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DENDROCHRONOLOGY OF SESSILE OAK (*QUERCUS PETRAEA*) ON THE TRANSITION BETWEEN THE SUB-MEDITERRANEAN AND TEMPERATE CONTINENTAL CLIMATIC ZONES IN SLOVENIA

DENDROKRONOLOGIJA HRASTA GRADNA (*QUERCUS PETRAEA*) NA PREHODU MED SUBMEDITERANSKIM IN ZMERNIM CELINSKIM PODNEBJEM V SLOVENIJI

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Izvleček / Abstract

Abstract: *A local tree-ring chronology of sessile oak (Qercus petraea) was constructed for the site Klanec pri Kozini (KLA), Slovenia (45.59° N, 13.92° E, 450 m a.s.l.) located on the Karst edge on the transition from the sub-Mediterranean climatic to temperate Continental zones. The chronology is 93 years long and covers the period 1925–2017. A comparison with four local oak chronologies from Slovenia and 38 from the surrounding countries (distance 65–220 km) showed that KLA agreed best with the local oak chronology of Rožnik, Ljubljana (ROZ), and two other oak chronologies from central Slovenia (the surroundings of Novo mesto and Ljubljana), one from Croatia and one from Austria. Dendroclimatological analysis showed that the main factor affecting tree-ring variation is June temperature (negative effect) and March precipitation (positive effect), which to a great extent explain the relation to other chronologies. The negative effect of June (maximal) temperature has become increasingly significant in the last few decades, which can be ascribed to warming related to ongoing climatic change.*

Keywords: *dendrochronology, tree-rings, oak = Quercus sp., Kozina, Slovenia, dendroclimatology, teleconnection, climate change*

Izvleček: *Sestavili smo lokalno kronologijo širin branik hrasta gradna (Qercus petraea) za rastišče Klanec pri Kozini (KLA) v Sloveniji (45,59°S, 13,92°E, 450 m n.m.), ki se nahaja na Kraškem robu na prehodu iz submediteranskega v zmerno celinski podnebni pas. Kronologija je dolga 93 let in pokriva obdobje 1925-2017. Primerjava s 4 lokalnimi hrastovimi kronologijami iz Slovenije in 38 iz okoliških držav, z rastišč, oddaljenih od 65 do 220 km, je pokazala, da se KLA najbolje ujema z lokalno kronologijo hrasta z Rožnika v Ljubljani (ROZ) in z dvema hrastovima kronologijama iz osrednje Slovenije, iz okolice Novega mesta in Ljubljane, ter po eno kronologijo iz Hrvaške in Avstrije. Dendroklimatološka analiza je pokazala, da sta glavna dejavnika, ki vplivata na variiranje širin branik, junijska (maksimalna) temperatura (negativni učinek) in padavine v marcu (pozitivni učinek), kar v veliki meri pojasnjuje tudi odnose do drugih kronologij. Negativni učinek junijske (maksimalne) temperature postaja vse bolj pomemben v zadnjih desetletjih, kar pripisujemo segrevanju ozračja zaradi podnebnih sprememb.*

Ključne besede: *dendrokronologija, širine branik, hrast = Quercus sp., Kozina, Slovenija, dendroklimatologija, telekonekcija, klimatske spremembe*

1 INTRODUCTION

1 UVOD

Oak is an important wood in European dendrochronology (e.g., Haneca et al., 2009). It is mainly represented by sessile (*Quercus petraea* (Matt.) Liebl.) and pedunculate oak (*Quercus robur* L.). The two species cannot be differentiated by wood anatomy, and therefore in historical dendrochronology (where the origin of wood is usually not exactly known) are often treated together as European oak (*Quercus* sp.) (e.g., Haneca et al., 2009). In Europe, numerous local and regional oak chronologies have

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been constructed, and many of them are multi-millennial (Baillie, 1995; Haneca et al., 2009; Prokop et al., 2017). The longest among them is the South German Hohenheim oak chronology, reaching back to 8480 BC (Friedrich et al., 2004).

Long regional chronologies have been successfully used to date the wood from the distant past and to explain numerous past events (e.g., Billamboz, 2003; Tegel et al., 2012; Rybníček et al., 2018). They have been used for reconstruction of the past climate and its effects on environment and cultural development (e.g., Tegel et al., 2010; Büntgen, et al., 2011; Cook et al., 2015; Dobrovolný et al., 2018).

As opposed to the various regional chronologies that have been composed, local chronologies of trees from known sites remain important to explore the ecology of oaks, and the relation of their tree-ring variations to climate and other factors (e.g., Friedrichs et al., 2009 a, b; Kolář et al., 2012; Stojanović et al., 2015; Nechita et al., 2017).

In Slovenia the first attempts with building oak chronologies were not encouraging, especially because of numerous sites where tree-ring variation is affected by micro-site conditions mainly related to ground water levels (Levanič, 1993; Čufar & Levanič, 1999; Čater & Levanič, 2004, 2015; Gričar et al., 2013; Jevšenak & Levanič, 2015) and not by supra regional climatic drivers.

The first longer chronology in Slovenia was a well-replicated 548-years long chronology covering the period A.D. 1456–2003 based on wood from living trees and historic constructions from SE Slovenia (Čufar et al., 2008 a, b). It proved to have a good teleconnection with various chronologies from sites up to 700 km away in Austria, Hungary, Serbia, Czech Republic and South Germany. Its tree-ring variation proved to be positively correlated with June precipitation and negatively with June temperature, and therefore could be used to reconstruct June conditions over the last five centuries (Čufar et al., 2008 b). It could also be included in the database used for the reconstruction of large droughts and pluvials during the last 2,000 years in Europe (Cook et al., 2015). Knowledge on the teleconnection of oak from Slovenia also helped to absolutely date the chronology of pile dwelling settlements from Ljubljansko barje, which spans the period of 3771–3330 BC by teleconnection with a combined German Swiss chronology (Čufar et al., 2015).

As the composed chronologies summarize the effects of different factors in trees from various sites, local effects can only be studied on networks of precisely known environments, as in an earlier study using 41 local chronologies from Austria, Croatia, Hungary, Serbia, and Slovenia (Čufar et al., 2014 a, b). In this work, all the chronologies showed a common positive response to precipitation in spring and summer (March and June) and a negative one to temperature in spring and summer (April and June), although it was also possible to show and explain the differences among them (Čufar et al., 2014 a, b).

Local studies and a better understanding of the variability of oak growth are needed to reveal how such trees store environmental information. This is important, among other reasons, when we attempt to fill the palaeoclimatic gaps and construct and prolong the regional chronologies which are needed to investigate the wood from the past (e.g., Ważny et al., 2014; Čufar et al., 2015).

Tree-ring investigations of oak in Slovenia with the aim of constructing chronologies for historical studies have mainly focused on central and southeast Slovenia with a temperate Continental climate, and identifying the teleconnection with oak from areas in the north, east and southeast of Slovenia. On the other hand, we lack such information for the oak from west and southwest Slovenia, at the transition from the temperate Continental to sub-Mediterranean climate, and on its relation to oak growth in Italy. Cooperation and exchange of data between Slovenian and Italian dendrochronological laboratories has already helped to clarify the relations among the chronologies of larch (*Larix decidua*) (Levanič et al., 2001), beech (*Fagus sylvatica*) (Di Filippo et al., 2007), and Norway spruce (*Picea abies*) (Bernabei et al., 2017) from the last millennium, as well as in relation to oak from prehistoric pile dwellings from the 4th millennium BC (Čufar & Martinelli, 2004). However, knowledge on the teleconnection of modern oak from Slovenia and Italy could not be clarified, due to a lack of an adequate network of oak chronologies.

This study therefore aimed to (1) construct a local chronology of sessile oak (*Quercus petraea*) for Klanec pri Kozini, on the Karst edge in SW Slovenia near the border with Italy, (2) to explore its teleconnection with available tree-ring chronologies in the surrounding areas, and (3) to show how climatic factors influence tree-ring variation in the transitional zone between the sub-Mediterranean and the temperate Continental climatic zones.

2 MATERIALS AND METHODS
2 MATERIAL IN METODE

2.1 STUDY SITE AND TREES
2.1 RASTIŠČE IN DREVESA

The sampling area Klanec pri Kozini (45.59°N, 13.92°E, 450 m a.s.l.) is located 15 km NE from Koper, on the Karst edge bordering the Slovenian Littoral. The distance (as the crow flies) to Trieste, Italy, is 10 km and to Ljubljana, Slovenia, 70 km (Table 1). The forest association is *Melampyro vulgati-Quercetum petraeae* var. geogr. *Fraxinus ornus* (Puncer & Zupančič, 1979) on flysch bedrock type. Sessile oak (*Quercus petraea* (Matt.) Liebl.) is the dominant species on the site, which has shallow brown dystric soil. The deep root system here is oak's advantage compared to other tree species.

For analyses we selected nine dominant or co-dominant *Q. petraea* trees (height ca. 20 m and DBH (diameter at breast height) ca. 40 cm). The trees were felled during regular felling activities in winter 2017. We collected the discs from the stems at 5 m above the ground.

2.2 DENDROCHRONOLOGICAL ANALYSIS
2.2 DENDROKRONOLOŠKA ANALIZA

For dendrochronological investigations the wood was polished and the tree-ring widths measured along two representative radii, to the nearest 0.01 mm using the TSAP-Win program (Frank Rinn, Heidelberg, Germany) and the CDendro/Coo Recorder image analysis program (Cybis Elektronik, 2010). The tree-ring series were visually and statistically cross dated and compared with each other by calculating the t-values as proposed by Baillie and Pilcher (t_{BP}) and Hollstein (t_H) and sign test (Gleichläufigkeit - Glk) using TSAP-Win.

Cross-dated tree-ring series of individual trees were assembled into a chronology using the ARSTAN program (Holmes, 1994). We calculated two versions of ARSTAN chronologies: a non-detrended - raw-data and a detrended residual chronology.

2.3 TREE RINGS AND CLIMATE
2.3 ŠIRINE BRANIK IN KLIMA

The climatic influence on tree growth was studied using the residual version of the chronology. This chronology shows tree-ring indexes vs. time, for which the original tree-ring width series were standardized in a two-step procedure. First, the long-term trend was removed by fitting a negative exponential function (regression line) to each tree-ring series. Second, a more flexible detrending was made by applying a cubic smoothing spline with a 50% frequency response of 30 years to further reduce non-climatic variance. Subsequently, autoregressive modelling of the residuals and biweight robust estimation of the mean were applied (Cook & Peters, 1997).

As the local climatic data series was short and incomplete, we used the closest grid point from the monthly high-resolution grids of mean temperature and precipitation for the period 1901–2016, obtained from CRU TS 1.2, publicly available at http://www.cru.uea.ac.uk/ (Mitchell et al., 2004), for dendroclimatic analysis. The database is constructed with a 10 min resolution for the whole of Europe, as well as some territories from the surrounding

Table 1. Site and source of climatic data for oak chronology for Klanec pri Kozini and Rožnik, Ljubljana used for comparison. ID_CRU – identification code for CRU climatic data (http://www.cru.uea.ac.uk/).
Preglednica 1. Osnovni podatki o rastišču in klimatskih podatkih za rastišče Klanec pri Kozini in Rožnik, Ljubljana za primerjavo. ID_CRU – identifikacijska šifra za klimatske podatke CRU (http://www.cru.uea.ac.uk/).

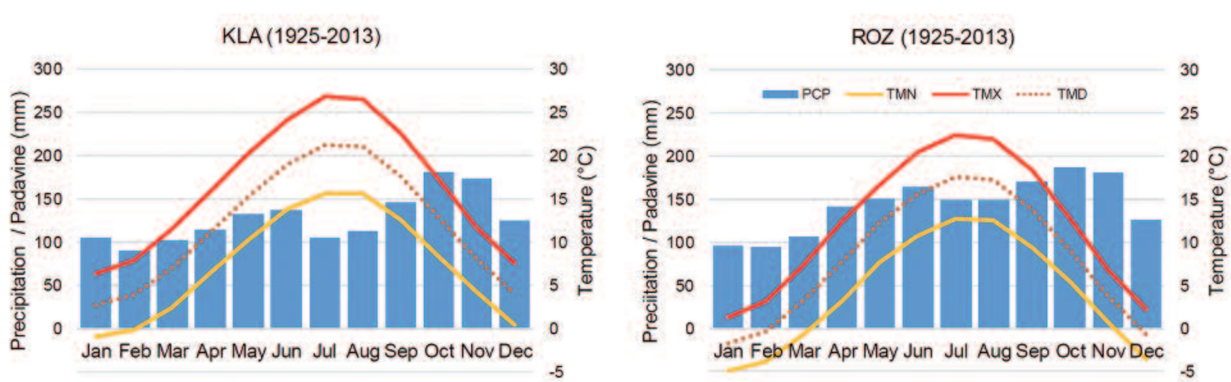
Location / Lokacija	Chronology / Kronologija	Altitude / Nadmorska višina m	Latitude / Zemljepisna širina °N	Longitude / Zemljepisna dolžina °E	ID_CRU
Klanec pri Kozini	KLA	450	45.59	13.92	195508
Rožnik, Ljubljana	ROZ	300	46.05	14.47	196229

areas; the dataset covers 11° W to 32° E longitude and 34° N to 72° N latitude.

The climatic data calculated from the representative CRU data (CRU ID 195508) for the period 1925-2013 show an annual sum of precipitation 1520 mm and the mean annual temperature 11.9 °C (Table 1, Figure 1 a). These CRU data correspond well with the data of the meteorological station Godnje (45.75° N, 13.85° E, 320 m a.s.l) of the Environmental Agency of the Republic of Slovenia (ARSO, 2018).

The climate/growth relationships were calculated using the program DendroClim2002 (Biondi & Waikul, 2004), whereby the residual version of the tree-ring chronology was the dependent variable and the regressors were the monthly mean, minimum and maximum temperatures and the monthly sums of precipitation for each biological year from the previous January to the current December over the time axis from 1925 to 2013 (a common period of KLA and ROZ chronology). DendroClim2002 uses correlation and response functions, which are the most common statistical models used in dendrochronology. The term 'function' indicates a sequence of coefficients computed between the tree-ring chronology and the monthly climatic variables, which are ordered in time from the previous-year growing season to the current-year one. In 'correlation' functions the coefficients are univariate estimates of Pearson's product moment correlation, while in 'response' functions the coefficients are multivariate estimates from a principal component regression model (Biondi & Waikul, 2004). The program applies a bootstrap process according to Guiot (1991) to assess the statistical significance of the correlation and response function.

The stability in time of the climate/growth relationships was checked by moving the correlation function, calculated for 30-year time window, over the period from 1925 to 2013 (Biondi, 1997).



	KLA	ROZ
Annual sum of precipitaion / Letna vsota padavin	1520 mm	1715 mm
Annual mean temperature / Srednja letna temperatura	11.9 °C	8.1 °C

Figure 1. Climatic diagrams with monthly average temperatures (lines) and mean monthly sum of precipitation (blue bars), representative for the location of the chronologies Klanec pri Kozini (KLA) and Ljubljana Rožnik (ROZ), for the period 1925–2013, summed from CRU data (CRU ID 195508 for KLA and CRU ID 196229 for ROZ) (http://www.cru.uea.ac.uk/). PCP – monthly sum of precipitation, TMN - minimum temperature, TMX – maximum temperature, TMD – mean monthly temperature.
Slika 1. Klimograma, ki v stolpcih prikazujeta mesečna povprečja padavin, s črtami pa so prikazana temperaturna povprečja, reprezentativna za lokaciji Klanec pri Kozini (KLA) in Ljubljana Rožnik (ROZ) za obdobje 1925–2013, na osnovi CRU podatkov (CRU ID 195508 za KLA in CRU ID 196229 za ROZ) (http://www.cru.uea.ac.uk/). PCP – mesečna vsota padavin, TMN -minimalne, TMX – maksimalne in TMD – povprečne mesečne temperature.

2.4 TELECONNECTION AND HETEROCONNECTION
2.4 TELEKONEKCIJA IN HETEROKONEKCIJA

The residual chronology of oak for Klanec pri Kozini was also tested for teleconnection. For this purpose it was compared with oak chronologies from Slovenia, Austria, Hungary, Croatia and Serbia employed in the study of Čufar et al. (2014 a). As these chronologies mainly do not cover the most recent period, we also used a recently constructed but yet unpublished chronology of Rožnik, Ljubljana spanning the period 1830-2013. The comparisons were made by calculating the t-values and sign test (Gleichläufigkeit - Glk) using TSAP-Win.

In addition, the oak chronology of Klanec pri Kozini was tested for teleconnection with three unpublished oak chronologies from western Slovenia, and 13 oak chronologies from Italy (Bernabei, personal communication) and for heteroconnection (i.e. agreement with chronologies of other tree-species from Slovenia) by using more than 15 tree-ring chronologies of beech (*Fagus sylvatica* L.) (Čufar et al., 2008 c and unpublished data).

3 RESULTS
3 REZULTATI

3.1 THE CHRONOLOGY OF KLANEC PRI KOZINI KLA
3.1 PREDSTAVITEV KRONOLOGIJE KLANEC PRI KOZINI KLA

The constructed oak chronology of Klanec pri Kozini (KLA) is based on tree-ring data from nine trees (18 radii). The average tree-ring width is 1.87 mm (minimum 0.99, maximum 2.93). The tree-ring data cover the period 1922-2017, whereas the optimal replication with the expressed population signal (EPS≥ 0.848) is achieved for the period 1925-2017 (length 93 years) (Figure 2, Table 2).

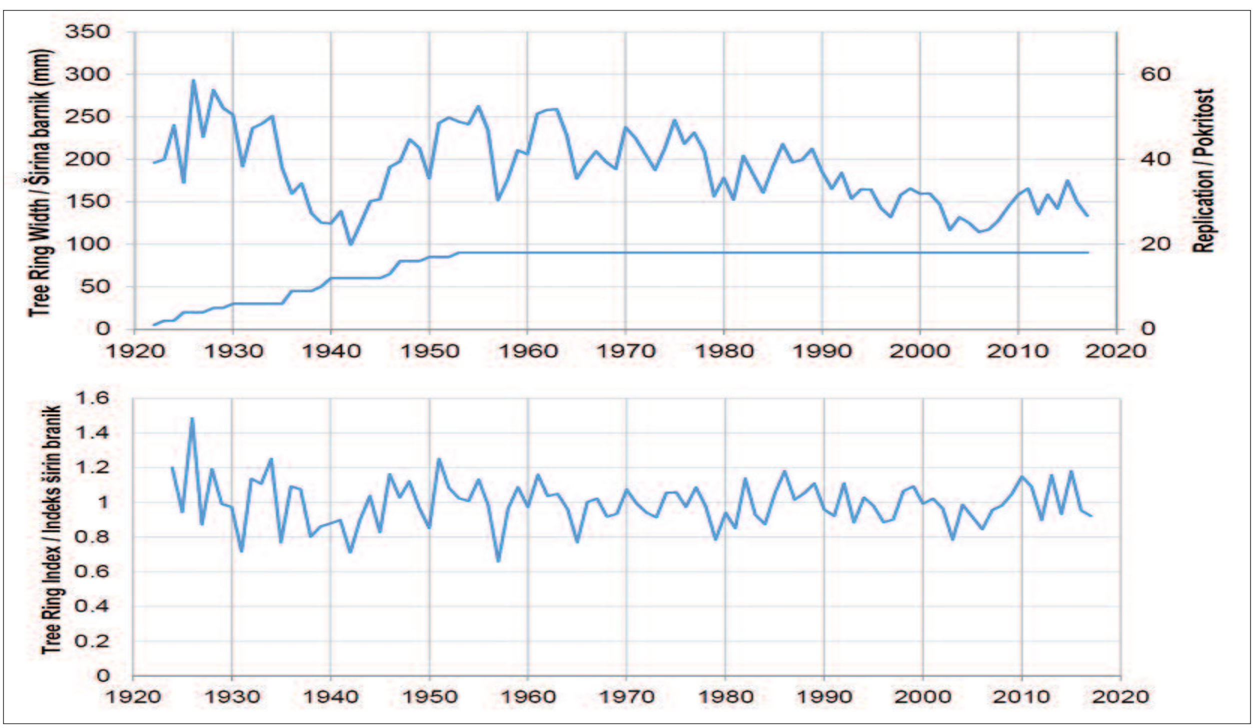


Figure 2. Oak tree-ring chronology of Klanec pri Kozini (KLA) vs. time in years: (1) tree-ring width raw-data chronology and replication (number of tree-ring series) (upper graph) and (2) tree-ring indices of detrended residual chronology. The chronology spans the period 1922–2017 and the optimally replicated part with expressed population signal strength (EPS) ≥0.848 spans 1925–2017.

Slika 2. Kronologija širin branik hrasta s Klanca pri Kozini (KLA) v odvisnosti od časa (koledarskih let): (1) kronologija širin branik in pokritost - število vključenih zaporedij širin branik (zgoraj) in (2) indeksi širin branik residualne kronologije. Razpon kronologije je 1922–2017, optimalna pokritost, ko je izražen populacijski signal (EPS) ≥0.848, ustreza obdobju 1925–2017.

Table 2. Descriptive statistics of residual oak chronology for Klanec pri Kozini and Rožnik, Ljubljana used for comparison. Rbar – running correlation between tree-ring series of the chronology, EPS – expressed population signal, SNR-signal to noise ratio, MS – mean sensitivity.
Preglednica 2. Opisna statistika residualne hrastove kronologije za lokacijo Klanec pri Kozini in za primerjavo Rožnik, Ljubljana. Rbar-drseča korelacija med zaporedji širin branik kronologije, EPS-izraženi populacijski signal, SNR- razmerje signala in šuma, MS - srednja občutljivost.

Location / Lokacija	Chronology / Kronologija	Start / Začetek	End / Konec	Period 1925–2013 / Obdobje 1925–2013			
				Rbar	EPS	SNR	MS
Klanec pri Kozini	KLA	1922	2017	0.269	0.848	5.588	0.2344040
Rožnik, Ljubljana	ROZ	1830	2013	0.192	0.900	9.039	0.2215007

3.2 TREE-RING VARIATION AND CLIMATE
3.2 VARIIRANJE ŠIRIN BRANIK IN KLIMA

Correlation coefficients (CFCs) calculated between the residual version of the KLA chronology and monthly mean (TMD), minimum (TMN), and maximum (TMX) temperature showed that June temperature is the main climatic factor governing the tree-ring variation of oak on Klanec pri Kozini. The highest CFC values were obtained with TMX (CFC= -0.412), which indicates that going above the average maximal temperature in June negatively affects tree-ring width (Figure 3). In contrast, precipitation in March (CFC= 0.321) positively affects the growth of oak on the same site. Furthermore, statistically significant CFC values also show that the temperatures in April and September (TMN, TMX, TMD) as well in January (TMN) have positive effect on tree-ring width. CFC values for precipitation in June were positive and just below the significance values.

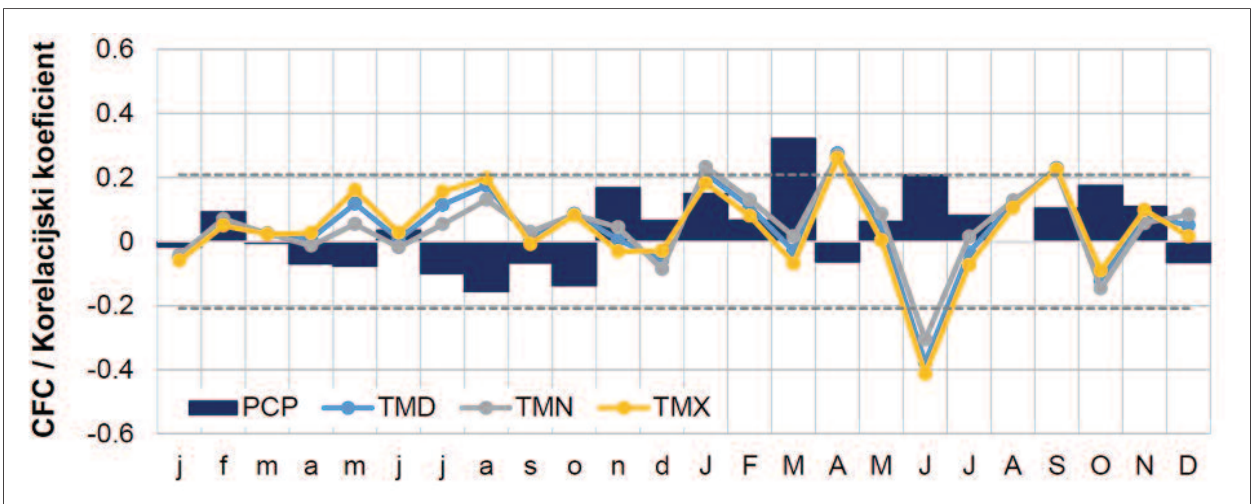


Figure 3. Correlation coefficients (CFC) calculated between the residual version of oak chronology from Klanec pri Kozini (KLA) and monthly mean (TMD), minimum (TMN), and maximum (TMX) temperature (lines) and precipitation (bars) from previous January (j) to current December (D) for the period 1925–2013. CFC values are statistically significant (p<0.05) if >0.2084 or <-0.2084 (dashed horizontal lines).
Slika 3. Korelacijski koeficienti, med residualno verzijo hrastove kronologije s Klanca pri Kozini (KLA) in mesečnimi srednjimi (TMD), minimalnimi (TMN) in maksimalnimi (TMX) temperaturami (črte) ter padavinami (stolpci) od preteklega januarja (j) do decembra (D) tekočega leta za obdobje 1925–2013. Vrednosti koeficientov so statistično značilne (p<0,05), če so manjše od -0,2084, ali večje od 0,2084 (črtkane vodoravne daljice).

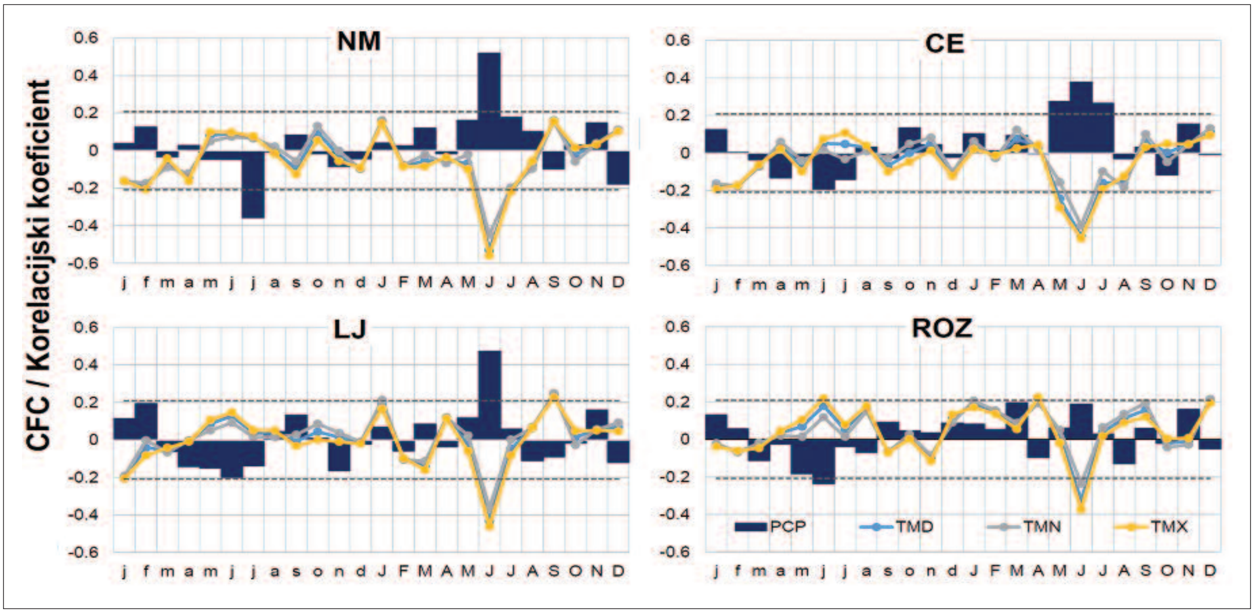


Figure 4. Correlation coefficients (CFC) calculated between tree-ring indices of the residual oak chronologies from the sites NM (Novo mesto), CE (Celje), LJ (Ljubljana) and ROZ (Rožnik, Ljubljana) and monthly mean (TMD), minimum (TMN), and maximum (TMX) temperature (lines) as well as precipitation (PCP, bars) from the previous January (j) to current December (D) for the period 1925-2013. CFC values are statistically significant (p<0.05) if >0.2084 or <-0.2084 (dashed horizontal lines).

Slika 4. Korelacijski koeficienti (CFC), med indeksi širin branik residualnih kronologij hrasta z rastišč NM (Novo mesto), CE (Celje), LJ (Ljubljana) in ROZ (Rožnik, Ljubljana) ter mesečnimi srednjimi (TMD), minimalnimi (TMN) in maksimalnimi (TMX) temperaturami (črte) in mesečnimi padavinami (PCP, stolpci) od preteklega januarja (j) do decembra (D) tekočega leta za obdobje 1925–2013. CFC vrednosti so statistično značilne (p<0,05), če so manjše od -0,2084, ali večje od 0,2084 (vodoravne črtkane daljice).

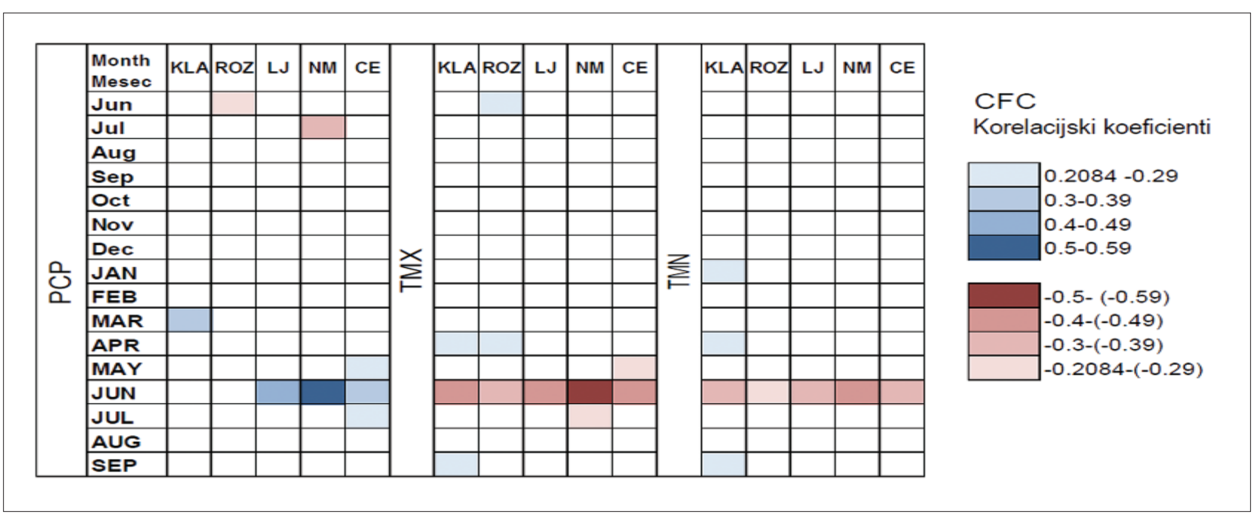


Figure 5. Overview of statistically significant correlation function coefficients (CFC) between residual chronologies and precipitation (PCP), maximum (TMX) and mean (TMD) temperatures (compare Figures 3 and 4).

Slika 5. Primerjalni pregled statistično značilnih korelacijskih koeficientov med residualnimi kronologijami in padavinami (PCP), maksimalnimi (TMX) ter minimalnimi (TMN) temperaturami (prim. sliki 3 in 4).

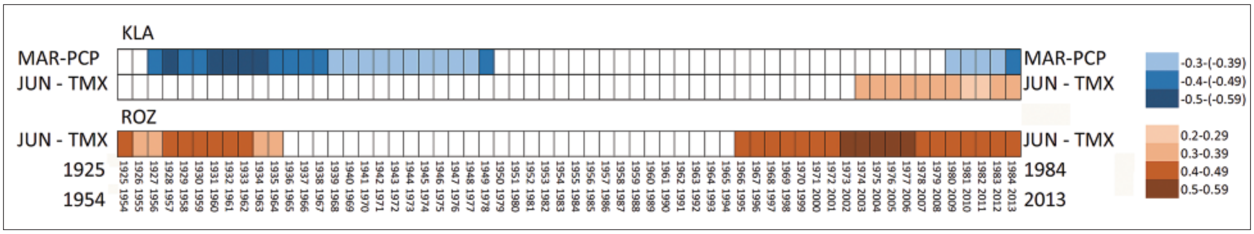


Figure 6. Moving correlation values for current March precipitation (MAR-PCP) and June maximum temperatures (JUN-TMX) for the KLA chronology and JUN-TMX for ROZ computed with DendroCLIM2002 using an interval length of 30 years; the first interval goes from 1925 to 1954 and last one from 1984 to 2013. Blue colour indicates positive and brown negative values. Darker colours indicate higher values. Only statistically significant (p<0.05) correlation values lower than -0.3610 or greater than 0.3610 are shown.
Slika 6. Vrednosti drsečih korelacij za padavine v tekočem marcu (MAR-PCP) in maksimalne temperature v juniju (JUN-TMX) za kronologijo KLA ter JUN-TMX za ROZ, izračunanih s programom DendroCLIM2002, za intervale dolge 30 let; prvi interval zajema obdobje od 1925 do 1954, zadnji pa 1984 do 2013. Modra barva nakazuje pozitivno korelacijo, rjava pa negativno. Temnejša barva nakazuje višjo korelacijo. Prikazane so le statistično značilne (p<0,05) korelacije manjše od -0,3610 ali večje od 0,3610.

CFCs were calculated according to the same methodology used for the residual versions of oak chronology ROZ (Tables 1, 2) and for the chronologies from three denoted as sites NM (Novo mesto), CE (Celje) and LJ (Ljubljana) in Slovenia, i.e. sites SI1, SI2 and SI3 in the study of Čufar et al. (2014 a) (Figures 2, 3, 4, 5, Tables 2, 3). The location of ROZ partly overlaps with that of LJ, which included trees from a slightly larger area. The data show that tree-ring variation at NM, CE, and LJ is positively affected by June precipitation and negatively by June temperature. This signal is the most pronounced in the case of NM. In contrast, CFCs in case of ROZ only show the negative effect of June temperature and, as in KLA, no statistically significant effect of June precipitation. The correlation was always the highest when using the maximum temperature (TMX).

Moving correlation (Figure 6) for the most relevant climatic parameters, i.e. current June maximum temperatures (JUN-TMX) and March precipitation (MAR-PCP) for the KLA chronology showed that the negative effect of JUN-TMX is statistically significant for the period 1974-2003 and that there is a positive effect of March from 1980-2009 onwards. March precipitation was also significant in the juvenile period of tree growth till 1949-1978. However, ROZ showed that the negative effect of JUN-TMX was statistically significant for the period 1925-1954 until 1935-1964 and again from 1966-1995 till 1966-2013. The correlation values are generally higher in the last few decades.

3.3 COMPARISON WITH OTHER CHRONOLOGIES - TELECONNECTION

3.3 PRIMERJAVA Z DRUGIMI KRONOLOGIJAMI - TELEKONEKCIJA

Similarities (and differences) among the climatic signals in KLA and the chronologies from other sites in Slovenia are reflected in the visual agreement of their tree-ring patterns (Figure 8) and in the dendrochronological statistical parameters of their agreement (t-values, t_{BP} or t_H ≥4, Glk≥65%) (Table 3, Figure 7).

Comparison of KLA with other oak chronologies from Slovenia using standard dendrochronological statistical parameters confirmed that KLA agreed best with ROZ (t_{BP} = 6.7). The highest t-value can be ascribed to the longest overlap (89 years) and the strong negative effect to the June temperature on both chronologies (Table 3, Figure 8).

KLA also agreed well with the chronology NM (t_{BP} = 6.3). Slightly lower values were found for KLA and LJ (t_{BP} = 4.2). The lowest similarity is found between KLA and CE, with a t-value just below the significance level (t_{BP} = 3.8).

Furthermore, cross-dating of KLA with 38 chronologies from Austria, Croatia, Hungary and Serbia (Čufar et al., 2014 a) showed significant agreement with the chronology HR1 from the surroundings of Zagreb, Croatia (t_{BP} = 4.3) and with the chronology A4 of Fehring, Austria (t_{BP} =4.1) (Table 3, Figure 8). Other chronologies did not show statistically significant agreement with KLA (Figure 8).

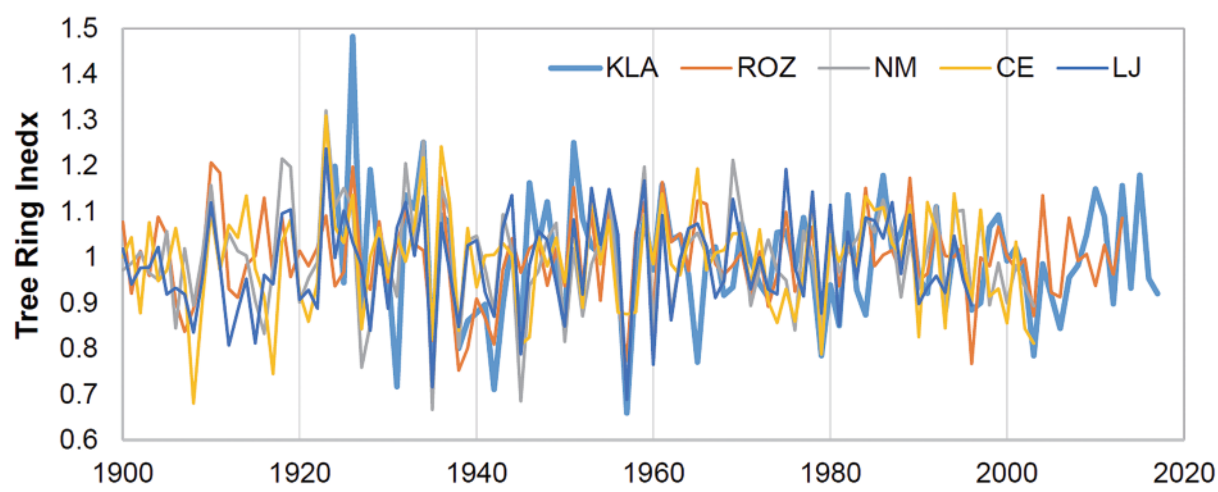


Figure 7. Residual chronologies of oak from KLA compared with those from other sites (ROZ, NM, CE and LJ) in Slovenia (compare with Table 3).

Slika 7. Hrastove kronologije residual za KLA v primerjavi s slovenskimi kronologijami hrasta ROZ, NM, CE in LJ (prim. preglednico 3).

Table 3. Comparison of Klanec pri Kozini oak chronology (KLA) with local oak chronologies from Slovenia and surrounding countries (compare with Fig. 9). All chronologies used for comparison, except ROZ, are presented in Čufar et al. (2014 a). t_{BP} - t-value after Baillie and Pilcher, or t_H - t-value after Hollstein, Glk – sign test – Gleichläufigkeit. The agreement is considered statistically significant if t-value (t_{BP} or t_H) ≥4 and Glk ≥65%.

Preglednica 3. Primerjava hrastove kronologije s Klanca pri Kozini (KLA) z lokalnimi hrastovimi kronologijami iz Slovenije in bližnjih držav (prim. sliko 9). Vse kronologije razen ROZ, so bile predstavljene v Čufar et al. (2014 a). t_{BP} - t-vrednost Baillie in Pilcher, t_H - t-vrednost Hollstein, Glk - koeficient ujemanja - Gleichläufigkeit. Ujemanje je statistično značilno, če je t – vrednost (t_{BP} ali t_H) ≥ 4 in Glk ≥ 65 %.

Code / Oznaka	End Date / Zadnje leto	Overlap / Prekrivanje [years / leta]	t_{BP}	t_H	Glk [%]	Location / Lokacija	Country / Država	Longitude / Dolžina	Latitude / Širina	Altitude / Nadm. višina [m]	Distance / Razdalja [km]
KLA	**2017**					**Klanec pri Kozini**	**Slovenia**	**13.92°**	**45.59°**	**450**	**0**
ROZ	2013	89	6.7	6.2	69***	Ljubljana, Rožnik	Slovenia	14.47°	46.05°	300	65
NM (SI1)	2003	79	6.3	7.6	68***	Novo mesto	Slovenia	15.18°	45.80°	220	100
HR1	2009	85	4.3	3.1	61*	Zagreb	Croatia	16.03°	45.82°	140	160
LJ (S3)	1996	72	4.2	4.8	67**	Ljubljana	Slovenia	14.48°	46.07°	300	65
A04	2007	83	4.1	4.1	66**	Fehring	Austria	16.02°	46.93°	270	220
CE (S2)	2003	79	3.8	4.4	66**	Celje-Kozjansko	Slovenia	15.25°	46.25°	240	130

However, no statistically significant matches were found between KLA and three unpublished chronologies of western Slovenia (Lipica, Panovec, and Posočje – Plave), more than 15 tree-ring chronologies of beech from Slovenia (*Fagus sylvatica* L.) (Čufar et al., 2008 d and unpublished data) or with 10 oak chronologies from remote sites in NW Italy (Bernabei, personal communication). Among the reasons for this are short overlaps, as many chronologies have end dates in the 1990s, or great distances between the geographical areas of the chronologies.

4 DISCUSSION

4 DISKUSIJA

The tree-ring chronology of sessile oak for Klanec pri Kozini (KLA) is 93 years long and spans the period 1925-2017. It is shorter and has a more recent end date than the other available oak chronologies in Slovenia used for comparison. Therefore, its overlap with other chronologies is short and consequently the t-values of comparison are lower (Table 3). On the other side, KLA covers the most recent two decades which are characterized by a pronounced rise in temperature (De Luis et al., 2014; Cegnar, 2017), therefore it is useful to study the recent effects of climatic change.

Tree-ring width at KLA is negatively affected by high temperature in June (especially maximum tem-

Figure 8. Teleconnection of oak chronology KLA (Klanec pri Kozini) with local oak chronologies from Slovenia and surrounding countries. The chronologies showing t_{BP} ≥4 are indicated with progressively larger red points and labels, small black points represent chronologies with t_{BP} <4; for details of teleconnection see Table 3, for data on chronologies used for comparison see Čufar et al. (2014 a).

Slika 8. Telekonekcija hrastove kronologije KLA (Klanec pri Kozini) z lokalnimi hrastovimi kronologijami iz Slovenije in bližnjih držav. Kronologije s t_{BP} ≥4 so prikazane z različno velikimi rdečimi pikami in oznakami, medtem ko so kronologije s t_{BP} <4 označene z majhnimi črnimi pikami. Osnovni podatki so na voljo v preglednici 3, informacije o primerjalnih kronologijah pa tudi v Čufar et al. (2014 a).

perature), and the moving average correlation values (Figure 6) show that the negative effect became statistically significant in the last eleven 30-year intervals, i.e. from 1975-2004 until 1984-2013. This indicates that the maximum temperatures are becoming increasingly limiting for the growth of oak. In the last two decades over 70% of the years had June temperatures higher than the long-term average of the 1925-2013 period (Figure 9). The increasing significance of the negative effect of June temperature in the last two decades can possibly be ascribed to rising temperature due to climatic change. It should be also noted that the temperature at KLA is systematically higher than that at ROZ, Ljubljana (June TMX at KLA=24.1°C and at ROZ=20.4°C) (Figure 1, 9).

In addition, tree-ring width at KLA is positively affected by March precipitation. This points to the great importance of early spring moisture for the onset of wood production by the cambium, which in oak in central Slovenia may already start in March (Gričar, 2008; 2010). March precipitation could thus cause the earlier onset of cambial production and therefore a longer growth period and a wider tree-ring.

Tree-ring width at KLA is also positively affected by temperatures in April (TMX and TMN) and January (TMN). Higher temperatures at the beginning of the year, especially in April, are of great importance for early phenology, like the onset of cambial production and leaf unfolding (e.g., Čufar et al., 2008 d; Gričar, 2008, 2010; Puchałka et al., 2017).

KLA compared with other chronologies from Slovenia showed the highest similarity with ROZ chronology. KLA and ROZ have the longest overlap (89 years) due to similar end dates (2017 and 2013) and the highest statistical agreement (t_{BP}=6.7, Glk=69%). Both chronologies showed a pronounced negative response to June temperature, and in contrast to other chronologies in Slovenia (NM, CE and LJ) used in this study, no significant positive response to June precipitation. Furthermore, KLA and ROZ are based on samples of *Q. petraea*, whereas the other chronologies are based on *Q. petraea* and *Q. robur*. This could be another reason for the high similarity between KLA and ROZ.

KLA also agreed well with the local chronology HR1 from the surroundings of Zagreb, Croatia, and with the chronology A04 from a 220 km distant site Fehring in Austria. However, the data on the climatic signal of these two chronologies (HR1 positive response to May and June precipitation, negative response to June temperature, A04 strong positive response to May precipitation (Čufar et al., 2014 a)) do not seem to explain the similarity over a greater distance.

All oak chronologies which agree with KLA are from the areas 65 – 220 km north east from KLA. However, the question as to the possible agreement of KLA with Italian oak chronologies remains open due to the lack of an adequate chronology network in Italy (Bernabei, personal communication).

Although KLA originates from the location on the Karst edge, less than 10 km from the Adriatic coast, its tree-ring variation agrees unexpectedly well with oak in central Slovenia. The high similarity

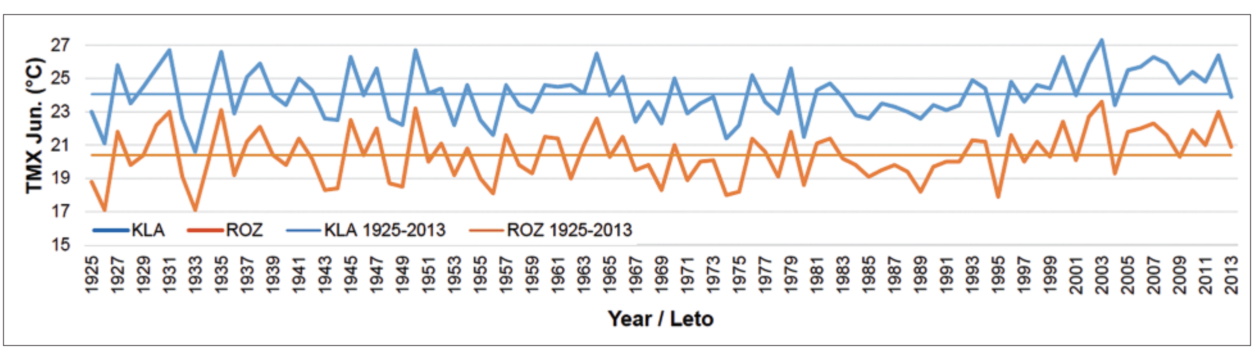


Figure 9. Maximum temperatures (TMX) in June compared with average June TMX in the reference period 1925-2013 (lines) based on CRU data representative for the sites Klanec pri Kozini (KLA) and Rožnik, Ljubljana (ROZ) (for CRU see Table1).
Slika 9. Maksimalne temperature (TMX) za junij v obdobju 1925–2013 v primerjavi s povprečjem za celotno referenčno obdobje (premici) na osnovi CRU podatkov, reprezentativnih za lokaciji Klanec pri Kozini (KLA) in Rožnik, Ljubljana (ROZ) (za CRU glejte Preglednico 1).

between KLA and ROZ is probably also due to the relatively similar weather conditions, as shown by the climograms representative for KLA and ROZ (Figure 1). Although the KLA and ROZ sites generally belong to different climatic zones, the differences in climatic regimes (especially the higher temperature at KLA) do not seem to have any significant effect.

Klanec pri Kozini is located in the sub-Mediterranean climatic zone of the hinterlands, where precipitation is greater than 1200 mm, whereas Rožnik (Ljubljana) and Novo mesto (NM) are located in the temperate continental climatic zone, which still has some sub-Mediterranean influence on the precipitation regime. The transition area between the sub-Mediterranean and temperate continental climate extends widely over west, central and south Slovenia (Ogrin, 1996). Metzger et al. (2005) who divided the whole of Europe into two large climatic regions, set the border between warm South Europe and cold North Europe somewhere very close to the KLA site. This supports the assumption that the impacts of both the Mediterranean and continental climates are strong there.

Larger differences in oak chronologies could probably be found with sites under the Karst edge, i.e. close to sea level, and this remains an open question for future research. Only 6 km away from KLA towards Koper or Trieste the elevation drops from ca. 450 m a.s.l. to sea level, where the influence of the Mediterranean would be much stronger. The climate there is considered to be sub-Mediterranean – littoral, with a lower annual amount of precipitation (between 1000 to 1200 mm) and higher temperatures than on the Karst edge and in central Slovenia (Ogrin, 1996). The difference in climatic affects could be also seen by examining typical Mediterranean tree species like olive (*Olea europaea*) and Aleppo pine (*Pinus halepensis*) which grow below the Karst edge where the elevation approaches sea level, although they do not survive on sites like KLA (450 m a.s.l.) with below zero monthly minimum temperatures in January and February.

5 CONCLUSIONS
5 ZAKLJUČKI

The tree-ring chronology of *Quercus petraea* for Klanec pri Kozini (KLA) constructed in the current work is 93 years long and spans the period 1925-2017, and this shows that tree-ring width at KLA is negatively affected by high temperature in June (especially the maximum temperature) and positively by precipitation in March. The negative effect of June is especially pronounced in recent decades.

Comparison of KLA with other chronologies from Slovenia showed the highest similarity with an oak chronology of Rožnik, Ljubljana (ROZ), with a similar negative response to June temperature.

KLA also significantly agrees with two Slovenian chronologies from the area of Novo mesto (NM) and Ljubljana (LJ), which are characterized by a negative response to June temperature and a positive one to June precipitation, as well as with one from Croatia and one from Austria. Agreement of KLA with oak in Italy could not be confirmed due to lack of adequate chronologies for comparison.

Although KLA is at a location on the Karst edge, less than 10 km from the Adriatic coast, its similarity with the chronology ROZ of central Slovenia can be explained by climatic effects, although the KLA site is slightly warmer and drier than ROZ.

The increasing significance of the negative effect of June temperatures, especially in recent decades can be ascribed to rising temperatures due to climatic change.

The present study shows that further research in the transitional area between the Mediterranean climate and the temperate Continental one could be of great importance to better understand the response of oak to the environment, to improve the network of oak chronologies in the region and to possibly fill the current spatial and chronological gaps in the region south of the Alps.

6 SUMMARY
6 POVZETEK

Hrast je pomemben les v evropski dendrokronologiji. Ker najpogostejših hrastov gradna (*Quercus petraea* (Matt.) Liebl.) in doba (*Quercus robur* L.) ne moremo zanesljivo razlikovati po lesu, ju v dendrokronologiji povezani s kulturno dediščino pogosto obravnavamo skupaj kot evropski hrast (*Quercus* sp.) (npr. Haneca et al., 2009). V Evropi so sestavili številne hrastove kronologije, med njimi več regionalnih, ki so dolge več tisoč let (Baillie, 1995; Haneca et al., 2009; Prokop et al., 2017). Najdaljša je južno-nemška Hohenheimska hrastova kronologija, ki sega do 8480 pr. n. št. (Friedrich et al., 2004). Poleg sestavljenih regionalnih kronologij so za razumevanje ekologije hrasta pomembne tudi lokalne kronologije.

V Sloveniji prvi poskusi sestave hrastovih kronologij niso bili spodbudni, ker na rast hrasta pogosto vplivajo lokalni dejavniki kot je npr. nivo podtalnice (Levanič, 1993; Čufar & Levanič, 1999; Čater & Levanič, 2004, 2015; Gričar et al., 2013; Jevšenak & Levanič, 2015) in ne nad-regionalni podnebni dejavniki, ki omogočajo sestavljanje kronologij. Prva daljša sestavljena kronologija hrasta v Sloveniji je bila 548-letna kronologija za obdobje 1456–2003, ki temelji na lesu dreves in zgodovinskih konstrukcij iz JV Slovenije (Čufar et al., 2008 a, b). Izkazalo se je, da ima dobro telekonekcijo z različnimi kronologijami iz do 700 km oddaljenih krajev v Avstriji, na Madžarskem, v Srbiji, na Češkem in v Južni Nemčiji. Na variiranje širin branik te kronologije pozitivno vplivajo junijske padavine, negativno pa junijske temperature. Zato so kronologijo uporabili za rekonstrukcijo junijskih vremenskih razmer v zadnjih petih stoletjih (Čufar et al., 2008b) skupaj z drugimi podatki pa tudi za rekonstrukcijo sušnih in deževnih obdobij v Evropi v zadnjih 2000 letih (Cook et al., 2015). Znanje o telekonekciji hrasta iz Slovenije je tudi pripomoglo k absolutnemu datiranju kronologije koliščarskih naselij iz Ljubljanskega barja (razpon 3771 in 3330 pr.n.št.), s pomočjo dolge nemško švicarske hrastove kronologije (Čufar et al., 2015).

Ker sestavljene kronologije seštevajo učinke različnih dejavnikov na rast dreves iz širših območij, potrebujemo tudi lokalne raziskave oz. mreže podatkov iz znanih okolij, kot npr. v študiji, kjer so uporabili 41 lokalnih kronologij iz Avstrije, Hrvaške, Madžarske, Srbije in Slovenije (Čufar et al., 2014 a, b) in pokazali, da je vsem kronologijam skupen pozitiven odziv na spomladanske in poletne padavine (marec in junij) in negativen na spomladanske in poletne temperature (april in junij) ter razložili razlike med rastišči (Čufar et al., 2014 a, b).

Dosedanje raziskave hrasta v Sloveniji s ciljem izdelave daljših kronologij za raziskave lesa iz preteklih obdobij so bile osredotočene predvsem na osrednjo in Jugovzhodno Slovenijo z zmerno celinskim podnebjem in na telekonekcijo z območji severno, vzhodno in jugovzhodno od Slovenije, ki so vse bolje pokrita z dendrokronološkimi podatki. Po drugi strani še vedno premalo poznamo dendrokronologijo hrasta iz zahodne in jugozahodne Slovenije ob prehodu iz zmernega kontinentalnega v submediteransko podnebje in na možnost telekonekcije z rastišči v Italiji. Sodelovanje med slovenskimi in italijanskimi laboratoriji je na primer že pripomoglo k razjasnitvi odnosov med kronologijami macesna (*Larix decidua*) (Levanič et al., 2001), bukve (*Fagus sylvatica*) (Di Filippo et al., 2007) in smreke (*Picea abies*) (Bernabei et al., 2017) iz zadnjega tisočletja, pa tudi za hrast iz prazgodovinskih kolišč iz 4. tisočletja pr. n. št. (Čufar & Martinelli, 2004), primanjkuje pa podatkov o možnosti telekonekcije modernega hrasta iz Slovenije in Italije, kjer še ni ustrezne mreže hrastovih kronologij (Bernabei, osebna komunikacija).

Namen te študije je zato (1) sestaviti lokalno kronologijo hrasta gradna (*Quercus petraea*) za Klanec pri Kozini, na kraškem robu v JZ Sloveniji blizu meje z Italijo, (2) raziskati njegovo telekonekcijo z razpoložljivimi kronologijami hrasta na širšem območju in (3) prikazati, kako podnebne spremembe vplivajo na variacije branik pri hrastu na meji med submediteranskim in zmerno celinskim območjem.

Na rastišču Klanec pri Kozini (45,59° S, 13,92° V, 450 m nadmorske višine), ki se nahaja na kraškem robu približno 15 km od Kopra, smo pridobili kolute 9 dominantnih ali kodominantnih dreves hrasta gradna *Quercus petraea*, posekanih pozimi 2017. Kolute smo gladko zbrusili in vzdolž 2 radijev izmerili širine branik. Datirana zaporedja širin branik smo s pomočjo programa ARSTAN (Holmes, 1994) združili v različne verzije kronologije ARSTAN, v nadaljevanju pa smo residualno verzijo (RES) uporabili za dendroklimatološke analize. Klimatske podatke smo pridobili iz javno dostopne baze CRU (http://www.cru.uea.ac.uk /) (Mitchell et al., 2004) (Preglednica 1). Za analize smo uporabili program DendroClim2002 (Biondi & Waikul, 2004). Za raziskavo telekonekcije smo kronologijo hrasta za Klanec pri Kozini (KLA) primerjali s hrastovimi kronologijami iz študije (Čufar et al., 2014 a, b) in novejšo še neobjavljeno kronologijo Rožnika, Ljubljana (ROZ) za obdobje 1830–2013. Uporabili smo tudi nekaj še neobjavljenih kronologij hrasta, kronologije bukve (Čufar et al., 2008c) in nekaj kronologij hrasta in bukve iz Italije (Bernabei, osebna komunikacija).

Kronologija za Klanec pri Kozini (KLA) z ustreznim populacijskim signalom (EPS≥ 0.848) je dolga 93 let in pokriva obdobje 1925–2017 (slika 2). Dendroklimatološka analiza in izračun korelacijskih koeficientov (CFC), med RES kronologijo KLA in mesečno povprečno (TMD), minimalno (TMN) in maksimalno (TMX) temperaturo, sta pokazala, da na variabilnost širin branik najbolj vpliva junijska temperatura (slika 3). Pomemben je tudi pozitiven vpliv padavin v marcu ter temperatur v aprilu in septembru (TMN, TMX, TMD), ter v januarju (TMN).

Korelacije so bile po isti metodologiji izračunane tudi za primerjalne hrastove kronologije ROZ (preglednici 1, 2) ter NM (Novo mesto), CE (Celje) in LJ (Ljubljana) (označene kot SI1, SI2 in SI3 v raziskavi Čufar et al., 2014a, b) (slike 4, 5, 6 in Preglednica 3). Lokaciji kronologij ROZ in LJ se delno prekrivata, vendar LJ zajema širše območje, dve vrsti hrasta (dob in graden), ter se konča že pred letom 2000. Podatki kažejo, da na variabilnost širin branik pri NM, CE in LJ pozitivno vplivajo junijske padavine in negativno junijska temperatura. Ta signal je najbolj izrazit pri NM z območja Novega mesta. Nasprotno, korelacije v primeru ROZ tako kot pri KLA kažejo le negativni učinek junijskih temperatur, vpliv junijskih padavin pa ni statistično značilen. Korelacijske vrednosti so bile vedno najvišje pri uporabi maksimalne temperature (TMX).

Analiza drsečih sredin je pokazala, da pomen negativnega učinka junijskih temperatur v zadnjem obdobju narašča tako na KLA kot na ROZ, kar je mogoče pripisati splošnemu naraščanju temperatur zaradi globalnega segrevanja.

Tudi dendrokronološka statistika potrjuje najvišjo podobnost KLA s kronologijo ROZ (t_{BP}=6.7, Glk=69%). KLA se dobro ujema tudi s kronologijama s področja Novega mesta (NM) in Ljubljane (LJ) v Sloveniji, ter s po eno lokalno kronologijo iz Hrvaške in iz Avstrije (preglednica 3, slika 8). Tako smo potrdili telekonekcijo KLA s kronologijami na rastiščih oddaljenih 65-220 km severno-vzhodno od KLA. Ujemanja KLA s hrastom v Italiji pa ni bilo mogoče potrditi zaradi pomanjkanja ustreznih kronologij za primerjavo (Bernabei, osebna komunikacija).

Ker se rastišče KLA nahaja na kraškem robu (450 m n.m.v.), manj kot 10 km od jadranske obale, je velika podobnost s kronologijo ROZ iz centralne Slovenije nekoliko presenetljiva, najverjetneje zaradi podobnosti klimatskih podatkov (slika 1) reprezentativnih za lokaciji KLA in ROZ. Lokacija KLA je sistematično toplejša (vključno z zimskimi meseci kjer so samo minimalne januarske in februarske temperature rahlo pod lediščem (slika 1) in ima nekoliko nižjo količino padavin kot osrednja Slovenija.

Pričujoča študija kaže, da so raziskave na prehodnem območju med glavnima klimatskima območjema, sredozemskim in kontinentalnim, s predstavljeno kronologijo KLA pomembne za boljše razumevanje rasti in odzivov hrasta na okoljske dejavnike, za izboljšanje mreže hrastovih kronologij v regiji in za bodoče zapolnjevanje prostorskih in časovnih vrzeli v kronologijah v regiji južno od Alp.

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