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Dendroarchaeology in Greece – From humble beginnings to promising future

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ABSTRACT

It was back in the early 1960s when Bryant Bannister recognized the potential of dendrochronological research on wooden cultural heritage in Greece. More than two decades later, in the late 1980s, P.I. Kuniholm and C.L. Striker started collecting and analyzing tree-ring series from several historical buildings, forests, and archeological sites in Greece and the surrounding Aegean region. Despite highly promising results, especially from the northern and western parts of the country, dendroarchaeology did not attract much attention in the subsequent decades. It was only near the end of the 2000s that dendroarchaeology was reintroduced: first in Crete through the Cretan Dendrochronology Project, and then by another independent project concerning the restoration of a historical building on the island of Euboea. These isolated case studies inspired a five-year systematic research program called the "Balkan-Aegean Dendrochronology Project: Tree-Ring Research for the Study of Southeast-European and East Mediterranean Civilizations" (BAD Project). Dendroarchaeological surveys of historical buildings and archaeological sites were conducted throughout Greece with an emphasis on regions that had been previously ignored, such as the southern part of the country and the Aegean islands. Priority was given to buildings under restoration since in such cases original timbers were usually accessible and the architects, structural engineers, and archaeologists in charge were willing to collaborate. Our goals were not only to date timbers or provide information about the species used or the possible origin of the wood, but also to document the date, evolution, interventions and even the construction phases of historical buildings, as well as to help all those interested parties (academics, non-academics, researchers, professionals, local communities, etc.,) see the value of such information and how dendroarchaeology can contribute to the reconstruction of local history and the protection of cultural heritage. Tree-ring analysis led to the development of 18 chronologies from historical timbers and forests for six different species and different parts of the country from remote mountainous areas to small islands across the Aegean. The current dataset covers more than a thousand (1000) years and demonstrates the further potential of dendroarchaeology in the region.

1. Introduction

For many dendrochronologists Greece is known for its high mountains and multi-century-old living trees. Multi-centennial or even millennia-long chronologies have been developed for Bosnian pine (*Pinus heldreichii* Christ) from Mt. Olympus and Mt. Smolikas, the two highest mountains in Greece, and have been used for the study of past climate conditions (Klesse et al., 2015; Klippel et al., 2017, 2018; Esper et al., 2020, 2021). Mt. Smolikas is also home to the oldest dendrochronologically-dated tree in Europe: a 1075-year-old Bosnian pine (Konter et al., 2017). Multi-centennial chronologies for Greece going back to the 16th century CE exist for Black pine (*Pinus nigra* J.F.

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Arnold) (Brandes and Christopoulou, 2020) while deciduous oak (*Quercus* spp.) chronologies span the last ten centuries (Kuniholm and Striker, 1983; 1987).

Bryant Bannister was the first researcher who recognized the potential for dendroarchaeological research in Greece in 1961 (Schweingruber, 1989), but it took more than a decade before P.I. Kuniholm and C.L. Striker began to collect and analyze tree-ring series from historical buildings, old forests, and archaeological sites in Greece and the surrounding Aegean region (Kuniholm and Striker, 1983; 1987). Kuniholm and Striker visited and collected samples from more than 100 sites and developed the first reference chronologies for deciduous oaks in Greece, covering the last ten centuries. Nevertheless, these data cover mostly the northern and western parts of the country, while southern Greece and the islands were largely neglected (Christopoulou et al., 2020; 2021). During the following decades dendroarchaeology did not attract much attention and it was only near the end of the 2000s when dendroarchaeology was reintroduced; first in Crete through the Cretan Dendrochronology Project. This project was a collaboration between the Cretan Tree-ring Group, consisting of Professors Tomasz Ważny, Oliver Rackham, and Dr. Jennifer Moody and the Ephorate of Antiquities of Rethymno, and was funded by the Institute for Aegean Prehistory (INSTAP). The primary goal of the project was to study long-lived Cretan trees (cypress, oak, and pine) and use them to develop reference tree-ring chronologies that could be used to date construction timber and wooden artefacts. A further goal was to study past climatic conditions and to understand the demography and ecological history of dominant tree species on the island (Ważny et al., 2020). A separate, independent dendroarchaeological project took place on the Greek island of Euboea, when a dendrochronological investigation was requested by the restoration group of a Venetian building called "Bailo House"

Fig. 1. Study area. Green dots represent our study sites in Greece.

in Chalkis. Tree-ring analyses revealed the date and different construction phases of the building (Kourmadas and Tsakanika 2020). These initially isolated projects evolved into a five-year research project (2018–2022): the "Balkan-Aegean Dendrochronology Project: Tree-Ring Research for the Study of Southeast-European and East Mediterranean Civilizations" (BAD Project). The BAD Project's primary goal was to assess the potential for and/or to further develop dendroarchaeological research in these regions. To achieve this goal, a database consisting of absolutely-dated tree-ring chronologies was developed by examining wood and charcoal remains from numerous archaeological sites and historical buildings in the Aegean region and the Eastern Mediterranean. This independent archive of tree-ring chronologies provides a solid foundation for studying the environmental and cultural histories of the Balkans, Aegean, and their neighbors, serving as a tool for the study of forests and architectural heritage of these areas. In the current review paper, some of the major research results from Greece are presented. The review starts from the Northern Pindus National Park of Northwestern Greece, where dendroarchaeology was applied for the first time to buildings in which Bosnian pine is the most commonly used species for wooden structures and artifacts, and then continues towards south to the Peloponnese, the Aegean islands and Crete (Fig. 1).

2. Materials and methods

In each study site firstly the availability of timber was examined. Later accessible objects/sites that would have the highest potential for successful dating and development of the longest possible and new absolutely-dated chronologies were selected and sampled. In most cases, sampling from buildings was done in collaboration with the architects/civil engineers and/or archaeologists in charge, in order to get results that would be useful for the documentation and restoration of such buildings. It must be noted that timbers to be sampled should be carefully chosen and in close collaboration with the above-mentioned professionals since their provenance and structural, architectural, or decorative roles can help document the date, interventions, and/or even the construction phases of buildings. For example, samples from horizontal timber reinforcements of masonry can accurately date an original structure while samples from a floor or a roof may represent later interventions.

In the case of historical buildings, priority was given to buildings under restoration where original timbers were usually accessible and the responsible architects, civil engineers, and archaeologists were willing to collaborate. When local reference chronologies were missing, samples from dominant tree species that can be found in nearby forests were also collected.

The object type and the provenance and type of available timbers determined the type of samples taken. With living trees, increment cores were extracted with increment borers that reached the pith of the tree, thus representing the tree's entire radius. With dead trees (snags, downed logs, and stumps), stem disks were cut with a chainsaw. Stem disks were also collected from freshly feld beech trees (*Fagus sylvatica* L.) and log piles, probably cut for furniture production (see Section 3.1). In the case of historical buildings cores were collected with the use of a modified electric drill and stem disks with the use of a hand saw or chainsaw, depending on the specific characteristics of each building, the available timber, and the position of each element. Stem disks were collected especially when wooden elements would be replaced with new ones. In cases where the ends of timbers were exposed, non-destructive methods were used and tree-ring widths were measured on high-definition photographs of the prepared surfaces using the software application, CooRecorder (Cybis Elektronik & Data AB). The exact positions where sampling was done were decided collaboratively together with local authorities to maximize the possibilities of obtaining information about different constructional phases of buildings. Finally, in the case of archaeological sites all wood and charcoal remains and selected pieces that could be potentially useful for dendrochronological analysis were examined through.

Samples were analyzed in two different dendrochronological laboratories, one in Poland and one in Greece, because obtaining permission for exportation, especially for archaeological material, may take time, or even not be allowed if certain types of analyses can be performed inside the country. These boundaries have been set to protect Greek national cultural heritage.

All samples were properly prepared with the use of either progressively finer grade abrasive paper or razor blades to make tree-rings and xylem cells clearly visible under magnification. In the case of charcoal, it was sometimes enough to split the pieces so that a good cross-section was visible. Prior to tree-ring width measurements, taxonomical identification of archaeological samples was performed based on their wood anatomical properties. Identification was based on studying radial, tangential, and transverse sections under a biological microscope, and the comparison of wood structure against reference material from known tree species (e.g. Schweingruber, 1990; Schoch et al., 2004; Akkemik and Yaman, 2012).

Tree-ring widths were measured with the use of Time Series Analysis and Presentation (TSAP) software package (Rinn, 2011) and LINTAB measuring table (Rinntech®). Measurement accuracy was set to 1/100 mm. The measurements of each sample were compared with those from the rest of the samples from each site, using both statistical and visual cross-dating. Samples that correlated well with each other were used to develop a mean "floating" chronology for each site. The newly-developed chronologies were then cross-dated and synchronized with available reference chronologies from the broader area. The reference chronologies used for cross-dating are presented in Table 1. Visual and statistical cross-dating was performed using TSAP-Win and COFECHA (Holmes, 1983). For statistical cross-dating the following parameters were used: i) Gleichläufigkeit (Glk), which shows how well the growth of two trees parallel each other in an overlapping set of years; ii) t-value Ballie-Pilcher (TVBP) (Baillie and Pilcher, 1973) and t–value Hollstein (TVH) (Hollstein, 1980), which are sensitive to extreme values, such as marker years; and iii) Cross-Dating Index (CDI), which combines i and ii (Rinn, 2011). The number of overlapping years (OVL), expressing the common interval, was also taken into account. The analyses were performed separately for each species, although in some cases reference chronologies of other species were also used because using mixed chronologies is a common practice in dendroarchaeology, especially for conifers (e.g., Kuniholm et al., 2011).

In cases where the sample size was not sufficient and/or the available reference chronologies were limited, the dating results obtained by dendrochronology were rather uncertain. Therefore, radiocarbon dating and/or wiggle-matching analysis were also applied to such samples. Selected tree-rings were properly extracted and sent to the Laboratory of Absolute Dating in Kraków (Poland) for further analysis (for details see Christopoulou et al., 2023). Received results were calibrated using OxCal v 4.4 software (Bronk Ramsey, 2009) and the calibration curve IntCal20 (Reimer et al., 2020). In selected sets of tree-rings (see the next section), wiggle-matching modeling, a method which allows the age determination of a sequence/chronology with a higher precision than the C14 dates alone, was applied (Pearson, 1986).

3. Results and discussion

3.1. Dendroarchaeology in the Northern Pindus National Park

The Northern Pindus National Park is the largest terrestrial national park and one of the most ecologically important areas in Greece. One of the unique characteristics of the Pindus National Park is the presence of multi-century-old Bosnian pine stands that have been the focus of dendroecological and dendroclimatological studies (Klippel et al., 2017; 2018; Esper et al., 2020, 2021). These studies were conducted on both living and dead trees and the resulting developed chronology for Bosnian pine dates to 729 CE (Esper et al., 2021) with sufficient replication

Table 1
Reference chronologies used for dating the newly-developed chronologies in the current study. PIHE: *Pinus heldreichii*, PINI: *Pinus nigra*, JUSP: *Juniperus* sp., JUEX: *Juniperus excelsa*, QUSP: *Quercus* sp., CELI: *Cedrus libani*, CUSE: *Cupressus sempervirens*. For information about the chronologies in the column "Used against" see Table 2.

a/a	Species	Code	Site name/area covered	Reference	Time span	Used against
1	PIHE	EHS01	Mount Smolikas/ Northern Pindus National Park, Greece	Klippel et al., (2018)	575–2015	MAVRO01m, MTFAD01m, ANMPIHE, ANMPINI1, ANMPINI2, THPH01m, PADH01m, PALH01m
2	PIHE	PIHE0001	Katara Pass Metsovo/Northern Pindus National Park, Greece	Schweingruber, (2002)	1673–1981	NAFP03PN
3	PIHE	GrGreven	Grevena forest, Greece	Kuniholm and Striker, (1983)	1243–2002	
4	PIHE	Albania2	Fushe Lura, Albania	Seim et al., (2012)	617–2008	
5	PIHE	POLPIHE	Mt Pollino, Italy	Serre-Bachet, (1985)	1148–1974	
6	PINI	GREE009	Mt Taygetos, Greece	Kuniholm and Groneman, (2007)	1657–1999	Black pine two-timber sequence
7	QUSP	GAPN001i	Agios Panteleimon, Larisa, Greece	Kuniholm and Striker, (1983)	1358–1557	TANQS1m
8	QUSP	GRCWest1	Western Greece	Kuniholm and Striker, (1983), (1987)	1162–1978	KORC01m
9	QUSP	GrThess1	Thessaly, Greece	Kuniholm and Striker, (1983), (1987)	1169–1847	AGDC01m
10	JUSP	GORKIZ	Gordion, Turkey	Kuniholm et al., (2011)	-1767–857	AGVAS01m, AGVAS02m
11	PINI	Turk053	Black pine forests in Turkey	Köse et al., (2017)	1537–2010	SIEPJ01m
12	JUEX	Turk014	Subatan, Konya, Turkey	Touchan and Hughes, (2003)	1246–2000	
13	PINI	Turk001	Eskişehir, Çatacık Orman, Turkey	Kuniholm, (2005)	1292–2001	
14	PINI	Turk013	Aziziye, Turkey	Touchan and Hughes, (2007)	1511–2001	
15	PINI	Turk033	Around Alanya-Cevizli, Turkey	Akkemik, 2007	1597–1995	SYMIPN01
16	CELI	ElmalıRa	Hüseyin Kuyusu, Turkey	Touchan et al., 2005	1449–2000	SYMICL03
17	CUSE	LEOR00CS	Lefka Ori, Crete, Greece	Wazny et al., in prep.	1110–2018	PREV00CS

Table 2
Descriptive statistics of the newly-developed chronologies representing local timbers: the mean correlation of individual series with the master chronology (MC) and standard deviation (SD). MC and SD are not presented for the cases with less than three synchronized sequences. PIHE: *Pinus heldreichii*, PINI: *Pinus nigra*, FASY: *Fagus sylvatica*, JUSP: *Juniperus* sp., QUSP: *Quercus* sp., CUSE: *Cupressus sempervirens*.

a/a	Species	Code	Reference	Site name/area covered	Number of synchronized series	Type of object/ site	Average age	Time span	MC (SD)
1	PIHE	MAVRO01m	Christopoulou et al. (2022a, 2022b)	Northern Pindus National Park	51	forest	405 (126–735)	1284–2018	0.589 (0.078)
2	PINI	MALPINI	Christopoulou et al. (2022a)	Northern Pindus National Park	19	forest	292 (189–344)	1677–2020	0.584 (0.077)
3	FASY	MTFAD01m	current paper	Northern Pindus National Park	25	forest	190 (121–285)	1734–2022	0.564 (0.117)
4	PIHE	ANMPIHE	Christopoulou et al. (2022a)	Monastery of St. Nicholas	7	historical building	127 (60–199)	1349–1745	0.370 (0.104)
5	PINI	ANMPINI1	Christopoulou et al. (2022a)	Monastery of St. Nicholas	8	historical building	128 (56–220)	1374–1618	0.518 (0.067)
6	PINI	ANMPINI2	Christopoulou et al. (2022a)	Monastery of St. Nicholas	3	historical building	124 (97–169)	1677–1857	0.668 (0.044)
7	PIHE	THPH01m	current paper	Tsanaka's house	15	historical building	96 (38–244)	1437–1772	0.472 (0.115)
8	PIHE	PADH01m	Elzanowska et al. (submitted)	Pades	12	historical building	179 (49–413)	1260–1812	0.480 (0.179)
9	PIHE	PALH01m	current paper	Palaioseli	20	historical building	137 (52–293)	1271–1862	0.473 (0.080)
10	PINI	NAFP03PN	Makris et al. (2021)	Venetian building, Nafplio	6	historical building	76 (72–83)	1903–1997	0.519 (0.086)
11	PINI	Black pine two-timber sequence	Makris et al. (2021)	Venetian building, Nafplio	2	historical building	99 (97–100)	1771–1870	-
12	QUSP	TANQS1m	Christopoulou et al. (2023)	NW Tower of the Androusa Castle	4	historical building	41 (38–44)	1447–1495	0.765 (0.070)
13	QUSP	KORC01m	Christopoulou et al. (2023)	Koroni Castle	7	historical building	84 (45–128)	1410–1540	0.516 (0.058)
14	QUSP	AGDC01m	Christopoulou et al. (2023)	Church of Agios Dimitrios	2	historical building	76	1632–1722	-
15	JUSP	AGVAS01m	Christopoulou et al. (in press)	Agios Vasileios	26	archaeological site	36 (19–79)	-1518–1324	0.385 (0.167)
16	PINI	AGVAS02m	Christopoulou et al. (in press)	Agios Vasileios	18	archaeological site	39 (23–56)	-1717–1619	0.460 (0.245)
17	JUSP	SIEPJ01m	current paper	Episkopi church, Sikinos island	8	historical building	73 (63–86)	1510–1657	0.3770 (0.147)
18	CUSE	PREV00CS	Christopoulou et al. (2021)	Preveli Monastery, Crete	6	historical building	57 (37–78)	1710–1826	0.220 (0.059)

(>20 trees).

Our research activities started in Metsovo, a town inside the Pindus National Park and the centre of Vlach population and culture, where *Pinus heldreichii* has been traditionally used for the construction of buildings and manufacture of wooden objects (Christopoulou et al., 2022a). This species has not yet been systematically investigated from a dendroarchaeological perspective due to its limited distribution. An early exploration of the historical and traditional buildings in the region of Metsovo suggested that, in addition to Bosnian pine, other species, such as Black pine and beech, that can be also found in the area were used for different types of wooden elements. From the nearby forests local chronologies were developed. For Bosnian pine a 735-year-long chronology (MAVRO01m, Table 2) was developed from trees growing on a summit called Mavrovouni (Fig. 2a), only 9 km N–NW of Metsovo (Christopoulou et al., 2022b). For Black pine a 344-year-long chronology (MALPINI, Table 2) was developed from a Black pine forest (Fig. 2b) located ~9 km E-NE of Metsovo (Christopoulou et al., 2022a). Finally, for beech (Figs. 2c, 2d), the first chronology from the study area was developed, covering the last 285 years (MTFAD01m, Table 2). Both Black pine and beech chronologies correlate very well with the Bosnian pine chronology (Fig. 3). Descriptive statistics of the newly-developed chronologies representing local timbers are presented in Table 2 while the chronologies themselves are provided in Appendix I.

The first building we examined was an auxiliary edifice at the Monastery of St. Nicholas (Fig. 4a), a prominent monastery of the region mentioned in historical documents since the 14th century CE that was destroyed, rebuilt, and restored over the following centuries. Cores were collected from a total of 21 elements, mostly from the floor beams, vertical elements supporting the floor beams and cantilever beams on the ground floor supporting the floor beams with extra timbers. Eight (8) of the samples were stem disks, cut from a pile of discarded timber inside the basement, mostly originating from old planks that had been removed for safety reasons. Wood identification suggests that both Bosnian and Black pine were almost equally used for the construction of the auxiliary building at the monastery. The crucial anatomical difference between the two species is visible in the radial section as described by Christopoulou et al. (2022b). All the Black pine samples as well as all but three samples of Bosnian pine were dated. For *Pinus heldreichii* a 397-year-long chronology, spanning from 1349 to 1745 CE, was developed (ANMPIHE) while for *Pinus nigra* two non-overlapping chronologies were constructed that cover the periods of 1374–1618 CE (ANMPINI1) and 1677–1857 CE (ANMPINI2). The later dates probably come from the timber used in the more recent restorations of the building. All the three chronologies were dated against local reference chronologies (Christopoulou et al., 2022a). The newly-developed chronologies correlate also with the chronologies developed for dendroclimatological studies from the nearby mountains (Klippel et al., 2018) that have t-values higher than ten (10) (Christopoulou et al., 2022a). This shows that chronologies developed for climate reconstruction can also be used for dating historical timber.

Bosnian pine was also the main timber used for the construction of the Tsanaka's house, an old mansion located in Metsovo that serves as a museum. Thirty-two (32) samples were collected from this site, mostly from the roof and the timbers of the horizontal reinforcement system of the masonry walls that were accessible either from the inside or outside of the building (Figs. 4b-4d). The original roof was made of Bosnian pine after 1772 CE (THPH01m, Fig. 5), while Black pine and beech were most probably used for restorations, the most recent of which took place after 2007 CE.The 2007 CE date, also confirmed by the locals, came out while cross-dating the two Black pine samples with our newly-developed chronology from living Black pines. Although the majority of the beech samples remained undated, one sample was dated to 1818 CE against our newly-developed beech chronology, MTFAD01m. The same year came out while cross-dating this sample with the MAVRO01m Bosnian pine chronology and also against the Bosnian pine chronologies developed by other researchers (e.g. GrGreven, Kuniholm and Striker, 1983;

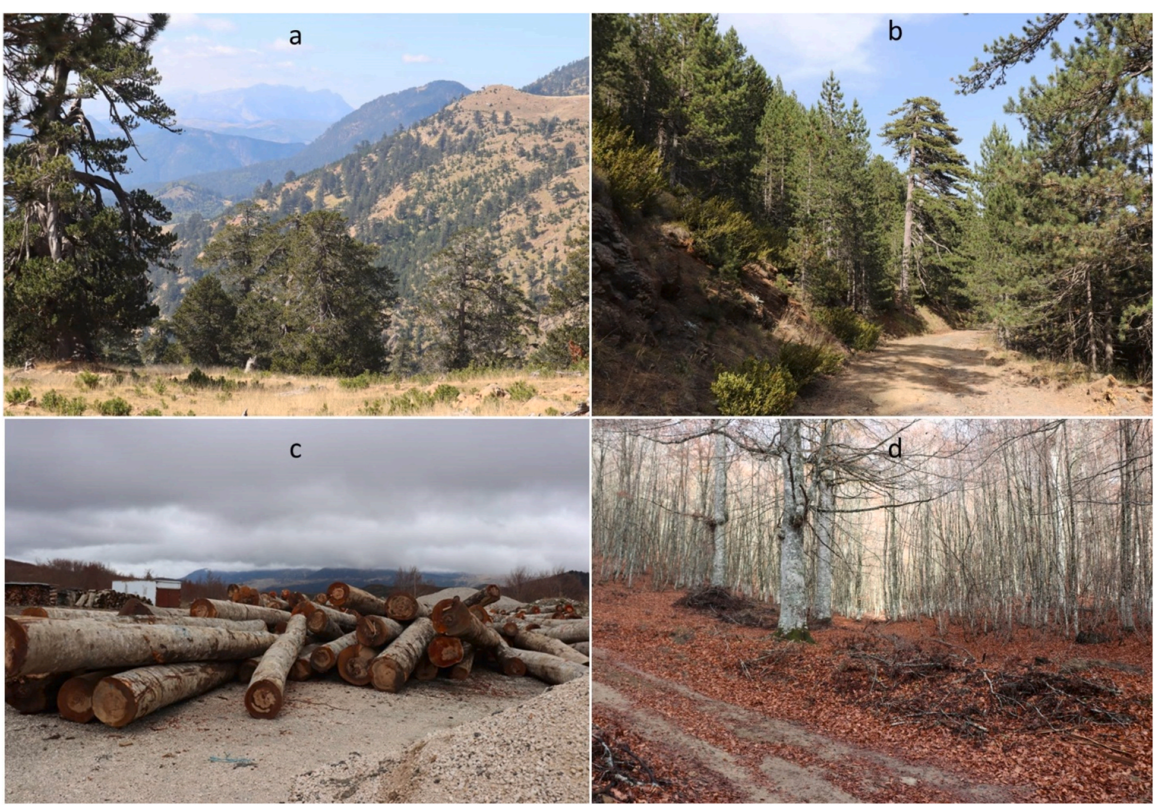

Fig. 2. Study sites where trees were sampled in the region of Metsovo: (a) Bosnian pines on the Mavrovouni summit, (b) a Black pine forest close to Metsovo, (c) a pile of beech logs from freshly-cut trees, (d) the original position of the sampled beech logs.

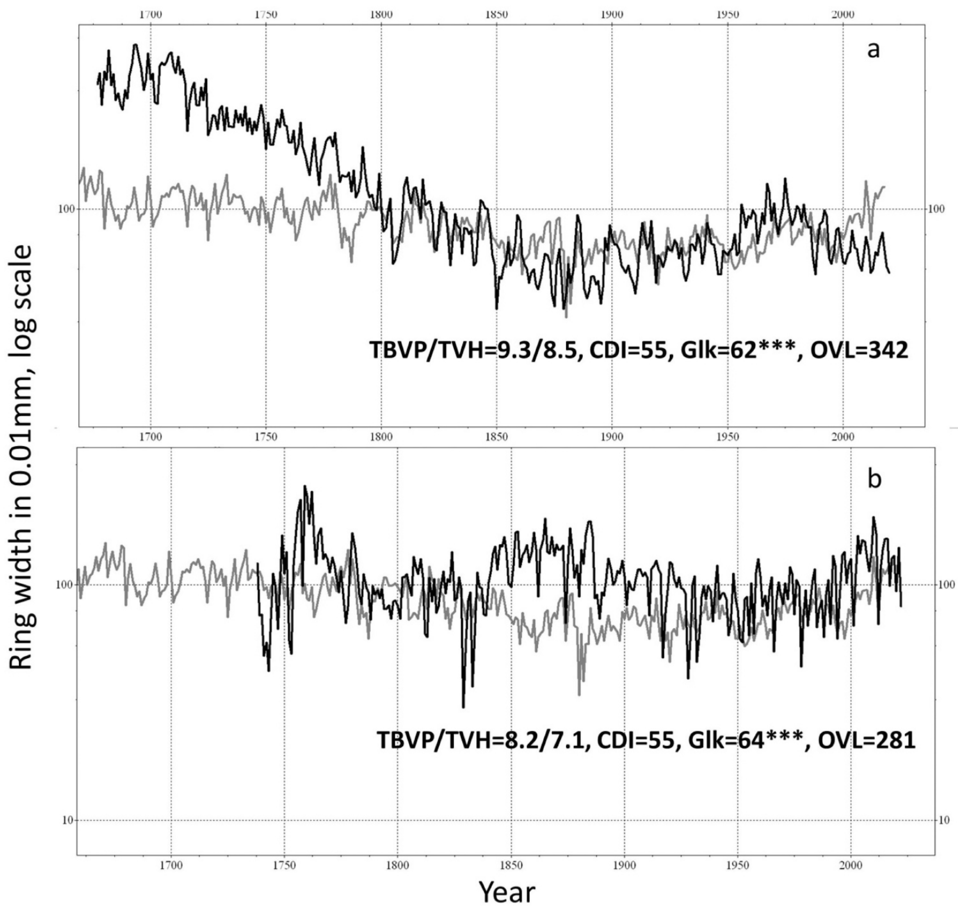

Fig. 3. Visual cross-matching of the Black pine (MALPINI, in black) (a) and the beech (MTFAD01m, in black) (b) chronologies with the Bosnian pine chronology (MAVRO01m, in grey) from the Northern Pindus National Park. Only the overlapping years/range of the Bosnian pine chronology are presented here. The results of statistical cross-dating are also provided: TVBP/TVH = t-value Ballie-Pilcher and t–value Hollstein; CDI = Cross-Dating Index; Glk = Gleichlaeufigkeit; OVL = the number of overlapping years.

Fig. 4. Historical buildings in Metsovo within the Northern Pindus National Park where dendroarchaeology was applied: (a) Monastery of St. Nicholas, (b) Tsanaka's house, (c) The roof construction of the Tsanaka's house that was recently renovated using original timbers that are still preserved (white box), (d) The timber reinforcement of the masonry wall made of Bosnian pine.

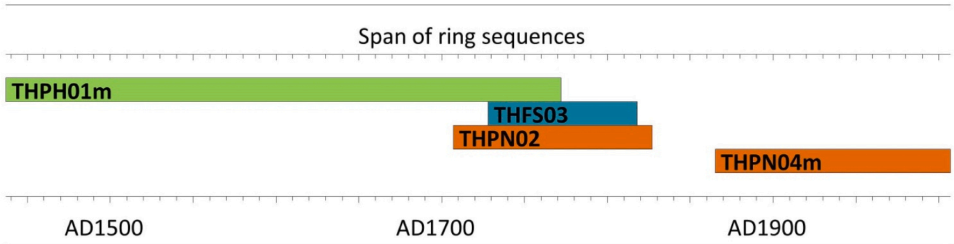

Fig. 5. The chronological span of the dated timbers from the roof of the Tsanaka's house: Bosnian pine in green, beech in blue, and Black pine in orange. The graph was prepared in DENDRO for Windows (Tyers, 2004).

PIHE0001, Schweingruber, 2002; EHS01, Klippel et al., 2018, Table 1). These results may suggest that if beech and Bosnian pines are growing in the same area, they can be used to date one another. Nevertheless, further evidence of interspecies correlation is needed to strengthen this hypothesis.

Within the borders of the Northern Pindus National Park two other historical buildings were under restoration, and therefore, they could also be dendrochronologically examined. Both are old churches that are protected as cultural heritage monuments. The first building is in Pades (Fig. 6a) and the second one in Palaioseli (Fig. 6b), two small villages on the slopes of Mt Smolikas at 1,000+ meters. Both cases represent complex, multi-phase structures where a large number of timbers was available and therefore, many samples were collected: 75 from Pades and 41 from Palaioseli. The two churches had roof constructions made of Bosnian pine as the main timber (Fig. 6c). In some of the collected samples the waney edge was present. This suggests that the dates obtained from these samples give their felling dates. The second most frequent species was Black pine, which was especially dominant in the church in Pades and used in its different structural elements, including the roof, ceiling, narthex floor, and narthex columns. In the church in Pades, the timbers used in the walls to reinforce them against earthquakes were made of deciduous oaks (Fig. 6d). It should be noted that in such old mansions a different species was preferred intentionally for the timbers in walls, a species that is more durable than those used for floor and roof constructions, in order to protect them from decay, a common threat for timbers embedded in walls.

The percentage of the dated samples was high for both churches: 77% for Pades and 87% for Palaioseli. In both cases, the developed chronologies for Bosnian pine covered more than 500 years (Table 2, Appendix I) and correlated with reference chronologies developed from the nearby forests, showing that the timber used was of local origin. The highest t-values for Pades were obtained against GrGreven (Kuniholm and Striker, 1983) (TVBP/TVH =12.6/14.0) and for Palaioseli against EHS01 (Klippel et al., 2018) (TVBP/TVH =15.8/14.8) while t-values higher than ten (10) were also obtained against Bosnian pine chronologies from Albania (Seim et al., 2012) and Italy (Serre-Bachet, 1985). Another shared characteristic was that in both churches re-used timbers with cuttings (Fig. 6e) were also found, which do not overlap with their existing structural system as indicated by the structural study of their roofs. Some of these re-used timbers date back to several centuries prior

Fig. 6. Churches under restoration on the slopes of Mt. Smolikas where dendroarchaeology was applied: (a) the Pades church of the Assumption of Virgin Mary, (b) the Palaioseli church of Agia Paraskevi, (c) The roof construction in the Palaioseli church, (d) A timber inside the masonry wall made of deciduous oak in the Pades church, (e) The re-used timber from the 15th century CE in Palaioseli's roof construction.

Fig. 7. Examples of study sites in the Peloponnese: (a) the Venetian building in Nafplio with a dendrochronologically confirmed Venetian first phase and extensive constructions in the early 1700s CE, (b) the Agios Dimitrios church from the first half of the 18th century CE, (c) the NW tower of the Androusa castle that dates back to the late 15th century CE, (d) the castle of Koroni that dates back to the 1540s CE, (e) the Mycenaean palace at Agios Vasileios, (f) a Black pine charcoal fragment with enough number of rings to be selected for further dendrochronological analysis from Agios Vasileios.

to the construction age the both churches. This finding suggests that Bosnian pine timber was recycled, confirming the high quality and resistance of Bosnian pine wood (Klippel et al., 2017).

3.2. Peloponnese

The Peloponnese is a region in Southern Greece where the available published data have remained, until recently, very limited despite previous dendroarchaeological surveys (Christopoulou et al., 2023). In a Venetian building in Nafplio (Fig. 7a), our dendroarchaeological analysis provided new information oon its earlier phase that was proved to be of the Second Venetian period (the end of the 17th century CE). Moreover, several different tree species were used for its construction, including local and imported timber (Makris et al., 2021). On the other hand, in three buildings of different status and from different historical periods in the Western Peloponnese (Figs. 7b-7d), local deciduous oaks (*Quercus* spp.) were the only timber type that was used (Christopoulou et al., 2023). In Table 2 our chronologies, which, in both cases, most probably represent local timber, are presented. In the case of the three buildings in the Western Peloponnese, because the sample size was less than ten (10) per site, radiocarbon dating and wiggle-matching methods were additionally used. Radiocarbon dating and wiggle-matching analysis were also applied to material from archaeological sites in the same region. One such example is Agios Vasileios, a Bronze Age Mycenaean palace located to the south of Sparta (Lakonia) (Fig. 7e) where several Linear B tablets have been discovered (Karadimas, 2016; Vasilogamvrou et al., 2022). The site was visited several times and our in-situ examinations of charcoal pieces and wood fragments led to a final selection of 103 samples, mostly charcoal, for which species identification and an estimation of the minimum number of rings in cross-sections were carried out (Fig. 8f). Wood identification revealed seven different species, all corresponding to local timber. Juniper (*Juniperus* sp.) and Black pine (*Pinus nigra*) were the dominant tree species, from which two "floating" chronologies were developed, covering 195 and 99 years respectively (Table 2). Both chronologies were dated against juniper chronologies from Anatolia (Türkiye), which are the only available reference Bronze Age tree-ring chronologies for the broader area, developed by P. Kuniholm and his team (Kuniholm et al., 2011) (TVBP/TVH =5.1/5.3 for AGVAS01m juniper chronology and TVBP/TVH =5.2/5.1 for AGVAS02m Black pine chronology). Radiocarbon dating and wiggle-matching analysis confirmed the suggested dating, placing the juniper samples in the 15th century CE and the Black pine samples in the 17th century CE (Christopoulou et al., in press). Charcoal is often dated only by radiocarbon analysis (Blondel et al., 2018) due to its low number of preserved tree-rings. However, material from this site shows that even with small charcoal pieces, as they can be part of larger trunks, it might be possible to develop sequences that are long enough and worth testing with cross-dating, provided that the number of samples is sufficient and reference chronologies are available.

3.3. The Aegean islands

Although several chronologies have been developed for the Aegean region (Kuniholm and Striker, 1983; 1987; Griggs et al., 2007), they include little, if any, tree-ring series from the Aegean islands. Within the framework of the BAD Project the dendroarchaeological potential of several islands was explored. Below research results from one Cycladic and one Dodecanesian island are briefly presented. On Sikinos, one of the smallest Cycladic islands, the Episkopi church, a historically protected monument that was being restored, was examined (Fig. 8a). The monument of Episkopi was initially a third century CE Roman mausoleum, but in Byzantine times it was converted into a church. The most recent restoration project of the building was carried out by the Ephorate of Antiquities of the Cyclades. The monument had numerous timber elements that needed to be replaced during the latest restoration completed in 2022. This allowed us to collect 24 out of 30 samples as stem disks. The samples were mainly collected from door frames and lintels, beams inside the walls used as timber reinforcements, and wedges that were used to stabilize the beams. Ninety percent (90%) of the collected samples were juniper (*Juniperus* sp.), but deciduous oak

Fig. 8. Examples of study sites on the Aegean islands: (a) the monument of Episkopi on Sikinos (Cyclades), (b) the door of Episkopi made of three different tree species, (c) a juniper (*Juniperus* sp.) sample from Episkopi that includes several false rings, (d) the standing windmills located on a hill to the east of the village of Symi (Dodecanese), (e) Valonia oak (*Quercus ithaburensis* subsp. *macrolepis*) on Symi, (f) Brutia pine (*Pinus brutia*) forest on Symi, (g) Cypress (*Cupressus sempervirens*) on Symi.

(*Quercus* sp.) and olive (*Olea europaea* L.) were also observed especially on the main door (Fig. 8b). All the three species are native to the region, with juniper being the most common tree species and the main source of timber on the island. Due to the small sample size for deciduous oak (n=2) and olive (n=1), the only samples that could be synchronized were of juniper. But even in this case, it was not an easy process due to the presence of multiple false rings (Fig. 8c). The existence of false rings suggests that the timber originated from low-altitude trees that grew where there was a strong summer dry season (Schweingruber, 1993). Such conditions are typical on a Cycladic Island. The developed floating chronology (SIEPJ01m) consisted of eight (8) samples and had a length of 148 rings. It was cross-dated against existing juniper and other conifer chronologies from the broader area since no juniper chronology had been developed for the Aegean islands. After cross-dating, at least four independent chronologies provided the same ending year: 1657 CE (Table 1). The best match (TVBP/TVH =4.5/4.6) was with the Turk053 Black pine chronology from Türkiye (Köse et al., 2017). Although interspecies dating is reliable (Loader et al., 2021), especially between different conifer species (Kuniholm et al., 2011), radiocarbon dating and wiggle-matching methods were also applied to confirm the suggested dates. Radiocarbon dating results (not shown here) also placed the samples into the 16th or 17th century CE, which is consistent with historical sources suggesting that the church must have taken its current form during the Ottoman period.

On Symi, a small island in the Dodecanese Island chain, samples were collected from windmills under restoration (Fig. 8d) where local timber was expected to have been used. In order to have reference material for the local historical timber, we collected cores from living trees for the three dominant tree species of the island: Brutia pine (*Pinus brutia* Ten.), cypress (*Cupressus sempervirens* L.) and valonia oak (*Quercus ithaburensis* subsp. *macrolepis* (Kotschy) Hedge and Yalt.) (Figs. 8e-8g). Although rather long chronologies, covering more than 100 years, were developed for all these three species, they were not useful in dating the historical timber because wood identification and cross-dating results suggested that most of the timber was imported from the nearby Turkish coast (Christopoulou et al., 2020), a common practice with many buildings of this area. Mid to high-altitude pine, most probably *P. nigra* and cedar (*Cedrus* sp.) represented the majority (43.5%) of the identified tree species. Both Black pine and cedar chronologies were dated against reference chronologies from Türkiye (TVBP/TVH =5.5/5.3 for SYMIPN01 Black pine chronology and TVBP/TVH =4.9/4.4 for SYMICL03 cedar chronology; reference chronologies are shown in Table 1).

3.4. Crete

On Crete, natural stands of cypress (*Cupressus sempervirens*) occur from sea level up to 2000 m asl. In the Lefka Ori, cypress trees form two different types of woodlands with very open canopies: the first one is in the lower and middle montane-Mediterranean belts at 1000−1400 m asl, and the second one is at the timberline (1400–1800 m asl) in the upper montane-to-oro-Mediterranean belts (López-Sáez et al., 2019). Ważny et al. (2014) developed a 903-year-long cypress chronology from trees at the timberline, however, the sample size is sufficient for further statistical and dendroclimatological studies only after 1870 CE. Cypress trees from lower altitudes were not included because of the presence of false rings (Schweingruber, 1993; Christopoulou et al., 2021). Since 2014 this cypress chronology has been enriched and strengthened by incorporating more samples (Fig. 9a) and now contains more than 50 trees (Ważny et al., in prep.). Apart from its usefulness for long-term climate reconstruction, this chronology has been particularly useful in dating historical wood from buildings in Crete where cypress is one of

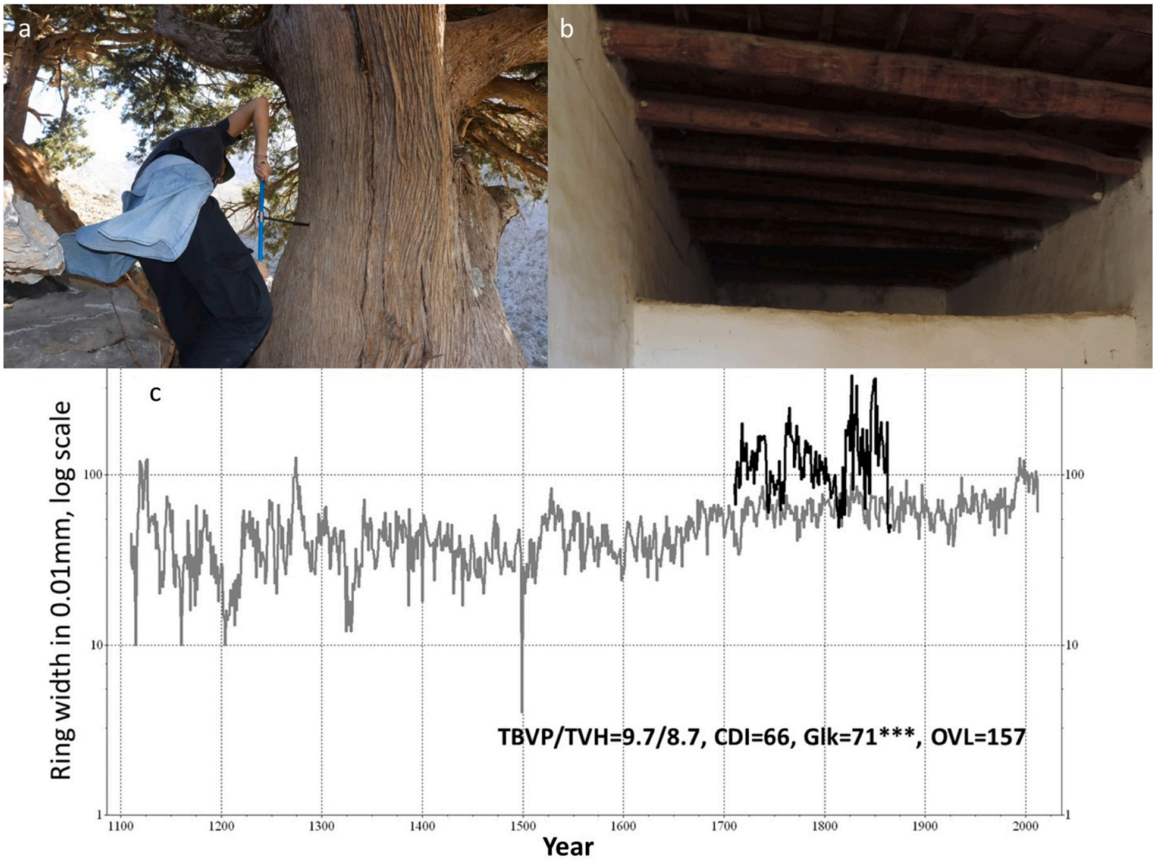

Fig. 9. (a) Collecting samples from old living cypress trees, (b) Cypress floor beams in historical buildings, (c) Visual cross-matching of the cypress chronology developed from the seven (7) synchronized samples from Preveli Monastery (in black) against the cypress chronology from the Lefka Ori (in grey). The results of statistical cross-dating are also provided: TVBP/TVH = t values; CDI = Cross-Dating Index; Glk = Gleichlaeufigkeit; OVL = the number of overlapping years.

the main local timber types (Fig. 9b). For example, in Preveli Monastery, a historic monastery located on the southern coast of Rethymno, cypress timber was used for different types of beams, including floor beams and beams of the horizontal roof (Christopoulou et al., 2021). Out of the 41 collected cypress samples, only seven (7) could be synchronized, mainly due to the presence of false rings. The synchronized samples were used to develop a 157-year-long chronology (PREV00CS, Table 2) that was dated against the cypress chronology developed from the Lefka Ori (Fig. 9c, Table 1). Extending the current cypress chronology further back in time would be useful for dating numerous cypress charcoal remains found in archaeological sites, especially in West and Central Crete.

4. Conclusions

The activities of our five-year project in Greece demonstrate that there is great potential for dendroarchaeological studies in the region. A major scientific goal of our project was to extend and update the previously established chronologies from and around the region. The data presented in the current paper, although representing only a small part of the dataset developed by the BAD Project, cover 752 years in the CE (Fig. 10) and 294 years in the BCE. New tree-ring data for the six tree species presented here emerge from previously neglected or not sufficiently explored areas in Greece - from remote mountainous areas to small islands.

In addition to dating available timbers and providing information about their species and origins, another major goal of the BAD Project was to showcase the inevitable role of dendroarchaeology in the reconstruction of local histories with annual precision and how it can contribute to the protection of cultural heritage. The case studies discussed above demonstrate how professionals from different backgrounds (academics, non-academics, researchers, etc.) and local communities can benefit from the diverse information generated through dendroarchaeology at multiple scales.

Our experience also showed us that timbers must be properly and carefully chosen before sampling in close collaboration and consultation with the responsible architects, civil engineers, and archaeologists. This is crucial for a full understanding and proper documentation of the construction date, later interventions and phasing of historical structures and buildings. To this end, collaboration with experts from different fields is essential (Edvardsson et al., 2021) and through mutual understanding dendrochronological results acquire new values and interpretations.

We believe that priority should be given to historical buildings under restoration since in such cases original timbers are often accessible, which makes sampling procedures and collaboration with local stakeholders and participants less problematic. The results produced could potentially promote and facilitate the further development of dendroarchaeology in the region.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Anastasia Christopoulou, Yasemin Özarslan, Anna Elzanowska and Tomasz Ważny report that financial support was provided by National Science Centre, Poland.

Data Availability

Data are available in Appendix.

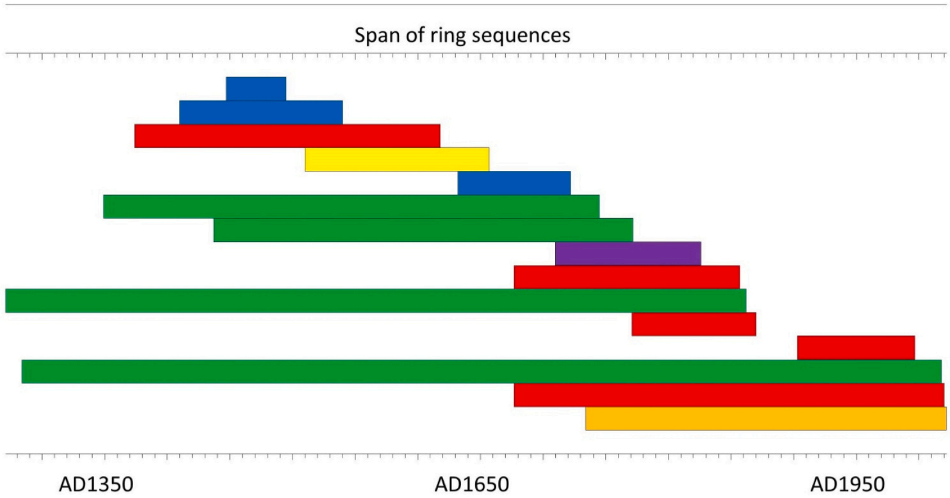

Fig. 10. The chronologies developed within the BAD Project from historical buildings, covering the last eight (8) centuries in the CE, for six (6) different species: blue for *Quercus* sp., red for *Pinus nigra*, yellow for *Juniperus* sp., green for *Pinus heldreichii*, purple for *Cupressus sempervirens*, orange for *Fagus sylvatica*. The graph was prepared in DENDRO for Windows (Tyers, 2004).

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.dendro.2024.126196.

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