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GROWTH RESPONSES OF SESSILE OAK TO CLIMATE AND HYDROLOGICAL REGIME IN THE ZBYTKA NATURE RESERVE, CZECH REPUBLIC

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Abstract: Complex of Nature reservation Zbytka is the rest of various fen vegetation in the northeast part of the Czech Republic. It represents an important spring area which provides high quality potable water for more than 150 000 inhabitants. Waterworks utilization was started in the 1960s and the change of land-use practices has had a strong effect on the ecosystem. Oak chronology has been showing different tree growth trends since the start of the waterworks utilization. Also the occurrences of negative pointer years differ markedly before and after initiation of pumping underground water. Dendroclimatological analyses primarily revealed a close relationship between the temperature and tree growth - positive influence of spring and summer temperature. The period 1983-1992 of maximum artesian water pumping is expressed as higher tree-ring increments, but linear model analyses showed that the growth reaction of oak is not due to simple causality between temperature and underground water level. The radial increments reacted positively to the combination of high temperature during the vegetation season and low or, the contrary, high depth of underground water level. No direct relationship was detected between tree growth and fluctuation of underground water level; despite of the results dendrochronological data may be useful in historical ground water modelling studies. Results are also crucial for conflict of interests between nature preservation and potable water supply.

Keywords: dendrochronology; oak tree; water pumping; hydrology

1. INTRODUCTION

Complex of Nature reservation Zbytka is the rest of various fen vegetation in the northeast part of the Czech Republic. The reserve area is a valuable habitat of endangered species (e.g. *Calamagrostis varia, Arabis nemorensis, Taraxacum mendax, Viola elatior, Carex hostiana, C. lepidocarpa, Orchis militaris, Dactylorhiza incarnata, Allium angulosum, Ophioglossum vulgatum*) and it is an object of botanist interest from the 1930s (e.g. Rohlena and Dostál, 1936; 1937-1938; Prokeš and Válek, 1944; 1946; Krčan and Kopecký, 1959; Kopecký, 1960; Krahulec, 1995; Hájek, 2009). For a long time, surroundings of Zbytka consist of agricultural landscape and therefore fens have been gradually changing by cultivation. Drained fens have been used as fertile cabbage fields, as

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well as pastures and meadows since the 19th century. During the 20th century, exploitation and drainage were continuing and non-exploited stands were reforested (Hájek, 2009).

The Zbytka nature reserve is a part of the spring area Litá – Mokré. Waterworks utilization was initiated in the 1960s and a progressive pumping started in 1978 (Hermann, 1995; Hrkal, 1998). The spring area has fundamental significance for the Hradec Králové region; it provides high-quality potable water for more than 150 000 inhabitants (Růžička, 2006).

Changes in land-use practices have had an effect on ecosystem characteristics and it is related to climate and hydrology changes (Ford and Brooks, 2003; Dale, 1997). Alluvial forests are markedly influenced by the level of underground water and floods frequency. In wetlands, water can be both a limiting resource and a chronic stressor (Mitsch and Gosselink, 2007). Hydrology is a dominant driver of stand composition structure and growth, as well as tree architecture in wetland forests (Rodríguez-González *et al.*, 2010). Effects of changes in hydrology regime vary among forest vegetation types, between young and mature stands and tree species (Becker *et al.*, 1996). Attention has been usually paid to the effect of fluctuating hydrological condition (e.g. drainage, floods, pumping of water or dilution) on the growth of coniferous species, less on broadleaved species (Becker *et al.*, 1996; Choi *et al*,. 2007; Dang and Lieffers, 1989; Freléchoux *et al.*, 2000; Douda *et al.*, 2009; Linderholm 1999; Linderholm and Leine 2004; Lageard and Drew 2008).

Our objective was to analyse the response of sessile oak trees to hydrological and climatic variations; specifically (1) to find out the role in fluctuations of the groundwater table caused by pumping on tree growth and (2) to investigate the relationship between tree growth and climate conditions influenced by specific site conditions. The results are crucial for conflict of interests between nature preservation and supply of potable water in the Hradec Králové region. Another important merit of this study was the application of tree-ring and hydrological records from Zbytka for the assessment of sustainability of the habitat. It will be subsequently useful for the development of strategies for conserving vulnerable fens and allow for better management of ground water resources.

2. MATERIAL AND METHODS

Study site

Zbytka reserve is a part of the spring area Litá - Mokré in the northeast Bohemia (**Fig. 1**). It is situated near the left bank of Dědina stream on a flat alluvial plain (256-264 m a.s.l.) interlaced by drainage channels and depressions with intermittent streams (Hájek 2009).

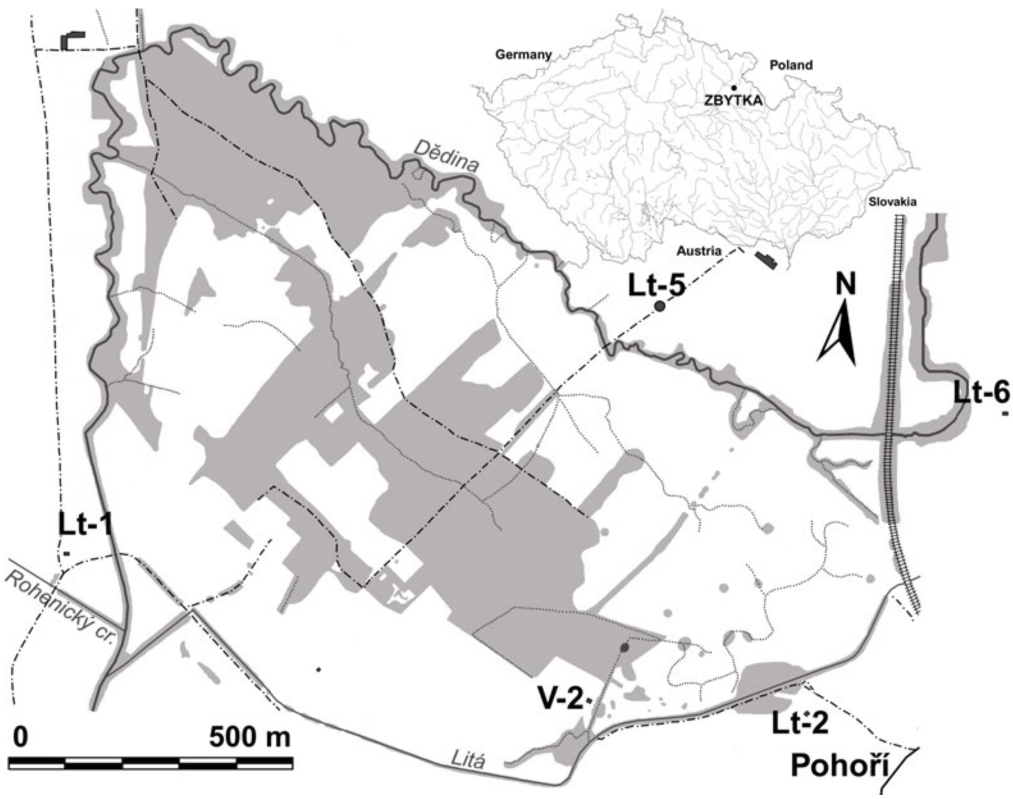

Fig. 1. *Map of study area – Zbytka nature reserve with boreholes Lt-1, Lt-2, Lt-6, V-2 and monitoring Lt-5.*

The Zbytka Nature Reserve was established for the purpose of protection of the fen ecosystem, intermittently wet Molinia meadows and oak-hornbeam forests on the area 79.42 ha in 1994 (Faltysová *et al.*, 2002). This territory was included to the European Natura 2000 network by government provision n. 132/2005.

The geological basement of the site is formed by mesozoic sedimentary bedrocks of Middle-Late Turonian Age – calcareous siltstone, calcareous clayey sandstone, marlstone and spongilit. The rigid bedrocks of Middle Turonian Age created artesian impervious strata of fissure aquifer (Hermann, 1995; Hrkal, 1998). Artesian water has neutral to weak alkaline reaction. The specific chemistry of water has caused fens character of wetlands and created quaternary freshwater limestone (Hrkal, 1998).

The average annual precipitation ranges from 550 to 600 mm, the average yearly temperature is 8-9°C, and the average monthly temperature is approximately -2 to -3°C in January and 17 to 18°C in July (Tolasz *et al.*, 2007).

Waterworks utilization

Plan of waterworks utilization of the spring area Litá – Mokré arose at the 1940s. The first dwell built sugar refinery from České Meziříčí and used it between 1962 and 1966 (Kroupa, 1986; Hájek, 2009). During the 1960s artesian boreholes Lt-1, Lt-2, V-2, Lt-5 and Lt-6 were made within the Nature reserve or near the boundaries. Lt-5 is a monitoring borehole from 1968; the others are pumping ones (Hájek, 2009).

Outlying boreholes Lt-01, Lt-02, V-1 have started operation in 1978-1979 (total uptake 50 l/s), but measurement of boreholes inside Zbytka area did not show any influence of underground water level. Boreholes Lt-6, Lt-8, and Lt-10 were joined in 1980, Lt-4 in 1983. Total sum of uptake between 1981 and 1983 reached 200 l/s and was reflected by water level fluctuation and subsidence with minimum 1982/1983 in Zbytka area. Accelerated pumping coincided with adjunction of the next boreholes Lt-1, Lt-2, V-2 (boreholes within the reserve or near the boundaries) in 1984. The total sum of uptake exceeded 250 l/s with month maximum 340 l/s in April 1988. Massive decrease of water table was measured in 1984-1985 and 1990-1991. The decrease was intensified by precipitation deficit in 1983-1984 and 1989-1991, but during the period with higher precipitation in 1985-1988 the water table of the monitoring borehole fluctuated few meters below normal. The pumping has been reduced to 200 l/s in 1993. The water table in the monitoring borehole Lt-5 has been sustained at 257.5 m a.s.l. since 1997 (Hermann, 1995; Hrkal, 1998; Uhlík *et al.*, 2006; Hájek, 2009).

The average level of water non-affected by pumping fluctuates between 258-259 m a.s.l. in the spring area. An assumption exists that pumping of artesian water has caused a reduction of waterlogging period in the situation above 257.5 m a.s.l. only to water full springtime and has caused desiccation above this level (Bušek 2006). Artesian water saturates southern fenny part of Zbytka whereas waterlogging of the northern part depends on relatively regular spring floods (Hájek, 2009).

Field and laboratory procedures

Sampling sites were chosen at stands clear of surface moisture stagnation at the woodland part of the natural reservation Zbytka with alluvial forest *Pruno-Fraxinetum* (Oberdofer, 1953), approximately 0.5 km to the south from borehole Lt5 (**Fig. 1**). Twenty sessile oak trees with relatively similar character (sturdy, without visible signs of trunk and tree-top damage, without fungi attack grown) were chosen and two increment cores were taken from each tree at the height of 1.3 m above ground.

Tree-ring widths were measured at an accuracy of 0.01 mm using a measuring device (TimeTable) and the Past4 software (Knibbe, 2004). The synchronization of the raw ring-width series was done using Past4 software (Knibbe, 2004) using visual comparisons and well-established statistical parameters: tBP (Baillie and Pilcher, 1973) and GLK% (Eckstein and Bauch, 1969). Values of tBP greater than 10.0 and GLK% values greater than 75% were considered significant.

Chronology computation

We produced a residual tree-ring index chronology using the ARSTAN software (Cook and Holmes, 1986). Index chronologies were generated by fitting each series with a negative exponential or linear function, and computing the index by dividing the observed tree-ring values by the expected values (Cook and Kairiukstis, 1990). This served the standardized removal of the age trend (Cook and Peters, 1981; Ford and Brooks, 2003). Autoregressive modelling was performed on each standardized series to remove temporal autocorrelation from the data (Cook, 1985; Cook and Kairiukstis, 1990). The mean residual chronology Q01-ZB were computed from individual indices of each year by means of biweight robust estimation (Cook and Holmes, 1986; Cook and Kairiukstis, 1990) and used in all further analyses. We chose to use the residual index in our analyses to avoid using autocorrelated data which violate the assumptions of the regression analyses (Ford and Brooks, 2003).

Dendroclimatological and dendrohydrological analyses

A climate-growth relationship was investigated using the two different approaches. To understand the relationship between the tree growth and complex actions of climate, the software DENDROCLIM2002 was used that computes the bootstrapped response and correlation functions (Biondi and Waikul, 2004). First, the bootstrapped correlation (CF) and response (RF) function (Cook and Kairiukstis, 1990) were computed for the period 1969-2008. Correlation was sought between residual chronologies and for monthly climatic data (means air temperature (°C) and total precipitation (mm) from October of the previous year's growth to September of the year of growth. This approach ordinarily provides an idea about the average response of trees to the range of climate factors (e.g. Rolland *et al.*, 1998; Solberg *et al.*, 2002; Esper *et al.*, 2002; Wilson *et al.*, 2005a; Wilson *et al.*, 2005b).

This mentioned procedure has not revealed climatic forcing of single extreme years (e.g. Kienast *et al.*, 1987; Schweingruber, 1996). To determine the synchronous extreme growth reaction of trees - pointer years (Lebourgeois, 2007; Schweingruber *et al.*, 1990) using the method of normalization in a moving window (moving window: 5 y, thresholds of index value: ≥ 1 and ≤ –1 for positive and negative pointer years, respectively; Cropper, 1979). A year was considered to be a pointer year when an extremely narrow or wide tree-ring was detected in at least 50% of trees per site (Meyer, 1999).

We analysed the influence of water pumping on tree growth using mean residual chronology Q01-ZB and monthly data about level of underground water in monitoring borehole Lt5 from 1968 to 2005. First, we shifted off the influence of temperature in vegetation season (March till September) that mainly affects tree growth. Subsequently, we tested the relationship between the growth and level of underground water by linear models (LM) in program R (www.cran-project.org). We adopted 5 models explaining the tree-growth (no relationship, only temperature influenced, temperature and underground water in linear, quadratic or cubic term influenced) and than we choose the best one according to AIC (Akaike in-formation criterion) value. AIC is a measure of the relative goodness of fit of a statistical model. Finally we tested the significance of the dependence by ANOVA (Analysis of variance).

Meteorological data were obtained from the close meteorological stations, total precipitation from České Meziříčí (approximately 2 km) and mean air temperature from Hradec Králové (approximately 20 km).

3. RESULTS

Composite of chronology and growth characteristics

Mean tree ring-width series for 20 trees exhibited no growth anomaly and produced a 159-y mean chronology spanning the period 1850-2008. The obtained mean chronology had a high statistical quality e.g.: mean sensitivity was 0.22, low first-order autocorrelation 0.42, agreement with population chronology 0.95 and mean correlation among trees 0.54.

Chronology Q01-ZB has been showing different growth trends since 1970s when the waterworks utilization started (**Fig. 2**). Almost regular decadal fluctuation of tree growth has been coincident with the start of the underground water pumping in 1978.

The analysis of pointer years found 15 years with extremely narrow or wide increments; eight negative and seven positive pointer years (**Fig. 3**). The occurrence of negative pointer years differed markedly before and after the initiation of pumping underground water. The period 1948-1978 was characterized by frequent strong negative pointer years (1948, 1952, 1956, 1959, 1967 and 1974). A reverse trend was clearly visible during the period 1978-2008. The number of extremely narrow increments declined to two weaker negative pointer years (1996, 2005).

Dendroclimatological and dendrohydrological analyses

Dendroclimatological and dendrohydrological analyses were targeted at the period 1968-2008; climatic and underground water level Lt-5 records exist for these 40 years.

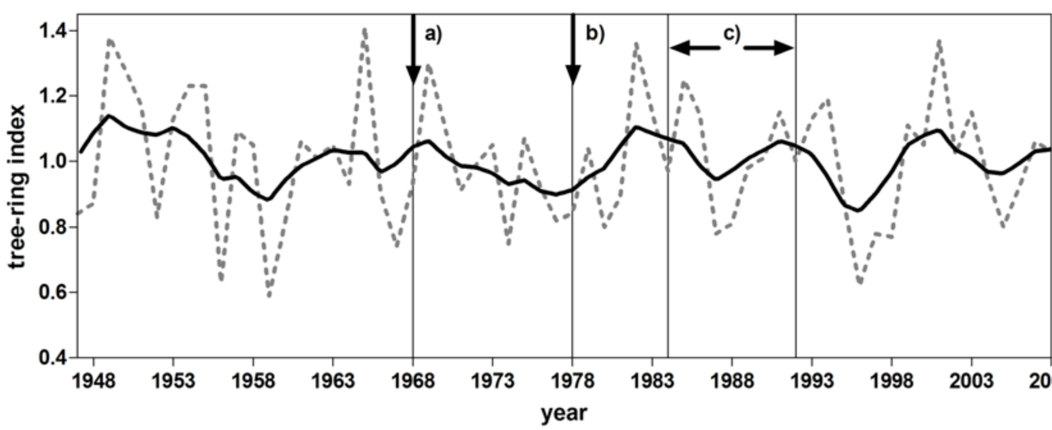

Fig. 2. *Residual chronology Q01-ZB (dotted grey line – tree-ring index, black line – 5-year cubic smoothing spline of tree-ring index). a) Start of measuring water table of monitoring borehole Lt5; b) start of waterworks' utilization of the spring area Litá - Mokré, c) period of the strongest pumping artesian water.*

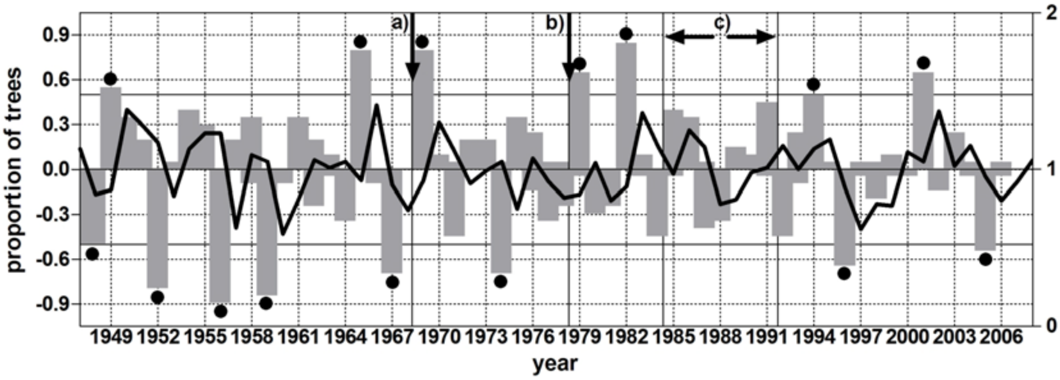

Fig. 3. *Extreme growth reactions of trees. The y-axis characterizes the proportion of trees with extremely wide (+) or narrow (–) increments during the same year. Years with synchronous reaction in at least 50% trees were considered as pointer years (black dots). a) Start of measuring water table of monitoring borehole Lt5; b) start of waterworks' utilization of the spring area Litá - Mokré, c) period of the strongest pumping artesian water.*

Influence of climate

Dendroclimatological analyses mainly revealed a close relationship between temperature and tree growth – positive influence of high March, May, July and September temperatures (**Fig. 4**). The shape of tree-ring curve and mean temperature during vegetation season was almost identical (**Fig. 5**). Negative correlation was found between the tree growth and high July precipitation and high February temperature/precipitation. Only sporadic reaction to climatic conditions of a year before tree-ring formation was detected – positive influence of high previous September precipitation.

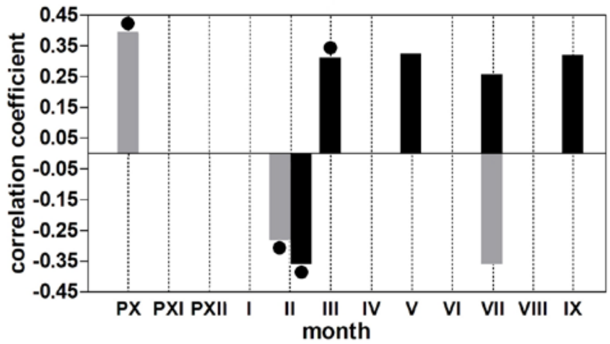

Fig. 4. *Climate-growth relationship: significant correlation (columns) and response (dots) functions coefficients ($P < 0.05$) for chronology Q01-ZB, related to mean monthly temperature (black) and precipitation (grey) from October of the previous year's growth (p) to September of the year of growth.*

Influence of water pumping

Influence of fluctuation of underground water on tree growth is related to climate, notably with temperature. The best model of influence on chronology Q01-ZB was

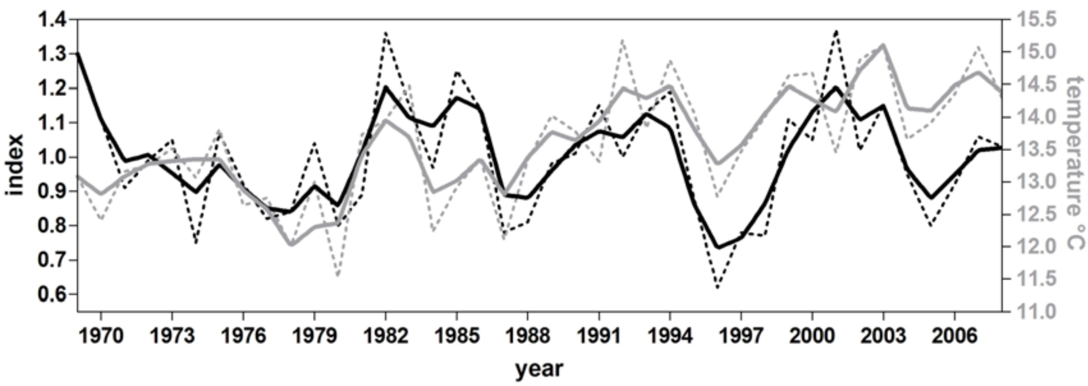

Fig. 5. *Correlation between tree-ring index of chronology Q01-ZB (dotted black line, black line – 5-year cubic smoothing spline of tree-ring index) and mean temperature from March to September (dotted grey line, grey line – 5-year cubic smoothing spline of mean temperature).*

created by average temperature and quadratic term of the underground water level (**Table 1**). The growths of trees decreased with low temperature during growing season together with average underground water level (**Fig. 6**). Growth depressions concided with high water table of the monitoring borehole Lt-5 to the year 1982 (**Fig. 7**). The period 1983-1992 of maximum artesian water pumping is expressed by higher tree-ring increments. Pumping reduction of artesian water has been displayed as growth depression since 1993. The recovery tree growth was probably a consequence of 5 year period of higher

Table 1. *Models of influence of average temperature (av.temp.) and underground water level (und.wat.) on Q01-ZB. AIC – Akaike information criterion, df – degrees of freedom, F – test statistics of ANOVA, p – significance.*

	df	AIC	F	p
Q01-ZB ~1	2	304.5		
Q01-ZB ~av.temp.	3	302.6	4.8	0.036
Q01-ZB ~av.temp.+und.wat.	4	304.4	0.3	0.6
Q01-ZB ~av.temp.+und.wat.^{2}	5	295.7	10.8	0.002
Q01-ZB ~av.temp.+und.wat.^{3}	6	297.5	0.11	0.7

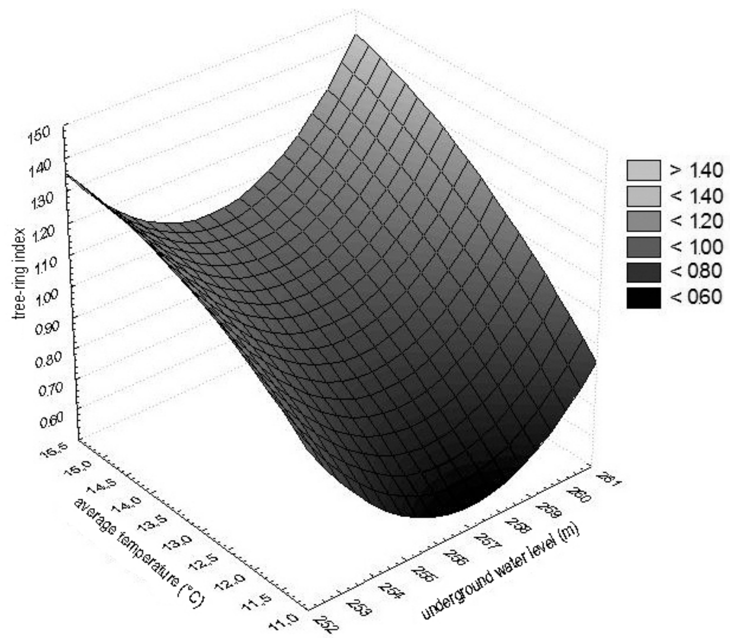

Fig. 6. *Relationship between fitted values of tree-ring index of chronology Q02-PR (grey scale reflects range of the values, see legend in the figure), average temperature and underground water level.*

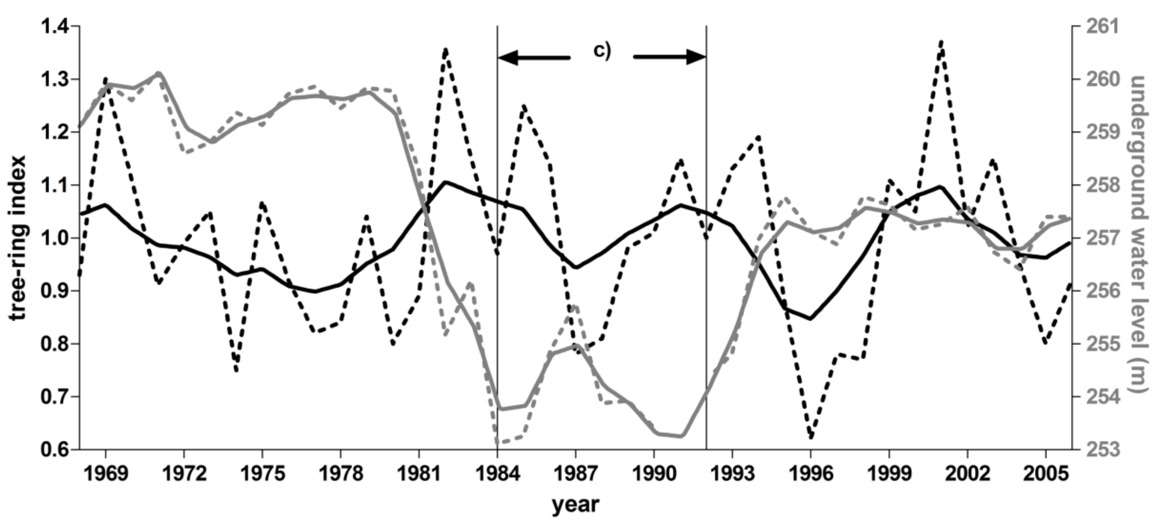

Fig. 7. *Tree-ring index of chronology Q01-ZB (dotted black line, black line – 5-year cubic smoothing spline of tree-ring index) and mean year water table of monitoring borehole Lt-5 (dotted grey line, grey line – 5-year cubic smoothing spline of water table).*

temperature and lower precipitation against long term mean during the vegetation season at the end of the 1990s.

4. DISCUSSION

Influence of climate

The amount of precipitation during vegetation season had no positive effect on oak growth in the Zbytka area (**Fig. 4**). This output was rather surprising, because oaks respond mainly to water balance and drought (Bréda and Badeau, 2008). The growth of oak trees is usually limited by precipitation during the vegetation season and amplifying negative factor is high temperature, which deepen site water deficit across the European continent (e.g. Siwecki and Ufnalski, 1998; Horáček *et al*., 2003; Lebourgeois *et al*., 2004; Cedro, 2007; Neuwirth, *et al*., 2007; Čufar, *et al*., 2008; Drobyshev, *et al*., 2008; Friedrichs *et al*., 2009; Ruseckas, 2006; Andersson, 2009). These studies indicated that oak sensitivity to water stress is especially high during spring and early summer – June and July precipitation are essential controlling factors for oak growth.

Reason of a positive reaction tree-ring increment to high temperature during vegetation season could be caused by sufficient water supply this forest vegetation in Zbytka (**Figs. 4**, **5**). Similar results were obtained by Ruseckas (2006) in Lithuania. Radial increment of the oak stands was positively correlated with the mean air temperatures of March, May, July, August, summer and annual means in the temporarily overmoistured sites on fine or coarse-on-fine textured soils with a shallow water table. Ruseckas (2006) connected the positive growth reaction of the oak stands with the increase in annual temperatures and oak's tolerance to xero-mesophytic conditions. Negative reaction to the high precipitation in July (**Fig. 4**) can be explained by temporarily overmoisturing of the sites. In very wet years, anoxic stresses may cause growth rates to be suppressed if the root zones become saturated (Stromberg, 2001). A special case was oaks growing in currently extinct natural mire woodlands of NW Europe where growth was apparently negatively correlated to the amount of precipitation during the growth season (Sass-Klaassen and Hanraets, 2006).

The tree ring growth in Zbytka reserve also reacted significantly to climatic conditions before the vegetation season. This is in agreement with the results of previous studies (e.g. Nola, 1996; Drápela and Zach, 1995; Lebourgeois *et al*., 2004; Cedro, 2007; Drobyshev *et al*., 2008; Fridrichs *at al*., 2009; Ruseckas, 2006; Andersson, 2009), wherein the tree ring growth and primarily earlywood with large vessels is influenced by climatic conditions of the previous year, winter temperatures and tree-ring width in the previous year.

The positive influence of high March temperature (**Fig. 4**) is related to the production of new earlywood for the spring recovery of hydraulic conductivity before leaf expansion (Cruiziat *et al*., 2002). Carbohydrate storage has a high spring mobilization and is allocated to tree organs before bud burst. The phenology and anatomy pattern of the ring-porous species cause this typical seasonal dynamic of stored nutrients, when about 30 % of the total annual stem increment (mainly earlywood formation) is added before bud burst (e.g. Barbaroux and Bréda, 2002). In general, large diameter vessels were more prone to freezing-induced dysfunction than small vessels (Tyree and Cochard, 1996). The large vessels of earlywood in oaks are very sensitive to embolism caused by frost events and a large part of the previous year's earlywood vessels are embolized by low winter temperatures (Hacke and Kauter, 1996; Cruiziat *et al*., 2002). High March temperature has also favourable effect on the rooting of the trees owing to the permeability of the subsoil (Becker *et al*., 1994).

The negative influence of high February temperature (**Fig. 4**) is apparently discordant with oak ecophysiology, but high February temperature and precipitation could prematurely stimulate production of earlywood and subsequently the vascular tissue could less withstand sudden spells of low temperatures. The resistance of oak trees to low temperatures may increase a high amount of translocation carbohydrates in plant tissues (Drobyshev *et al*., 2008). Carbohydrate storage (starch and sugars) mainly occurs in autumn and favourable autumn temperature enables more carbohydrates to complete relocation of transportable assimilates from leaves to perennial parts of the tree. This results in more available energy reserves during the following growing season (Andersson, 2009; Drobyshev *et al*., 2008). Moreover, adequate water saturation during autumn (**Fig. 4**) prolongs production and accumulation of nutrients, which gives a support to the roots growth at the end of vegetation season, until the soil temperatures become too low (Lebourgeois *et al*., 2004). Resulting extensive root system provides for higher tree-ring increment next year (Santini *et al*., 1994).

Influence of water pumping

The shape of the chronology curve demonstrated more fluctuation after the start of pumping than before, but with less abrupt negative events. Higher proportion of negative pointer years is typical for period before pumping. Widespread growth anomaly occurred only before the start of pumping and after pumping reduction since 1992. The strong pointer years 1956, 1959 and 1996 of oak are expressed in numerous sites across Europe (Neuwirth *et al*., 2007; Drobyshev *et al*., 2008; Bréda and Badeau, 2008). The spatial pattern of the pointer year expressions is controlled by sub-regional variation in the expression of weather extremes (Drobyshev *et al*., 2008).

Decreasing underground water presumably weakens the influence of unfavourable climatic conditions, especially abrupt deviations. Extensive growth depressions could be caused by long-term stresses, such as competition, water regime or changes of climate, while shorter growth depressions are more likely to be caused by short-duration stress factors, such as insect defoliations or extreme droughts (Andersson, 2009). Nowadays in wetland oak sites, many old oaks died due to a rising groundwater table (Sass-Klaassen and Hanraets, 2006). Waterlogging caused root damage due to lack of oxygen in the root zone. Also mycorrhizas are very sensitive to changes of the soil hydrology, because prolonged wet conditions cause the die-off (Vasilas *et al*., 2004).

Underground water table sink is connected with growth release of sampled trees (**Fig 7**). It corresponds with findings about tree growth reaction to drainage (e.g. Becker *et al*., 1996; McDonald and Yin, 1999; Linderholm, 1999; Choi *et al*., 2007; Freléchoux *et al*., 2000) or generally to drier periods (Sass-Klaassen and Hanraets, 2006). Underground water tables sink generally starts decomposition and release of nutrients.

Many oaks were locally found dying due to increasing wetness at the low parts of Zbytka forests during the 1990s. Waterlogging was caused by dysfunction of drainage channels, reduction of pumping artesian water and floods (Krahulec in Herrmann, 2005).

Also the study of Vacek and Podrázský in Hermann (1995) detected deceleration of radial increment of trees in the Zbytka alluvial forest since the 1980s. Contrariwise to Krahulec (in Herrmann, 2005) and part of our findings, they related the decrease phenomenon to deficit of water in alluvial forest ecosystem due to drainage and water pumping, aside from natural climatic fluctuation.

Interestingly, the linear model analyses (**Fig. 6**) showed that the growth reaction of oak has not simple causality between temperature and underground water level, what indicated depicted curves chronology Q01-ZB and mean underground water level (**Fig. 7**) or mean temperature (**Fig. 4**). The radial increments reacted positively to the combination of high temperature during vegetation season and low or the contrary high depth of underground water level.

This contradiction can be caused by: (i) trees, especially oaks in modern wetland woods favourably germinate on rather higher and thus drier spots which makes them less susceptible to a temporary high groundwater level or flooding and could provide better chances to survive wet periods (Sass-Klaassen, 2004; Sass-Klaassen and Hanraets, 2006); (ii) inundation represented by spring floods in Zbytka area, changing water chemistry, particularly the concentration of nutrients and dissolved oxygen (Davidson *et al.* 2006). Additionally floods are a rich source of nutrients (Stromberg, 2001); (iii) climate changes could be a driving factor of earlier start of the growth period; oak stands become more sensitive to the soil moisture regime (Ruseckas, 2006) and proved inconsistent growth reaction to fluctuation of underground water level.

5. CONCLUSION

Although there is no direct relationship between tree growth and fluctuation of underground water level, the study indicates the usability of dendrochronology as one of the tools to evaluate human impact in this area. Our results also suggest that dendrochronological data may also be useful in historical ground water modelling studies.

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