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### ► To cite this version:

Manuela Capano, Nicoletta Martinelli, Marco Baioni, Thibaut Tuna, Mauro Bernabei, et al.. Is the dating of short tree-ring series still a challenge? New evidence from the pile dwelling of Lucone di Polpenazze (northern Italy). *Journal of Archaeological Science*, 2020, 121, pp.105190. 10.1016/j.jas.2020.105190 . hal-03050674

**HAL Id: hal-03050674**

**<https://hal.science/hal-03050674>**

Submitted on 22 Aug 2022

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# Is the dating of short tree-ring series still a challenge?

## New evidences from the pile dwelling of Lucone di Polpenazze (Northern Italy)

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**Key words:** short tree-ring series, dendrochronology, dendrotypology, annual <sup>14</sup>C calibration curve, woodland management, Bronze Age

### Abstract

Young wood posts discovered at the Bronze Age pile-dwelling site of Lucone D show tree-ring series not exceeding 40 rings. Dendrochronological analysis allowed us to cross-match 10 short series, which fail to find a cross-match against the site chronology and the regional GARDA1 chronology. Their precise dating, however, would invite new scenarios to better understand both the construction activity and the woodland management practices of ancient populations. Here, we examine the dating of these posts and speculate as to the young wood use in the context of pile dwellings.

In order to precisely <sup>14</sup>C date the subchronology of the 10 posts, we isolated random annual rings from two posts. Then, using wiggle-matching, the annual <sup>14</sup>C measurements of the young woods were dated against a new absolute annual calibration curve (spanning 136 years from -2065 to -1929), which we built measuring the <sup>14</sup>C content in absolutely-dated subfossil trees. An offset of ca. 25 years compared to IntCal13 was revealed and an attempt was made to recalibrate the GARDA1 chronology against the new calibration curve.

<sup>14</sup>C results of the young woods permitted the identification of the correct ring position on the GARDA1 chronology. Our results highlight the possibility of a newly-discovered fourth construction phase for the Lucone D settlement, just prior to the abandonment of the village, and they also underline the potential utilization of young woods solely for purposes of renovation of ancient structures.

### 1. Introduction

The context of this study is the Alpine pile-dwelling phenomenon, spanning 6 countries around the Alps, where pile-dwelling villages were inhabited during a wide temporal range, i.e. from the Neolithic to the Iron Age (from about 5000 to 500 BC). Due to the substantial amount of wooden material discovered in these sites, a very precise chronology of settlement development is

42 available in those countries having undertaken extensive archaeological excavations for which  
43 multi-millennial reference curves are available (e.g. France, Germany and Switzerland). However,  
44 dendrochronological analysis has also highlighted other aspects of ancient human life, such as the  
45 interaction of these early peoples with their **environment**.

46 This topic has been widely addressed using **dendrotypology**. The technique consists of the  
47 analysis of several parameters of tree-ring series, both forestry-related (cambial age, growth trend,  
48 trunk diameter) and techno-morphology-related (tree species, proportion of sapwood, degree and  
49 type of stem conversion; Billamboz 2011).

50 Dendrotypology has been widely employed in the study of pile dwellings of Southern  
51 Germany by André Billamboz, who developed the model for its utilization (Billamboz 2011). The  
52 first step of the analysis consists in grouping the tree-ring series according to the above-mentioned  
53 parameters, which allows the building of dendrogroups (DGs). When applying dendrotypology to  
54 large sample series, it is possible to link DGs to the history of forestry **practices**. A recurrent  
55 problem encountered has been the dating of posts exhibiting short tree-ring **series**, which are  
56 difficult to match against site and reference chronologies (Billamboz 2008; Trouet et al. 2017).

57 We investigate this task in a pile-dwelling settlement in Northern Italy, Lucone D, dated to  
58 the Early Bronze Age (EBA). Two main problems hamper research at this site and at all prehistoric  
59 pile-dwelling sites of Northern Italy where oak is the main exploited wood. Firstly, there are no  
60 existing oak multi-millennial reference chronologies for the region and attempts to teleconnect the  
61 floating chronologies with references from regions north of the Alps have usually been  
62 unsuccessful (Haneca et al. 2009; Martinelli et al. 2019). In addition, the lack of large-scale  
63 archaeological excavations limits the available information. However, pile dwellings from the  
64 beginning of the EBA are not attested in the other Alpine countries, making the study of this site  
65 extremely important for the understanding of pile dwelling dynamics in relation to climatic and  
66 environmental **changes**.

67 The objective of our **project is** to analyze the woodland management practiced by the  
68 ancient population of the Lucone D settlement **on a long prospective**, by adding into the  
69 dendrotypological model the short tree-ring series which had previously been excluded due to the  
70 difficulties involved in dendrochronological synchronization. **In the present investigation, in** order  
71 to overcome the **challenge** of dating the short tree-ring series, we combine dendrochronology and  
72 high-resolution <sup>14</sup>C analysis and **speculate on the preliminary woodland patterns, highlighted from**  
73 **the dating of young woods**.

74

## 75 **2. Dating short tree-ring series**

76 With short tree-ring series it is possible to define **series** with fewer than 50 rings (Lambert  
77 and Orcel 1977; Hiram et al. 1987; Billamboz 2008; Haneca et al. 2009). **The classic method of**  
78 **dendrochronology, based on statistic correlations, is suitable for long and sensitive tree-ring series.**  
79 **At the opposite, in the analysis of short series the statistical parameters of comparison are generally**  
80 low and statistically insignificant or, if occasionally high, may lead to erroneous **dating**. **However,**

81 a large part of archaeological woods shows short tree-ring series (Hillam et al. 1984; Billamboz  
82 2003, 2008; Haneca et al. 2006, 2009).

83 In pile-dwelling contexts, timber from young wood is not rare and its dating is extremely  
84 important for the reconstruction of short-term settlement development, testifying timings and  
85 characteristics of building activity that are tightly linked to changing strategies of timber supply  
86 and woodland management (Billamboz 2008).

87 One proposed solution for the dating of short series is the initial synchronization through  
88 visual matching. Based on raw measurements of ring widths, visual matching considers specific  
89 characters of growth and variations at high and medium frequency, most highlighted from the  
90 analysis of detrended series. Statistical tests can be finally used to correlate groups between  
91 themselves and to cross-date them against a site or master chronology (Hillam et al. 1984, 1987;  
92 Billamboz 2003, 2008).

93 To guarantee the reliability and consistency of results, André Billamboz defined three  
94 levels of quality for dendro-dating (Billamboz 2008, 2011). Level A includes high-quality  
95 independent dendrochronological dating, with high statistical and visual correlations; level B  
96 indicates a lower quality of dating than level A, which is supported by external information, such  
97 as archaeological context, historical sources or  $^{14}\text{C}$  dating; and level C refers to first tentative of  
98 dating which is open to discussion within the research team. It is this level that generally pertains  
99 to short tree-ring series of fewer than 40 years. In these cases,  $^{14}\text{C}$  analysis can be used as support  
100 for dating.

101  $^{14}\text{C}$  dating, however, is far from having the same precision of dendrochronology. Normal  
102 error associated to AMS- $^{14}\text{C}$  ages are in the order of 2-3‰. The variability associated with  
103 measurements may then vary when calibrating the results, depending on the shape of the  
104 calibration curve, i.e. large slope and the presence of wiggles, which favors the precision of dating  
105 with respect to the flat parts of the curve (Reimer et al. 2013; Reimer et al. 2020). Wiggle-matching  
106 dating generally provides higher precision in dating wood series than does single measurement  
107 dating, because it combines in one model information concerning annual growth rings (i.e. known  
108 relative age interval between sampled rings) with  $^{14}\text{C}$  dating (Bronk Ramsey et al. 2001)  
109 Consequently, wiggle-matching should be applied to wood species exhibiting distinguishable  
110 annual rings, which is the case for the predominantly oak timbers discovered in pile-dwelling  
111 settlements.

112 If it has been shown that wiggle-matching models can yield reliable results for the dating  
113 of long tree-ring series (i.e. min 100-yr long; Galimberti 2004), the same cannot be guaranteed for  
114 the calibration of short tree-ring series (Bayliss et al. 2017; Hogg et al. 2017, 2019). Indeed, two  
115 main problems arise: I) the possibility that the  $^{14}\text{C}$  dating lands entirely on a long, flat section of  
116 the calibration curve, in which case the short length of the tree-ring series may lead to high dating  
117 uncertainty; and II) difficulties in the resolution of both the dated short-sequence sample and the  
118 calibration curve, where a different resolution reduces the probability of obtaining reliable results  
119 (Jacobsson et al. 2018; Marshall et al. 2019). Indeed, if single-year tree-ring measurement should,  
120 in principle, be preferable for maximizing the short-term radiocarbon variability, and hence the

121 precision of calibration results (Wacker et al. 2014), comparison with the IntCal13 calibration  
122 curve based on a minimal resolution of 10 years from 1500 AD back in time (Reimer et al. 2013),  
123 reveals that the desired increase in precision fails and that the obtained fit is in fact more likely to  
124 show a systematic offset (Jacobsson et al. 2017, 2018). The current effort of the IntCal working  
125 group concerns the reconstruction of the calibration curve at annual resolution, and several studies  
126 have already contributed to this task (Pearson et al. 2018; Capano et al. 2018, 2020; Sava et al.  
127 2019; Eastoe et al. 2019; Reimer et al. 2020).

128 In this study we try to overcome the challenge of dating short tree-ring **series** by coupling  
129 dendrotypology and high-resolution <sup>14</sup>C analysis. To remediate the problem of the low-resolution  
130 calibration curve and possible dating errors when comparing with high-resolution samples, we  
131 have dated at annual resolution subfossil trees included in a coniferous master curve and used the  
132 new calibration curve to date our annual-resolution samples of young woods from the Lucone D  
133 pile dwelling.

134

### 135 **3. The site**

136 The pile-dwelling settlement of Lucone D is located in the eastern part of the archaeological  
137 area of Lake Lucone (Brescia, Italy; 252 m a.s.l.), not far from Lake Garda (Figure 1). Pile-  
138 dwelling sites and other kinds of archaeological remains are scattered over five different sites (from  
139 Lucone A to Lucone E) in the basin around the small lake and along the slopes of the surrounding  
140 hills. The ancient small lake was reclaimed in the historical era and the archaeological site of  
141 Lucone D is today buried by peaty sediment. The site has been under excavation since 2007 and  
142 has produced a large number of archaeological artefacts (ceramic, stone, bone-antler, wood and  
143 fabric) together with botanical and zoological remains.

144 The settlement is dated to the first phases of **the EBA. Dendrodates** from samples with the  
145 waney edge indicate that frequent cutting operations for wood supply took place in nearby forests  
146 over a period of fewer than 70 years, from 2034 to 1967 ±10 cal BC, according to the previous  
147 dating result obtained using wiggle-matching (Martinelli 1996, 2013). **Dendrochronology** allows  
148 to ascertain that numerous felling episodes occurred very frequently, often in consecutive years,  
149 **highlighting the possibility of timber storage and reuse (Baioni et al. 2019; Baioni et al. in press).**

150 **Stratigraphic** analysis clearly identifies two main occupation phases, which are separated  
151 by a fire event (Baioni et al. 2019). **The dating of the fire event on the basis of tree-ring chronology**  
152 **is not yet defined, because of the absence of horizontal timbers in primary deposition.**  
153 **Dendrotypological** analysis identified 3 main phases of settlement construction. **During the three**  
154 **phases timber** supply comes from old-aged trees, both from dense stands and sparser ones, thus  
155 attesting the practices of clearing and thinning. Nevertheless, it is possible that this result may also  
156 have been affected by a paucity of data, i.e. the lack of samples from the non-investigated part of  
157 the village (Martinelli 2013). Furthermore, young woods, which account for more than 50 posts,  
158 are not represented in the models either, due to the ongoing inability to cross-date them.

159

### 160 **4. Materials and methods**

#### 161 4.1 Dendrochronology – dendrotypology

162 More than 1200 vertical and horizontal wooden elements have been identified at Lucone  
163 D (1060 in Sector 1), all of which have been carefully catalogued. Vertical posts belong to oak  
164 species (*Quercus* sp. Sectio *ROBUR*, with the exception of 1 post which belongs to *Quercus* sp.  
165 Sectio *CERRIS*) *sensu* Cambini (1967a and 1967b). Horizontal elements belong to different  
166 species (alder, ash, beech, hazelnut tree, maple, silver fir), with a high prevalence of oak (Baioni  
167 et al 2019). Twenty samples were analyzed after the first sampling campaign in 1986. From the  
168 excavations carried out from 2005 to 2019, more than 400 samples have been subjected to  
169 dendrochronological analysis and more than 300 have been dated against the local oak site  
170 chronology. A first chronology built for Lucone D has become part of the original oak regional  
171 chronology GARDA1 (2171 – 1837 ±10 cal BC), which was <sup>14</sup>C dated by wiggle-matching 9  
172 decadal (or larger) groups of rings against the decadal calibration curve by Suiver and Becker  
173 (1993; Martinelli 1996). For woods from Lucone D, precise annual dates in relative chronology  
174 are available for 83 items bearing a waney edge. For the other 84 samples, in which the outermost  
175 sapwood was subject to erosion, a precision within 2-3 years is possible, while 112 dates have  
176 been determined through sapwood estimates, within a range of between 4 and 30 years.

177 The young-wood posts analyzed in this study, as well as the other posts and horizontal  
178 beams from the site, were sampled in the archaeological excavation by means of a hand saw. An  
179 approximately 10 cm thick section was taken for dendrochronological analysis. Wet wood samples  
180 were wrapped in plastic film and transported to the laboratory for processing in water-filled plastic  
181 bags to prevent drying and to thus limit deterioration.

182 At least 2 radii were selected and prepared with razor blades and ring width was measured  
183 using LINTAB measuring system with a precision of 0.01 mm. Data processing was done using  
184 Catras (Aniol 1983) and TSAPWin softwares (TSAP-Win<sup>TM</sup> 1996 e 2003), following the  
185 dendrochronological standard procedures (Baillie 1982). Posts with short tree-ring series (i.e. <50  
186 rings) were also involved in the creation of dendrogroups. Visual and statistical comparisons were  
187 used for this purpose. Dendrotypological parameters (e.g. cambial age, trunk diameter, sapwood  
188 thickness, growth trend and pointer years) were then analyzed in order to update the previously  
189 elaborated model of forest management reconstruction, which fail to take into account the short  
190 tree-ring series (Martinelli 2013).

191 In order to date the tree felling years, the series of young woods and their subchronology  
192 were matched against the local chronology created for the Lucone D settlement and the DG series  
193 elaborated for dendrotypology (Martinelli 2013, Martinelli unpublished).

194

#### 195 4.2 <sup>14</sup>C analysis

196 For the dating of a floating subchronology, two posts from Lucone D were selected for <sup>14</sup>C  
197 analysis: post no. 553, 33-years long, and post 641, 34-years long. Several rings were selected at  
198 annual resolution for <sup>14</sup>C measurements (rings n. 1, 4, 7, 11, 15, 19 and 23 from P. 553 and no. 1,  
199 5, 9, 11, 13, 15, 17, 19, 21, 23, 26 from P. 641).

200 In northern Italy deciduous oak species guarantee the annual radial growth of trees on the  
201 whole stem circumference, without the occurrence of missing rings. Oak has distinct ring porous  
202 structure with large earlywood vessels, which are formed at the beginning of the growing season,  
203 before the complete foliation. For the cellulose formation of earlywood vessels, therefore, trees  
204 need to use photosynthates from previous years (Pilcher 1996). In ideal conditions, only the  
205 latewood from oak posts would be sampled, but the state of preservation of waterlogged wood is  
206 generally critical and the scalpel separation of rings not as clearly-defined as with dry wood.  
207 Moreover, we did not expect to get a sufficient yield after the chemical pretreatment. For all these  
208 reasons, we sampled the whole ring, including both earlywood and latewood.

209 Rings were separated using a scalpel under a binocular microscope and sliced into small  
210 pieces. They were oven-dried at 50 °C for 48 hours, after which at least 200 mg of dry wood for  
211 each sample was treated for cellulose extraction using the ABA-B method at CEREGE (Aix-en-  
212 Provence, France). This method consists in a classic ABA treatment, with solutions of HCl and  
213 NaOH at 4% concentration, followed by a bleaching step performed with 60 g of NaClO<sub>2</sub> in 1 L  
214 of ultrapure water in acid solution (HCl) at pH 3 (Capano et al. 2018).

215 Two coniferous subfossil woods from the Eastern Italian Alps were chosen for the new  
216 calibration curve measured at annual resolution (the new annual calibration curve is named Aix-  
217 BA): LDM\_55A from a lake context (46.267N-10.816E; 1900 m a.s.l; Lago delle Malghette, Italy)  
218 and MGM\_421 from a peat bog context (46.137N-10.694E; 1900 m a.s.l; Malga Germenega, Italy;  
219 Figure 1). Both trees belong to *Picea abies* Karst. species and are synchronized in a conifer  
220 chronology of 3219 years, absolutely dated to 4961-1743 BC against the Eastern Alpine Conifer  
221 Chronology (EACC) with high statistical values: GIK = 64%; TBP = 25.2; TH = 27.4 (Nicolussi  
222 et al. 2009, 2015; Bernabei et al. 2018). Sampling was performed on a selection of rings from each  
223 tree: rings corresponding to years from -2065 to -1986 for LDM\_55A and from -1983 to -1929 for  
224 MGM\_421. Every third ring of the two sequences was measured for <sup>14</sup>C, which has been  
225 demonstrated to be sufficient for obtaining reliable results (Capano et al. 2020). Moreover, the  
226 rings corresponding to years -2013, -2010, -2004 and -1998, which are already measured in  
227 LDM\_55A, were repeated in MGM\_421 for further confirmation of <sup>14</sup>C ages. The rings dated to -  
228 2032 and -2031 of LDM\_55A were coupled in one sample for the small ring width (Figure 2).

229 In contrast to deciduous trees, evergreen conifers perform year-round photosynthetic  
230 activity (Adams et al. 2004), which means that earlywood cellulose is produced by carbon  
231 assimilated in the corresponding growth year. Indeed, for Norway Spruce woods, the whole ring  
232 was used for analysis. The described ABA-B pretreatment was performed for the cellulose  
233 extraction of samples.

234 After chemical pretreatment, the dried residues of archaeological and subfossil woods were  
235 weighed in tin capsules, combusted with the elemental analyzer, and the evolved CO<sub>2</sub> was finally  
236 transformed into graphite with the AGE III system. The graphite target was then analyzed for its  
237 <sup>14</sup>C/<sup>12</sup>C and <sup>13</sup>C/<sup>12</sup>C ratios using the AixMICADAS system (Bard et al. 2015). Standards (OxA2  
238 NIST SRM4990C) and blanks (VIRI-K, chemically treated like the other wood samples) were  
239 processed together with samples and used for normalization and blank correction, respectively. In

240 addition, IAEA-C3 (cellulose) and IAEA-C8 (oxalic acid) standards were pretreated (IAEA-C3  
241 also underwent the chemical pretreatment) and measured for  $^{14}\text{C}$  in the same batches, serving as  
242 control standards.

243 High precision  $^{14}\text{C}$  measurements were performed with long AMS runs to reach at least  
244 800,000 ion counts for each OxA2 standard target on the same magazine. An additional uncertainty  
245 of 1.6 ‰ was propagated in the  $^{14}\text{C}$  analytical errors and background correction following the  
246 convention described in Capano et al. (2018). The successful participation of the Aix laboratory  
247 in a recent International Intercomparison on annual tree-ring dating guarantees, moreover, the  
248 precision and accuracy of  $^{14}\text{C}$  results (Wacker et al. 2020); indeed, data produced at the Aix  
249 laboratory will also be included in the upcoming IntCal20 calibration curve (Capano et al. 2020;  
250 Reimer et al. 2020). The data are reported in terms of conventional  $^{14}\text{C}$  age in years BP (Stuiver  
251 and Polach 1977).

252 The  $^{14}\text{C}$  ages of the archaeological materials were finally wiggle-matched with the IntCal13  
253 and the new Aix-BA calibration curves. The OxCal v.4.3 wiggle-matching program was used for  
254 calibrations (Bronk Ramsey 1995; Bronk Ramsey et al 2001). Moreover, the new Aix-BA curve  
255 was compared to IntCal13 to investigate possible differences of  $^{14}\text{C}$  oscillations in time.  
256

## 257 **5. Results**

### 258 *5.1 Dendrochronological analysis of pile-dwelling posts*

259 Among the 400 analyzed posts for this site (all *Quercus* sp. Sectio *ROBUR*), about 50  
260 present less than 50 rings: woods do not exceed 35 years, with the exclusion of 1 post with 41  
261 rings, sampled in 1986, that we have excluded from  $^{14}\text{C}$  analysis due to suspected suboptimal wood  
262 preservation.

263 To increase the chances of finding dendromatches between the series, only the series with  
264 at least 20 rings have been analyzed in this study, i.e. 32 posts. Twenty-seven of these posts have  
265 bark/cambium. Visual comparison between series allowed the crossdating of 10 posts and the  
266 elaboration of a 44-year long subchronology (the subchronology of 10 posts is named M912Q;  
267 Table 1; Figure 3). The series in the subchronology M912Q show different felling dates on the  
268 relative chronological scale (Figure 3), thus indicating that the posts belong to different felling  
269 episodes over 12 years.

270 All these posts come from young trees, aged between ca. 30 and 40 years, with relatively  
271 small dimensions. With the exception of the element P468 (estimated diameter about 30 cm), all  
272 the others are thought to have been from 12 to 23 cm in diameter. Despite their size, the trunks  
273 were split into from 2 to 8 longitudinal sections

274 Due to its short length, the tree-ring subchronology (M912Q), 44-years long, revealed two  
275 possible different matches against the local chronology from Lucone D and the regional  
276 chronology GARDA1, thus preventing dating of the series on the relative scale of the settlement  
277 and the region. For this study, a newly formulated version of the first 309-year long part of the  
278 chronology, named GARDA1-I (Martinelli, in press) has been used. The site chronology of  
279 Lucone is part of the GARDA1-I chronology from ring 32 to 238; while the last year of the

280 **subchronology** M912Q may correspond to years 126 or 252 of GARDA1-I, but **no** felling date is  
281 attested by the long-series elements from Lucone D, dated between the years 170 and 238 of  
282 GARDA1-I.

283 The choice of the correct position from the solely dendrochronological analysis is not  
284 possible, because of the good visual comparison of both the date and the similarity of the statistical  
285 values (Table 2). Moreover, cross-dating against the local chronology from Lucone D reveals an  
286 overlap of only 30 years. The shortness of the series prevents the choice of one or the other, leaving  
287 M912Q **subchronology** undated.

288

### 289 5.2 <sup>14</sup>C measurement for calibration purposes

290 Two tree-ring series from spruce subfossil trees have been analyzed and their <sup>14</sup>C content  
291 measured in selected rings. The yield percentage after cellulose extraction was in the range of well-  
292 preserved wood (between 30% and 40%; Capano et al. 2018). The rings corresponding to 4 years  
293 (-2013, -2010, -2004 and -1998) were measured in both series for a further validation of the results;  
294 the <sup>14</sup>C values of duplicate rings for each year are strongly consistent at 1  $\sigma$  range (Table 3),  
295 confirming the reproducibility of <sup>14</sup>C measurements. Indeed, the <sup>14</sup>C values of each couple were  
296 averaged and the series of the two posts were incorporated in a 136-year long sequence, dated to  
297 4015-3879 cal BP (i.e. 2065-1929 BC). This sequence was compared with the IntCal13 calibration  
298 curve and with the raw data of the **sequences** that make it up (Figure 4; Reimer et al 2013). In the  
299 period that we measured at annual resolution, IntCal13 is composed of three records of 2-year  
300 range (11 measurements on woods from the German oak chronology, measured at Pretoria), 10-  
301 year range (20 measurements on woods from the German oak chronology, measured at  
302 Heidelberg) and 20-year range (7 measurements on woods from the Irish oak and the German oak  
303 chronologies, measured at Belfast). We did not compare Aix-BA with the upcoming IntCal20,  
304 because the latter is not yet available. However, we do know that the period of our concern  
305 indicates no important changes in the upcoming calibration curve (Reimer et al. 2020). A clear <sup>14</sup>C  
306 offset is present in annual measurements compared to the IntCal13 curve, with oscillations of new  
307 data mostly versus older ages and an average offset of 25 $\pm$ 8 years (Table 4). However, <sup>14</sup>C values  
308 of Aix-BA fall within the 2  $\sigma$  range of most of the raw <sup>14</sup>C data of IntCal13 (Figure 4). In Figure  
309 5, the Aix-BA curve is constructed with the same Bayesian statistics as IntCal13 and compared  
310 with it (Niu et al. 2013). The highest offset concerns the period 3966-3960 cal BP (Figure 6), into  
311 which fall two of the rings with replicated <sup>14</sup>C measurements: years 3960 and 3963 cal BP (i.e. -  
312 2013 and -2010), whose very good agreement confirms the accuracy of the measurements (Table  
313 3). Moreover, a previous study analyzed the <sup>14</sup>C annual oscillation in trees of the BA for a younger  
314 period (i.e. 1700-1500 cal BC) and found a similar offset of annual measurement with respect to  
315 IntCal13 data (Pearson et al. 2018).

316 Indeed, the previously discovered offset in <sup>14</sup>C values for the BA period, in addition to the  
317 consistency of our repeated measurements for 4 rings and the successful participation of the Aix  
318 laboratory in a recent International Intercomparison on annual tree-ring dating (Wacker et al. 2020)  
319 have prompted us to exclude the possibility of laboratory bias concerning the found offset.

320 In order to test the accuracy of dating when using the IntCal13 calibration curve, we  
321 compared our Aix-BA curve as an unknown age sequence against IntCal13 using the OxCal  
322 wiggle-matching model (Bronk Ramsey et al. 2001). As expected, because of the offset the  
323 calibration revealed reliable results, with a high percentage of agreement, only when applying a  
324  $\Delta R(-50,50)$  offset to IntCal13 (Table 4; Bronk Ramsey 2009).

325

### 326 5.3 <sup>14</sup>C dating *of the archaeological sequences*

327 The low yield after cellulose extraction of the archaeological woods (between 1 and 4%)  
328 confirms the advanced state of degradation supposed for these materials and supports our decision  
329 to sample the whole ring instead of only the latewood for oak species.

330 <sup>14</sup>C results for posts 553 and 641 confirm their dendrochronological synchronization,  
331 despite post 553 showing more dispersed values, in particular ring 19, whose cellulose yield after  
332 chemical pretreatment was only 0.6 mg (approximately 250  $\mu$ g of C; Table 5, Figure 7). For this  
333 reason, rings 19 and 23 of the **subchronology** M912Q, which presented the highest dispersion,  
334 were also measured in post 641. The results of the measurements for these two rings are in  
335 agreement (at  $2\sigma$  range for ring 19 and  $1\sigma$  range for ring 23; Figure 7; Table 5). Indeed, the values  
336 were averaged for each year and the **sequences** of posts 553 and 641 were combined for the  
337 calibration (LucD <sup>14</sup>C sequence, 34-years long). <sup>14</sup>C results for this **sequence** are positioned along  
338 a “plateau”; thus predicting difficulties in the high-precision calibration purpose (Figure 7).

339 The <sup>14</sup>C **sequence** of each post and the LucD <sup>14</sup>C sequence were calibrated to the new Aix-  
340 BA curve and, for further comparison, against the IntCal13, using the OxCal wiggle-matching  
341 program (Bronk Ramsey et al. 2001). The results of the calibration of the **sequences** of posts 553  
342 and 641 are the same as the LucD <sup>14</sup>C sequence both after comparison with Aix-BA and with  
343 IntCal13 (Table 6). When comparing the LucD <sup>14</sup>C sequence with Aix-BA, the last ring of the  
344 **sequence** is dated to 3936-3894 cal BP (-1986 to -1944) with 95.4% probability: indeed, the LucD  
345 <sup>14</sup>C **sequence** is dated to 3948-3915 $\pm$ 21 cal BP (-1998/-1965 $\pm$ 21; Figure 8; Table 6). The results  
346 of calibration against the IntCal13 curve with the same 95.4% probability indicate a dating to 3978-  
347 3927 cal BP (-2028 to -1977) for the last ring of the LucD <sup>14</sup>C sequence, enabling dating the  
348 **sequence** to 3986-3953 $\pm$ 26 cal BP (-2036/-2003 $\pm$ 26; Figure 9; Table 6). The age difference when  
349 using Aix-BA or IntCal13 is, indeed, ca. 40 years, with older ages obtained when using IntCal13.  
350 Examination of the 68.2% probability results reveals that the age difference increases to ca. 50  
351 years (Table 6). It should also be noted that the agreement of OxCal when calculated by Bayesian  
352 statistics is higher when matching the LucD <sup>14</sup>C sequence with the Aix-BA curve than with  
353 IntCal13 (Table 6). Accepting this last calibration as the best possibility, the M912Q  
354 **subchronology** can be dated to 3948-3905 $\pm$ 21 cal BP (-1998/-1955 $\pm$ 21), while the last ring of the  
355 M912Q **subchronology** (i.e. ring 44) dates to 3905 $\pm$ 21 cal BP (-1955 $\pm$ 21).

356 After examination of the results of the calibration of the LucD <sup>14</sup>C **sequence** and the  
357 discordances of the results when using the IntCal13 or Aix-BA curves, we decided to recalibrate  
358 the <sup>14</sup>C values of the GARDA1-I chronology as well, in the aim of avoiding all possible bias in the  
359 calibrated ages, which are now 33 years longer vs previous ages than was the previous <sup>14</sup>C-dated

360 chronology (Martinelli 1996). However, we limited the **sequence** to the first part of the chronology  
361 for the highly consistent dendro-matches (GARDA1-I; Martinelli, in press), and to the first 7 <sup>14</sup>C  
362 dated tree-ring groups of GARDA1-I, thus excluding the last two groups of 50 and 80 rings from  
363 Lazise-La Quercia. We initially recalibrated: I) a portion (5 samples out of 7) of the previous <sup>14</sup>C  
364 measurements of GARDA1-I with Aix-BA, as the entire sequence is longer than the new Aix-BA  
365 curve; and II) the entire sequence of GARDA1-I with IntCal13, by substituting the new <sup>14</sup>C data  
366 of Aix-BA to IntCal13 values from 4015 to 3879 cal BP (Aix-BA+IntCal13; Table 7). Then, for  
367 comparison, we contrasted the GARDA1-I sequence with IntCal13 twice, with and without  
368 introducing a  $\Delta R$  offset (N,  $25\pm 8$ ), corresponding to the offset calculated by OxCal when  
369 comparing Aix-BA with the IntCal13 curve (Table 4). Examination of the results of calibration in  
370 the  $2\sigma$  range indicate that all four options are in agreement, but the calibrations against IntCal13  
371 (without offset) show slightly older ages and smaller uncertainties, which could potentially lead to  
372 erroneous absolute ages (Table 7). The highest agreement was obtained when GARDA1-I was  
373 compared against Aix-BA+IntCal13 (Figure 10), which enabled to date the last ring of the <sup>14</sup>C  
374 **sequence** (i.e. ring 208, as the middle point of rings 193-223) to 3954-3908 cal BP (i.e. 2004-1958  
375 BC); the **chronology** GARDA1-I is thus dated to  $4138-3831\pm 23$  cal BP ( $-2188/-1881\pm 23$ ).

376 The dendrochronological **series** of Lucone is part of the GARDA1 chronology.  
377 Considering the results of the last ring of Lucone series only (i.e. ring 238 of GARDA1), it now  
378 dates to  $3901\pm 23$  cal BP ( $-1951\pm 23$ ).

379

## 380 6. Discussion

### 381 6.1 High-resolution calibration curve and its implication for the dating of short tree-ring series

382 The offset discovered between annual <sup>14</sup>C values of the Aix-BA and IntCal13 curves  
383 (Figures 5-6) highlights the possibility of erroneous calibration of archaeological materials. We  
384 present two examples of calibration of archaeological wood series with both the IntCal13 and Aix-  
385 BA curves. Regarding the calibration of the LucD <sup>14</sup>C **sequence**, the **comparison** of high-resolution  
386 data against IntCal13 gives ages of ca. 40 years older than are obtained when using Aix-BA.  
387 Moreover, the higher percentage of agreement found for calibration against Aix-BA confirms the  
388 importance of comparing datasets at the same resolution (Jacobsson et al. 2018; Marshall et al.  
389 2019).

390 With regard to the recalibration of previous low-resolution, but long-time **sequences**, <sup>14</sup>C  
391 values for the GARDA1-I chronology (made up of samples comprising 10 to 30 rings, comparable  
392 to the resolution of IntCal13), we obtained the same results using the two curves, but with a smaller  
393 age range for the calibration against IntCal13, which limits dating to older ages than are obtained  
394 when calibrating with Aix-BA. In this last case, the lower error associated to calibration with  
395 IntCal13 increases dating precision, but may also lead to erroneous dating.

396 We also tried to **calibrate** the absolute new sequence Aix-BA against IntCal13 and obtained  
397 reliable results with very good agreement indices at 68.2% probability only when applying a  $\Delta R$   
398 offset (-50,50) to IntCal13. At 95.4% probability, the offset for obtaining true ages is not necessary,  
399 but the very low agreement results in uncertainty concerning the accuracy of the results (Table 4).

400 A previous study analyzed a tree-ring sequence of cedar wood dated to the BA and  
401 compared the low-resolution (i.e. mostly 10-ring samples)  $^{14}\text{C}$  values of their sequences against  
402 the IntCal13 calibration curve (Manning et al. 2014). Those authors found a mean offset of  $17\pm 6$   
403 years in the period -2200 to -1900, increasing notably at ca. -2103. They interpreted this offset as  
404 being due to the different growing seasons of trees originating from different climate regions, i.e.  
405 central Europe for trees of the IntCal calibration curve, and the south-eastern Mediterranean areas  
406 for their investigated samples. This variation was deemed to have been accentuated by the cold  
407 climate episode that occurred at ca. 4200 BP (Manning et al. 2014). Other earlier studies had also  
408 explained  $^{14}\text{C}$  offsets as the result of different growing seasons of trees (Bronk Ramsey et al. 2010;  
409 Dee et al. 2010). However, the  $^{14}\text{C}$  offset revealed by Manning et al. (2014) in tree-ring series is  
410 very similar to and occurs in the same years as the offset we found in the Aix-BA **sequence**, which  
411 is built using trees from the Italian Alps at roughly 2000 m altitude. The Italian Alps, as well as  
412 Central Europe including areas of provenance of IntCal13 subfossil trees, were characterized by a  
413 cold-humid phase during the 4200-BP event (Frisia et al. 2005), which attests to a similarity in  
414 climate variability. If  $^{14}\text{C}$  values from the Italian Alps and south-eastern Mediterranean areas show  
415 the same offset with respect to central Europe due to being characterized by the same climate  
416 variabilities as the Italian Alps, then the theory used to explain the offset, which posits the  
417 accentuation of different growing seasons during periods of cold climate, seems to be debateable,  
418 meaning that the  $^{14}\text{C}$  offset of cedar wood compared to IntCal13 is very probably an analytical  
419 bias of previous low-resolution  $^{14}\text{C}$  measurements. In fact, when dating a sample composed of  
420 many rings (e.g. 10 rings) the short-time fluctuations of  $^{14}\text{C}$  are lost (Miyake et al. 2012, 2013). In  
421 the dating of short tree-ring **series** this loss can lead on one hand, to a lack of accuracy in the  
422 calibration of  $^{14}\text{C}$  data (Wacker et al. 2014), and on the other hand, to erroneous dating, as our  
423 LucD  $^{14}\text{C}$  sequence demonstrated.

424 A calibration curve at high resolution (i.e. annual) is, indeed, extremely important for high-  
425 precision dating of short tree-ring **series**. The IntCal community is working to increase the  
426 precision of datasets. The forthcoming update of IntCal13 (IntCal20) will replace many parts of  
427 the 2013 version with new annual data derived from tree-rings. However, the majority of the curve  
428 will remain at the mostly decadal/bidecadal low resolution of the 2013 IntCal13 (Reimer et al.  
429 2020).

430

### 431 *6.2 Woodland management in the light of dating of new short tree-ring series*

432 Three main phases of construction have been identified at the Lucone D settlement. All are  
433 characterized by thinning activity in a dense forest, as is associated with clearing, and by the use  
434 of mature trees only (Martinelli et al. 2013, 2018). This supposed partiality for old trees has been  
435 associated with a presumed limited potential for forest regeneration (Billamboz 2011) and led to  
436 the hypothesis of a strong sufferance of vegetation in the settlement surrounding. This depletion  
437 was thought to have resulted in the need to explore the depths of the forest with the consequent  
438 abandonment of the village (Martinelli 2013).

439 The analysis and dating of short tree-ring series change this model, by attesting the use of  
440 and, indeed, the choice of young trees.

441 The dendrotypological analysis of young woods highlighted the presence of two main  
442 groups in the forest stand: a majority of young trees of fast growth with small number of sapwood  
443 rings, indicating trees with low competition; and others of more reduced growth with high number  
444 of sapwood rings, indicating trees with higher competition (Figure 11). However, the small number  
445 of cross-dated posts (i.e. 10) enables the identification of several DGs from the M912Q  
446 subchronology and does not provide sufficient material to statistically distinguish a preference for  
447 coppice or young trees as opposed to mature canopy forest. Nor indeed, does it permit to identify  
448 the kind of woodland management practiced by ancient populations. Nevertheless, the analysis of  
449 new posts with short tree-ring series that will come to light in the ongoing archaeological  
450 excavation will help clarify this point.

451 However, several factors can be considered on the basis of the dating of these young woods.  
452 We have already discussed the two possibilities of cross-dating the M912Q subchronology against  
453 the GARDA1 chronology at the relative ring positions 126 and 252 of GARDA1 (Table 2).  
454 Examination of the  $^{14}\text{C}$  dating of the M912Q subchronology (i.e.  $3905\pm 21$  cal BP, or  $-1955\pm 21$ )  
455 enables us to definitively exclude the position at ring 126, whose new  $^{14}\text{C}$  dating ( $4013\pm 23$  cal BP,  
456 or  $-2063\pm 23$ ) does not match with the  $^{14}\text{C}$  results of the M912Q subchronology. The only dating  
457 possibility of the M912Q subchronology is, indeed, at ring position 252 of the GARDA1  
458 chronology ( $3887\pm 23$  cal BP, or  $-1937\pm 23$ ). This dating position is posterior to the previously  
459 analyzed felling dates of Lucone D posts, ending at ring position 238 of the GARDA1 chronology.  
460 However, most of the felling episodes of the 44-yr long M912Q subchronology occur between  
461 rings 32 and 35, dated at ring positions 240-243 of the GARDA1 chronology, or just 2-5 years  
462 after the last felling episode already attested at the Lucone D site (Figure 12).

463 The dating of the young wood posts at the end of settlement occupation bears no  
464 correspondence with the cycle of woodland management of Neolithic and Bronze Age pile  
465 dwellings at north of the Alps (Billamboz 2014). Indeed, at sites in Southern Germany, it has been  
466 seen that the construction of new villages is related to the clearing of dense forests, as is reflected  
467 in the presence of slow-growth tree-ring series from trees of different ages. The development  
468 phases of the village are characterized by expanding building activity with the extensive use of  
469 coppice practices, as is seen through the presence of short and fast-growth tree-ring series. Finally,  
470 the last phase of the village is characterized by the reduction of building activity and the practice  
471 of thinning with the use of old trees only (Billamboz 2014).

472 The EBA is unfortunately not attested north of the Alps, but in the village of Bande di  
473 Cavriana (Mantova, Northern Italy), coeval to Lucone D, the last phase of occupation is  
474 characterized by the additional use of young woods, in opposition to the 2 earlier phases during  
475 which the use of young woods was almost exclusively coupled to the use of old woods (Martinelli  
476 2017, 2018). However, the young woods of Bande di Cavriana are large in circumference (ca. 40  
477 cm) and 60-80 rings, thus excluding a possible analogy with the Lucone D settlement where the  
478 tree circumference of young woods is equal to or less than 30 cm, and where the tree-ring series

479 do not exceed 41 rings. Strong forest exploitation is attested in other villages beginning only in the  
480 18<sup>th</sup> century BC (e.g. the pile dwelling of Frassino, near Verona; Martinelli 2013), with increasing  
481 human impact in the following centuries (e.g. the pile dwelling of Sabbione, near Varese, dated to  
482 the end of 17<sup>th</sup> – beginning of 16<sup>th</sup> century; Martinelli 2013). In these last two examples, the last  
483 phase of the settlement is characterized by the use of other less prestigious species of wood than  
484 *Quercus* sp. Sectio *ROBUR*, such as *Quercus* sp. Sectio *CERRIS* at the Frassino site (Martinelli  
485 2018) and *Fagus* sp., *Betula* sp. and *Corylus* sp. at the Sabbione site (Martinelli 2013). This has  
486 been interpreted as evidence of the final exploitation of the surrounding forest before the  
487 abandonment of the site. This is not the case at Lucone D, where the analyzed posts all belong to  
488 deciduous oak species. The young woods from the Lucone D settlement seem, indeed, to be in no  
489 way analogous to other villages. It should be noted, however, that posts such as the ones analyzed  
490 in this study, with short tree-ring series but unearthed from other pile dwellings remain undated. It  
491 seems essential therefore to precisely date all short tree-ring series from all pile-dwelling sites in  
492 order to enable more realistic comparisons.

493 Considering the small number of posts with short tree-ring series discovered until now at  
494 Lucone D and the small dimension of these posts (trees with a diameter  $\leq 30$  cm were split into 2-  
495 to-8 longitudinal sectors before being used), two hypotheses can be advanced:

496

497 1. The presence of a short fourth phase of building construction before the abandonment  
498 of the site, characterized by the use of available trees in the surrounding forest. These  
499 trees would not have been selected according to desired characteristics (e.g. age of the  
500 tree, diameter of the trunk or typology of the forest), but rather, would have been chosen  
501 on the basis of the low availability of suitable trees remaining in a collapsed forest, in  
502 which regeneration was highly limited by the previous strong thinning activity. This  
503 strong diminution of vegetation in the forests surrounding the settlement may have  
504 contributed to the abandonment of the village.

505

506 2. A second hypothesis suggests that young trees may have been selected only for  
507 renovation of already existing structures, in which case, the presence of small posts  
508 does not necessarily imply forest collapse. It does appear, however, that the  
509 investigated area of the settlement was abandoned shortly after this renovation phase  
510 involving young woods; indeed, this change in forest management strategy seems to  
511 have anticipated the abandonment of the village.

512

513 The pursuit of archaeological excavations and newly discovered wooden elements provide  
514 insights into the use of young wood in the context of forest management. The dating of young  
515 woods from other EBA villages in Northern Italy will also permit the creation of comparative  
516 models to improve understanding of how young woods were used, thus providing significant  
517 assistance in the planimetric reconstruction of pile-dwelling structures.

518

519 **Conclusions**

520 The posts from the Lucone D pile dwelling showing short tree-ring series have been  
521 analyzed in this study. Dendrochronological analysis provided information concerning age (not  
522 exceeding 40 years), presence of bark, trunk diameter and portion of sapwood, whose width and  
523 ring thickness point to the presence of both coppice and isolated stems.

524 Randomly-sampled annual rings from two posts included in a subchronology of 10 series  
525 were <sup>14</sup>C measured with high precision and then wiggle-match dated against a new calibration  
526 curve (Aix-BA, spanning 136 years from -2065 to -1929), obtained from the annual measurement  
527 of absolutely-dated subfossil trees. From the comparison of the new calibration curve with  
528 IntCal13, an offset of ca. 25 years emerged, highlighting possible bias in the IntCal13 curve in the  
529 analyzed period, probably due to the low-resolution, decadal and bidecadal samples of IntCal13.  
530 The dating of short tree-ring series, in fact, shows 40-year difference depending on the calibration  
531 curve used, where with Aix-BA the ages are younger than with IntCal13.

532 A combination of dendrochronological and <sup>14</sup>C analyses has permitted to find the correct  
533 dating position of young woods on the regional chronology GARDA1-I, which has, in turn, been  
534 recalibrated on the new calibration curve.

535 The felling episodes of the young woods are dated 2-14 years later than the previously  
536 identified final construction phase of the Lucone D settlement, highlighting the possibility of either  
537 a fourth construction phase, or the use of small posts for the renovation of the already existing  
538 structures of the village. The analysis of new young woods emerging from the ongoing  
539 archaeological excavations will give insights to better describe woodland management. However,  
540 the dating of young woods illustrates their utilization just prior to the abandonment of the  
541 settlement.

542

543 **Acknowledgements**

544 AixMICADAS and its operation are funded by the Collège de France, the EQUIPEX  
545 ASTER-CEREGE and the ANR project CARBOTRYDH (PI E.B.). We wish to thank the  
546 anonymous reviewers, especially the second one, for his detailed and helpful suggestions.

547 Dendrochronological and dendrotypological analysis on samples from Lucone D were  
548 funded by the Italian Ministry of Cultural Heritage (Fondi Legge 20 febbraio 2006 n. 77 “Misure  
549 speciali di tutela e fruizione dei siti e degli elementi italiani di interesse culturale, paesaggistico e  
550 ambientale, inseriti nella “lista del patrimonio mondiale”, posti sotto la tutela dell’UNESCO” and  
551 Regione Lombardia (years 2009, 2011, 2013, 2017 and 2019).

552

553 **Author contributions**

554 Manuscript writing and development by M.C. with the support of N.M. and E.B. <sup>14</sup>C analyses and  
555 interpretation by M.C. with the support of E.B. and T.T. Archaeological investigation,  
556 interpretation and sampling of archaeological posts from Lucone D by M.Ba. Dendrochronological  
557 and dendrotypological analysis of archaeological posts from Lucone D by N.M., data interpretation

558 by N.M. and M.C. Sampling, dendrochronological analysis and absolute dating of subfossil trees  
559 from Trentino by M.Be. Revisions by all authors.

560

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740

741 Tables

742

Posts	Code lab	N. rings	MRW	Pith	Bark/cambium
16	0003076Q	31	165	Yes	Yes
28	0003483Q	32	189	Yes	Yes
169	BS03012Q	35	164	Yes	Yes
553	BS04822Q	33	295	Yes	-
18	0003068Q	41	160	Yes	Yes
669	BS04837Q	29	250	Yes	Yes
468	BS04803Q	29	345	Yes	-
99	BS03119Q	30	279	Yes	Yes
641	BS04890Q	26	315	Yes	Yes
613	BS04885Q	24	260	Yes	Yes

743 Table 1. Characteristics of the short tree-ring series averaged in the M912Q **subchronology**: code  
 744 of Dendrodata Laboratory (VR, Italy); mean ring width (MRW); pith and bark presence.

745

746

OVL	G1k	GSL	TV	TVBP	TVH	CDI	Position
44	73	**	5.3	3.4	4.0	27	126
44	67	*	7.5	3.5	4.4	26	252

747 Table 2. Statistical values from the dendrochronological cross-dating of the M912Q  
 748 **subchronology** against the GARDA1-I chronology.

749  
750

Code Lab	Tree_Ring	Abs. age	Age BP	<sup>14</sup> C	err
11473.1.1	LDM55A_-2065	-2065	4015	3700	20
11474.1.1	LDM55A_-2062	-2062	4012	3729	19
11475.1.1	LDM55A_-2059	-2059	4009	3722	20
11476.1.1	LDM55A_-2056	-2056	4006	3735	19
11477.1.1	LDM55A_-2053	-2053	4003	3764	20
11478.1.1	LDM55A_-2050	-2050	4000	3728	20
11479.1.1	LDM55A_-2047	-2047	3997	3692	20
11480.1.1	LDM55A_-2044	-2044	3994	3708	20
11481.1.1	LDM55A_-2041	-2041	3991	3691	20
11482.1.1	LDM55A_-2038	-2038	3988	3736	20
11483.1.1	LDM55A_-2035	-2035	3985	3682	19
11484.1.1	LDM55A_-2032/-2031	-2031.5	3981.5	3692	20
11485.1.1	LDM55A_-2028	-2028	3978	3706	20
11486.1.1	LDM55A_-2025	-2025	3975	3674	20
11487.1.1	LDM55A_-2022	-2022	3972	3680	20
11488.1.1	LDM55A_-2019	-2019	3969	3663	20
11489.1.1	LDM55A_-2016	-2016	3966	3687	19
11490.1.1	LDM55A_-2013	-2013	3963	3690	21
11582.1.1	MGM421_-2013	-2013	3963	3689	20
11491.1.1	LDM55A_-2010	-2010	3960	3671	20
11583.1.1	MGM421_-2010	-2010	3960	3695	19
11492.1.1	LDM55A_-2007	-2007	3957	3646	20
11493.1.1	LDM55A_-2004	-2004	3954	3668	21
11584.1.1	MGM421_-2004	-2004	3954	3660	19
11494.1.1	LDM55A_-2001	-2001	3951	3633	20
11495.1.1	LDM55A_-1998	-1998	3948	3665	20
11585.1.1	MGM421_-1998	-1998	3948	3689	19
11496.1.1	LDM55A_-1995	-1995	3945	3649	20
11497.1.1	LDM55A_-1992	-1992	3942	3650	20
11579.1.1	LDM55A_-1989	-1989	3939	3673	20
11580.1.1	LDM55A_-1986	-1986	3936	3656	19
11586.1.1	MGM421_-1983	-1983	3933	3681	18
11587.1.1	MGM421_-1980	-1980	3930	3646	20
11588.1.1	MGM421_-1977	-1977	3927	3655	19
11589.1.1	MGM421_-1974	-1974	3924	3659	19
11590.1.1	MGM421_-1971	-1971	3921	3644	19
11591.1.1	MGM421_-1968	-1968	3918	3646	19
11592.1.1	MGM421_-1965	-1965	3915	3642	19
11593.1.1	MGM421_-1962	-1962	3912	3669	19
11594.1.1	MGM421_-1959	-1959	3909	3644	19
11595.1.1	MGM421_-1956	-1956	3906	3613	19

11596.1.1	MGM421_-1953	-1953	3903	3614	20
11597.1.1	MGM421_-1950	-1950	3900	3637	18
11598.1.1	MGM421_-1947	-1947	3897	3622	18
11599.1.1	MGM421_-1944	-1944	3894	3618	18
11600.1.1	MGM421_-1941	-1941	3891	3601	18
11601.1.1	MGM421_-1938	-1938	3888	3602	18
11602.1.1	MGM421_-1935	-1935	3885	3541	18
11603.1.1	MGM421_-1932	-1932	3882	3577	18
11604.1.1	MGM421_-1929	-1929	3879	3576	18

751 Table 3. Results of  $^{14}\text{C}$  dating of selected years from two absolutely dated subfossil trees (Bernabei  
752 et al 2018) and their  $1\sigma$  errors.

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	<b>68.2%</b>	<b>95.4%</b>	<b>99.7%</b>	<b>A<sub>comb</sub></b>	<b>real age BP</b>	<b>offset</b>
no offset	3894-3880	3901-3875	3908-3871	11.4	3879	-
$\Delta\text{R}(-50,50)$	3887-3872	3890-3860	3896-3854	172.8	3879	25 $\pm$ 8

755 Table 4. Comparison of the Aix-BA series with IntCal13 using the OxCal wiggle-matching model  
756 (Bronk Ramsey et al 2001): ages are reported for probabilities at 68.2%, 95.4% and 99.7%. A  
757 reliable dating is obtained at 68.2%, with high percentages of agreement (A<sub>comb</sub>), when applying  
758 an offset to IntCal13.

759  
760

<b>Code Lab</b>	<b>Post</b>	<b>Ring</b>	<b>Position in M912Q subchronology</b>	<b><math>^{14}\text{C}</math></b>	<b>err</b>
11391.1.1	553	1	1	3661	19
11392.1.1	553	4	4	3684	19
11393.1.1	553	7	7	3630	20
11394.1.1	553	11	11	3658	19
11395.1.1	553	15	15	3634	20
11396.1.1	553	19	19	3718	23
11397.1.1	553	23	23	3619	21
11399.1.1	641	1	9	3660	20
11400.1.1	641	5	13	3657	20
11401.1.1	641	9	17	3662	21
11577.1.1	641	11	19	3648	19
11402.1.1	641	13	21	3653	19
11578.1.1	641	15	23	3634	20
11403.1.1	641	17	25	3648	20
11407.1.1	641	19	27	3652	19
11404.1.1	641	21	29	3640	19
11405.1.1	641	23	31	3655	19
11406.1.1	641	26	34	3644	19

761 Table 5. LucD <sup>14</sup>C series, composed of rings from post 553 and 641. Errors of <sup>14</sup>C values are at  
 762 1σ.

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 764

Series	IntCal13				Aix-BA			
	68.2%	95.4%	99.7%	A <sub>comb</sub>	68.2%	95.4%	99.7%	A <sub>comb</sub>
P.553	3975-3955	4054-3920	4060-3908	30.6	3935-3902	3950-3893	3965-3890	46.7
P.641	3974-3929	3978-3920	3980-3910	170.4	3925-3905	3945-3895	3956-3891	156.7
LucD	3972-3956	3978-3927	3980-3915	72.3	3925-3905	3936-3894	3950-3890	116.8

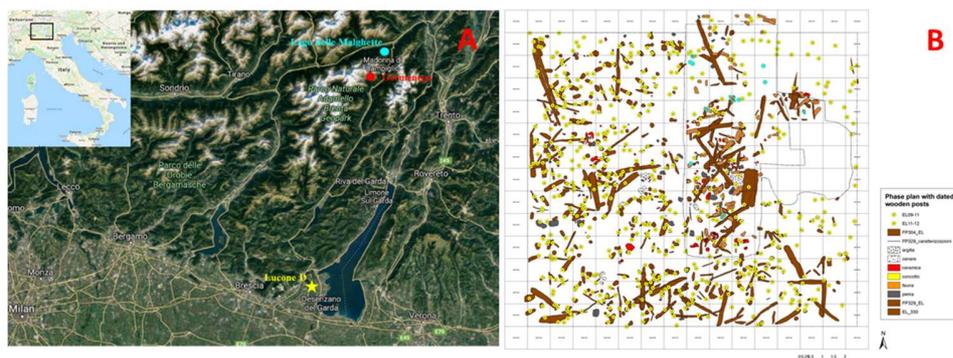
765 Table 6. Comparison of <sup>14</sup>C results of posts 553 and 641 and of LucD <sup>14</sup>C series against IntCal13  
 766 and Aix-BA calibration curves. The ages cal BP are reported with probabilities at 68.2%, 95.4%  
 767 and 99.7%, with the index of agreement given by OxCal (A<sub>comb</sub>).

768

Calibration curve	Samples of GARDA1-I	Cal BP (68.2%)	Cal BP (95.4%)	Cal BP (99.7%)	A <sub>comb</sub>
Aix-BA	Rings 158-208	3952-3926	3959-3895	3993-3886	77.2
Aix-BA+IntCal13	Rings 48-208	3949-3912	3954-3908	3959-3889	86.6
IntCal13	Rings 48-208	3957-3947	3961-3940	3965-3931	62.5
IntCal13_DeltaR(N 25,8)	Rings 48-208	3954-3914	3959-3906	3961-3878	45

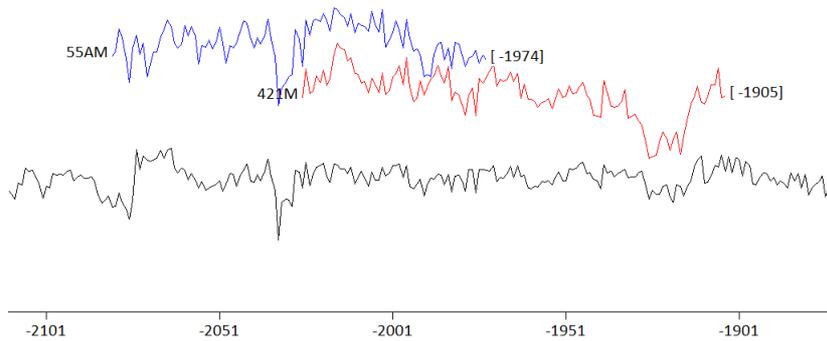
769 Table 7. Part of the ancient <sup>14</sup>C values of ring groups from the GARDA1-I chronology was  
 770 calibrated with the new calibration curve Aix-BA, with a combination of Aix-BA and IntCal13  
 771 and with IntCal13, with and without a ΔR offset (N25,8). We report the part of the recalibrated  
 772 chronology, the ages cal BP with probabilities at 68.2%, 95.4% and 99.7% and the index of  
 773 agreement given by OxCal (A<sub>comb</sub>).

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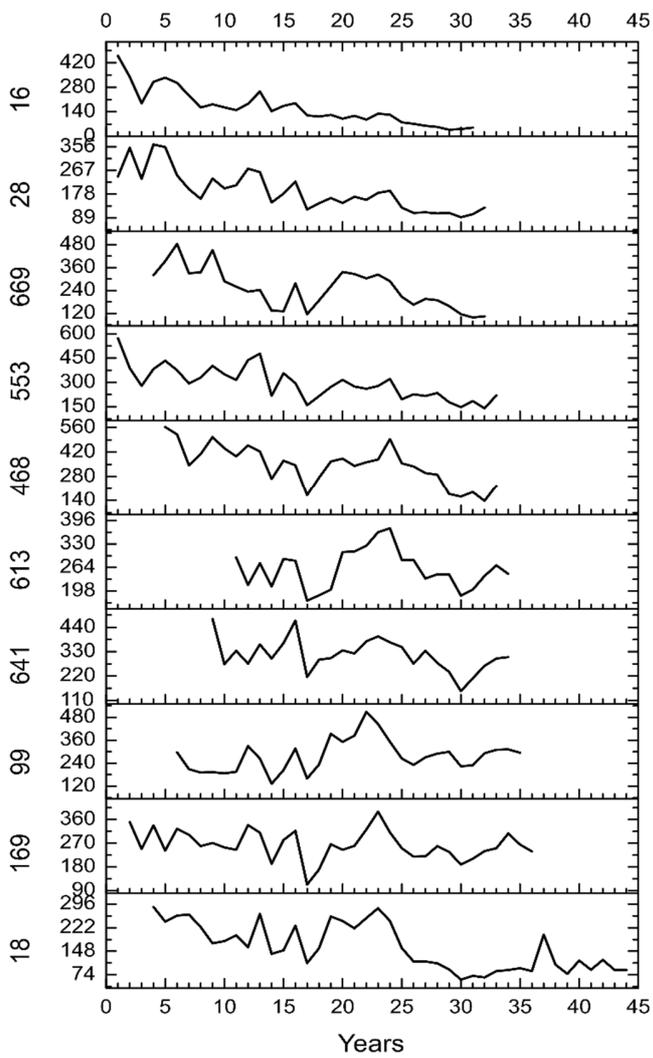


776 Figure 1. A) Map of Northern Italy with the location of I) the Lucone D pile dwelling  
 777 archaeological site (yellow star) and II) the sites of the absolutely-dated subfossil trees that have  
 778 been used herein for the realization of a new calibration curve (red and blue points). B) Map of the  
 779 archaeological excavation of Lucone D site: wooden elements in brown.

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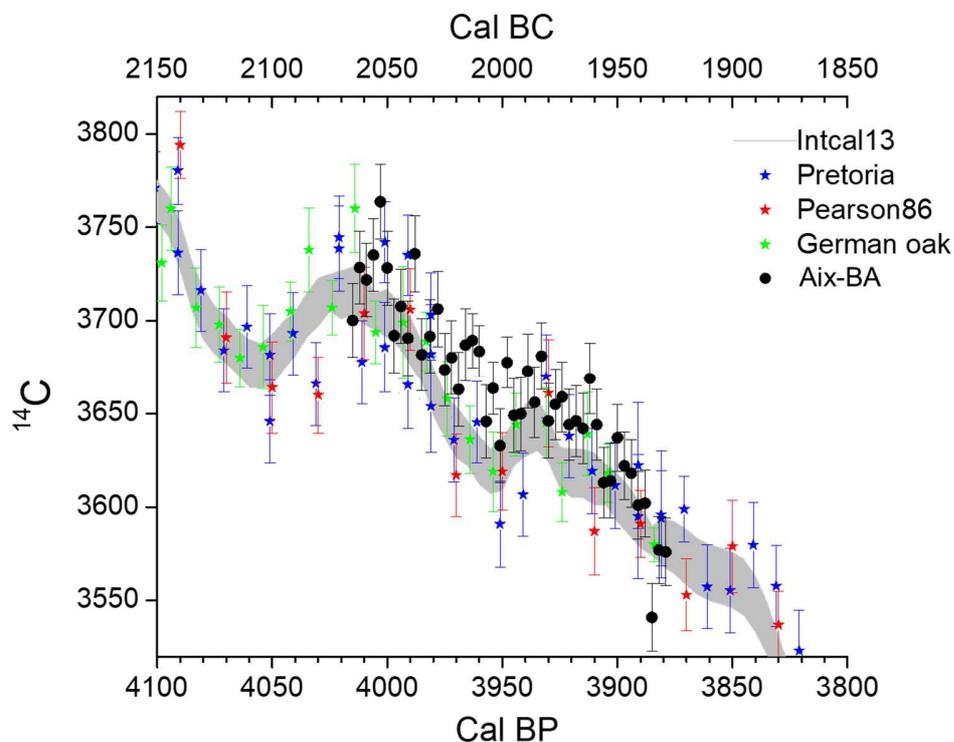


783  
 784 Figure 2. Dendrochronological matching of tree-ring sequences of subfossil trees (LDM\_55A and  
 785 MGM\_421) used for the realization of the new  $^{14}\text{C}$  calibration curve.  
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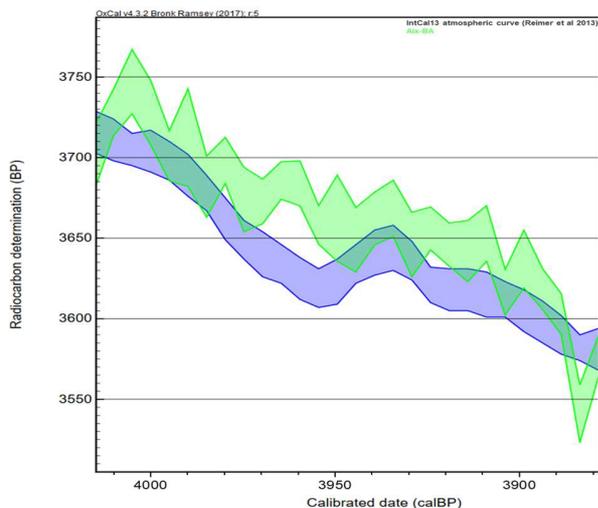


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789 Figure 3. Dendrochronological matching of short tree-ring series from the Lucone D pile dwelling.  
 790 A **subchronology** of 44 rings (called M912Q) is derived from the matching of short **series**.  
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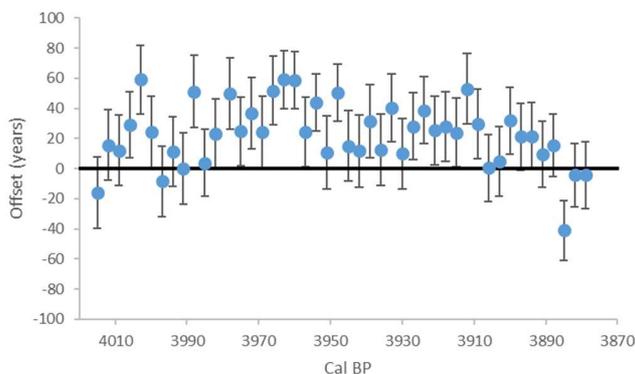
794  
 795 Figure 4. Comparison between the IntCal13 curve, its raw data and the new Aix-BA series. Errors  
 796 are at  $1\sigma$  range. A clear  $^{14}\text{C}$  offset is present in annual measurements of the Aix-BA compared to  
 797 the IntCal13 curve, with oscillations of new data mostly versus older ages.  $^{14}\text{C}$  values of Aix-BA  
 798 fall within the  $2\sigma$  range of most of the raw  $^{14}\text{C}$  data of IntCal13.  
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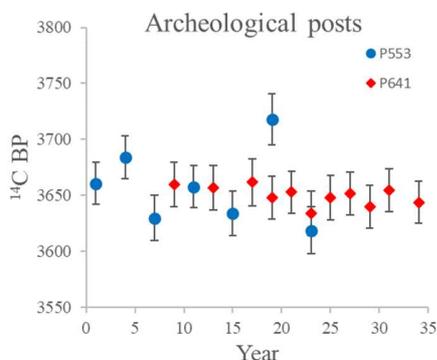
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801 Figure 5. Comparison between the IntCal13 (blue) and the Aix-BA (green) series, modelled with  
 802 the same statistics as IntCal13 (Niu et al. 2013). Both curves are represented at 1 $\sigma$  range.  
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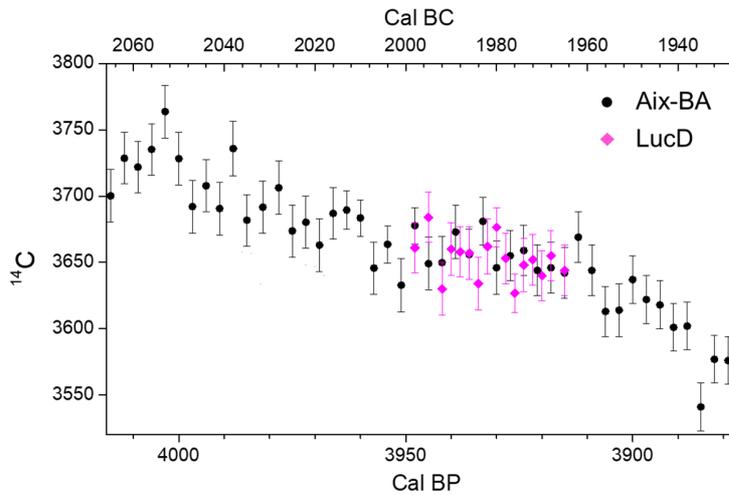


804  
 805 Figure 6. Offset between the Aix-BA and IntCal13 curves. The black line indicates mid-point  
 806 values of the linear interpolation of IntCal13; blue points represent the deviation of <sup>14</sup>C values of  
 807 the Aix-BA curve from IntCal13; the error bars of the blue points were calculated taking into  
 808 consideration both the measured errors of Aix-BA values and the errors of the interpolated annual  
 809 IntCal13 curve. An average offset of 25 $\pm$ 8 years has been calculated (Table 4). The highest offset  
 810 concerns the period 3966-3960 cal BP, into which fall two of the rings with replicated <sup>14</sup>C  
 811 measurement: years 3960 and 3963 cal BP (i.e. -2013 and -2010): their very good agreement  
 812 confirms the accuracy of the measurements.  
 813



814  
 815 Figure 7. <sup>14</sup>C results of random rings sampled from posts 553 and 641 from the Lucone D pile  
 816 dwelling confirm their dendrochronological synchronization, despite post 553 showing more  
 817 dispersed values. For this reason, rings 19 and 23 of the M912Q **subchronology**, which presented  
 818 the highest dispersion, were also measured in post 641. The results of the two measurements for  
 819 ring are in agreement (at 2 $\sigma$  range for ring 19 and 1 $\sigma$  range for ring 23; indeed, the values were  
 820 averaged for each year and the series of posts 553 and 641 were combined for the calibration  
 821 (LucD <sup>14</sup>C sequence, 34-years long). <sup>14</sup>C results of this series are positioned along a “plateau”;  
 822 thus suggesting difficulties in the high-precision calibration purpose. Errors are at 1 $\sigma$  range.  
 823

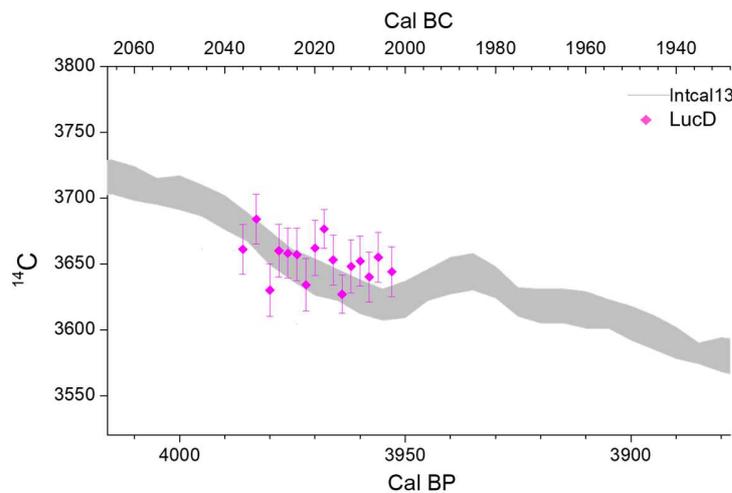
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826 Figure 8. Results of the wiggle-matching dating of the LucD series against the Aix-BA curve.  
827 Errors are at  $1\sigma$  range. When comparing the LucD  $^{14}\text{C}$  sequence with Aix-BA, the last ring of the  
828 series is dated to 3936-3894 cal BP (-1986 to -1944) at 95.4% probability, which dates the LucD  
829  $^{14}\text{C}$  series to **3948-3915 $\pm$ 21 cal BP (-1998/-1965 $\pm$ 21)**.

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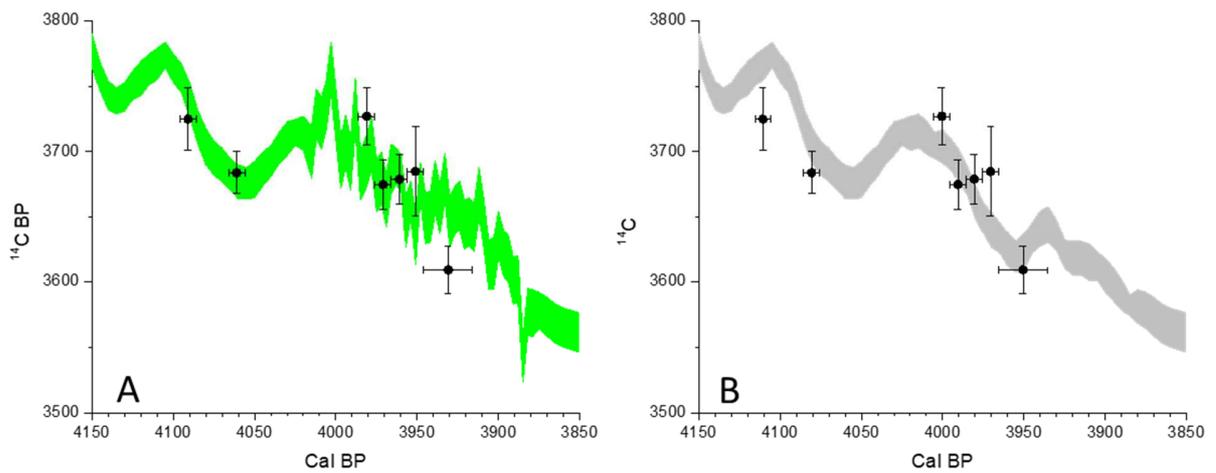


831

832 Figure 9. Results of the wiggle-matching dating of the LucD series against the IntCal13 curve.  
833 Errors are at  $1\sigma$  range. The results of calibration against IntCal13 curve date, at 95.4% probability,  
834 the series to 3978-3927 cal BP (-2028 to -1977) for the last ring of the LucD  $^{14}\text{C}$  sequence, enabling  
835 to date the series to **3986-3953 $\pm$ 26 cal BP (-2036/-2003 $\pm$ 26)**.

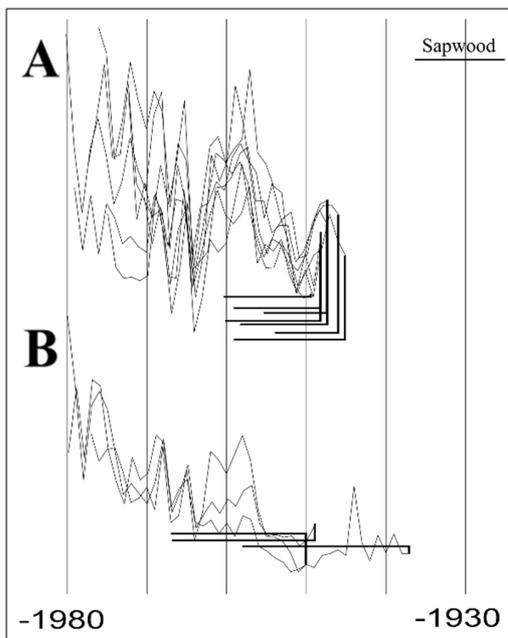
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Figure 10. Calibration of the GARDA1-I chronology against A) the Aix-BA calibration curve, completed in the missing portion by IntCal13 (Aix-BA+IntCal13) and B) against the IntCal13 calibration curve. The highest agreement is obtained when comparing GARDA1-I against Aix-BA+IntCal13, which enables to date the last ring of the  $^{14}\text{C}$  series (i.e. ring 208, as the middle point of rings 193-223) to 3954-3908 cal BP (i.e. 2004-1958 BC), whereas when using IntCal13 it is dated to 3961-3940 cal BP (i.e. 2011-1990 BC).

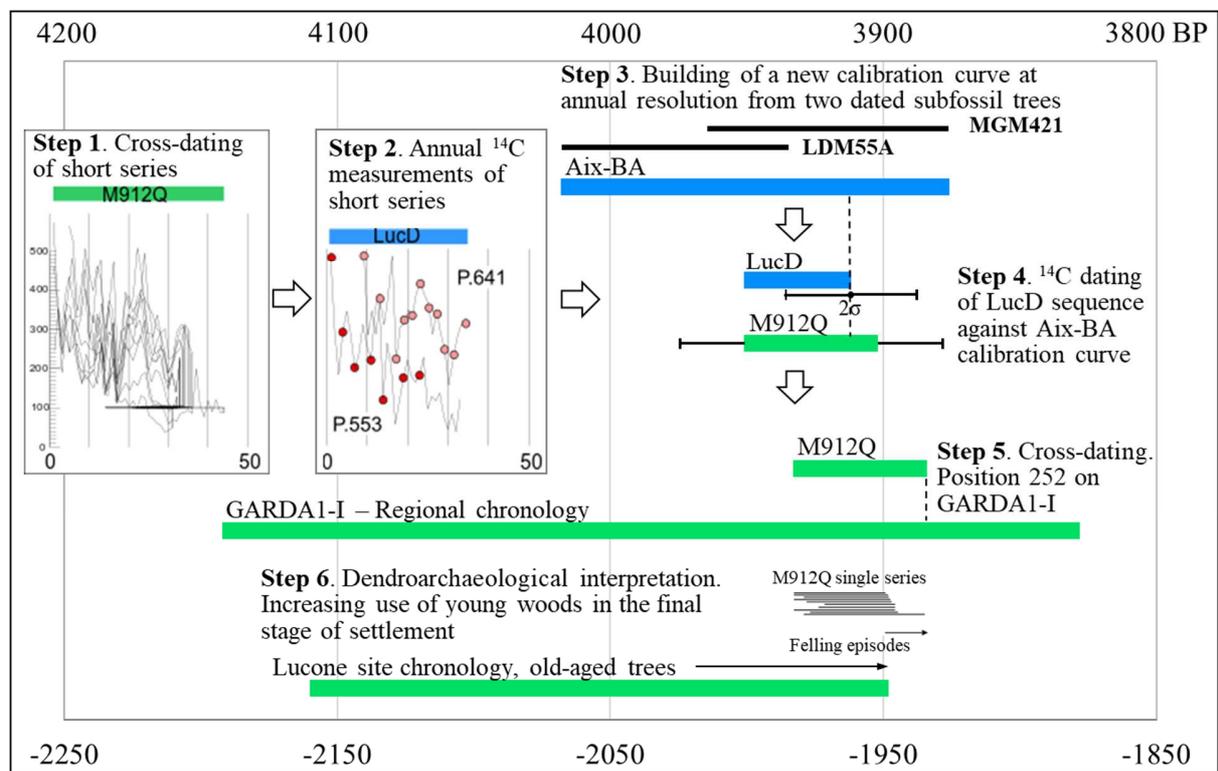


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Figure 11. Two groups highlighted by preliminary dendrotypological analysis: A) high growth-rate series with small number of sapwood rings, indicating young trees with low competition; B)

850 negative growth trend series with high number of sapwood rings, indicating young trees with  
851 higher competition.

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854 Figure 12. Schematic summary of the methodological and interpretative steps of the research. In  
855 blue <sup>14</sup>C sequences and in green dendrochronological series. With the exception of step 1 and 2,  
856 with their own relative scale, all the other steps are on the same chronological scale. It should be  
857 noted that GARDA1-I chronology and the related Lucone and M912Q chronologies are dated by  
858 <sup>14</sup>C wiggle-matching with an uncertainty of  $\pm 23$  years ( $2\sigma$ ).