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BRIDGING THE GAPS IN TREE-RING RECORDS: CREATING A HIGH-RESOLUTION DENDROCHRONOLOGICAL NETWORK FOR SOUTHEASTERN EUROPE

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ABSTRACT

Dendrochronological research in North-Central Europe and the East Mediterranean has produced networks of long regional oak (*Quercus* sp.) reference chronologies that have been instrumental in dating, provenancing, and paleoclimate research applications. However, until now these two important tree-ring networks have not been successfully linked. Oak forests and historical/archaeological sites in southeastern Europe provide the key for linking the North-Central European and East Mediterranean tree-ring networks, but previous dendrochronological research in this region has been largely absent. This article presents the initial results of a project, in which we have built oak tree-ring chronologies from forest sites and historical/archaeological sites along a north-south transect between Poland and northwestern Turkey, with the aim of linking the North-Central European and East Mediterranean tree-ring networks and creating a new pan-European oak data set for dendrochronological dating and paleoclimatic reconstruction. Correlation among tree-ring chronologies and the spatial distribution of their teleconnections are evaluated. The southeastern European chronologies provide a solid bridge between both major European dendrochronological networks. The results indicate that a dense network of chronologies is the key for bridging spatial and temporal gaps in tree-ring records. Dendrochronological sampling should be intensively continued in southeastern Europe because resources for building long oak chronologies in the region are rapidly disappearing.

Keywords: dendrochronology, *Quercus* sp., teleconnection, southeastern Europe, tree rings.

INTRODUCTION

Oak (*Quercus* sp.) has been the most important genus in the development of long tree-ring chronologies in both North-Central Europe and the East Mediterranean. Deciduous oak trees grow under a wide variety of ecological conditions throughout Europe from Turkey and Greece to southern Sweden and the Norwegian coast (Ducousso and Bordacs 2004). Strong teleconnections have been observed among oak chronologies from forest sites across North-Central Europe (Baillie 1983; Pilcher *et al.* 1984; Ważny and Eckstein 1991; Haneca *et al.* 2005, 2009; Kolar *et al.* 2012); moreover, there are generally strong heteroconnections among different oak species (Ufnalski 2006; Cedro 2007). Similarly strong teleconnections and heteroconnections have been observed in oak chronologies built from sites in the Aegean and East Mediterranean (Kuniholm and Striker 1987; Hughes *et al.* 2001; Griggs *et al.* 2007, 2009).

Oak wood is durable and resistant to degradation (Meiggs 1982; Haneca *et al.* 2009). These properties have contributed to the ubiquity of oak wood in historical and archaeological sites throughout Europe and the Mediterranean, allowing the extension of oak tree-ring chronologies far beyond the dates of the oldest oak trees in these regions (Haneca *et al.* 2005, 2009; Ważny 2009).

The North-Central European (NCE) oak tree-ring network has been built as the result of intensive work performed in a vast area from Ireland in the west (Baillie 1982) through the Alps and the Alpine foothills (Schweingruber and Ruoff 1979; Billamboz 2003), the Netherlands (Jansma 1995), NW Germany (Eckstein *et al.* 1979), and W Germany (Hollstein 1980) to Estonia (Läänelaid *et al.* 2008; Sohar *et al.* 2014) in the east. This work has resulted in the development of the longest continuous oak tree-ring chronology in the world, which spans the last 10,489 years (Friedrich *et al.* 2004). This series has been extended by overlapping pine chronologies (from the time when central Europe was still too cold for oak growth), so that for the NCE tree-ring network, there is a continuous tree-ring sequence spanning approximately 12,000 years, from the Younger Dryas until today (Schaub *et al.* 2008).

In 1973, Peter I. Kuniholm launched the Aegean Dendrochronology Project, and began building tree-ring chronologies in Turkey, later expanding his research to sites in Greece, the Balkans, and Italy. The results of this work include a continuous tree-ring network for the East Mediterranean (hereafter EM) region comprised of oak sampled from forests and dendrochronologically dated historical and archaeological material that extends reliably back to AD 1089 from the present (Kuniholm and Striker 1987; Kuniholm 2000; Griggs *et al.* 2007, 2009; Pearson *et al.* 2012). Recent dendrochronological research on oaks from the Yenikapı excavations in Istanbul, Turkey, may extend this chronology back to at least the 4th century BC (Pearson *et al.* 2012). Additional floating tree-ring chronologies built from oak and other species span much of the period between today and 7000 BC and may extend tree-ring chronologies in the EM even further back in time (Kuniholm and Striker 1987; Kuniholm 1996).

The development of long oak tree-ring chronologies for both the NCE and EM regions has provided data for paleoclimatic reconstructions (e.g. Griggs *et al.* 2007; Büntgen *et al.* 2011) and absolute dates for numerous historical and archaeological sites (Kuniholm and Striker 1987; Kuniholm 2000; Haneca *et al.* 2009). Dendrochronological analysis of NCE and EM oaks imported through long-distance trade has also provided dates for sites outside of these regions in the southern Levant (Bernabei and Bontadi 2012; Lorentzen 2014) and the Red Sea (Müller and Heußner 2012).

However, despite strong teleconnections and heteroconnections among oaks within the NCE and EM regions and success in using these chronologies for dendrochronological dating and other research applications, previous research efforts have been unable to link these two large chronological networks with one another. Finding such a link would verify the placement of the EM chronologies covering a significant part of the 1st and 2nd millennium AD and could provide absolute dating of the now floating Aegean BC chronology. The geographic distance between sites sampled in the NCE and EM networks is less than 200 km across the Alps, and yet no dendrochronological linkages between the two networks could be found. After preliminary investigations of these two tree-ring networks, it was therefore concluded that in North-Central Europe and southeastern Europe/northern Anatolia there are two separate dendrochronological "zones," with the Alps creating a distinct boundary (Čufar *et al.* 2008; Ważny 2009).

After unsuccessful efforts to link the NCE and EM tree-ring networks across the Alps, we decided to investigate building a dendrochronological "bridge" through southeastern Europe. Other than a few published dendroclimatological studies on non-oak species (e.g. Popa and Kern 2008; Panayotov *et al.* 2010; Trouet *et al.* 2012), there are few dendrochronological data sets from the area between Poland—the home of the first author (where a dense network of dendrochronological data is available, e.g. Ważny 1990; Krąpiec 1998; Haneca *et al.* 2005; Ufnalski 2006; Cedro 2007)—and "Kuniholm's empire" in the northeastern Mediterranean.

Short feasibility trips to Romania, Bulgaria, Ukraine, and Slovakia confirmed the potential of the region to link the NCE and EM tree-ring records, both in terms of available timber resources and tree-ring teleconnections. The distance between the NCE and EM tree-ring networks is much larger (ca. 700–900 km) in southeastern Europe than across the Alps. Yet, preliminary results from this work suggested that tree-ring chronologies from the region along the Carpathian Mountains successfully bridge the NCE and EM tree-ring networks (Ważny 2009).

Southeastern Europe also served as an important source of timber both within the region and beyond. For example, forests growing on the flooded area near Satu Mare in Romania, close to the Hungarian border, delivered timber to Venice and the US about 150 years ago, according to information from the Forest Service in Satu Mare. The Danube, the second largest river in Europe, and its tributaries provided excellent opportunities for long-distance trade and transport both within Europe and even to the EM. For example, Pearson *et al.* (2012) provided the first dendrochronological evidence of the Danube Basin as a source of timber for Justinianic Constantinople. Dendroprovenancing methods developed for NCE (Eckstein *et al.* 1986; Bonde *et al.* 1997) are applicable also to southeast Europe (hereafter SE Euope).

Additionally, fossil pollen data indicate that the southern Balkan Peninsula and the western Black Sea coast served as refugia for deciduous oak during the last glacial period (ca. pre-10 ka BP) (Brewer *et al.* 2002). Consequently, paleoenvironmental sites in southeastern Europe may produce oak tree-ring data from time periods preceding those of the oldest oak tree-ring data from either the EM or northern Europe and therefore the longest oak tree-ring chronologies in Europe.

Given the great potential importance of southeastern Europe for dendrochronological research, we decided to sample modern and historical/archaeological sites and build a tree-ring data set along an approximately 1300-km transect from southeastern Poland in the NCE network to northwestern Turkey in the EM tree-ring network, bridging both sides of the Carpathian Mountains. The objectives for this project consisted of the following:

- to link the East Mediterranean chronologies to the long, absolutely dated North-Central European master chronologies;
- to develop tree-ring data sets as a tool for dating historical objects and for determining the origin of these materials (i.e. dendroprovenancing);
- to delineate geographic areas along this transect in which there are common tree-ring patterns (i.e. areas with the same "dendrochronological signal").

MATERIAL AND METHODS

The study area for this project includes forest, historical, and archaeological sites in seven countries. In total, 480 samples from

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26 sites were collected along a transect extending from Poland to northwestern Turkey. The location of the sites and of pre-existing oak reference chronologies used in this study are shown in Figure 1. Five oak species [*Quercus robur* L., *Quercus petraea* (Mattuschka) Liebl., *Quercus cerris* L., *Quercus frainetto* Ten., and *Quercus pubescens* Willd.] were included in this project. The location and description of each site and oak species sampled is given in Table 1.

Forest Sampling Locations and Methods

Sampling of living trees targeted oaks growing primarily in protected nature reserves (in which there had been theoretically minimal anthropogenic disturbance), supplemented by groups of old trees surviving in managed forests. Cores were taken from each tree with a Haglof increment borer at breast height (1.3 m), and in some cases sections were cut from felled trees with a chainsaw.

The ecological and geographic diversity of the study area is enormous, ranging from the Black Sea coast and including both the European and Asian sides of northwestern Turkey, to the Danube and Dniester River valleys, and from the Carpathian Mountains to the Middle European Plain. Oaks grow in environments including open park forests, mixed broadleaf forests, monotypic managed forests, humid broadleaf forests, and even subhumid tropical broadleaf forests.

Particularly unique ecological areas sampled include forest sites in Romania (Figure 1, sites #9–15) and in the Strandja Mountains on the SE Bulgarian-NW Turkish border (Figure 1, sites #22 and #24). Romania is a central and critical transition zone in our study area, because it is the location where the Euroasiatic deciduous forest, Atlantic domain (dominated by deciduous broad-leaved trees), and Mediterranean forest domain converge (Ozenda 1994; Bodnariuc *et al.* 2002). The Strandja Mountains contain humid continental to subhumid tropical relict broadleaf forests containing high biodiversity and species richness. The area's unique ecology is because of its location at a biogeographic crossroad between Europe and Asia, and because Strandja was a refugium for broadleaf forests (including oak) during the Late Glacial Period. Oaks from both sides of the mountains—the Strandja Nature Park (Figure 1, site #22) in Bulgaria along the northern mountain slopes, and managed forests at Soğuksu (Figure 1, site #24) in the Demirköy district in Turkey on the southern slopes—were sampled and compared.

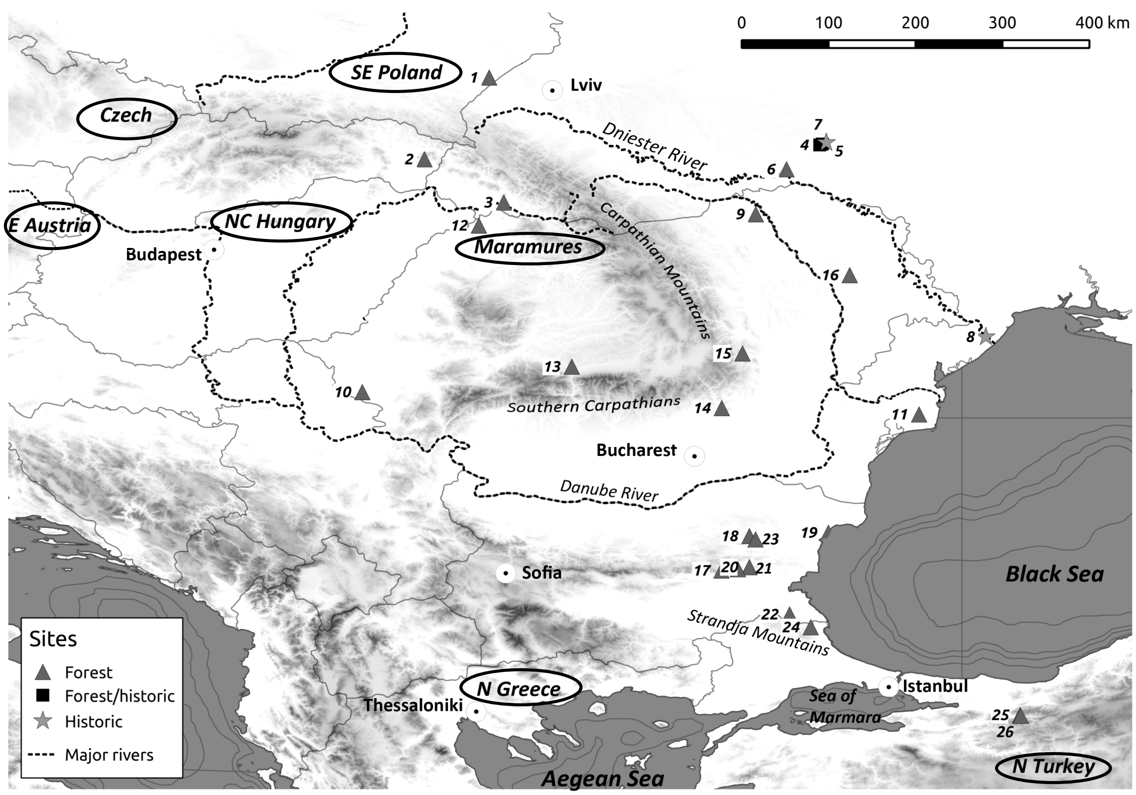

Figure 1. Map of SE Europe indicating the sampling locations of the forest sites (*gray triangles*), historical buildings (*gray stars*), both forests and historical buildings (*black squares*), and pre-existing oak reference chronologies (*black ovals*). The site chronologies corresponding to the site numbers on the map are listed in Table 1.

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Table 1. Location and description of sites sampled in this study.

No.	Country	Site	Longitude (E)	Latitude (N)	Altitude (m asl)	Type of site	No. of trees/ samples collected	Species
1	Poland	Kosobudy	23.06	50.04	280–300	forest/publ. data[1]	20	*Q. robur/Q. petraea*
2	Slovakia	Jovsianska Hrabina	22.11	48.83	180–200	forest	16	*Q. robur*
3	Ukraine	Khust	23.27	48.19	250–270	forest	18	*Q. robur*
4	Ukraine	Czerniatyn	27.91	49.04	320–325	forest+historical	16+11	*Q. robur*
5	Ukraine	Severinovka	27.90	49.06	280–310	forest+historical	16+27	*Q. robur*
6	Ukraine	Naddnistrie	27.42	48.68	280	forest	17	*Q. robur*
7	Ukraine	Mezhiriv	28.01	49.08	266	historical	11	*Quercus* sp.
8	Ukraine	Akkerman	30.35	46.20	ca. 10	historical	10	*Quercus* sp.
9	Romania	Avrămeni	26.97	48.01	199	forest	15	*Q. robur*
10	Romania	Banloc	21.20	45.38	93	forest	17	*Q. robur*
11	Romania	Caraorman	29.37	45.05	3	forest	18	*Q. robur*
12	Romania	Satu Mare	22.91	47.85	127	forest	34	*Q. robur*
13	Romania	Sibiu	24.27	45.76	440	forest	15	*Q. robur*
14	Romania	Tisau	26.47	45.15	270	forest	35	*Q. petraea*
15	Romania	Vizantea	26.78	45.95	628	forest	30	*Q. petraea*
16	Moldova	Lozova	28.35	47.11	237	forest	16	*Q. robur*
17	Bulgaria	Sinije Kamni	26.47	42.74	780–830	forest	11	*Q. cerris*
18	Bulgaria	Szumensko Plateau	26.88	43.25	480–490	forest	24	*Q. petraea/Q. cerris*
19	Bulgaria	Zlatni Piasci	28.04	43.30	100–130	forest	20	*Q. cerris*
20	Bulgaria	Lazarevo	26.88	42.79	280–290	forest	16	*Q. cerris/Q. pubescens*
21	Bulgaria	Czubra	26.71	42.76	210	forest	16	*Q. cerris*
22	Bulgaria	Zvezdec	27.47	42.09	300–340	forest	21	*Q. frainetto/Q. cerris*
23	Bulgaria	Marash	26.97	43.20	95	forest	2	*Q. robur*
24	Turkey	Soğuksu	27.78	41.90	360–370	forest	20	*Q. petraea/Q. frainetto*
25	Turkey	Sakir	30.85	40.60	770	forest	20	*Q. cerris/Q. petraea*
26	Turkey	Güzlek	30.86	40.59	610	forest	8	*Q. cerris*

1. Ważny (1990).

Historical and Archaeological Sampling Locations and Methods

In Eastern Europe, it is extremely difficult to find oak trees over 200 years old. Therefore, to extend our recent chronologies further back in time, we also collected materials from historical and archaeological sites (Figure 1; Table 1). Historical and archaeological material were sampled either by cutting cross-sections of the wood or by obtaining cores of the material with a dry-wood borer.

In Ukraine, it was possible to obtain an especially rich collection of historical timber in Podolia. This area is located near the Dniester River, which flows from the Polish-Ukrainian border to the Black Sea and historically served as a conduit for transporting timbers used to build a series of Moldavian-Ottoman fortresses (like the Akkerman Fortress in Bilhorod Dnistrovskyi; Figure 1, site #8). In Podolia, it was possible to find 18th–19th century buildings adjacent to contemporary forest stands containing old trees. Buildings sampled in this area include a ruined sugar factory (built in 1873) and nearby forest park in Severinovka (Figure 1, site #5); the remains of the Church of the Assumption of the Virgin Mary (built in 1794) in Mezhiriv (Figure 1, site #7); and the roof of the palace in Czerniatyn, which was the estate of the Vitoslavskyi-Lvov family from the 17th–19th centuries, as well as modern oaks from a nearby park that is likely a remnant of an old forest (Figure 1, site #4).

Laboratory and Analysis Methods

Sample preparation, crossdating, and chronology building were carried out using classical dendrochronological methods (e.g. Baillie 1982; Schweingruber 1988; Hillam 1998). All ring widths were measured to the nearest 0.01 mm using a stereomicroscope, traveling stage, and the TSAPWin (Rinn 2005) and CORINA (Harris *et al.* 2008) dendrochronological analysis programs. Samples from the same forest site or building structure were crossdated with one another and synchronized to build composite site chronologies. Historical site chronologies were crossdated against local chronologies developed from living trees and absolutely dated reference chronologies from Slovakia developed by T. Kyncl (unpublished).

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Crossdating was evaluated using multiple statistical parameters—namely, *t*-values (Baille and Pilcher 1973), percent parallel variation (Gleichläufigkeit) (Eckstein and Bauch 1969), and the TSAP Crossdating Index—using the software TSAPWin (Rinn 2005), CORINA (Harris *et al.* 2008), and DENDRO for Windows (Tyers 2004). Crossdating was verified by visual inspection and by the COFECHA software (Holmes 1983). In cases when various oak species were sampled from the same forest site, separate chronologies for each sampled species were built and compared. However, because visual and statistical similarities between oak species at the same site were so strong, the tree-ring series of different oak species were pooled together into composite oak chronologies for each site. Tables 2 and 3 list the chronologies developed from the study area and regional reference chronologies analyzed.

Intersite correlation of oak chronologies in the study area (and thus the strength of the SE European tree-ring signal) was evaluated by examining the *t*-values obtained between different pairs of chronologies (Baillie 1982; Baillie and Pilcher 1973). In this study, *t*-values >4.0 indicate significant correlation between chronologies.

Applying different indexing and autoregression models to standardize tree-ring curves can greatly affect the *t*-values calculated between two chronologies, particularly between chronologies with moderate to poor correlation (Wigley *et al.* 1987). Tests carried out by Sander and Levanič (1996) further demonstrate that different dendrochronological software packages may produce different *t*-values, even when similar or even the same formulas are used in their calculation. Therefore, we used *t*-values calculated in TSAP (Rinn 2005) according to the Hollstein algorithm (t_H) (Hollstein 1980) to keep the results consistent. Calculated t_H-values between chronologies were cross-checked with their corresponding Baillie-Pilcher *t*-values (t_{BP}) (Baillie and Pilcher 1973) in TSAPWin and their visual fit to assess overall correlation. Additional transformation and standardization of the tree-ring data beyond that applied in the Hollstein and Baillie-Pilcher algorithms was not performed, as our raw tree-ring data did not exhibit particularly strong undesirable trends caused by age or stand dynamics.

Table 2. Oak chronologies developed for the project. Site #1 is already published (Ważny 1990).

Site no.	Country	Chronology	No. of series	Length (years)	Date begin	Date end
1	Poland	Kosobudy	20	207	1782	1988
2	Slovakia	Jovsianska Hrabina	15	110	1902	2011
3	Ukraine	Khust	18	142	1867	2008
4	Ukraine	Czerniatyn forest	12	197	1813	2009
4	Ukraine	Czerniatyn palace	6	160	1677	1836
5	Ukraine	Severinovka forest	11	217	1793	2009
5	Ukraine	Severinovka factory	13	199	1643	1841
6	Ukraine	Naddinstrie	14	100	1910	2009
7	Ukraine	Mezhiriv church	6	118	1676	1793
8	Ukraine	Akkerman fortress	21	116	1677	1792
9	Romania	Avrămeni	15	141	1867	2007
10	Romania	Banloc	15	156	1852	2007
11	Romania	Caraorman	6	168	1839	2006
12	Romania	Satu Mare	32	129	1882	2010
13	Romania	Sibiu	13	198	1810	2007
14	Romania	Tisau	35	167	1844	2010
15	Romania	Vizantea	28	173	1838	2010
16	Moldova	Lozova	11	136	1871	2006
17	Bulgaria	Sinije Kamni	11	95	1915	2009
18	Bulgaria	Szumensko Plateau	24	115	1895	2009
19	Bulgaria	Zlatni Piasci	20	103	1907	2009
20	Bulgaria	Lazarevo	16	112	1898	2009
21	Bulgaria	Czubra	16	202	1808	2009
22	Bulgaria	Zvezdec	21	223	1787	2009
23	Bulgaria	Marash	2	217	1793	2009
24	Turkey	Soguksu	20	146	1864	2009
25	Turkey	Sakir	21	222	1788	2009

Table 3. List of reference oak chronologies.

Chronology	Length	Date begin	Date end	Reference
SE Poland	895	1100	1994	Krąpiec (1998)
Czech	1655	352	2006	Kolar *et al.* (2012)
E Austria	833	1172	2003	Grabner (unpublished)
N Central Hungary	405	1590	2004	Grynaeus (unpublished)
Maramures	588	1406	1994	Eggertson and Babos (2002)
N Greece	794	1186	1979	Kuniholm and Striker (1987)
N Turkey	924	1081	2004	Griggs *et al.* (2009)

RESULTS

Regional Teleconnections among Site Chronologies

The main goals of the project were to link the absolutely dated NCE and EM tree-ring networks for the period of the last several centuries and assess the common dendrochronological "signal" of trees growing in SE Europe. Figure 2 shows the site chronologies in the study area that have significant correlation with one another, which are linked with black lines.

As shown in Figure 2, the NCE oak chronologies in Poland, East Austria, and the Czech Republic have successfully been linked to the EM dendrochronological network of NW Turkey through the SE European dendrochronological "bridge." There are substantial long-distance east-west teleconnections in the study area across the Greater Hungarian Plain. The 600-year Maramures chronology (Eggertson and Babos 2002) has strong correlation ($t_H = 9.6$) with Grabner *et al.*'s (unpublished data) E Austria reference chronology that is over 600 km distant. Such long-distance east-

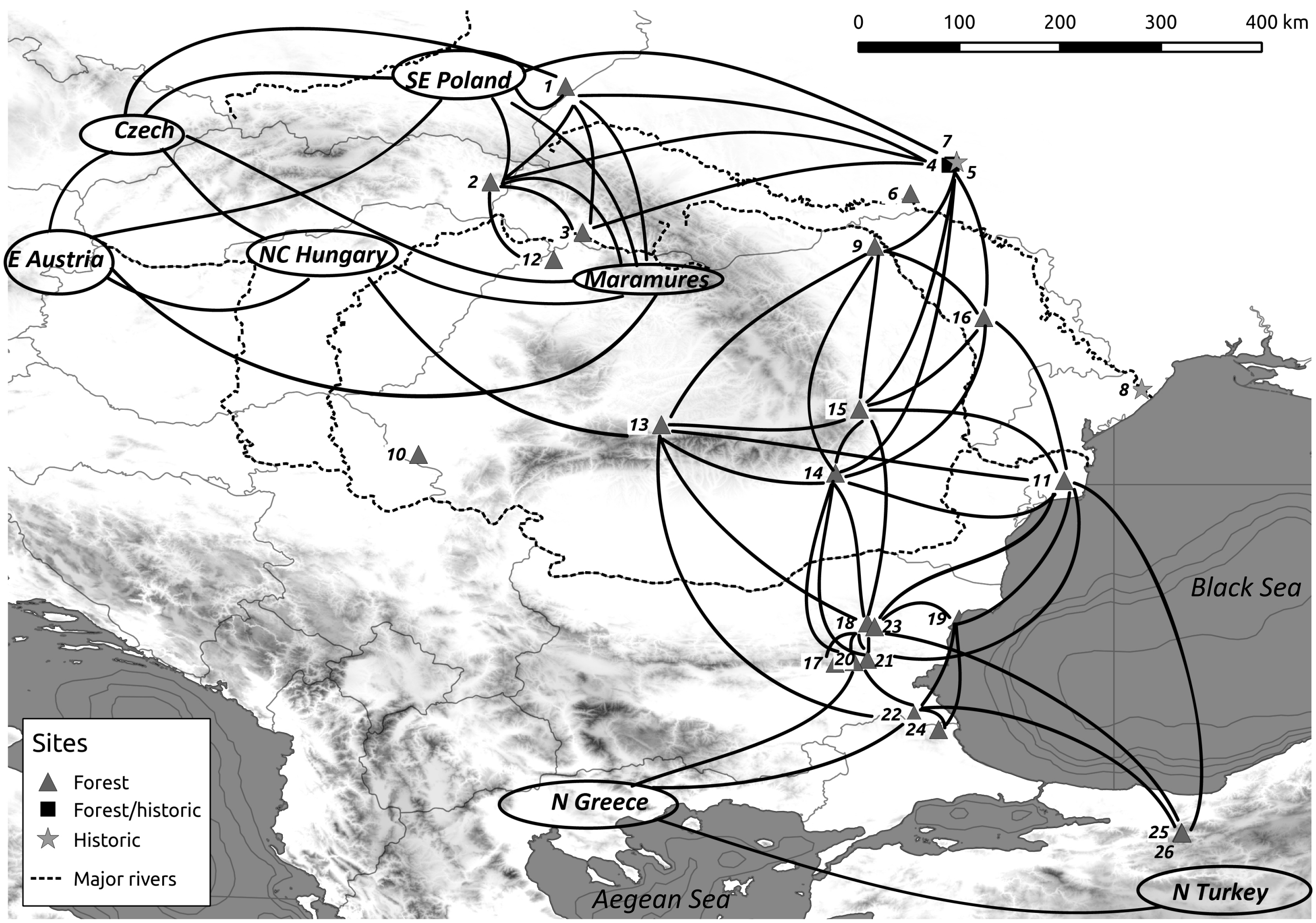

Figure 2. Map of SE Europe with lines indicating significant ($t \geq 4.0$) correlation between pairs of oak chronologies. Site chronologies corresponding to the site numbers on the map are listed in Table 1. Ovals indicate regional reference chronologies.

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west teleconnections also exist among site chronologies for which the overlap is much shorter (n<220). The Ukrainian chronologies from Czerniatyn (#4) and Severinovka (#5) have t-values of 6.3 and 7.0, respectively, against the SE Poland reference chronology (Krąpiec 1998), which is located approximately 500 km away. It should be noted that in northern Poland, Ważny and Eckstein (1991) previously observed high correlation between sites over distances of about 400 km. They also noted that in some periods a common dendrochronological signal might exist far beyond this distance.

However, teleconnections obtained among individual site chronologies and their spatial distributions (shown in Figure 2, and in detail in Figures 3 and 4) do not entirely match our original hypothesis. We had expected primarily teleconnections running in a N-S direction in SE Europe, reflecting a common tree-ring signal in sites running parallel to the main chain of the Carpathians, and poor correlation between sites on the eastern and western sides of these mountains. There is indeed a distinct boundary between Maramures in northwest Romania (which clearly belongs to the NCE dendrochronological zone) and the neighboring regions of Bukovina (#13) and Transylvania (#9) only slightly further east in Romania (ca. 200 km). Additionally, the Maramures chronology does not have significant correlation with any sites located to its south, east, or northeast across the Carpathians. This general pattern likely results from the influence of the Carpathian Mountains, which restrict the influence of continental air masses from central Europe to western Romania, and the influence of Black Sea air masses to the country's east (Bojariu and Giorgi 2005). Yet, contrary to our expectations, we note strong correlation between Sibiu (Figure 2, site #13), which is located in Bukovina west of the Carpathians, and forest sites on the eastern slopes of the Carpathians and in eastern Romania (e.g. Figure 2, sites #9, 14, and 15). Furthermore, sites in Transylvania belong to the dendrochronological zone east of the Carpathians and do not exhibit strong teleconnections to the Great Hungarian Plain.

For some sites, a lack of significant teleconnections likely arises from local environmental conditions, disturbances, or anthropogenic influences dominating the tree-ring signal. For example, Satu Mare in NW Romania (#12) is located in a flooded area, and its site chronology exhibits poor correlation even with nearby sites. Forest management and anthropogenic disturbance can reduce the strength of the dendrochronological signal significantly and consequently the value of sites for long-distance crossdating. For example, the forest site of Naddnistrie (#6) in Ukraine shows only very low correlation with the sites of Czerniatyn (#4) and Severinovka (#5) despite a distance of less than 80 km. The

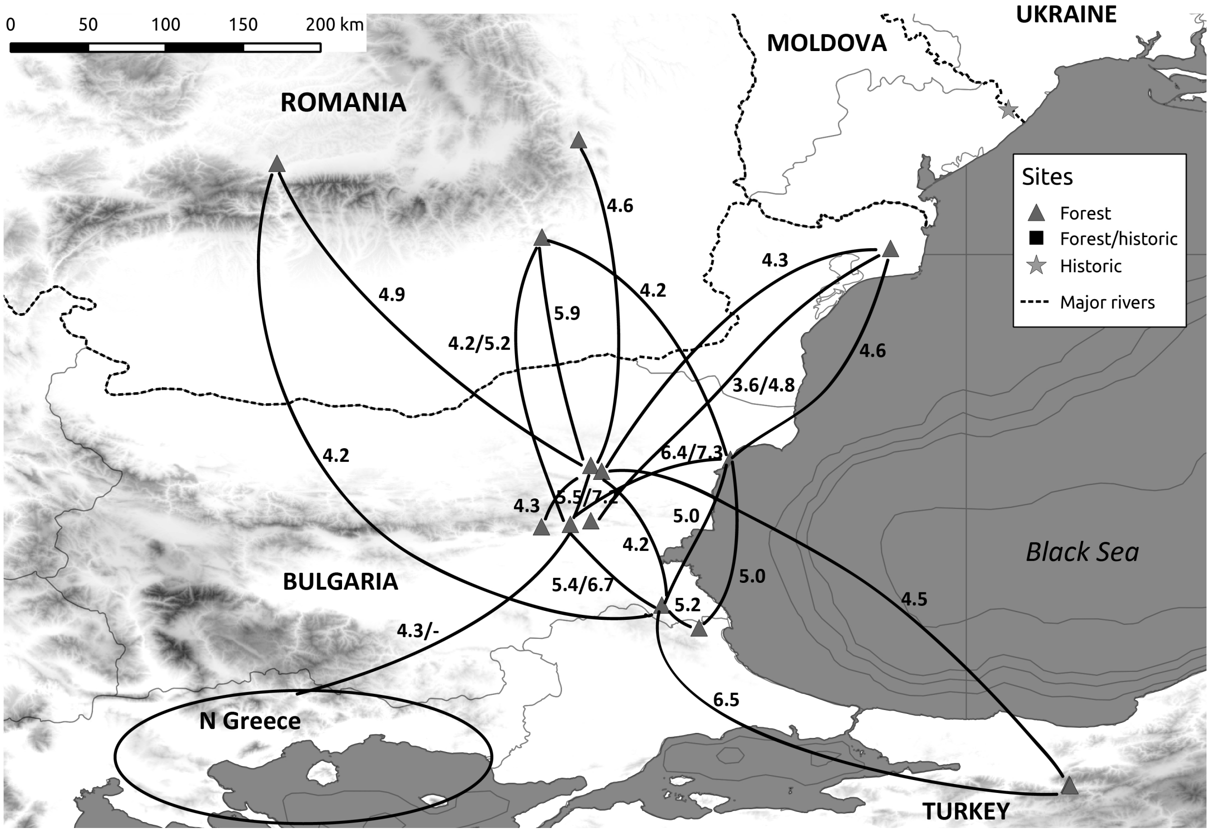

Figure 3. Location of and correlation among Bulgarian, Romanian, and Turkish oak forest chronologies. The N Greece reference chronology is indicated with an oval. t-values show the correlation strength between chronologies (connected with an arc) are displayed. All t-values shown here are calculated using the Hollstein algorithm (t_H). In a few cases where there is a large difference between t_H-values and t-values calculated using the Baillie-Pilcher algorithm (t_{BP}), both t_H (listed first) and t_{BP} (listed second) statistics are given.

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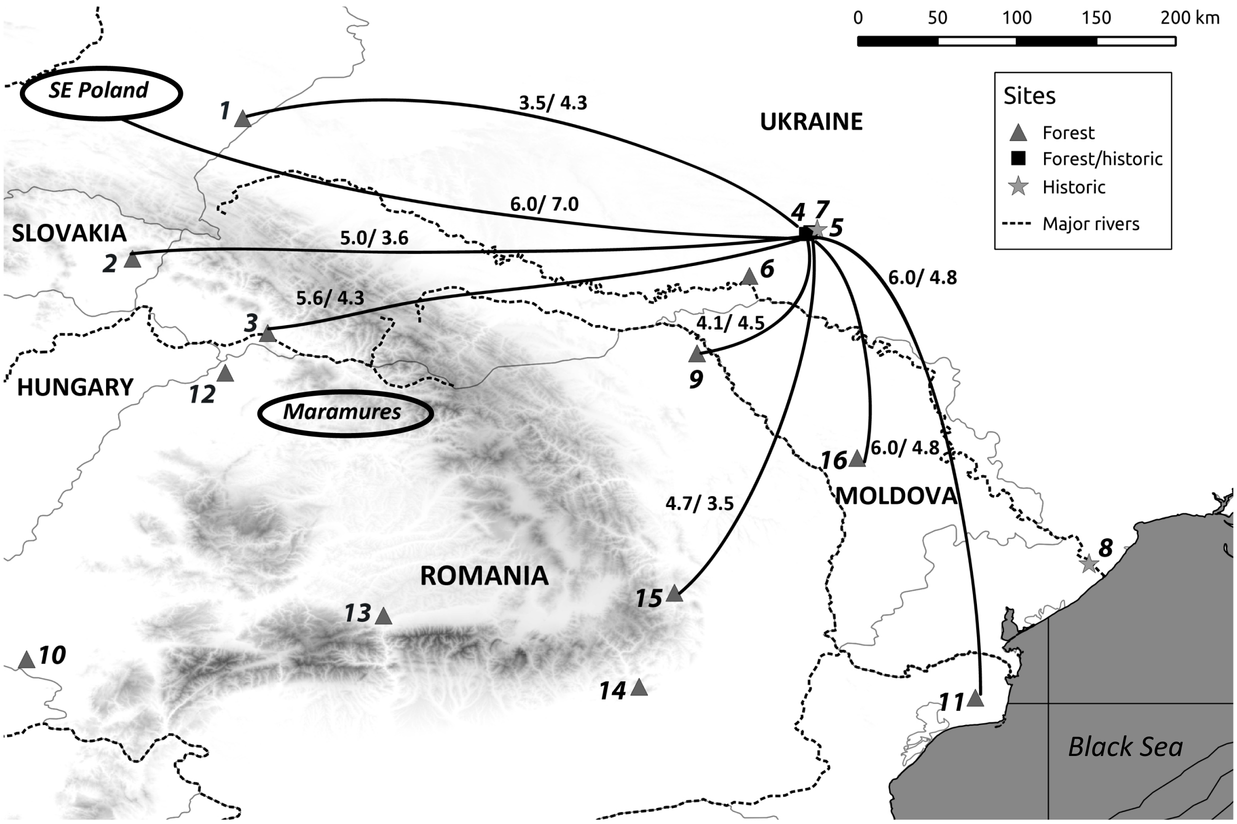

Figure 4. Historical and modern oak chronologies representing the region of Podolia in Ukraine. *t*-values show the significance of relationships between chronologies (connected with an arc). All *t*-values shown here are calculated using the Hollstein algorithm (t_H listed first) and using the Baillie-Pilcher algorithm (t_{BP} listed second). Ovals indicate regional reference chronologies. The site chronologies corresponding to the site numbers on the map (in bold italics) are listed in Table 1.

effects of forest management are also clear when we compare the teleconnections of two chronologies from forest sites in the Strandja Mountains on the western coast of the Black Sea. The site of Zvezdec (#22), which is in a protected nature reserve natural forest in Bulgaria, has stronger correlation (t_H = 6.5) with the unmanaged forest site of Sakir on the Asian side of Turkey (a distance of ~300 km) than with the managed forest site of Soğuksu (#24) (t_H = 5.2), which is only 35 km away on the other side of the Strandja Mountains.

Both Kuniholm's (2000) and Griggs *et al.*'s (2007, 2009) Aegean oak master reference chronologies for north Greece and north Turkey show limited teleconnections with the SE European tree-ring network and consequently reduced usefulness for crossdating with SE European oak chronologies (Figure 3). The north Greece oak chronology has only moderate correlation (t_H = 4.3) against two Bulgarian site chronologies, Lazarevo and Zvedec (#20 and #22, respectively), whereas the north Turkey oak reference chronology does not show significant correlation with any chronology except Sakir (#25) in NW Turkey. In contrast, Sakir has significant correlation with two Bulgarian sites: Zvezdec (#22; t_H = 6.5) and Shumensko Plateau (#18; t_H = 4.5). There is even a significant link (t_H = 4.0) across the Black Sea between Sakir and Caraorman (#11) in Romania. These results suggest that the north Turkey oak chronology—which comprises several site chronologies whose locations range from the European provinces of Turkey to Turkey's eastern Black Sea coast—should be divided into smaller, well-replicated units that better capture mesoscale to local variability in the dendrochronological record. Such "deconstruction" of the Aegean oak master chronologies will improve our ability to date wood from the SE European "transition zone" and improve the use of such chronologies in dendroprovenancing applications. This process of "dismantling" large-scale oak reference chronologies into robust, smaller-scale regional tree-ring chronologies has already begun elsewhere in western Europe with chronologies such as Eckstein's Schleswig-Hollstein oak chronology (Eckstein and Wrobel 2007).

Dating and Provenancing Historical and Archaeological Sites

Historical timbers from Severinovka (#5), Czerniatyn (#4), and Mezhiriv (#7) extended our Ukrainian oak chronologies by 150 years, so that a regional chronology for Podolia now extends back to AD 1643 from the present. The successful dating of these timbers and developed chronologies also solved the problem of dating the Akkerman-Late chronology developed for the Late Ottoman structures built during the modernization of the Akkerman Fortress in Bilhorod Dnistrovski, 15 km north of the Black Sea

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coast (Bilyayeva *et al.* 2010). This chronology had remained undated even after three sampling campaigns. The Akkerman-Late chronology crossdates with the newly developed Severinovka Sugar Factory chronology with a high t_H-value of 8.0, indicating that the timbers were imported from Podolia. This chronology covers the period of AD 1677–1792.

Not all attempts to sample historical and archaeological material in the study area were successful. We attempted to sample from the Tombul Mosque (the Sherif Halil Pasha Mosque, ca. 1740–1744), which is the largest mosque in Bulgaria and one of the largest mosques in the Balkans. However, we discovered that the mosque's original wooden construction was replaced during restoration in 2010, and the timbers thrown out. Only three original timbers, probably originating from the cupola construction, were found in the mosque courtyard below a pile of lead waste from the roof cladding. This mosque is one of many examples of fast-disappearing historical timber resources for dendrochronological research in the Balkans.

DISCUSSION

Oak Teleconnections and Atmospheric Circulation Patterns

Oaks are present throughout almost the entire length of the transect in our study area, except at higher elevations in the mountains. We sampled and analyzed oaks growing on both sides of the Carpathian Arc through the following three phytogeographical provinces of the Boreal Subkingdom: Central–European Lowland–Upland Province, Pontic–Pannonian Province, and Illyrian Province. The southernmost part of our transect extends into the Mediterranean Kingdom (classification based on Medwecka-Kornaś 1972).

The spatial distribution of teleconnections in our study area's tree-ring records most likely has a climatological basis, because the teleconnections generally follow the paths of large-scale atmospheric circulation patterns. Previous studies indicate that precipitation, particularly during spring and summer months, has an important impact on radial growth in oaks (e.g. Ważny and Eckstein 1991; Akkemik *et al.* 2005; Cedro 2007; Griggs *et al.* 2007). Cyclone trajectory and frequency are highly correlated with the spatial and temporal variability of precipitation in this region and can therefore impact site and regional tree-ring signals (Karaca *et al.* 2000; Bielec-Bakowska 2010; Kaznacheeva and Shuvalov 2012).

The northernmost sites in the study area are strongly influenced by cyclones originating over the North Atlantic. These cyclones travel from west to east across either Iceland or the British Isles and through northern Europe. SE Poland and central Europe have a continental climate that is also strongly influenced by cyclones that form in the Gulf of Genoa in the central Mediterranean and then travel to the northeast through central Europe (Bielec-Bakowska 2010). This common climatic influence may explain the long-distance teleconnections running from the west in Austria and the Czech Republic through to central Hungary, Maramures, and western Ukraine.

Precipitation in northwest Turkey and north Greece, at the southernmost point in our transect, is primarily influenced by cyclones of Mediterranean origin. These cyclones, originating in the western or central Mediterranean, move to the northeast toward the Black Sea and affect the Balkans (including sites in the Strandja Mountains), areas around the Sea of Maramara, and central-eastern Black Sea region. Northwest Turkey, Greece, and southeastern Bulgaria may also be influenced by cyclones originating in the Balkans, which move to the southeast and over the Sea of Marmara and Black Sea coast (Karaca *et al.* 2000).

Romania—the critical "bridge" linking the NCE and EM dendrochronological zones in our study area—is also located at an important climatic junction of multiple atmospheric circulation patterns. Precipitation in northwest Romania, including the Maramures area, is influenced by the cyclone track that also influences much of central Europe and southeast Poland (Bielec-Bakowska 2010). Southwestern and southern Romania receive Mediterranean cyclones originating in either the Adriatic or north Aegean Seas, which also pass through the Balkans (including the southern part of our study area) (Bojariu and Giorgi 2005; Kaznacheeva and Shuvalov 2012). Mediterranean cyclones passing through the Balkans and northwest Turkey may also be intensified by the Black Sea and follow a trajectory along the sea's western coast (Bojariu and Giorgi 2005). The trajectory of these types of cyclones largely follows the north-south teleconnections running from the Strandja Mountains through eastern Romania and Moldova to southern Ukraine.

The Carpathian Mountains and other local topography heavily restrict movements of continental and Mediterranean air masses and modulate the effects of atmospheric circulation patterns on both precipitation and temperature in our study area (Bojariu and Giorgi 2005). The limited tree-ring teleconnections across the Carpathian Arc (particularly between the Maramures chronology and other chronologies to the south and east of the Carpathians) in the study area indicate the critical role that these mountains have on the region's climate and (consequently) tree-ring signals. Nevertheless, as noted previously, significant teleconnections exist between the Sibiu site chronology (site #13) and other sites across the southern and eastern Carpathian chains. This suggests that Sibiu may be part of a unique microclimate that is influenced by both central European and Black Sea/Mediterranean air masses. The forthcoming addition of several new oak chronologies from Romania (Nechita 2013), particularly from the Transylvanian Plateau, may further illuminate the extent of, and bioclimatic conditions leading to, such trans-Carpathian teleconnections.

Oak Teleconnections and Post-Glacial Migration Routes

The spatial distribution of teleconnections among the tree-ring site chronologies also corresponds to the pathways along which oaks likely migrated from their primary refugia in SE Europe to northern Europe at the beginning of the Holocene. Palynological and DNA evidence indicate that during the last glaciation, de-

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ciduous oak taxa survived in three primary refugia in southern Europe: southern Spain, southern Italy, and the southern Balkans (Brewer *et al.* 2002; Petit *et al.* 2002). Over 71% of oaks examined in Poland (the northernmost end of the transect in our study area) belong to the Balkan haplotype (Dering *et al.* 2008), indicating that these oaks originated from the Balkan refugia.

The most probable locations of the Balkan glacial refugia are in western Greece in the region of Ioannina and on the western coast of the Black Sea (Brewer *et al.* 2002). Oak refugia were located usually in mid-altitude sites in unglaciated mountainous areas, where there was enough warmth and moisture to provide a suitable habitat. Geological evidence indicates that one of the areas sampled in this study, the Strandja Mountains, was left unglaciated during the last glaciation. Strandja's proximity to the Black Sea creates a mild, moist microclimate that today supports the only subtropical rainforest in Europe. This unique environment in Strandja was very likely one of the refugia for oaks during the Late Glacial period, and the area's forests preserve one of Europe's only pre-glacial relict populations.

The transition to moister and warmer climate conditions ca. 13,000 years ago provided an impulse for oaks to spread northwards from glacial refugia like Strandja. Pollen data indicate local expansion of *Quercus* into NW Romania by ca. 10,750 cal yr BP. Pollen and macrofossil data suggest that oak advanced to southern Poland by around 10–9.139 cal kyr BP (Goslar and Pazdur 1985; Milecka *et al.* 2004).

Quercus migration is much slower than that of many other genera, approximately 5–500 m/year (Lang 1994), because oak acorns cannot be dispersed over long distances by wind and are distributed mainly by jays and squirrels. It would have been difficult for heavy acorns to cross high mountains (which would have had largely unsuitable environmental conditions for oak), but sheltered mid-altitude mountain slopes would have provided favorable warm, moist environments for oak populations (Björkman *et al.* 2003).

The eastern and northeastern slopes of the Carpathians and their foreland contain large mid-altitude areas and deep incised river valleys that could have provided favorable shelter for migrating oak populations and a pathway through the Carpathians to NCE (Bodnariuc *et al.* 2002; Björkman *et al.* 2003; Tanţău *et al.* 2011). The same sheltered mid-altitude sites and valleys that provided oaks with a post-glacial colonization pathway from the Balkans to NCE also provide conditions that favor common tree-ring growth patterns that can be dendrochronologically crossdated (i.e. at the site of Sibiu, #13).

Dendrochronological Research Applications of the SE European Oak Network

The SE European tree-ring network developed here links the networks of oak chronologies in NCE and the EM. With this project, we have delineated geographic areas with common patterns of year-to-year tree-ring variability, i.e. areas with the same "dendrochronological signal," over the past 200 years. The chronologies built for this project can now be gradually extended back in time with dendrochronologically dated timbers from historical, archaeological, and paleoenvironmental sites.

The extension of the chronologies presented here will allow us to determine if the borders of the delineated dendrochronological zones are consistent over time or shift in response to long-term changes in climate and environment. Future research will also identify the climate response patterns of site chronologies within our study area and investigate the impact of large-scale atmospheric circulation patterns on spatial and temporal variability in the tree-ring network. The development of these long oak chronologies for SE Europe will contribute additional tree-ring data for paleoclimatic research, building on previous dendroclimatic work with other species in the region (e.g. Popa and Kern 2008; Panayotov *et al.* 2010; Trouet *et al.* 2012).

A dense spatial network of long tree-ring chronologies is the key to bridging spatial and temporal gaps in the existing NCE and EM tree-ring records. The dense network of local chronologies will increase the effectiveness of dendrochronological dating of wood by providing new reference chronologies that capture a wider range of regional variability in the tree-ring record. This denser network also allows us to define the boundaries of distinct dendrochronological zones in Europe, which in turn improves the precision with which we can determine the provenance of wood used in buildings, ships, works of art, and other objects. Such improvements in dendroprovenancing for Europe and the Aegean will make it possible to reconstruct past patterns and intensities of timber trade, building on similar research efforts elsewhere in Europe (e.g. Haneca *et al.* 2005).

The results of this project are in effect an introductory chapter to a yet unwritten book on the history and paleoecology of SE Europe based on the area's tree-ring archives. There is only one serious obstacle: as we observed during fieldwork, potential sources of long tree-ring sequences—including old living trees and timber from historical/cultural heritage sites—are rapidly disappearing in the region, and without immediate action, the book on SE European tree rings will never be written. Consequently, the research efforts summarized here should be continued and intensified before these valuable resources are lost. Fortunately, archaeological research in this region continues, and efforts continue to unearth wooden material for writing the rest of the region's history in tree rings.

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