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RADIAL GROWTH OF PEDUNCULATE OAK AND EUROPEAN ASH ON ACTIVE RIVER TERRACES. HYDROLOGIC AND CLIMATIC CONTROLS

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Abstract

The aim of this study was (1) to assess relationships binding hydroclimatic factors and radial growth of pedunculate oak and European ash growing on active terraces of river valleys; (2) to compare the growth reaction of these species from this location. Research site was located in a floodplain valley, within mid-course of the lowland section of the Warta River in the Lasy Czeszewskie Forest, Poland. The Warta River (length 808 km, basin area: 54,529 km^2) is a mid-size European river, a tributary of the Odra River draining the North European Plain to the Baltic Sea. The sampled forest stand was an old growth composed of pedunculate oak and European ash mixed with other mature tree species. The main conclusions are: (1) ash in comparison to oak growing on the same site located on floodplains appeared to be both more sensitive to hydroclimatical features and less ecologically flexible as far as monthly pattern of water requirements is concerned, therefore adaptation to changing climatic conditions and drought may be a greater ecological challenge for ash than for oak in river valleys; (2) streamflow could be considered as the parameter that substituted precipitation well, or even was more important than precipitation, as far as availability of water for development of tree rings of ash and oak growing on active terraces of river valleys is concerned; however, the role of streamflow in radial growth developing decreased substantially during 20th century; (3) Standardized Precipitation Evapotranspiration

Index (SPEI) as a measure of drought is a prospective parameter in dendroecological analysis, since it conveys real availability of water for trees.

Keywords: oak, ash, floodplain forest, radial growth

INTRODUCTION

Main exogenous controls of radial growth of trees are environmental factors (Fritts 2001, Schweingruber 1996). Wood can retain environmental signal at different levels of its structure. These environment sensitive wood structures are tree ring, seasonal wood, cell and sub-cell structures (Zielski and Krąpiec 2004, Speer 2010). Ecological relationships binding the environment and tree growth can be investigated according to the classic methods of dendrochronology by studying tree ring width (TRW). Thus radial tree ring growth is an indicator of tree health, a measure of forest integrity and sustainability (Fritts and Swetnam 1989, Banks 1991, Schweingruber 1996).

Water availability is the main ecological driver modulating tree growth (Czarnowski 1989, Pallardy 2008). The biomass production of trees is in positive relation with their water utilization. This general ecological rule is particularly important if water is a permanent or occasional limiting factor for the forest ecosystem (Cook 1987, Kozlowski and Pallardy 1997, Falińska 2012). The limiting role of water in interaction between water and forest growth can either be related to scarcity of water or its excess. For both cases water could be a stress factor for trees. If water is in excess, the stress mechanism is related to waterlogging of soil and asphyxia of tree roots (e.g. Kozlowski 1997, Glenz *et. al*. 2006, Parent *et al*. 2008). If supply of water is limited, trees suffer from drought (e.g. Epron and Dreyer 1993, Orwig and Abrams 1997, Smith 2011). Water can be provided for forest ecosystems by various hydrologic processes. Some ecosystems are supplied solely by precipitation, some use other sources of water in combination with precipitation in various temporal scales (Chang 2012).

The forests growing on floodplains are very unique ecosystems regarding water – ecosystem interactions (Junk *et al*. 1989, Tockner *et al*. 2000, Bridge 2003, Gurnell and Petts 2011). The water input for floodplain ecosystems is provided by both local precipitation and by hydrologic processes of river regime controlled by the climatic conditions over river basin area. Sources and temporal pattern of streamflow, rising and falling of water levels, overbank flow and surface flooding of floodplains, connectivity of groundwater with streamflow are the elements of river regime as well as the determinants of water availability to forest environment on active terraces of river valleys (Dynowska 1971, Richards 1982, Haines *et. al*. 1988, Bridge 2003, Olden and Poff 2003, Charlton 2008, Bartnik and Jokiel 2012). The river vicinity can be recognized as a stable source of water for the valley vegetation. However, the variability of streamflow volume can result either in the periods of optimal availability of water or in episodic stress caused by excess of water or its scarcity. These stress events cause unfavourable tree growth conditions at various temporal scales. Therefore strong drought episodes can affect not only higher elevated areas but also such ecosystems as active terraces of river valleys (Klimo and Hager 2001, Parolin *et al.* 2010, Schneider *et al.* 2011). These episodes of drought stress to forest vegetation are more frequent recently under temperate climate across Central Europe due to evident shift of air temperature (Arnell 1999, Schneider *et al*. 2011, Schneider *et al*. 2013).

Pedunculate oak (*Quercus robur* L.) and European ash (*Fraxinus excelsior* L.) are the main tree species composing floodplain forests of Atlantic and part of Mediterranean Europe (Bohn *et al*. 2000, San-Miguel-Ayanz *et al*. 2016). The aim of this study was to asses relationships binding hydroclimatic factors and radial growth of pedunculate oak and European ash growing on active terraces of river valleys. The decline of oak and ash forest stands is a huge challenge for European foresters and forest ecologists nowadays (e.g. Siwecki and Ufnalski 1998, Thomas *et al*. 2002, Pautasso *et al*. 2013, Cleary *et al*. 2014,, Tulik and Bijak 2016). The riverine ecosystems in Europe are often highly anthropogenically transformed (Wilgat 1991, Solon 1999, Klimo and Hager 2001, Tockner and Stanford 2002, Tockner *et al*. 2009). Restoration and rehabilitation schemes of floodplain forests require better understanding of connection between environment factors and tree growth processes to introduce good forestry practices and verify ecological effects of introduced projects.

MATERIALS AND METHODS

Research site was located within mid-course of the lowland section of the Warta River in the Lasy Czeszewskie Forest, Poland. The Warta River (length 808 km, basin area: 54,529 km^2) is a mid-size European river, a tributary of the Odra River draining the North European Plain to the Baltic Sea (Figure 1). The forest stands are mainly old growth composed of pedunculate oak, European ash mixed with other tree species such as field and European whit elm, small-leaf lime, hornbeam, Norway and field maple. Tree ring sampling was performed in a forest stand growing on an active river terrace on well-developed alluvial soils. The WGS84 DMS coordinates of the sampling site are 52° 08’ 00” N, 17° 29’ 51”E. Pedunculate oak and European ash in the Lasy Czeszewskie Forest are situated roughly within the central area of species distribution limit.

The river regime is dominated by snow-melt or ground thawing in the late winter and early spring, sometimes coupled with substantial precipitation which triggers rising of streamflow to annual maximum peaks occurring normally from

January to April. Low water period occurs in the late summer and early autumn from July to October usually. The mean streamflow is ca. 100 m^3s^{-1}, absolute maximum and minimum flows noted in the instrumental period for the mid-section of the Warta are about 1700 m^3s^{-1} and less than 35 m^3s^{-1}. According to climate classification of Köppen-Geiger the sampling site lays within humid continental climate with warm summer (Dfb) (Peel *et al*. 2007). The mean annual air temperature and mean annual precipitation are 8.4°C and 517 mm, respectively, for the WMO reference period 1961-1990. The minimum and maximum monthly temperature occurs in January (-2.8°C) and July (18.4°C), minimum and maximum precipitation is in February (24mm) and July (73mm) (Figure 1).

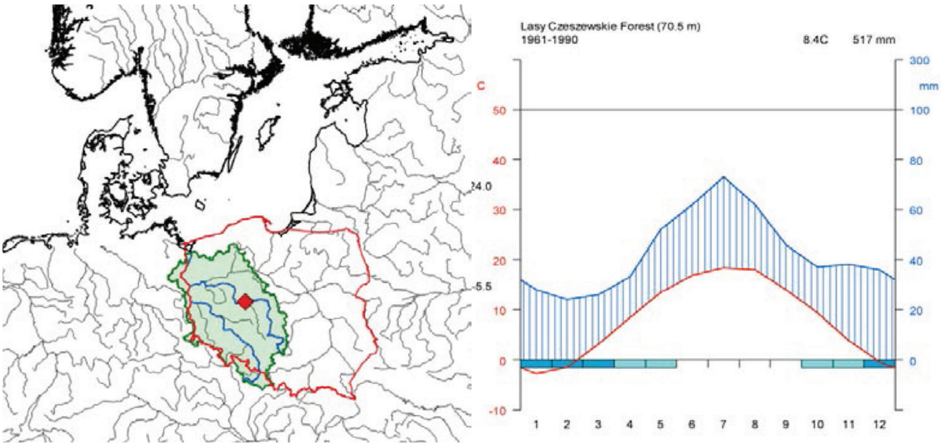

Figure 1. The location of research site (left). The basin of the Warta and Odra (green line), the rivers (blue line), sampling site indication (red diamond), the state borders (red line). Climatic diagram for the Lasy Czeszewskie Forest (right)

The sampling of 15 pedunculate oak and European ash trees was performed. The sample collection equalled 60 samples in total with 2 samples per each tree extracted at DBH (1.3 m height). The sampled stand was composed of pedunculate oak (approx. 60%) and European ash (approx. 10%) with admixture of hornbeam (30%) and sporadically small-leaf lime, field and European whit elm aged 130 year (as of 2016 year). The average height of sampled oaks was 30.0 m, crown height – 20.4 m, DBH – 54 cm. The average height of sampled ashes was 30.8 m, crown height – 20.3 m, DBH – 62 cm. The trees selected for sampling represented dominant biosocial position. The random selection of trees for producing the site collection was employed, provided that the biosocial assumption was obeyed for the living canopy trees. The individual TRW series were tested against master chronology in order to exclude the series of weak site signal from the collection (Bräker 2002). Standard sample collection methodology and sample preparing procedures were utilized. The selected trees were drilled with Pressler borer in 2012 year (European ash) and 2011 year (pedunculate oak). The samples were glued in fixation planks, dried, sanded, undusted and chalked to expose wood structure (Zielski and Krąpiec 2004, Speer 2010). The tree ring width measurements were performed on scanned samples (1200 dpi resolution) by CooRecorder software with accuracy of 0.01 mm. Then the TRW series were cross-dated, preliminarily quality tested and combined into a collection by CDendro software (URL: http://www.cybis.se). The ultimate cross-dating and verification of individual sample series, to be included in the master series representing the forest stand, was conducted by means of COFECHA software (Holmes 1983, Grissino-Mayer 2001). As raw tree ring width series contain age trends and are usually highly autocorrelated, they have to be processed to reduce these biases and prepare TRW series for year-to-year analysis. To exclude the age trend, cross-dated raw TRW time series were detrended with negative exponential curve so that standardized time series of indices were produced (standard chronologies) (Cook *et al*. 1990, Fritts 2001). Then, by employing autoregressive modelling, residual series of indices were produced (residual chronologies) (Fritts 2001). General statistics of individual and master TRW time series such as interseries correlation, autocorrelation, mean sensitivity, GLK and EPS were calculated (Wigley *et al*., 1984, Schweingruber 1988, Fritts 2001). The R software package dplR was used to prepare both the indexed chronologies (standard and residual) and calculate abovementioned TRW statistics (R Development Core Team, Bunn 2008). Pearson correlation analysis and response function analysis were conducted to determine temporal changes in limiting hydroclimatic factors of oak and ash growth (Zang and Biondi 2015). Hydroclimatic factors were set as independent variables and residual chronologies of TRW set as dependent variable for the period of 1901-2011. Both the static (the entire period) and dynamic analysis (the entire period in moving window of 30-year interval) were employed. The correlation and response function analyses were conducted by treeclim R package (Zang and Biondi 2015). The hydroclimatic independent variables were precipitation (P), temperature (T), standardized precipitation evapotranspiration index (SPEI (S)), mean river streamflow (Q).

The raw climatic data on temperature (T) and precipitation (P) were obtained from the network of Institute of Meteorology and Water Management meteorological stations Poznań, Nowa Wieś Podgórna, Kórnik; streamflow (Q) series derived from gauging station Poznań. The raw data were processed to produce the monthly time series for the period of 1901-2011. The Standardized Precipitation Evapotranspiration Index values were obtained from the Global SPEI dataset for the period of 1901-2011. SPEI is robust information about drought conditions, with a 0.5 degrees spatial resolution and a monthly time resolution. The dataset has a multi-scale dimension, time-scales between 1 and 48 months accumulated periods. SPEI is based on the difference between precipitation (P) and potential evapotranspiration (PET) calculated by the Penman-Monteith method. Standardized Precipitation Evaptranspiration Index is recently introduced, yet a recognized measure of drought applied worldwide (Vicente-Serrano *et al*. 2010, Serrano *et al*. 2012, Beguería *et al*. 2014), and gaining ground over well-established drought indices such as temperature, precipitation, standardized precipitation index (SPI), evapotranspiration, Palmer Drought Severity Index/self-calibrated Palmer Drought Severity Index (PDSI/sc-PDSI) (Palmer 1965, McKee *et al*. 1993, Keyantash and Dracup 2002, Wells *et al.* 2004). The processing of SPEI time series was conducted in R environment with SPEI package (Vicente-Serrano *et al*. 2010). The assumed significance level for all statistical analyses employed in research described here was at p <0,05. The time-scales applied for hydroclimatic factors were set as independent data monthly periods. Monthly time scales (each month) were set for 12 months, April to September for the previous (prior) year to tree ring formation (marked by exclamation sign) and the current year of tree ring formation (Table 1).

Table 1. The combination of timescales and hydroclimatic parameters used for dendroecological analysis

Temporal scale	Hydrologic parameter		Precipitation	Temperature	Standardized Precipitation Evapotranspiration Index	Streamflow
			P	T	S (SPEI)	Q
Current year	April	4	4P	4T	4S	4Q
	May	5	5P	5T	5S	5Q
	Jun	6	6P	6T	6S	6Q
	July	7	7P	7T	7S	7Q
	August	8	8P	8T	8S	8Q
	September	9	9P	9T	9S	9Q
Previous year	April	4!	4!P	4!T	4!S	4!Q
	May	5!	5!P	5!T	5!S	5!Q
	Jun	6!	6!P	6!T	6!S	6!Q
	July	7!	7!P	7!T	7!S	7!Q
	August	8!	8!P	8!T	8!S	8!Q
	September	9!	9!P	9!T	9!S	9!Q

RESULTS AND DISCUSSION

General statistics of the raw oak and ash tree ring series showed that variability, integrity and suitability for ecological analyses is slightly higher for the ash series than for the oak series; however, both series express high coherence and their statistical parameters are over recognized threshold levels as far as ecological analyses requirements are concerned (Table 2). EPS conveys common variability of individual chronologies from the site and indicates suitability of chronology for ecological analyses. The EPS threshold value set at 0.85 is exceeded for both series (oak EPS=0.94, ash EPS=0.96). Mean sensitivity at ca. 0.2 to 0.4 provides usually the best suitability of series for dendroecological analyses. Mean sensitivity of raw oak series and ash series equalled 0.26 and 0.32, respectively, which showed that series for both species are relatively not complacent and therefore sensitive to environmental factors, such as hydroclimatic features affecting tree growth. GLK is a measure of the common growth reaction for each pair of individual series from the collection. It showed for both oak and ash that average growth reaction of over 70% percent of trees is in the same direction (either positive or negative).

Table 2. Statistics of raw pedunculate oak and European ash series

Species	Max interval	Mean series length	Correlation with master series	Mean TRW measurement	Maximum TRW measurement	SD of TRW measurement	Mean sensitivity	Autocorrelation	Mean Gleichläufigkeit (GLK – G-score)	Men Expressed population signal (EPS)
	[years]	[years]	[-]	[mm]	[mm]	[mm]	[-]	[-]	[-]	[-]
Oak	1889-2011	116	0.74	1.88	6.09	0.69	0.26	0.58	0.72	0.94
Ash	1884-2012	112	0.76	1.67	8.98	0.78	0.32	0.54	0.75	0.96

The dynamics of the mean raw tree ring width time series for oak and ash showed no effect of juvenile wood. The widths of tree ring series in the initial section are not higher than the widths for the other sections of tree ring series. Consequently, the decreasing radial growth due to tree aging is also not visible especially for oak series. The oak series are more coherent without any visible growth peaks and falls on the smoothed line, which are apparent for ash series.

For the ash series the decreasing trend of tree ring width growth can be observed from the early 1970s onward. The sample depth exceeding 10 trees or 20 samples is considered as prospective to be coherent, site-representative and prone to bear environmental signal. For the oak series the threshold level of 20 samples was reached in 1897 and for the ash series in 1901 (Figure 2).

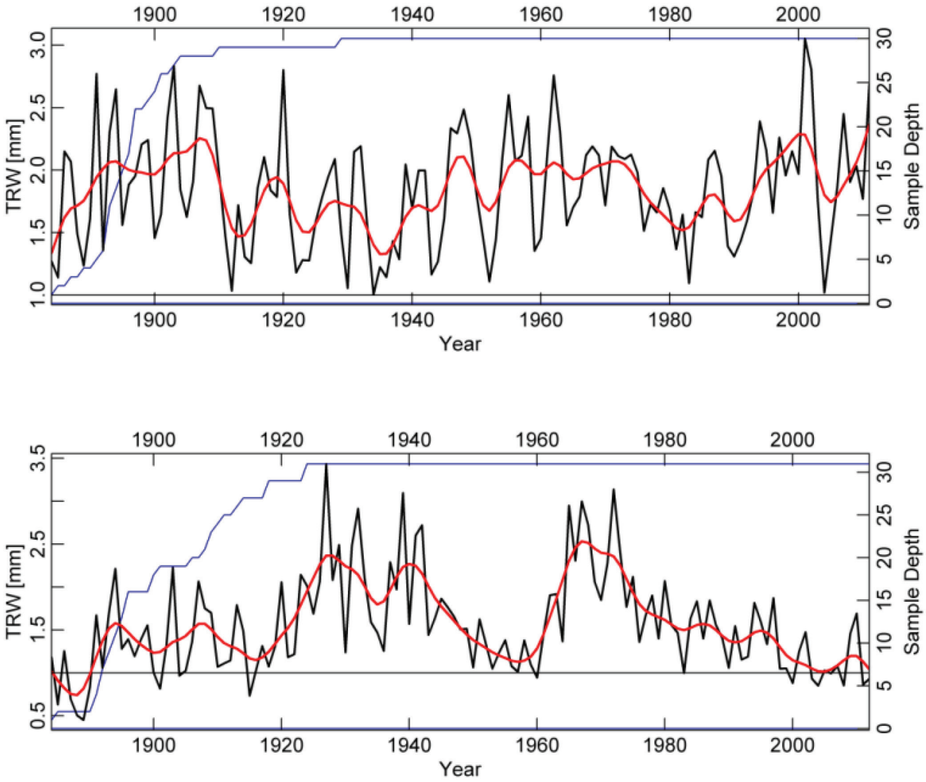

Figure 2. Mean raw tree ring width series (black line) for oak (top), ash (bottom). Sample depth (blue line), smoothing 10-years spline (red line)

Negative relationships, for the entire period of study, were identified only for temperature (Figure 3). These negative relationships occurred for correlation between temperature of August of previous year (oak) and temperature of July to September of previous year, April and June of current year (ash) and tree ring width. The strength of the relationships binding temperature and TRW can be considered as weak to moderate with *r* between ~-0.15 and – 0.33.

Positive static correlation relationships between mean streamflow and tree ring width occurred for April, August, September of previous year and April to September of current year (oak); for September of previous year and April to September of current year (ash). The strength of the relationships between streamflow and TRW is weak to moderate with *r* between 0.18 and 0.55; the strength of relationships for the same months for ash is usually higher than for oak, however. The response function analysis returned positive relationships for ash only for streamflow of May and June. The strength of these relationships was weak with *r* lower than 0.20 (Figure 3).

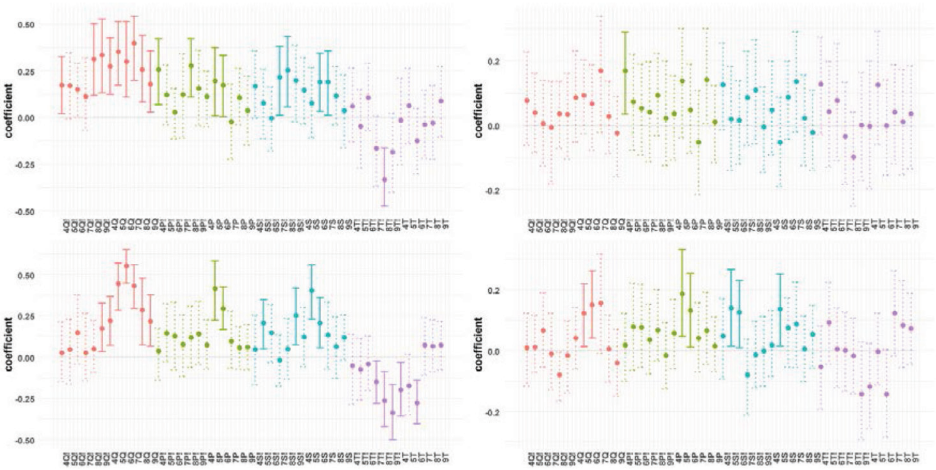

Figure 3. Correlation (left) and response function (right) coefficients for static relationships between hydroclimatic factors and TRW of oak (top) and ash (bottom). Red (streamflow), green (precipitation), blue (Standardized Precipitation Evaporation Index), violet (temperature), (!) previous year. Solid line significant values

As far as precipitation is concerned, the positive static correlation relationships occurred in April, August of previous year, May, June of current year (oak) and May, June of current year (ash). The response analysis returned positive relationships between precipitation of May, June of current year and ash tree ring growth. The strength of the relationships between precipitation and TRW is considered as weak to moderate with *r* between 0.17 and 0.42, but again the strength of relationships for the same months for ash is higher than for oak. The static response function analysis returned positive relationships for streamflow of April (oak) and May, June (ash). These relationships were weak with *r* lower than 0.20.

As for SPEI, the positive static correlation relationships were found for July, August of the previous year, June, July of the current year (oak); for May, September of the previous year and May, June of the current year (ash). The positive static response function relationships were found for ash only. The relationships occurred in May, June (the previous year), May (the current year). These relationships were weak with *r* lower than 0.20.

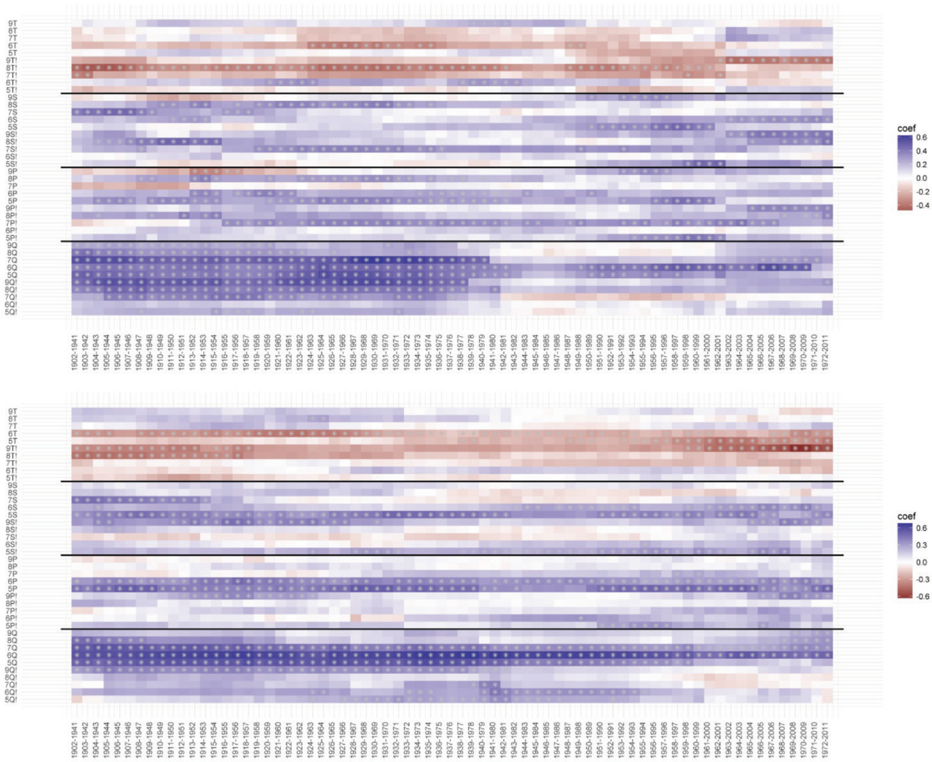

Figure 4. Correlation coefficients for dynamic relationships between hydroclimatic factors and TRW of oak (top) and ash (bottom)

The analysis of dynamic relationships between hydroclimatic parameters and tree ring width was conducted for moving window of 40-year interval in the period of 1901-2011. The negative relationships prevailed for temperature, while for the other parameters positive relationships dominated (Figure 4). The strongest relationships between temperature and tree ring width of ash occurred at the begging and the end segment of the period of 1901-2011. This general rule was not observed for oak, for which the short periods of increased strength of the relationship were irregularly distributed over time. The most regular strength of the temperature relationship over the study period occurred for August of the previous year for oak. As for ash, no stable strength of the relationship for any month was identified, because of the presence of “the gap of lower strength” in the middle of the period of 1901-2011.

The highest regularity of strength of the relationship between precipitation and tree ring growth of ash occurred for May and June of the current year. As for ash and Standardized Precipitation Evapotranspiration Index, the highest regularity of the strength of the relationship was for September of the previous year and May of the current year. Unlike in the case of ash, for oak the periods of higher strength of relationships for three parameters: temperature, precipitation and SPEI, were distributed very irregularly across months over the time span of study period, therefore no general pattern of regularity can be identified.

The trends of strength of the relationship were observed only for streamflow. The decreasing strength of relationships binding streamflow and tree ring width can be observed over the time for the both species. For ash the decrease was gradual, but for oak the decrease was abrupt at the early 1940s. As for oak, the most stable strength of the relationship between streamflow and TRW was observed for June and also July, May of the current year. As for ash, the regular high strength of the relationship between streamflow and TRW was observed for June of the current year.

The pattern of relationships identified between climatic factors is consistent with the results that are frequently the outcome of studies on relations between hydroclimatic parameters and TRW of ash and oak. These relations for the months of vegetation period are usually negative for temperature, and positive for precipitation in similar regional climatic conditions. The climatic factors for months of previous year (frequently July, August, September) and current year (frequently May, June, July) are usually in relation with tree ring width (Karpavičus and Adomas 2006, Ważny 2006, Okoński and Koprowski 2012, Matisons *et al*. 2016). Other water-availability-related factors, like river regime elements, are yet not quite often investigated in the domain dendroecological research. Furthermore, unlike oak, ash was infrequently the subject of dendroecological investigation, therefore the results for compassion are less available. A general problem of these analyses is the pronounced intercorrelation of the hydroclimatic variables used as predictors (Cropper 1984, Zang and Biondi 2015).

Ash growing on active terraces of river valleys appears to be more sensitive to hydroclimatic factors than oak from the same site. This notion was supported not only by the higher strength of relationships between the hydroclimatic parameters and TRW for ash than for oak, but also by tree ring width statistics regarding variability, sensitivity and integrity of tree ring width series. Thus, it seems that hydroclimatic factors acting on floodplains are more limiting for the radial growth of ash than for oak. Further, the relationships of hydroclimatic parameters and ash TRW were more regular and stable for the same months throughout the entire period 1901-2011. For oak, different months of the vegetation period dominated during shorter temporal segments as decisive for radial growth. This showed that ash in comparison with oak seems to be less ecologically flexible species for adapting to changing climatic conditions and therefore more prone to stress caused by drought. Streamflow, a river regime element acted as a good substitute of precipitation being a significant, if not dominant, source of water availability for both species of trees. This role of streamflow decreased substantially during the period of 1901-2011 for both tree species. This change was gradual for ash and abrupt for oak (the early 1940s threshold). The question has arisen about potential effect of climate changes on radial growth of ash and oak especially for the period since the end of 20th century. The results of research did not allow for drawing more firm conclusions regarding climate changes, because no visible shifts between monthly relations or shifts in strength of relations for that period occurred (except for the streamflow relation which can be also attributed to different than climatic factors e.g. such as erosion of riverbed). On the suitability of SPEI as a variable used in dendroecological analysis, good example of application of this parameter was ash and the relationships for May and Jun of current year. The pattern of relation for both precipitation and temperature was not as regular and firm as for SPEI (biding both precipitation and evapotranspiration together) showing that water availability for these months is very important for ash growth. Finally, the decreasing trend of tree ring width growth can be recorded for ash from the early 1970s onward – this fact, coupled with tree defoliation and crown damage assessed during sampling (ca. 25% loss of foliage and young branches damage), can be both symptoms of ash decline.

MAIN CONCLUSIONS

1. Ash in comparison to oak appeared to be both more sensitive to hydroclimatical features and less ecologically flexible as far as monthly pattern of water requirements is concerned, therefore adaptation to changing climatic conditions and drought may be a greater ecological challenge for ash than for oak in floodplain valleys of rivers.
2. Streamflow could be considered as the parameter that substituted precipitation well, or even was more important than precipitation, as far as availability of water for formation of tree rings of ash and oak from active terraces of river valleys is concerned; however, the role of streamflow in radial growth decreased substantially during 20th century.
3. Standardized Precipitation Evapotranspiration Index (SPEI) as a measure of drought is very prospective parameter in dendroecological analysis, since it precisely conveys real water input for ecosystems and availability of water for trees e.g. as in the case of ash radial growth and water availability in May and June of current year in this study.

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