relation to leaf phenology in pedunculate oak and European ash. *Dendrochronologia 29*, 171–175

Schweingruber, F.H., 1993: Trees and wood in dendrochronology: Morphological, anatomical, and tree-ring analytical characteristics of trees frequently used in dendrochronology. Springer-Verlag, Berlin, 1–27.

Smith, P., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E.A., Haberl, H., Harper, R., House, J., Jafari, M., Masera, O., Mbow, C., Ravindranath, N.H., Rice, C.W., Robledo Abad, C., Romanovskaya, A., Sperling, F., and *Tubiello, F.,* 2014: Agriculture, Forestry and Other Land Use (AFOLU). In (Eds.: *Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E. Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C., Zwickel, T., Minx, J.C.*) Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Somogyi, Z., 2007: A klíma, a klímaváltozás és a fanövekedés néhány összefüggéséről. In: (Eds.: *Mátyás, Cs.* and *Vig, P.*): Erdő-klíma V. NyME, Sopron. 281–294. (in Hungarian)

Somogyi, Z., 2008: Recent Trends of Tree Growth in Relation to Climate Change in Hungary. *Acta Silv. Lign. Hung. 4,* 17–27.

Speer, J., H., 2011: Fundamentals of tree-ring research. The University of Arizona Press. Tucson, p 76.

Stafasani, M. and *Toromani, E.,* 2015: Growth-climate response of young Turkey oak (*Quercus cerris* L.) coppice forest stands along longitudinal gradient in Albania. *South-East Eur. Forest. 6*, 25-38.

Stahle, D.W., Cook, E.R., Cleaveland, M.K., Therrell, M.D., Meko, D.M., Grissino-Mayer, H.D., Watson, E., and *Luckman, B.H.,* 2000 Tree-ring data document 16th century megadrought over North America. *EOS Earth Space Sci. News 81*, 121–125.

Stokes, M.A., and *Smiley, T.L.,* 1968: An Introduction to Tree-Ring Dating. University of Chicago Press.

Szabados, I., 2008: A csapadék hatása a cser évgyűrűméretére. *Erdészeti Kutatások 92*, 121–128. (in Hungarian)

Tardif, J. 1996: Earlywood, latewood and total ring width of a ring- porous species (Fraxinus nigra Marsh) in relation to climatic and hydrologic factors. In (Eds.: *Dean, J.S., Meko, D.M., Swetnam T.W.*): Tree Rings, Environment and Humanity. Radiocarbon. Dept. Univ. Arizona, Tucson, 315–324.

Thornthwaite, C.W., 1948. An approach toward a rational classification of climate. *Geograph.rev. 38*, 55–94.

Venkatesh, B., Lakshman, N., Purandara, B.K., and *Reddy, V.B.,* 2011: Analysis of observed soil moisture patterns under different land covers in Western Ghats, India. *J. Hydrol. 397*, 281–294.

Wareing, P.F., 1951: Growth studies in woody species. IV. The initia- tion of cambial activity in ring-porous species. *Physiol. Plant. 4*, 546–562.

Weigl, M., Grabner, M., Helle, G., Schleser, G.H., and *Wimmer, R.,* 2008: Characteristics of radial growth and stable isotopes in a single oak tree to be used in climate studies. *Sci. Total Environ. 393*, 154–161.

Woodhouse, C.A. and *Overpeck, J.T.,* 1998: 2000 years of drought variability in the central United States. *Bull. Amer. Meteorol. Soc.79*, 2693–2714.

Zapater, M., Hossann, C., Breda, N., Brechet, C., Bonal, D., and *Granier, A.,* 2011: Evidence of hydraulic lift in a young beech and oak mixed forest using ^{18}O soil water labelling. *Trees-Struct. Funct. 25*, 885–894.