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ORIGINAL ARTICLE

The Suceava oak chronology: A new 804 years long tree-ring chronology bridging the gap between central and south Europe

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ABSTRACT

Although the importance of centuries-long tree ring width oak chronologies in dating wood, eastern European regions are still lacking a reference chronology. To fill this geographical gap, we combined living and historical chronologies from the Moldova region, including part of Romania and the Republic of Moldova. Here we present the "Suceava oak chronology" as the first 804 years long chronology continuously covering the 1216–2019 period. Our analyses further revealed the strong teleconnection of the Suceava oak chronology with south European ones. The link between Romania and northern Turkey chronologies is of particular importance in the context of the high abundance of undated subfossil and archaeological/historical oak wood in eastern Europe and intense wood trades with central Europe in XV-XVII centuries. The availability of the Suceava oak chronology will provide a good base for precise dating and climatic reconstructions.

1. Introduction

From the second half of the 20th century, European dendrochronology has been dynamically developing toward building centuries long tree-ring width chronologies. The first millennia-long tree-ring chronologies have been constructed for oak (Baillie, 1977; Eckstein et al., 1972; Huber and Giertz-Siebenlist, 1969). Long oak chronologies combining living trees with historical and archaeological wood are very well represented for western and central Europe (Čukar et al., 2008; Friedrich et al., 2004; Prokop et al., 2017). Whereas towards southern Europe, limited wood availability hampered the development of long chronologies. But strenuous efforts by Kuniholm in the Aegean (Kuniholm, 1994) and Italian dendrochronologists (Martinelli, 2020) finally brought significant progress also in this part of Europe.

A comparison of oak chronologies from central and southern Europe clearly showed two separated tree-ring patterns, with the Alps marking a distinct geographical separation (Wazny, 2009). Even if some similarities among chronologies still exists, the reliability of dendrochronological wood dating decreases as distance increases from central Europe, especially towards the east (Kolář et al., 2012).

In 2010–2011 systematic efforts were undertaken to bridge both central and southern major European dendrochronological networks. A subset of oak tree-ring chronologies developed for the vast area including Poland and Turkey delineated geographic areas with common patterns of year-to-year tree-ring variability over the past 200 years (Ważny et al., 2014). Moreover, Romania and the Carpathian Arch were identified as key regions to connect tree-ring chronologies from both parts of Europe. If for the Carpathians region several oak chronologies were developed for the last three centuries (Grynaeus, 2003; Kern et al., 2009; Nechita et al., 2018), for the southern and eastern areas outside the Carpathians only limited dendroclimatological studies are currently available (Nechita et al., 2019, 2017; Nechita and Chiriloaei, 2018; Popa et al., 2013; Roibu et al., 2020; Sochová et al., 2020). Furthermore, the Eastern Carpathians is shown to act as a barrier of oak growth response to climate and causing distinct climate signal patterns to be recorded on the two side of the mountain chain (Nechita et al., 2017). These patterns pointed to the main geographical area to explore in the attempt to further develop east European oak tree-ring chronologies back in time.

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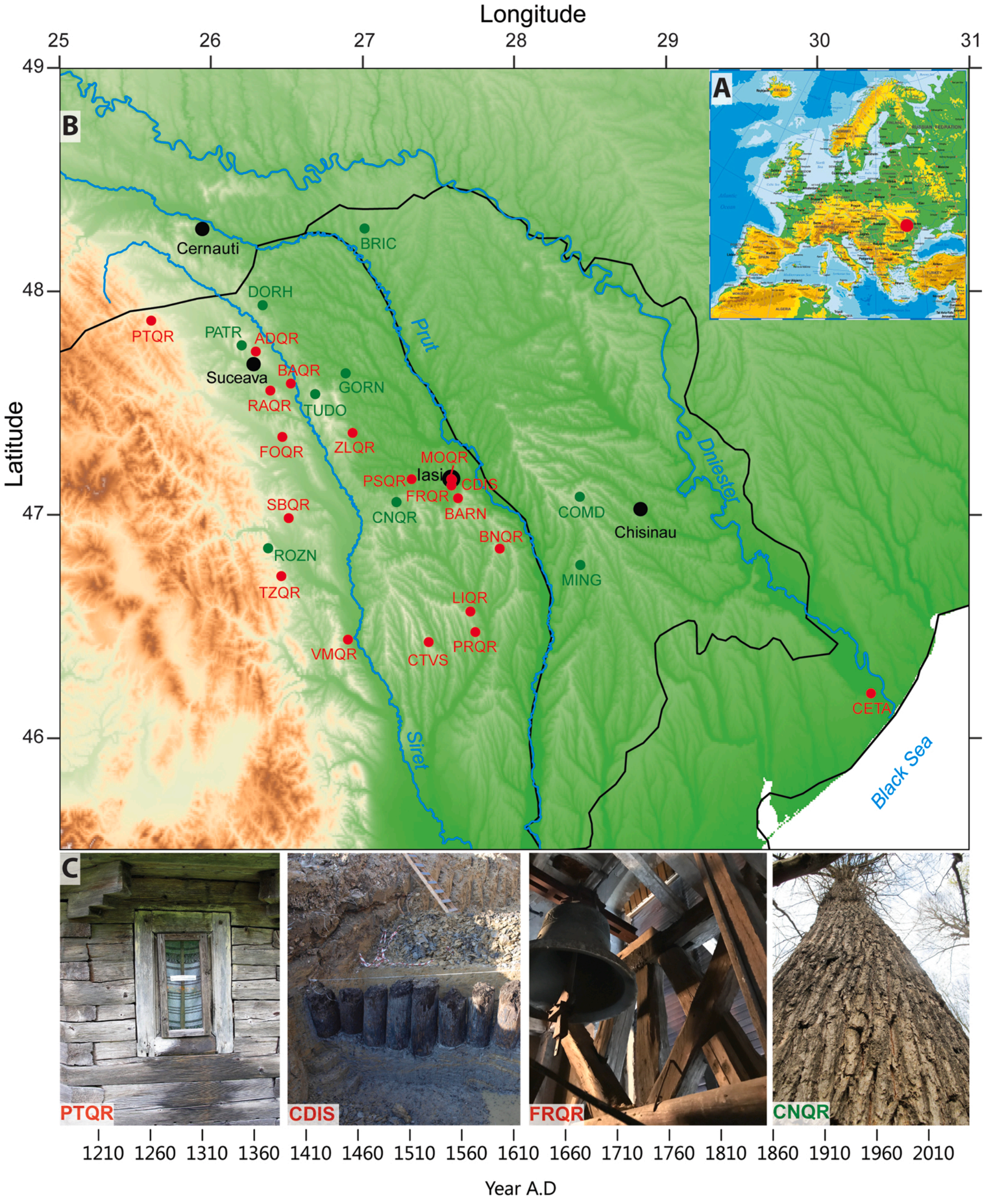

Fig. 1. Spatial and temporal site locations A- Physical map of Europe with the red dot showing the Moldova region **B –** Spatial distribution of sampling sites in Eastern Romania and Republic of Moldova (red: historical wood samples; green: living trees, black: old Moldova historical cities. **C** - Temporal distribution of historical and living wood sources (for site codes see Table 1). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The relatively high abundance of undated historical and archaeological oak wood in the Moldova region and documented intense timber trade with different European countries in the XV-XVII centuries, impose the development of a millennium-long oak chronology as a necessity for dating. Alongside historical wood, subfossil oak wood is a frequent finding, and has high potential to be absolutely dated (Becker, 1993; Kolář et al., 2012; Kolář and Rybníček, 2011; Leal et al., 2015; Pilcher et al., 1984).

In tree ring dating, the number of rings included in the sapwood is an important parameter, especially to approximate the felling date of a tree (Baillie, 1982). However, in processed wood, the sapwood is often totally or partially missing, but it can be estimated using the correlation between the sapwood rings and the hardwood rings (Jevšenak et al., 2019). Regional variability of sapwood ring number is relevant for dating purposes and for comparison with similar studies in the neighbouring regions (Jevšenak et al., 2019; Nechita et al., 2018; Wazny and Eckstein, 1991).

In this context, our research objectives are *i)* to develop a centuries-long oak reference chronology for the region between Eastern Carpathians (Romania) and Dniester river (Republic of Moldova); *ii)* to investigate the pattern of sapwood ring number specific for the tree from the Moldova region; *iii)* to explore the teleconnection of new proposed oak chronology with European ones.

2. Study location

The study sites are located in Eastern Romania and in the Republic of Moldova, between the Eastern Carpathian chain and the Dniester River (Fig. 1A). This region has an altitudinal range between 0–1000 m a.s.l. and is characterized by a monoclinic structure being sculpted in the upper structural part of the Moldova platform. The general slope aspect is east-south-east and bedrock is composed of a mixture of marls, clays, and sands. The soils are productive dominated by chernozems and phaeozems.

The vegetation type is a mixed forest of beech and oak species (on the hills upper part), and oaks with other broadleaf species (on the hills

Table 1
Site locations (listed by wood type and longitude). (Locations: RO – Romania, UA – Ukraine, MD – Rep of Moldova, GR – Greece; Sample Type: LT – Living tree, HW – Historical wood. * - Made with wood from Moldova region).

CODE	Location	Sample type	Longitude (decimal degrees)	Latitude (decimal degrees)	Altitude (m a.s.l.)	No of samples
PATR	Patrauti, RO	LT	26.20	47.76	400	28
DORH	Dorohoi, RO	LT	26.34	47.94	236	13
ROZN	Roznov, RO	LT	26.38	46.85	523	29
TUDO	Tudora, RO	LT	26.69	47.54	475	21
GORN	Gornet, RO	LT	26.89	47.63	178	13
BRIC	Briceni, MD	LT	27.01	48.28	266	30
CNQR	Cenusa, RO	LT	27.22	47.06	203	12
COMD	Codrii Natural Reserve, MD	LT	28.43	47.08	226	24
MING	Mingir, MD	LT	28.43	46.78	178	28
PTQR	Putna, RO (wooden church)	HW	25.60	47.87	560	19
ADQR	Adancata, RO (wooden church)	HW	26.29	47.73	370	11
RAQR	Meresti, RO (wooden church)	HW	26.39	47.56	366	12
TZQR	Tazlau Monastery, RO	HW	26.46	46.73	434	39
FOQR	Forasti, RO (wooden church)	HW	26.47	47.35	234	10
SBQR	Serbesti, RO (former inn)	HW	26.51	46.99	364	10
BAQR	Banesti, RO (wooden church)	HW	26.53	47.59	239	15
VMQR	Valea Mare, RO (wooden church)	HW	26.90	46.44	191	12
ZLQR	Zlodica, RO, (wooden church)	HW	26.93	47.37	246	4
PSQR	Pausesti, RO (wooden church)	HW	27.32	47.16	142	11
CTVS	Cetatuia, RO (wooden church)	HW	27.43	46.43	226	12
MOQR	Catholic Cathedral Iasi, RO	HW	27.58	47.16	45	4
FRQR	Frumoasa Monastery, RO	HW	27.58	47.13	234	30
CDIS	Iasi, RO (former royal court)	HW	27.59	47.16	43	34
BARN	Barnova Monastery, RO	HW	27.63	47.07	131	59
LIQR	Lipovat, RO (wooden church)	HW	27.71	46.57	146	23
PRQR	Parvesti Monastery, RO	HW	27.74	46.48	267	12
BNQR	Bradicesti, RO (wooden church)	HW	27.90	46.85	244	17
CETA	Akkerman Fortress, UA	HW	30.35	46.20	16	40
GRBA	Thessaloniki, GR (barrel staves) *	HW	NA	NA	NA	2

lower part). Seven spontaneous species and many subspecies and varieties of the genus Oak (Horeanu, 1996) cover 16 % of the Romanian forested area and it represent 13 % of the wood stock. Among them, *Q. robur* and *Q. petraea* timber is widely used in public and private construction, now and in the past.

East to the Carpathians, the climate is temperate continental with excessive potential. As we move forward to the Eastern European Plain, this continentalism behaviour manifests itself with cold winters, warm and dry summers. The presence of large river corridors allows colder and wetter Scandinavian-Baltic origin air masses to enter the region. The multiannual mean temperatures range between +6 to +8 °C (northern part) and + 9 to +10 °C (southern part) and the annual precipitation amount ranging from 500−800 mm in the north to 400−500 mm in the south (ANM, 2008).

3. Methodology

A total number of 554 total samples, 371 of which from historical wood (red dots, Fig. 1) and 183 from living trees (green dots, Fig. 1), were sampled to build the first reference oak chronology in the Eastern Carpathians area (Table 1). Sampling focused on the two dominating oak species in the region, namely English oak (*Quercus robur*) and sessile oak (*Q. petraea*). The wood of the two oaks cannot be differentiated based on wood anatomy (Crivellaro and Ruffinatto, 2019; Feuillat et al., 1997) and the growth sensitivity is known to be similar (Büntgen et al., 2010; Friedrichs et al., 2008; Tegel et al., 2010) justifying the fact that both might have been sampled.

One core per living tree was extracted with a Pressler borer or disks were collected with a chainsaw from recently cut down oaks (DORH and GORN). The living trees were randomly chosen according to two criteria: appearing old and growing in a site representing the entire Moldova environmental conditions.

Historical wood samples were collected either using a dry woodborer or a chainsaw (for replacement timbers). All samples were extracted from well-preserved construction timbers in a variety of buildings: ancient wooden churches, fortresses, church-roof frameworks, and from wooden pillars of old royal court recovered during archaeological excavations (Fig. 1B). The building selection was based on documentary evidences, chronicles, and inscriptions on the structures in order to assure an optimal replication over time. The timbers used in historical buildings were most likely provided from nearby forests, but some wood replacement and reuse occurred over the centuries. For example, the Putna wooden church was initially built near Rădăuți, but during the second half of the XIV century (1468) was moved to Putna (cc. 30 km NW). Another example is the Thessaloniki barrel staves, which was made with wood originating from the Moldova region.

Samples were processed using standard dendrochronological protocols (Gärtner and Nievergelt, 2010; Nash and Speer, 2011; Popa, 2004; Stokes and Smiley, 1968) at the Forest Biometrics Laboratory in Suceava (RO) (biometrie.usv.ro). The increment cores from living trees were scanned using *Silverfast v.8.1* software and an EPSON 11,000 XL flatbed scanner with 1600 dpi true resolution and saved in a 48bit color image format. The imagines were opened in *CooRecorder v.9.31* software to measure tree ring-widths with 0.01 mm precision (Cybis Elektronik, 2010). Historical wood tree ring-widths were measured using the Lintab 6 system and TSAPwin software (Rinn, 2003) with 1/1000 mm precision. All measurements from living trees were individually cross-dated using TSAPwin and statistically verified with COFECHA (Holmes, 1983) using correlation analysis of 50-year intervals with 25-year overlaps (Grissino-Mayer, 2001; Holmes, 1983).

This reference oak chronology was built testing the agreement between individual series by standard dating statistics, such as *t-tests* (Baillie and Pilcher, 1973; Hollstein, 1980) *Gleichläufigkeit-Glk* (Buras and Wilmking, 2015; Eckstein and Bauch, 1969), and *cross-date index – CDI* (Rinn, 2003) and by a careful visual inspection of the matching. Short tree-ring series (less than 50 rings) with different possible dating positions were eliminated. Tree-ring series collected from one specific object were grouped (e.g. a given number of cores samples from various individual beams of a church). Thanks to tree-ring series of older structures, the chronology was extended into the past.

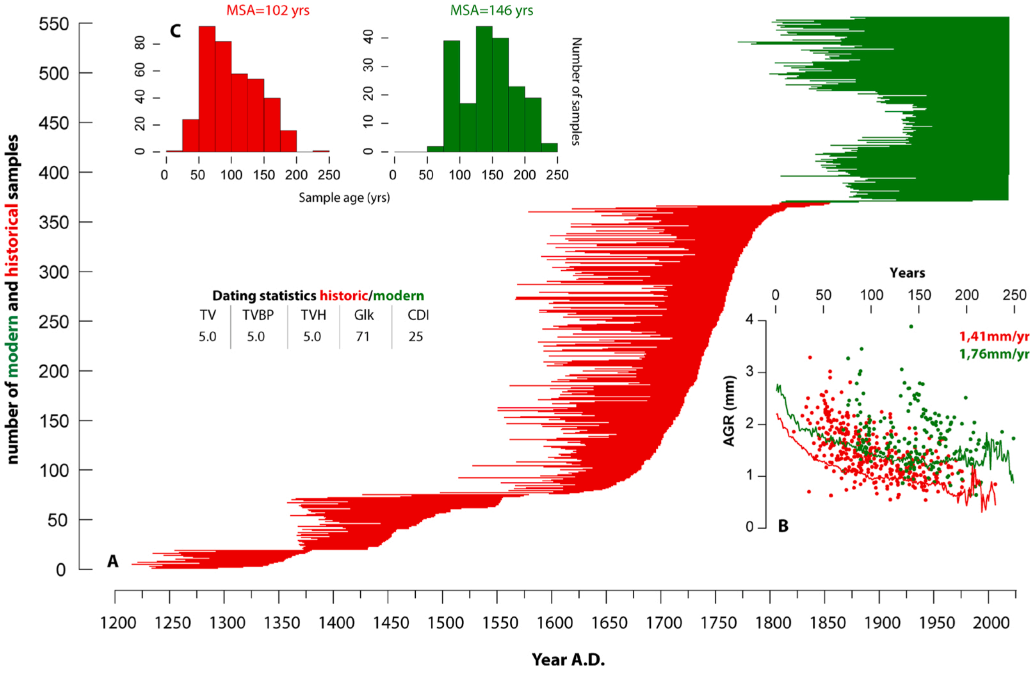

Fig. 2. **A -** Temporal distribution of the 183 living trees (dark green) and 371 historical wood (red) samples aligned to the outermost ring; **B –** The relationship between mean segment length and average growth rate (AGR) for modern and historic data (with dots) and mean growth variation in relation with cambial age (with lines); **C** – Histograms of the sample length (age) for living and historical wood. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

To remove the age-related growth trends, each raw tree ring width (TRW) series was transformed into growth index series in ARSTAN (Cook and Krusic, 2006). Three different detrending methods, a 150 years cubic smoothing spline with a 50 % frequency cut-off at 150-years, negative exponential function, and Regional Curve Standardization – RCS (Esper et al., 2003) were applied to each TRW series after power transformations (Cook and Peters, 1997). These functions were selected knowing their capacity to retain high to low-frequency information (Büntgen et al., 2011a). Also, the RCS method was performed for the historical and recent datasets separately, aligning the samples to their innermost ring (Esper et al., 2009). Tree ring indices were calculated as ratio between raw and detrending function, and the mean chronology (standard chronology) was obtained using a bi-weight mean (Cook and Peters, 1997; Fritts, 1976). The final chronology signal strength and the shared variance were assessed with expressed population signal (EPS) parameter and inter-series correlation (*rbar*), using a 50 years window lagged by 25 years (Wigley et al., 1984). Furthermore, standard dendrochronological statistics like mean sensitivity (MS), first-order autocorrelation (AC1), and signal to noise ratio (SNR) were computed. A moving 31 years standard deviation analysis was applied to highlight interval variability in chronologies.

Sapwood rings were counted for each living tree. The boundary between sapwood and hardwood was visually detected by the difference in colour and lack of tyloses in the sapwood vessels (De Micco et al., 2016; Jevšenak et al., 2019; Sohar et al., 2012). Furthermore, correlation analysis between the number of sapwood rings and geographical (latitude, longitude and altitude) and biometric (tree size and age) features were computed.

Teleconnections between our oak chronology and European oak chronologies (and thus the strength of the tree-ring signal) were evaluated by comparing the t-values obtained between different pairs of chronologies (Baillie, 1982; Baillie and Pilcher, 1973). In this study, t-values >4.0 indicate a significant correlation between chronologies. To keep our results consistent with other published studies, we calculated t-values in TSAP (Rinn, 2003) after detrending by the Wuchswert algorithm (Hollstein, 1980), according to the formula: $W_i = 100*\log10\ y_i/y_{i-1}$.

4. Results and discussions

4.1. Suceava oak chronology and its historical context

An 804 years long oak chronology was developed combing both living and historical wood (Fig. 2A) continuously covering the period 1216–2019 C.E. The mean length of individual series was 134 years (102 years from historical wood and 142 years from living trees) (Fig. 2C). The longest tree ring series has 249 rings (CNQR). Statistics for the Suceava chronology are presented in Table 2.

Oak timber has been considered an essential building material used for wooden churches, royal courts, fortresses, paving streets, obtaining potash and still is the most looked after timber in the hilly and plain regions of Eastern Europe (Giurescu, 1976). Oak timber was used to pay the tribute to the Ottoman Empire and has been an important commercial good for centuries. As a consequence, the Moldova Plateau is a region with numerous remnants of past cultures and civilizations located on the main route of migrations from Eurasian steppes to the West, intending to add key elements to one of the last gaps in the European dendrochronological network.

Table 2
Statistical parameters for the Suceava oak chronology (*samples* – number of chronologies, FY – first year; LY – last year; *AGR*-annual growth rate (mm); *MSL* – mean segment length; *corr* – correlation with master; *MS*-mean sensitivity; *AC (1)* - first-order autocorrelation; *rbar* inter-series correlation; *EPS*-expressed population signal; *SNR*-signal-to-noise-ratio);

Chronology	Unfiltered data								Filtered data		
	Samples	FY	LY	AGR ± SD	MSL ± SD	corr	MS	AC (1)	rbar	EPS	SNR
Living trees	183	1771	2019	1.75 ± 0.49	146 ± 40	0.50	0.29	0.627	0.32	0.97	24.65
Historical wood	371	1216	1855	1.46 ± 0.59	118 ± 22	0.58	0.24	0.656	0.37	0.93	21.13
All	554	1216	2019	1.57 ± 0.52	134 ± 25	0.54	0.25	0.628	0.34	0.95	25.15

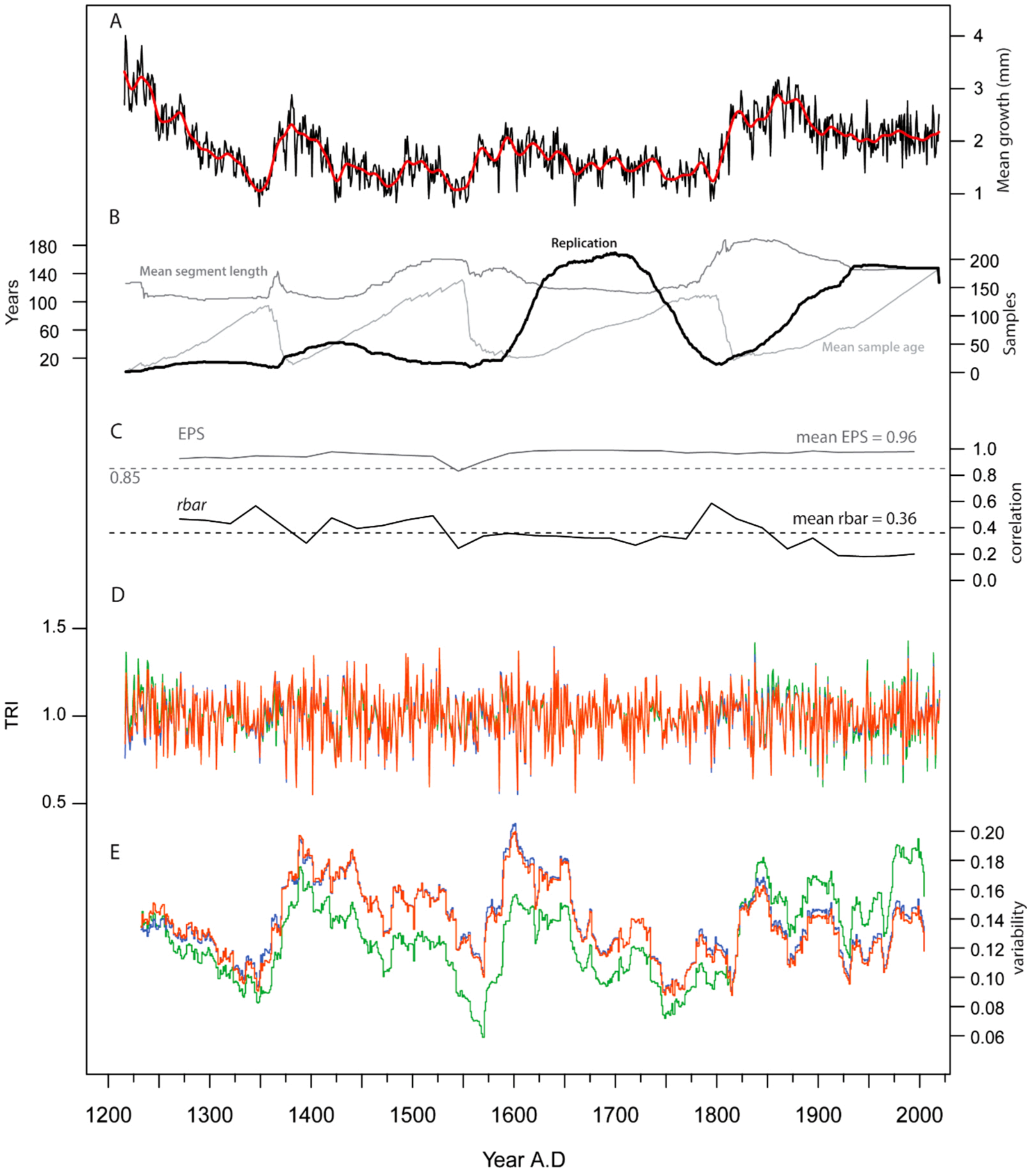

Fig. 3. Suceava chronology characteristics. A - Raw mean growth chronology for 1216-2019 period (red line 21-year low pass filter); **B -** Mean sample length (dark grey), means sample age (light grey) and replication (black) variations; **C -** 50-year moving Rbar and EPS statistics; **D -** Comparasion of three tree ring index chronologies for 1216-2019 period (green – RCS chronology, blue – negative exponential chronology and orange-red – 150 yrs. spline chronology) **E –** TRI variability inferred by 31 years moving standard deviation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The lack of oak trees older than 250 years can be explained by the economic strategy endorsed by the Romanian Principates after the Adrianople peace treaty (1829) when areas occupied by oak forests were intended to agriculture (Giurescu, 1976). According to the French botanist Charles Guebhard (cited by Giurescu, 1976), "… *after 1829, progressive destruction of the forests that once completely covered Lower Moldova*".

The length of the historical tree-ring series is an essential requirement in the cross-dating process (Haneca et al., 2009). The use of long chronologies allows obtaining high and significant correlations, as opposed to short chronologies. However, the optimal series length proper for dating is a highly debated topic in dendrochronology. According to previous studies, samples with less than 40 rings (Cook and Kairiukstis, 1990) or 50 rings (Baillie, 1982; Haneca, 2005; Haneca et al., 2006) are not suitable for accurate dating. In our case, 29 samples record less than 50 rings, which represent 7.81 % of the total of historical samples. The problem with their dating was solved by comparing a large number of series (Haneca et al., 2009), and even if showing low and significant correlation values, their dating was considered trustworthy by visual agreement of tree-ring curves. Likewise, 14 individual samples with more than 100 rings were eliminated from the final chronology, due to their low cross dating statistics. This misfit is justified by a high frequency of missing or discontinuous rings and extremely low earlywood vessels size in some rings (Haneca et al., 2009; Prokop et al., 2017).

The samples with short lengths were found in several buildings made of timber elements obtained from young trees. The use of small logs can be justified by the lack of craftsmen and iron tools for wood processing and limiting social-economic conditions. Furthermore, the timber size has been affected surely by the geopolitical influence of the Ottoman Empire. In these periods, the Ottomans exerted a higher economical pressure through heavy tribute requests, often paid in goods, including high quality oak timber (Giurescu, 1976; Giurgiu, 2002). These increased pressure on forests created the premisses for vassal rulers to enforce strict logging regulations.

Transition periods with almost no wooden archaeological findings were identified in 1380–1550 and 1560−1700. These periods were characterized by economic and political instability, pandemics, wars, and invasions (Büntgen et al., 2011b; Tegel et al., 2010). Because in the past, fire was mainly used both as defensive and offensive strategies, nowadays, there is paucity of well-preserved wood samples, suitable for dendrochronological studies. From these reasons, the possibility to

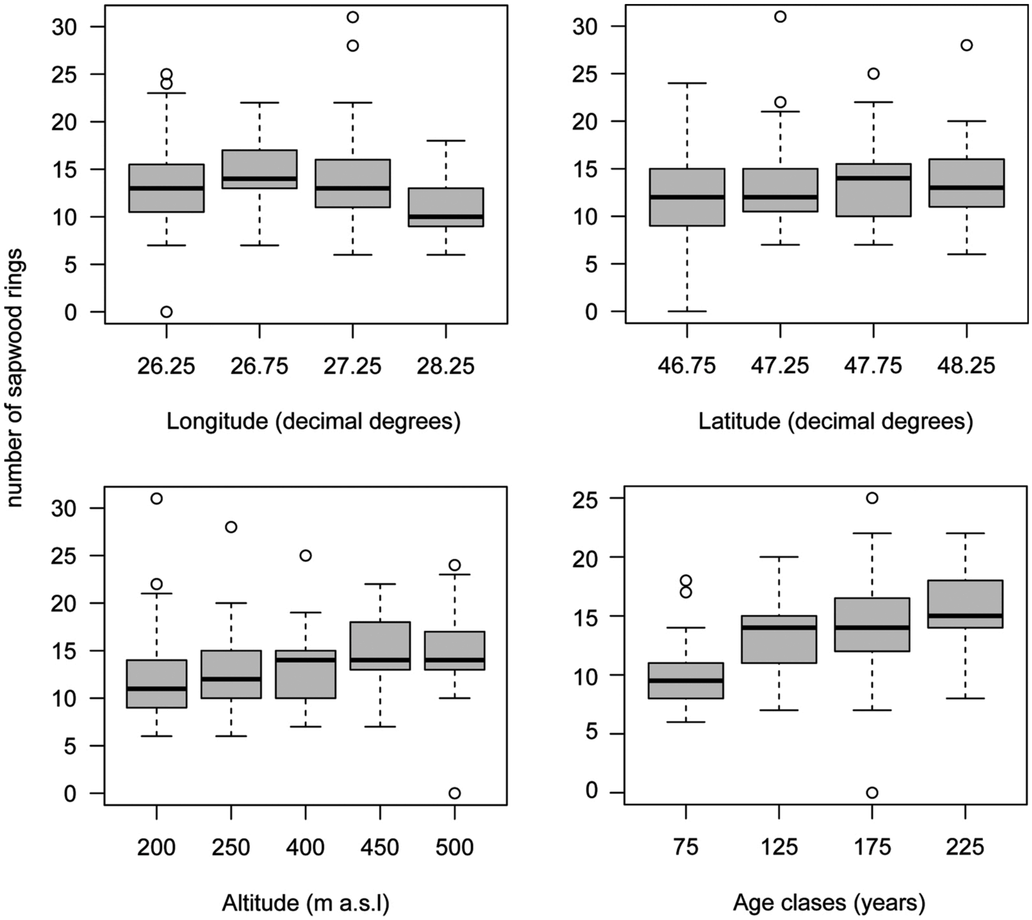

Fig. 4. Boxplot of average number of sapwood rings variation by latitude, longitude, altitude, and tree age.

increase the chronology sample replication could be very difficult.

In terms of growth performance, the mean growth rate is 1.57 mm year^{-1} but an evident difference between living (LT) and historical wood (HW) was detected. Living trees have higher growth rates (1.75 mm·yr^{-1}), compared to that observed in historical timber (1.46 mm·yr^{-1}). The LT - HW difference was observed in previous studies in Slovakia - 1.79 mm·yr^{-1} vs 1.33 mm·yr^{-1} (Prokop et al., 2016), Germany - 1.47 mm·yr^{-1} vs 1.28 mm·yr^{-1} (Büntgen et al., 2010) and North-Western Romania - 1.60 mm·yr^{-1} vs 1.01 mm·yr^{-1} (Nechita et al., 2018). This discrepancy is supported by the fact that the increase of CO_2 concentration can cause photosynthetic fertilization, inducing faster accumulation rates on modern wood (Büntgen et al., 2019; Friend et al., 2014). Besides, differences between growth rates can be assigned to changes in forest management regimes: primeval forests with selective cuttings, coppice with standards regime with short rotation periods for the historical timber, and high forest regime for living trees (Haneca et al., 2006; Muigg et al., 2020; Müllerová et al., 2016). It should also be considered that tree ring width in oak is highly correlated with its density and so to its mechanical properties; therefore, TRW has been a parameter for wood selection (Bergès et al., 2000; Tsoumis, 1991). The ontogenetic trend is similar for both sample sources (Fig. 2B) having a negative exponential pattern for the first 200 years. An increasing trend was detected for the last 50 years, but caution is advised because a reduced number of samples have these lengths (cc. 250 rings). Nevertheless, this increasing trend can be induced by the solitary trees which, after forest logging, developed large crowns ensuring higher photosynthetic active area, reflected in significant wider tree rings (Scharnweber et al., 2019).

Mean growth of Suceava chronology has a “wavy” trend (Fig. 3A), mainly induced by the combination of outer (juvenile) and inner (mature) wood tree ring width series. Similar long mean oak chronology trends were reported in previous studies (Nechita et al., 2018; Prokop et al., 2016). The correlation coefficient between living and historical datasets is 0.51 ($p < 0.05$) for their common period 1771–1855 (which corresponds to a mean of 35 samples). Moreover, the crossdating statistics have significant values, indicating a good agreement, even though we have a short overlap between historical and juvenile wood from living tree (Büntgen et al., 2010; Haneca et al., 2009). This relation is similar to previously reported relationships amongst different oak sites in Germany (Büntgen et al., 2010), Flanders (Haneca et al., 2009), North-Western Romania (Nechita et al., 2018).

Sample replication reaches the highest peak during the 17th to 18th century (206 series; Fig. 3B). Mean segment length stays fairly stable at ~130 years. The mean sample age increases from 1216 to 1368, 1400–1550, 1600–1800, and during the 20 centuries. An EPS value of 0.96 and mean *rbar* of 0.35, computed for the entire length, reveal a robust signal strength (Fig. 3C). The running EPS statistics exceed the quality threshold of 0.85, except for the year 1550 with an EPS of 0.83 which is corresponding to replication of 16 samples, and indicates that the theoretical population is well represented (Wigley et al., 1984). This high internal coherence over the last eight centuries implies a similar climatic control on oak growth in Moldova. The EPS, rbar MS, SNR, AC (1) values prove that the Suceava oak chronology has a high potential for climatic reconstruction (Büntgen et al., 2010; Čukar et al., 2008; Dobrovolný et al., 2018).

The use of three detrending methods highlighted that no long-term linear trends occur in tree ring indices (TRI), while the high-frequency signal is relatively strong indicating inter-annual and inter-decadal variability (Fig. 3D). Years with minimum TRI values were observed in 1904,1983, 1946, 1401, and 1660 and maximum values in 1837,

Table 3

Comparison of the Suceava oak chronology with European oak chronologies. "T(BP)" means "t-value" calculated according to Baillie-Pilcher algorithm, "T(H)" is "t-value" according to Hollstein, "CDI" means Cross Dating Index, "GL" – the percentage of agreement, "OVL" – the overlap of compared tree-ring series. We used raw (unprocessed) tree-ring widths for calculation. Possible imports: suggested by unusually high similarity of distant chronologies and possibility of far distance transportation by the Danube River or by land. Imports: dendrochronologically documented presence of tree-ring series from the Balkans used as components of chronologies.

Nr.	Chronology and author	Distance [km]	length [years]	t(H)	t(BP)	CDI	GL	OVL [years]
1	Maramures (Eggertsson and Babos, 2002)	150−200	1406−2016	**8.9**	9.2	42	64	611
2	Transylvania Csiik3T (Toth et al., 2014)	150−200	1526−1735	**7.4**	7.5	48	65	210
3	Podole 2 M (Ważny, Sagaydak, unpubl.)	150−200	1643−2009	**10.6**	11.5	75	67	367
4	SE Poland (Krąpiec, 1998)	450−550	1100−1994	**7.8**	8.6	50	62	779
5	Lower Silesia (Krąpiec, 1998)	750−850	1319−1994	**3.5**	3.9	21	58	779
6	North-Central Hungary (Grynaeus, 2003)	500	1590−1994	**6.4**	6.7	39	60	405
7	Slovakia (Kyncl, unpubl.)	300−350	1375−1941	**6.8**	6.6	40	60	567
8	Czech Republic (Kolář et al., 2012)	700	352−2006	**6.7**	6.2	37	58	790
9	E. Austria (Geihofer et al., 2005)	700−750	1172−2003	**6.8**	6.9	39	58	788
10	Slovenia (Čukar et al., 2008 updated ver.)	750−850	1151−2003	**4.6**	4.0	24	56	788
11	Croatia1 (Ważny, unpubl.)	750−850	1578−1911	**4.2**	5.0	28	62	334
12	W. Bulgaria (Ważny, unpubl.)	600	1224−1515	**3.0**	2.3	15	58	292
13	Zvezdec, Bulgaria (Ważny et al., 2014)	450−500	1787−2009	**5.2**	5.2	22	62	233
14	Crimea (Heussner, unpubl.)	550−650	1777−2011	**3.4**	3.0	19	61	235
15	N. Turkey (Kuniholm, 2000)	800−900	1081−2004	**4.0**	5.1	16	52	788
16	Sakir, Turkey (Ważny et al., 2014)	850	1788−2009	**3.6**	4.1	22	58	222
17	Northern Greece (Kuniholm and Striker, 1987) includes imported Balkan oaks	700−800	1186−1979	**7.2**	6.2	25	57	764
	Romanian object/site chronologies							
18	Bucharest (Botar, unpubl.)	350	1588−1702	**5.7**	5.4	37	66	115
19	Baia Mare (Ważny, unpubl.)	200−250	1174−1358	**4.4**	5.8	29	63	143
20	Sibiu (Nechita, 2013)	250−300	1810−2007	**4.5**	4.8	30	64	198
	Possible imports:							
21	Zatreni Cula (Botar, unpubl.)	350−400	1600−1848	**8.6**	8.2	52	62	249
22	Novo Brdo, Kosovo (Ważny, unpubl.)	700−750	1637−1770	**5.7**	4.8	32	61	134
23	Pristina, Kosovo (Kuniholm, unpubl.)	700−750	1635−1850	**6.2**	5.4	35	61	216
	Imports:							
24	Vezneciler 1S, Istanbul (Ważny, unpubl.)	750−800	1642−1753	**6.2**	5.6	38	65	112
25	Late Akkerman Fortress UAKK004 m (Bilyayeva et al., 2010)	250-350	1677-1792	**13.4**	11.7	101	80	116

1988, 1239, 1948, and 2013. The application of 31yrs moving standard deviation reveals three periods with evident higher variability: 1380–1480, 1580–1680, and since 1800 to series ends (Fig. 3E). Lower TRI variability occurs in 1216–1350 and 1700–1800 approximately. In terms of variability, TRI series are comparable for negative exponential and 150 years spline. The RCS method provides a chronology with lower variability before 1800, and higher thereafter. These findings are in agreement with previous studies (Dobrovolný et al., 2018) and are justified by the fact that RCS chronology variability reflects changes in the number of replications.

4.2. *Sapwood characteristics*

Sapwood ring estimation is important primarily for dendrochronological dating (Baillie, 1982; Hughes et al., 1981; Miles, 1997). The number of oak sapwood rings varies from site to site, and a generally accepted estimate number is not available. For the area, no sapwood tree ring number estimation was given until to present. According to our study, the mean English oak sapwood estimate is 13.1 ± 4.35, varying from 6 to 31 rings at tree level. At the site level, the sapwood mean ranges from 10 rings (COMD and MING) to 15 rings (ROZN and TUDO). These new values are relatively similar to Central European nearby sites: 14.6 rings for the Czech Republic (Prokop et al., 2017), 13.3 rings for south-western Pannonian Basin (Jevšenak et al., 2019), 14 rings for North-Western Romania (Nechita et al., 2018), 11.5 rings for Eastern Baltic (Sohar et al., 2012), 15 rings for Poland (Wazny and Eckstein, 1991).

We analysed the effect of different geographical and tree biometric features in number of sapwood rings (Fig. 4). A negative, but insignificant, relation between sapwood estimates and longitude ($R^2 = 0.15$, $p = 0.3$) was found. The low range of longitudinal distribution of the chronologies induces this result. For the rest of the geographical variables (altitude and latitude), no connection was found. Previous studies reported a general decreasing pattern of sapwood estimates from western to eastern sites (Haneca et al., 2009; Jevšenak et al., 2019) and can be related to different climatic conditions (Sohar et al., 2012) or oak chloroplast DNA variation (Petit et al., 2002). In addition to geographical variables, we tested the correlation intensity between the sapwood and tree age and size. Our data showed an increasing trend in sapwood numbers along with the mean tree age increase ($R^2 = 0.197$, $p < 0.05$) and no relationship with the tree size (*dbh*). The relationship between sapwood tree rings and tree age was confirmed in previous studies (Hillam et al., 1987; Hughes et al., 1981). Therefore, we recommend an estimation of 6–31, with a mean of 13 sapwood rings for dating purposes of historical and archaeological oak objects in Eastern Romania and the Republic of Moldova.

4.3. *Central and Eastern European perspective*

The Suceava oak chronology was compared with the main European master chronologies and with much shorter regional chronologies. Regional chronologies sometimes represent only a single historical object and t-values are lower due to the length of series and lower replication. We decided to use them in the teleconnection analysis due to the lack of longer oak master chronologies for the Balkans. Detailed results are presented in Table 3 and a map in Fig. 5.

The highest t-values were obtained for chronologies representing neighbouring regions, such as Maramures, Transylvania and Podolia. This is a perfect verification and confirmation of the quality of the Suceava chronology. Similar or slightly lower agreement has been observed with more distant regions of south-eastern Poland, eastern Slovakia and north-central Hungary (ca. 350−550 km). The correlation remained at the same level for the farther distance (700−800 km) but only towards the west – against the Czech and eastern Austrian oak chronologies. There is a very clear line of agreement of the common patterns of year-to-year tree-ring variability along the northern Carpathians. Oaks are present on both slopes of the Carpathians – northern and southern, except higher altitudes. This spatial distribution of

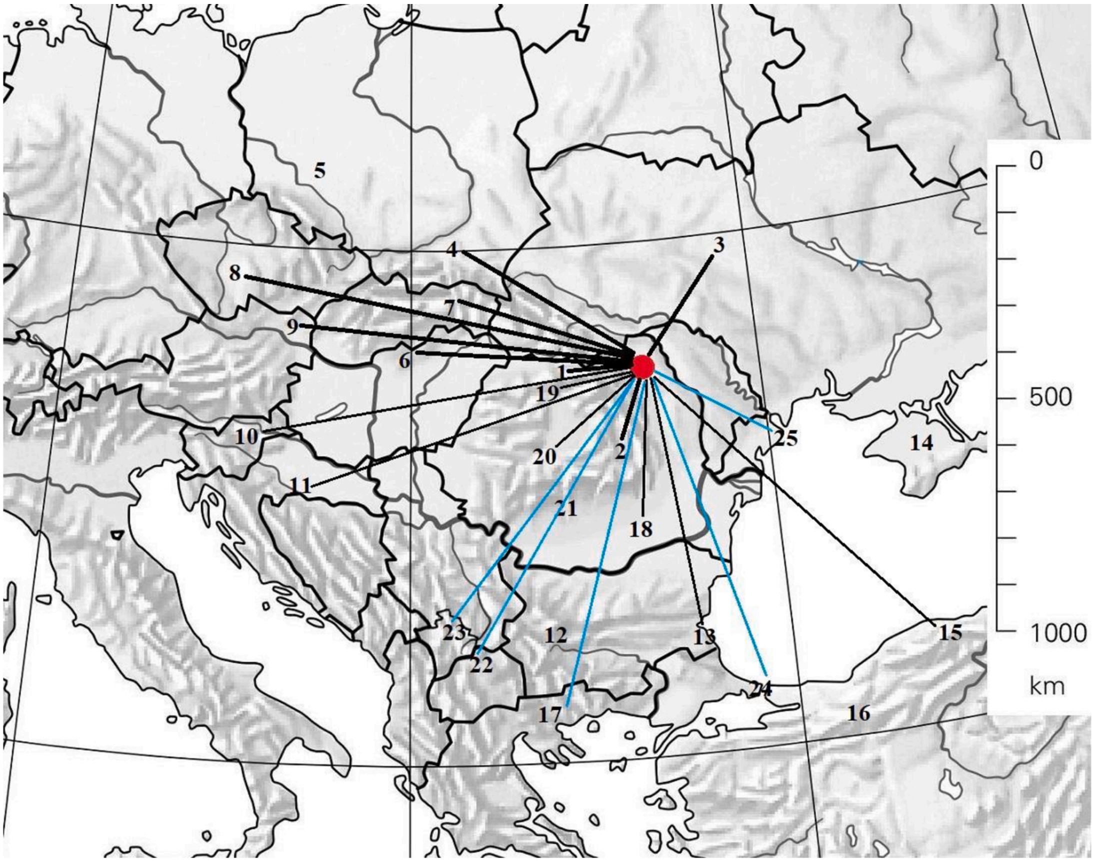

Fig. 5. Map of SE Europe. Teleconnections of the Suceava oak chronologies with reference chronologies. T-values above 6 are marked by thick lines, t-values 4 < t < 6 - thin lines, blue lines illustrate significant correlations with chronologies containing or based on tree-ring series from imported timbers. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

teleconnections of tree-ring records confirms former observations along the NS transect of dendrochronological signal of living oak trees in the E Balkans (Ważny et al., 2014). The most likely it has a climatological basis because the teleconnections generally follow the paths of large-scale atmospheric circulation patterns. The Carpathian chain is a dominant feature of the central and eastern European region. By topographic forcing of atmospheric signal, it modulates the precipitation and temperature variability (Bojariu and Giorgi, 2005). In addition, the influence of the mountain climate should be considered – this was already observed by Kolar et al. (2012) comparing the chronologies between the Czech Republic, foothills of the Alps in Austria and northern Switzerland.

The correlations in the south-west, south and south-east direction - Slovenia, north-east Croatia, Greece and northern Turkey are characterized by lower values. This is probably due to of various degrees of Mediterranean climate regime influence in the regions. Oak tree ring network developed by Cufar et al. (2014) for eastern Austria, Slovenia and Pannonian Plain clearly demonstrates that similarities and differences among the studied chronologies are affected by climatic conditions. Moreover, some surprisingly high values may have been artificially increased by unconscious introduction to the chronologies tree-ring series of non-local origin – result of wood transportation from other parts of the Balkans. Timber trade meant that real distance between compared oak chronologies may not reflect the actual distance between the growing regions and thus affect the correlation values. Danube River with its tributaries communicates several geographical regions and served for transportation in both directions: upstream and downstream. Significant importance in the supply of timber from the southern Balkans also had rivers flowing into the Aegean. Tree-ring series of imported timbers could become components of dendrochronological standards. Examination of timbers originating from 18th c. jetty in Istanbul demonstrates that for example the North Greek oak chronology undoubtedly includes tree-ring series from the southern Balkans (Akkemik et al., 2019).

In our study area, within the floodplain deposits of large out-Carpathian rivers was found abundant, well-preserved subfossil wood, (especially oak) (Chiriloaei et al., 2012; Rădoane et al., 2019, 2015). These so-called *"black oaks"* appear on river banks, usually after large floods and on the background of a continuous riverbed incision over the last century (Chiriloaei et al., 2012). There are several theories about the mechanism of subfossil trunks deposition and preservation, but the most cited is related to high fluvial activity in some periods during Holocene (Kalicki and Krąpiec, 1995; Máčka and Krejčí, 2009; Rădoane et al., 2019). These logs were recently carbon dated (^{14}C) and have the potential to bind the wooden structures from the Bronze and Iron Ages with more recent long oak chronologies.

Construction of multimillennia-long Romanian oak chronologies may provide the key solution to the problem of absolute dating of the Anatolian tree-ring chronologies developed by Kuniholm and Newton (Kuniholm and Newton, 2011). "An exact calendar-dated position for the tree-ring series" of Anatolian chronology (Pearson et al., 2020) is still based on radiocarbon calibration curve going up-and-down during successive improvements and this important scientific question still remains open. Only systematic and consistent, however time-consuming, and less spectacular work on the development of the chronology network can bring absolute and secure dating of Kuniholm's BC-chronologies. We just identified the existence of a common oak signal across the Black Sea - between Romania and northern Turkey. The Black Sea connection seems to be the shortest and the most promising way.

5. Conclusions

In this study we developed the first eight centuries-long oak reference chronology (named Suceava chronology) for the region located between Eastern Carpathians and Dniester river (Moldova) resulting the first well-replicated 804 years long oak chronology combing living trees and historical wood, continuously covering the period 1216–2019.

In addition, this study has explored the teleconnections of the new Suceava oak chronology with European ones and suggested the pattern of sapwood ring number specific for the region. The spatial distribution of teleconnections of tree-ring records confirms former observations along the NS transect of dendrochronological signal of living oak trees in the E Balkans. The most likely it has a climatological basis because the teleconnections generally follow the paths of large-scale atmospheric circulation patterns. The correlations in the south-west, south and south-east direction - Slovenia, north-east Croatia, Greece and northern Turkey are characterized by lower values. They are influenced by varying degrees by Mediterranean climate regime. The link between Romania and northern Turkey is of particular importance in order to solve the problem of absolute dating of floating Anatolian and Aegean tree-ring “BC-chronologies”.

In the context of the high abundance of un-dated subfossil and historical oak wood in region (from Carpathians to Dniester river) and intense wood trades with European countries in XV-XVII centuries, requires the development of a millennium-long oak chronology. The key steps for understanding the palaeo-environmental conditions, developing climatic reconstructions and identify teleconnections from Moldovia region may be provided by the construction of multimillennia-long Romanian oak chronologies.

Author’s contributions

CCR and TW designed the study and methodology, analysed the data and wrote the article draft; CCR, AM, TW, MIS collected and measured the cores; IP, AC, FC, MIS helped with the writing of original draft, interpret the results and review. All the authors contributed critically to the drafts writing and gave the final acceptance for publication.

Declaration of Competing Interest

The authors report no declarations of interest.

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