Is the dating of short tree-ring series still a challenge? New evidence from the pile dwelling of Lucone di Polpenazze (northern Italy)

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Manuela Capano[1]*, Nicoletta Martinelli[2], Marco Baioni[3], Thibaut Tuna[1], Mauro Bernabei[4], Edouard Bard[1]

[1]*CEREGE, Aix-Marseille University, CNRS, IRD, INRAE, Collège de France, Technopôle de l'Arbois, BP 80, F-13545 Aix-en-Provence, France*
[2] *Laboratorio Dendrodata, via Pigna 14, I-37121 Verona, Italy*
[3] *Museo Archeologico della Valle Sabbia, Piazzetta San Bernardino 5, I-25085 Gavardo (BS), Italy*
[4] *CNR-IBE, via Biasi 75 - 38010 S. Michele all'Adige (TN), Italy*
**corresponding author (mail: capano@cerege.fr)*

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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 ^{14}C date the subchronology of the 10 posts, we isolated random annual rings from two posts. Then, using wiggle-matching, the annual ^{14}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 ^{14}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.

^{14}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 available in those countries having undertaken extensive archaeological excavations for which multi-millennial reference curves are available (e.g. France, Germany and Switzerland). However, dendrochronological analysis has also highlighted other aspects of ancient human life, such as the interaction of these early peoples with their environment.

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

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

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

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

2. Dating short tree-ring series

With short tree-ring series it is possible to define series with fewer than 50 rings (Lambert and Orcel 1977; Hillam et al. 1987; Billamboz 2008; Haneca et al. 2009). The classic method of dendrochronology, based on statistic correlations, is suitable for long and sensitive tree-ring series. At the opposite, in the analysis of short series the statistical parameters of comparison are generally low and statistically insignificant or, if occasionally high, may lead to erroneous dating. However, a large part of archaeological woods shows short tree-ring series (Hillam et al. 1984; Billamboz 2003, 2008; Haneca et al. 2006, 2009).

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

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

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

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

If it has been shown that wiggle-matching models can yield reliable results for the dating of long tree-ring series (i.e. min 100-yr long; Galimberti 2004), the same cannot be guaranteed for the calibration of short tree-ring series (Bayliss et al. 2017; Hogg et al. 2017, 2019). Indeed, two main problems arise: I) the possibility that the ^{14}C dating lands entirely on a long, flat section of the calibration curve, in which case the short length of the tree-ring series may lead to high dating uncertainty; and II) difficulties in the resolution of both the dated short-sequence sample and the calibration curve, where a different resolution reduces the probability of obtaining reliable results (Jacobsson et al. 2018; Marshall et al. 2019). Indeed, if single-year tree-ring measurement should, in principle, be preferable for maximizing the short-term radiocarbon variability, and hence the precision of calibration results (Wacker et al. 2014), comparison with the IntCal13 calibration curve based on a minimal resolution of 10 years from 1500 AD back in time (Reimer et al. 2013), reveals that the desired increase in precision fails and that the obtained fit is in fact more likely to show a systematic offset (Jacobsson et al. 2017, 2018). The current effort of the IntCal working group concerns the reconstruction of the calibration curve at annual resolution, and several studies have already contributed to this task (Pearson et al. 2018; Capano et al. 2018, 2020; Sava et al. 2019; Eastoe et al. 2019; Reimer et al. 2020).

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

3. The site

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

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

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

4. Materials and methods

4.1 Dendrochronology – dendrotypology

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

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

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

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

4.2 ^{14}C analysis

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

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

Rings were separated using a scalpel under a binocular microscope and sliced into small pieces. They were oven-dried at 50 °C for 48 hours, after which at least 200 mg of dry wood for each sample was treated for cellulose extraction using the ABA-B method at CEREGE (Aix-en-Provence, France). This method consists in a classic ABA treatment, with solutions of HCl and NaOH at 4% concentration, followed by a bleaching step performed with 60 g of $NaClO_2$ in 1 L of ultrapure water in acid solution (HCl) at pH 3 (Capano et al. 2018).

Two coniferous subfossil woods from the Eastern Italian Alps were chosen for the new calibration curve measured at annual resolution (the new annual calibration curve is named Aix-BA): LDM_55A from a lake context (46.267N-10.816E; 1900 m a.s.l; Lago delle Malghette, Italy) and MGM_421 from a peat bog context (46.137N-10.694E; 1900 m a.s.l; Malga Germenega, Italy; Figure 1). Both trees belong to *Picea abies* Karst. species and are synchronized in a conifer chronology of 3219 years, absolutely dated to 4961-1743 BC against the Eastern Alpine Conifer Chronology (EACC) with high statistical values: GlK = 64%; TBP = 25.2; TH = 27.4 (Nicolussi et al. 2009, 2015; Bernabei et al. 2018). Sampling was performed on a selection of rings from each tree: rings corresponding to years from -2065 to -1986 for LDM_55A and from -1983 to -1929 for MGM_421. Every third ring of the two sequences was measured for ^{14}C, which has been demonstrated to be sufficient for obtaining reliable results (Capano et al. 2020). Moreover, the rings corresponding to years -2013, -2010, -2004 and -1998, which are already measured in LDM_55A, were repeated in MGM_421 for further confirmation of ^{14}C ages. The rings dated to -2032 and -2031 of LDM_55A were coupled in one sample for the small ring width (Figure 2).

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

After chemical pretreatment, the dried residues of archaeological and subfossil woods were weighed in tin capsules, combusted with the elemental analyzer, and the evolved CO_2 was finally transformed into graphite with the AGE III system. The graphite target was then analyzed for its $^{14}C/^{12}C$ and $^{13}C/^{12}C$ ratios using the AixMICADAS system (Bard et al. 2015). Standards (OxA2 NIST SRM4990C) and blanks (VIRI-K, chemically treated like the other wood samples) were processed together with samples and used for normalization and blank correction, respectively. In addition, IAEA-C3 (cellulose) and IAEA-C8 (oxalic acid) standards were pretreated (IAEA-C3 also underwent the chemical pretreatment) and measured for ^{14}C in the same batches, serving as control standards.

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

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

5. Results

5.1 Dendrochronological analysis of pile-dwelling posts

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

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

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

Due to its short length, the tree-ring subchronology (M912Q), 44-years long, revealed two possible different matches against the local chronology from Lucone D and the regional chronology GARDA1, thus preventing dating of the series on the relative scale of the settlement and the region. For this study, a newly formulated version of the first 309-year long part of the chronology, named GARDA1-I (Martinelli, in press) has been used. The site chronology of Lucone is part of the GARDA1-I chronology from ring 32 to 238; while the last year of the subchronology M912Q may correspond to years 126 or 252 of GARDA1-I, but no felling date is attested by the long-series elements from Lucone D, dated between the years 170 and 238 of GARDA1-I.

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

5.2 ^{14}C measurement for calibration purposes

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

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

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

5.3 ^{14}C dating of the archaeological sequences

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

^{14}C results for posts 553 and 641 confirm their dendrochronological synchronization, despite post 553 showing more dispersed values, in particular ring 19, whose cellulose yield after chemical pretreatment was only 0.6 mg (approximately 250 µg of C; Table 5, Figure 7). For this reason, rings 19 and 23 of the subchronology M912Q, which presented the highest dispersion, were also measured in post 641. The results of the measurements for these two rings are in agreement (at 2σ range for ring 19 and 1σ range for ring 23; Figure 7; Table 5). Indeed, the values were averaged for each year and the sequences of posts 553 and 641 were combined for the calibration (LucD ^{14}C sequence, 34-years long). ^{14}C results for this sequence are positioned along a "plateau"; thus predicting difficulties in the high-precision calibration purpose (Figure 7).

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

After examination of the results of the calibration of the LucD ^{14}C sequence and the discordances of the results when using the IntCal13 or Aix-BA curves, we decided to recalibrate the ^{14}C values of the GARDA1-I chronology as well, in the aim of avoiding all possible bias in the calibrated ages, which are now 33 years longer vs previous ages than was the previous ^{14}C-dated chronology (Martinelli 1996). However, we limited the sequence to the first part of the chronology for the highly consistent dendro-matches (GARDA1-I; Martinelli, in press), and to the first 7 ^{14}C dated tree-ring groups of GARDA1-I, thus excluding the last two groups of 50 and 80 rings from Lazise-La Quercia. We initially recalibrated: I) a portion (5 samples out of 7) of the previous ^{14}C measurements of GARDA1-I with Aix-BA, as the entire sequence is longer than the new Aix-BA curve; and II) the entire sequence of GARDA1-I with IntCal13, by substituting the new ^{14}C data of Aix-BA to IntCal13 values from 4015 to 3879 cal BP (Aix-BA+IntCal13; Table 7). Then, for comparison, we contrasted the GARDA1-I sequence with IntCal13 twice, with and without introducing a ΔR offset (N, 25±8), corresponding to the offset calculated by OxCal when comparing Aix-BA with the IntCal13 curve (Table 4). Examination of the results of calibration in the 2σ range indicate that all four options are in agreement, but the calibrations against IntCal13 (without offset) show slightly older ages and smaller uncertainties, which could potentially lead to erroneous absolute ages (Table 7). The highest agreement was obtained when GARDA1-I was compared against Aix-BA+IntCal13 (Figure 10), which enabled to date the last ring of the ^{14}C sequence (i.e. ring 208, as the middle point of rings 193-223) to 3954-3908 cal BP (i.e. 2004-1958 BC); the chronology GARDA1-I is thus dated to 4138-3831±23 cal BP (-2188/-1881±23).

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

6. Discussion

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

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

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

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

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

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

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

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

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

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

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

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

The EBA is unfortunately not attested north of the Alps, but in the village of Bande di Cavriana (Mantova, Northern Italy), coeval to Lucone D, the last phase of occupation is characterized by the additional use of young woods, in opposition to the 2 earlier phases during which the use of young woods was almost exclusively coupled to the use of old woods (Martinelli 2017, 2018). However, the young woods of Bande di Cavriana are large in circumference (ca. 40 cm) and 60-80 rings, thus excluding a possible analogy with the Lucone D settlement where the tree circumference of young woods is equal to or less than 30 cm, and where the tree-ring series do not exceed 41 rings. Strong forest exploitation is attested in other villages beginning only in the 18^{th} century BC (e.g. the pile dwelling of Frassino, near Verona; Martinelli 2013), with increasing human impact in the following centuries (e.g. the pile dwelling of Sabbione, near Varese, dated to the end of 17^{th} – beginning of 16^{th} century; Martinelli 2013). In these last two examples, the last phase of the settlement is characterized by the use of other less prestigious species of wood than *Quercus* sp. Sectio *ROBUR*, such as *Quercus* sp. Sectio *CERRIS* at the Frassino site (Martinelli 2018) and *Fagus* sp., *Betula* sp. and *Corylus* sp. at the Sabbione site (Martinelli 2013). This has been interpreted as evidence of the final exploitation of the surrounding forest before the abandonment of the site. This is not the case at Lucone D, where the analyzed posts all belong to deciduous oak species. The young woods from the Lucone D settlement seem, indeed, to be in no way analogous to other villages. It should be noted, however, that posts such as the ones analyzed in this study, with short tree-ring series but unearthed from other pile dwellings remain undated. It seems essential therefore to precisely date all short tree-ring series from all pile-dwelling sites in order to enable more realistic comparisons.

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

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

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

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

Conclusions

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

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

A combination of dendrochronological and ^{14}C analyses has permitted to find the correct dating position of young woods on the regional chronology GARDA1-I, which has, in turn, been recalibrated on the new calibration curve.

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

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Author contributions

Manuscript writing and development by M.C. with the support of N.M. and E.B. ^{14}C analyses and interpretation by M.C. with the support of E.B. and T.T. Archaeological investigation, interpretation and sampling of archaeological posts from Lucone D by M.Ba. Dendrochronological and dendrotypological analysis of archaeological posts from Lucone D by N.M., data interpretation by N.M. and M.C. Sampling, dendrochronological analysis and absolute dating of subfossil trees from Trentino by M.Be. Revisions by all authors.

References

Adams WW III, Zarter CR, Ebbert V, Demmig-Adams B. 2004. Photoprotective Strategies of Overwintering Evergreens. *BioScience* 54(1): 41-49.

Aniol RW. 1983. Tree ring analysis using Catras. *Dendrochronologia* 1: 45-53.

Baillie MGL. 1982. *Tree-ring dating and archaeology*. Chicago-London-Canberra.

Baioni M, Leonardi G, Fozzati L, Martinelli N. 2019. Le palafitte: definizione e caratteristiche di un fenomeno complesso attraverso alcuni casi di studio. Baioni M, Mangani C, Ruggiero MG (edited by), *Le Palafitte: Ricerca, valorizzazione, Conservazione, Atti del Convegno Internazionale (4-8 October 2011 – Desenzano del Garda – I), Palafitte/Palafittes/Pfahlbauten/Pile dwellings*, vol. 0: 27-42.

Baioni M, Bona F, Mangani C, Martinelli N, Nicosia C, Perego R, Quirino T, Saletta E. In press. Daily life in a north Italian Early Bronze Age pile dwelling: Lucone di Polpenazze del Garda (Italy – Brescia). *Lieux de vie et espaces domestiques : organisations fonctionnelles et stratégies sociales / Use of space and domestic areas: functional organisation and social strategies*, Proceedings of XVIII World UISPP Congress, Paris, 4-9 June 2018, Session XXXII-1, Archaeopress, UISPP Proceedings Series.

Bard E, Tuna T, Fagault Y, Bonvalot L, Wacker L, Fahrni S, Synal H-A. 2015. AixMICADAS, the accelerator mass spectrometer dedicated to 14C recently installed in Aix-en-Provence, France. *Nuclear Instruments and Methods in Physics Research* B 361: 80–86.

Bayliss A, Marshall P, Tyers C, Bronk Ramsey C, Cook G, Freeman SPHT, Griffiths S. 2017. Informing conservation: towards 14C wiggle-matching of short tree-ring sequences from medieval buildings in England. In *Radiocarbon* 59(3): 985-1007.

Bernabei M, Bontadi J, Nicolussi K. 2018. Observations on Holocene subfossil tree remains from high-elevation sites in the Italian Alps. *The Holocene* 28(12): 2017-2027.

Billamboz A. 2003. Tree rings and wetland occupation in southwest Germany between 2000 and 500 BC: dendroarchaeology beyond dating in tribute to F.H. Schweingruber. In *Tree-Ring Research* 59(1): 37-49.

Billamboz A. 2008. Dealing with heteroconnections and short tree-ring series at different levels of dating in the dendrochronology of the Southwest German pile-dwellings. *Dendrochronologia* 26: 145–155.

Billamboz A. 2011. Applying dendro-typology to large timber series. In Fraiture P (edited by), *Tree Rings, Art, Archaeology*. Proc. Internat. Conference (10–12 February 2010) Brussels. Scientia Artis 7: 177–188.

Billamboz A. 2014. Regional patterns of settlement and woodland developments: Dendroarchaeology in the Neolithic pile-dwellings on Lake Constance (Germany). *The Holocene* 24(10): 1278-1287.

Bronk Ramsey C. 1995. Radiocarbon calibration and analysis of stratigraphy: The OxCal program. *Radiocarbon* 37: 425–430.

Bronk Ramsey C, van der Plicht J, Weninger B. 2001. "Wiggle matching" radiocarbon dates. *Radiocarbon* 43(2): 381–389.

Bronk Ramsey C. 2009. Dealing with outliers and offsets in radiocarbon dating. *Radiocarbon* 51(3):1023-45.

Bronk Ramsey C, Dee MW, Rowland JM, Higham TFG, Harris SA, Brock F, Quiles A, Wild EM, Marcus ES, Shortland AJ. 2010. Radiocarbon-based chronology for dynastic Egypt. *Science* 328: 1554–1557.

Cambini A. 1967a. Micrografia comparata dei legni del genere Quercus. *Contributi scientifico-pratici per una migliore conoscenza ed utilizzazione del legno, C.N.R.* X: 7-49.

Cambini A. 1967b. Riconoscimento microscopico del legno delle querce italiane. *Contributi scientifico-pratici per una migliore conoscenza ed utilizzazione del legno, C.N.R.* X: 51-79.

Capano M, Miramont C, Guibal F, Kromer B, Tuna T, Fagault Y, Bard E. 2018. Wood 14C dating with AixMICADAS: methods and application to tree-ring sequences from the Younger Dryas event in the southern French Alps. In *Radiocarbon* 60(1): 51-74.

Capano M, Miramont C, Shindo L, Guibal F, Marschal C, Kromer B, Tuna T, Bard E. 2020. Onset of the Younger Dryas recorded with 14C at annual resolution in French subfossil trees, in *Radiocarbon*. DOI:10.1017/RDC.2019.116

Dee MW, Brock F, Harris SA, Bronk Ramsey C, Shortland AJ, Higham TFG, Rowland JM. 2010. Investigating the likelihood of a reservoir offset in the radiocarbon record for ancient Egypt. *Journal of Archaeological Science* 37(4): 687-693.

Eastoe CJ, Tucek CS, Touchan R. 2019. Δ14C and δ13C in Annual Tree-Ring Samples from Sequoiadendron Giganteum, AD 998–1510: Solar Cycles and Climate. *Radiocarbon* 61 (3): 661-680.

Frisia S, Borsato A, Richards DA, Miorandi R, Davanzo S. 2005. Variazioni climatiche ed eventi sismici negli ultimi 4500 anni nel Trentino meridionale da una stalagmite della Cogola Grande di Giazzera. *Studi trentini di scienze naturali - Acta Geologica* 82: 205-223.

Galimberti M, Bronk Ramsey C, Manning SW. 2004. Wiggle-match dating of tree-ring sequences. *Radiocarbon* 2: 917-924.

Haneca K, Boeren I, Van Acker J, Beeckman H. 2006. Dendrochronology in suboptimal conditions: tree rings from medieval oak from Flanders (Belgium) as dating tools and archives of past forest management. *Vegetation History and Archaeobotany* 15(2): 137–144.

Haneca K, Čufar K, Beeckman H. 2009. Oaks, tree-rings and wooden cultural heritage: a review of the main characteristics and applications of oak dendrochronology in Europe. *Journal of Archaeological Science* 36: 1-11.

Hillam J, Morgan R, Tyers I. 1984. Dendrochronology and roman London. *Trans. London and Middlesex Archaeological Society* 35: 1-4.

Hillam J, Morgan R, and Tyers I. 1987. Sapwood estimates and the dating of short ring sequences. *British Archaeological Reports (International Series)* 333, 165-85.

Hogg A, Gumbley W, Boswijk G, Petchey F, Southon J, Anderson A, Roa T, Donaldson L. 2017. The first accurate and precise calendar dating of New Zealand Māori Pā, using Otāhau Pā as a case study. *Journal of Archaeological Science: Reports* 12: 124-133.

Hogg A, Heaton T, Bronk Ramsey C, Boswijk G, Palmer J, Turney C, Southon J, Gumbley W. 2019. The Influence of Calibration Curve Construction and Composition on the Accuracy and Precision of Radiocarbon Wiggle-Matching of Tree Rings, Illustrated by Southern Hemisphere Atmospheric Data Sets from AD 1500–1950. *Radiocarbon* 61(5): 1265-1291.

Jacobsson P, Hale A, Hamilton D, Cook G. 2017. Radiocarbon wiggle-match dating in the intertidal zone. *Journal of Island and Coastal Archaeology* 14(1): 61-70.

Jacobsson P, Hamilton W, Cook G, Crone A, Dunbar E, Kinch H, Naysmith P, Tripney B, Xu S. 2018. Refining the Hallstatt Plateau: Short-Term 14C Variability and Small Scale Offsets in 50 Consecutive Single Tree-Rings from Southwest Scotland Dendro-Dated to 510–460 BC. *Radiocarbon* 60(1): 219-237.

Kaennel M, Schweingruber FH. 1995. Multilingual glossary of dendrochronology: terms and definitions in English, German, French, Spanish, Italian, Portuguese and Russian. Bern-Stuttgart-Wien, 467 p.

Lambert GN, Orcel C. 1977. L'état de la dendrochronologie en Europe Occidentale. *Archives Suisses d'Antropologie Generale* 41(2): 73-97.

Manning S, Höflmayer F, Moeller N, Dee M, Ramsey C, Fleitmann D, Higham T, Kutschera W, Wild E. 2014. Dating the Thera (Santorini) eruption: Archaeological and scientific evidence supporting a high chronology. *Antiquity* 88(342): 1164-1179

Marshall P, Bayliss A, Farid S, Tyers C, Bronk Ramsey C, Cook G, Doğan T, Freeman SPHT, İlkmen E, Knowles T. 2019. 14C wiggle-matching of short tree-ring sequences from post-medieval buildings in England. *Nuclear Instruments and Methods in Physics Research* B 438: 218-226.

Martinelli N. 1996. Datazioni dendrocronologiche per l'età del Bronzo dell'area alpina. Randsborg K (edited by) Absolute Chronology. Archaeological Europe 2500-500 BC, Proceedings of the Conference (Verona, 20-23 aprile 1995), Acta Archaeologica, vol. 67, Acta Archaeologica Supplementa vol I: 315-326, Munsksgaart, Copenhagen.

Martinelli N. 2013. Dendro-typology in Italy: The case studies of the pile-dwelling villages Lucone D (Brescia) and Sabbione (Varese). Bleicher N, Gassmann P, Martinelli N, Schlichtherle H (edited by), Dendro–Chronologie–Typologie–Oekologie, Festschrift für André Billamboz zum 65. Geburtstag (Hemmenhofen, 4 ottobre 2013), Freiburg im Breisgau, 117-124.

Martinelli M. 2017. La dendrotipologia: una disciplina al confine fra le scienze per indagare e il rapporto delle comunità palafitticole con l'ambiente. Cupitò M, Vidale M, Angelini A (edited by), *Beyond limits. Studi in onore di Giovanni Leonardi*, Padova, 745-751.

Martinelli N. 2018. Dendrocronologia delle palafitte dell'Italia settentrionale: uno strumento per lo studio dell'evoluzione dell'intervento dell'uomo sul territorio nel corso dell'età del Bronzo, in Borgna E, Cassola Guida P, Corazza S (edited by), Preistoria e Protostoria del Caput Adriae, Studi di Preistoria e Protostoria, 5, Atti della XLIX Riunione Scientifica IIPP, Udine e Pordenone 11-12 ottobre 2014, IIPP, Firenze, 471-480. ISBN 978-88-6045-069-2

Martinelli N. In press. Dendrocronologia dell'età del Bronzo in Italia settentrionale: stato dell'arte e aggiornamenti, contribution to the "Round Table on absolute and relative chronology of Bronze Age on the basis of dendrochronology", Preistoria e Protostoria della Lombardia, LII Riunione Scientifica IIPP, Milan 17-20 october 2017, Istituto Italiano di Preistoria e Protostoria.

Martinelli N, Čufar K, Billamboz A. 2019. Dendroarchaeology between teleconnection and regional patterns. Baioni M, Mangani C, Ruggiero MG (edited by), Le Palafitte: Ricerca, valorizzazione, Conservazione, Atti del Convegno Internazionale (4-8 October 2011 – Desenzano del Garda – I), Palafitte/Palafittes/Pfahlbauten/Pile dwellings, vol. 0: 67-77.

Miyake F, Nagaya K, Masuda K, Nakamura T. 2012, A signature of cosmic-ray increase in AD 774-775 from tree rings in Japan. *Nature* 486(7402): 240-242.

Miyake F, Masuda K, Nakamura T. 2013. Another rapid event in the carbon-14 content of tree rings. *Nature Communications* 4: 1748.

Nicolussi K, Kaufmann M, Melvin TM, van der Plicht J, Schießling P, Thurner A. 2009. A 9111 yearlong conifer tree-ring chronology for the European Alps: A base for environmental and climatic investigations. *The Holocene* 19: 909–920.

Nicolussi K, Weber G, Patzelt G, Thurner A. 2015. A question of time: Extension of the Eastern Alpine Conifer Chronology backto 10 071 b2k. Wilson R, Helle G, Gärtner H (edited by) TRACE – Tree Rings in Archaeology, Climatology and Ecology 13 (Scientific Technical Report 15/06). Potsdam: GFZ German Research Centre for Geosciences: 69–73.

Niu M, Heaton TJ, Blackwell P, Buck CE. 2013. The Bayesian approach to radiocarbon calibration curve estimation: The IntCal13, Marine13, and SHCal13 methodologies. *Radiocarbon* 55, 1905–1922.

Nominaion Dossier 2011, *Prehistoric Pile-Dwelling around the Alps*. Nomination Dossier for the inscription in the UNESCO World Heritage List, International Group for the UNESCO Nomination, 2011.

Pearson CL, Brewer PW, Brown D, Heaton TJ, Hodgins GWL, Jull AJT, Lange T, Salzer MW. 2018. Annual radiocarbon record indicates 16th century BCE date for the Thera eruption. *Science Advances* 4: 1-7.

Pilcher JR. 1996. Biological considerations in the interpretation of stable isotope ratios in oak tree-rings. *Palaeoklimaforschung* 15: 157–161.

Reimer PJ, Bard E, Bayliss A, Beck JW, Blackwell PG, Bronk Ramsey C, Buck CE, Cheng H, Edwards RL, Friedrich M, Grootes PM, Guilderson TP, Haflidason H, Hajdas I, Hatté C, Heaton TJ, Hoffmann DL, Hogg AG, Hughen KA, Kaiser KF, Kromer B, Manning SW, Niu M, Reimer RW, Richards DA, Scott EM, Southon JR, Staff RA, Turney CSM, van der Plicht J. 2013. IntCal13 and Marine13 radiocarbon age calibration curves 0-50,000 years Cal BP. In *Radiocarbon* 55(4): 1869-1887.

Reimer PJ, Austin WEN, Bard E, Bayliss A, Blackwell PG, Bronk Ramsey C, Butzin M, Cheng H, Edwards RL, Friedrich M, Grootes PM, Guilderson TP, Hajdas I, Heaton TJ, Hogg AG, Hughen KA, Kromer B, Manning SW, Muscheler R, Palmer JG, Pearson C, van der Plicht H, Reimer RW, Richards DA, Scott EM, Southon JR, Turney CSM, Wacker L, Adophi F, Büntgen U, Capano M, Fahrni S, Fogtmann-Schulz A, Friedrich R, Köhler P, Kudsk S, Miyake F, Olsen J, Reinig F, Sakamoto M, Sookdeo A, Talamo S. In press. 2020. The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0-55 kcal BP). *Radiocarbon*.

Sava G, Popa I, Sava T, Meghea A, Mănăilescu C, Ilie M, Robu A, Tóth B. 2019. Intervalidation of Dendrochronology and 14C Dating on a 700-yr Tree-Ring Sequence Originating from the Eastern Carpathians. *Radiocarbon* 61(5): 1337-1343.

Stuiver M, Becker B. 1993. High-precision decadal calibration of the radiocarbon time scale AD 1950–6000 BC. *Radiocarbon* 35(1): 35-65.

Stuiver M, Polach HA. 1977. Discussion: reporting of 14C data. *Radiocarbon* 19(3): 355–63.

Trouet V, Domínguez-Delmás M, Pearson C, Pederson N, Rubino D. 2017. Dendro-archeo-ecology in North America and Europe: Re-purposing Historical Materials to Study Ancient Human-Environment Interactions. Amoroso MM, Daniels LD, Baker PJ, Camarero JJ (edited by), Dendroecology. Ecological Studies (Analysis and Synthesis), vol 231. Springer, Cham: 365-394.

UNESCO, World heritage list, Prehistoric Pile dwellings around the Alps. http://whc.unesco.org/en/list/1363 (30/10/2019).

Wacker L, Güttler D, Goll J, Hurni JP, Synal H-A, Walti N. 2014. Radiocarbon Dating to a Single Year by Means of Rapid Atmospheric 14C Changes. *Radiocarbon* 56(2): 573-579.

Wacker L, Scott EM, Bayliss A, Brown D, Bard E, Bollhalder S, Friedrich M, Capano M, Cherkinsky A, Chivall D, Culleton BJ, Dee MW, Friedrich F, Hodgins GWL, Hogg A, Kennett DJ, Knowles TDJ, Kuitems M, Lange TE, Miyake F, Nadeau M-J, Nakamura T, Naysmith JP, Olsen J, Omori T, Petchey F, Philippsen B, Bronk Ramsey C, Prasad GVR, Seiler M, Southon J, Staff R, Tuna T. In press. Findings from an in-depth annual tree ring radiocarbon Intercomparison. *Radiocarbon*.

Tables

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

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

OVL	Glk	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

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

Code Lab	Tree_Ring	Abs. age	Age BP	^{14}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

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

	68.2%	**95.4%**	**99.7%**	**A_{comb}**	**real age BP**	**offset**
no offset	3894-3880	3901-3875	3908-3871	11.4	3879	-
ΔR(-50,50)	3887-3872	3890-3860	3896-3854	172.8	3879	25±8

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

Code Lab	**Post**	**Ring**	**Position in M912Q** subchronology	**^{14}C**	**err**
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

Table 5. LucD ^{14}C series, composed of rings from post 553 and 641. Errors of ^{14}C values are at 1σ.

Series	IntCal13				Aix-BA			
	68.2%	**95.4%**	**99.7%**	**A_{comb}**	**68.2%**	**95.4%**	**99.7%**	**A_{comb}**
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

Table 6. Comparison of ^{14}C results of posts 553 and 641 and of LucD ^{14}C series against IntCal13 and Aix-BA calibration curves. The ages cal BP are reported with probabilities at 68.2%, 95.4% and 99.7%, with the index of agreement given by OxCal (A_{comb}).

Calibration curve	Samples of GARDA1-I	Cal BP (68.2%)	Cal BP (95.4%)	Cal BP (99.7%)	A_{comb}
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

Table 7. Part of the ancient ^{14}C values of ring groups from the GARDA1-I chronology was calibrated with the new calibration curve Aix-BA, with a combination of Aix-BA and IntCal13 and with IntCal13, with and without a ΔR offset (N25,8). We report the part of the recalibrated chronology, the ages cal BP with probabilities at 68.2%, 95.4% and 99.7% and the index of agreement given by OxCal (A_{comb}).

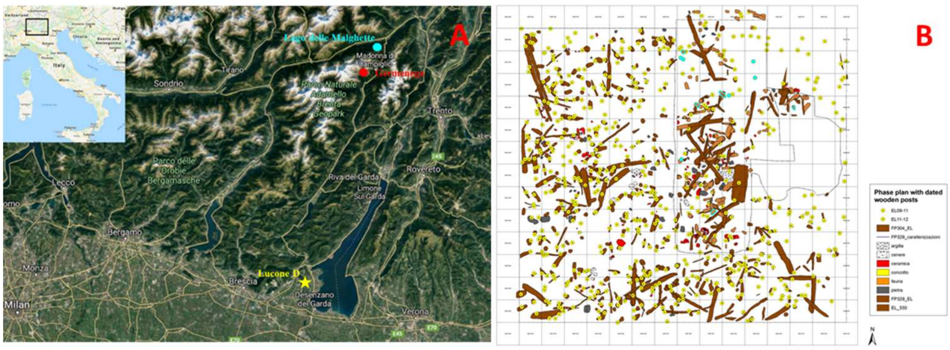

Figure 1. A) Map of Northern Italy with the location of I) the Lucone D pile dwelling archaeological site (yellow star) and II) the sites of the absolutely-dated subfossil trees that have been used herein for the realization of a new calibration curve (red and blue points). B) Map of the archaeological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

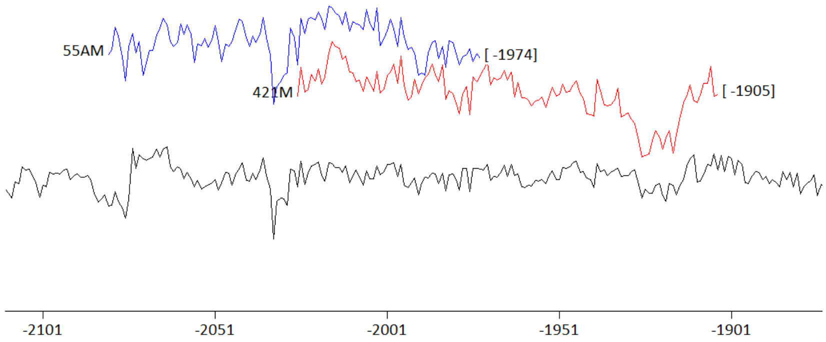

Figure 2. Dendrochronological matching of tree-ring sequences of subfossil trees (LDM_55A and MGM_421) used for the realization of the new ^{14}C calibration curve.

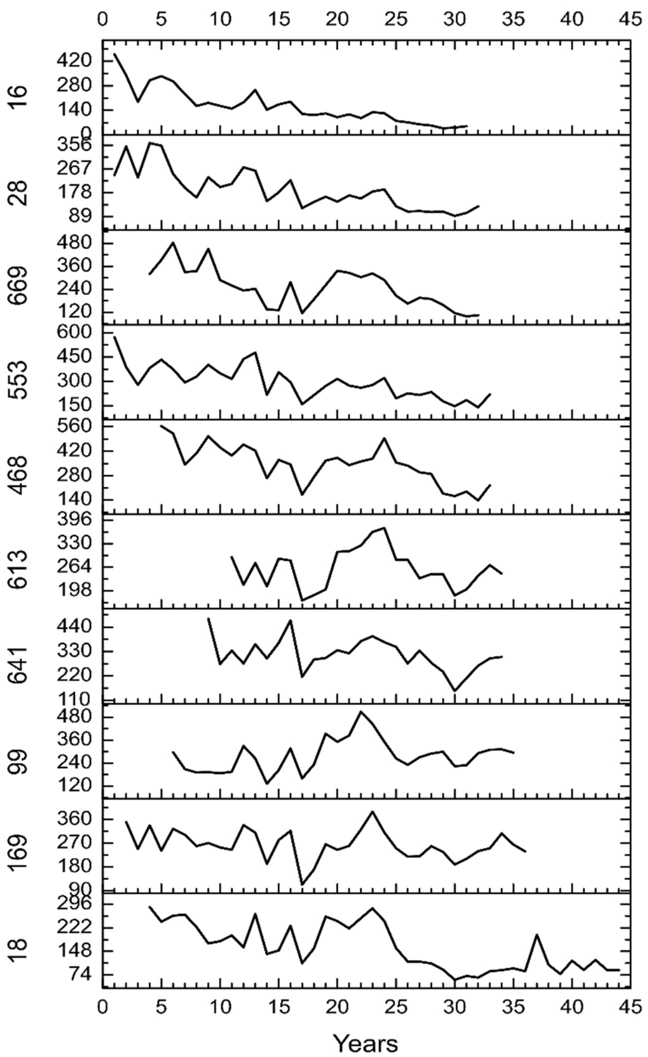

Figure 3. Dendrochronological matching of short tree-ring series from the Lucone D pile dwelling. A subchronology of 44 rings (called M912Q) is derived from the matching of short series.

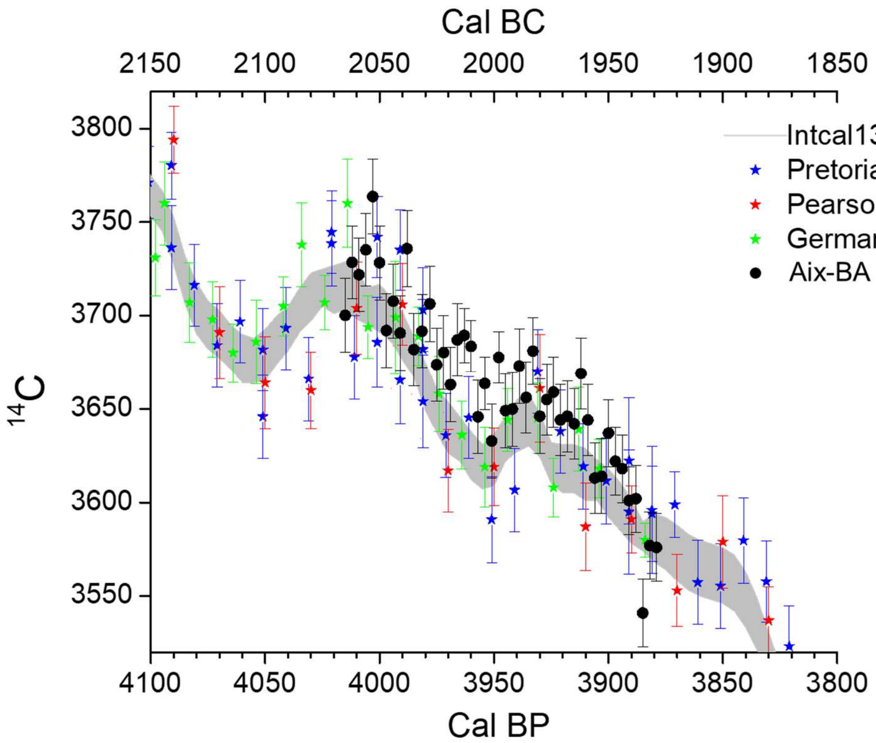

Figure 4. Comparison between the IntCal13 curve, its raw data and the new Aix-BA series. Errors are at 1σ range. A clear ^{14}C offset is present in annual measurements of the Aix-BA compared to the IntCal13 curve, with oscillations of new data mostly versus older ages. ^{14}C values of Aix-BA fall within the 2 σ range of most of the raw ^{14}C data of IntCal13.

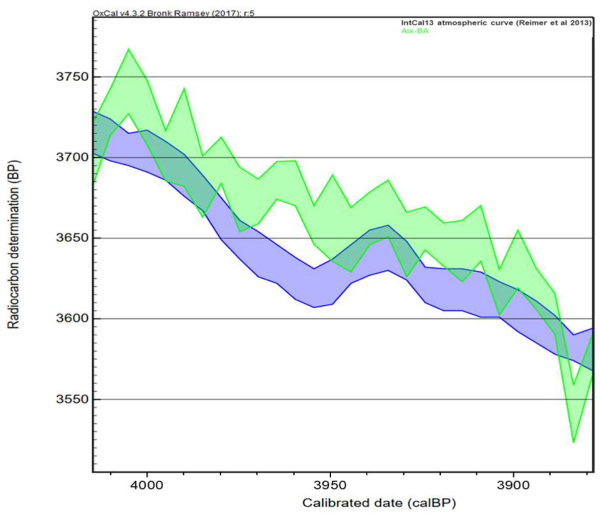

Figure 5. Comparison between the IntCal13 (blue) and the Aix-BA (green) series, modelled with the same statistics as IntCal13 (Niu et al. 2013). Both curves are represented at 1σ range.

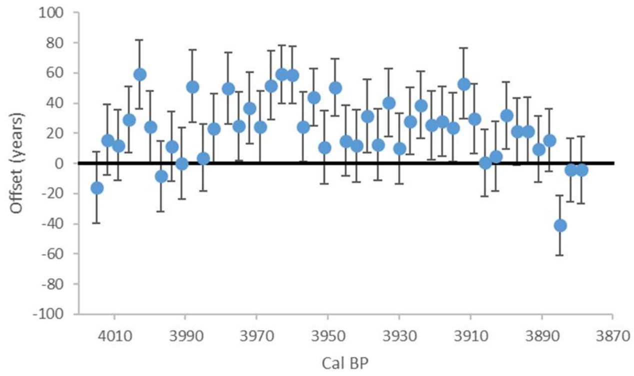

Figure 6. Offset between the Aix-BA and IntCal13 curves. The black line indicates mid-point values of the linear interpolation of IntCal13; blue points represent the deviation of ^{14}C values of the Aix-BA curve from IntCal13; the error bars of the blue points were calculated taking into consideration both the measured errors of Aix-BA values and the errors of the interpolated annual IntCal13 curve. An average offset of 25±8 years has been calculated (Table 4). The highest offset concerns the period 3966-3960 cal BP, into which fall two of the rings with replicated ^{14}C measurement: years 3960 and 3963 cal BP (i.e. -2013 and -2010): their very good agreement confirms the accuracy of the measurements.

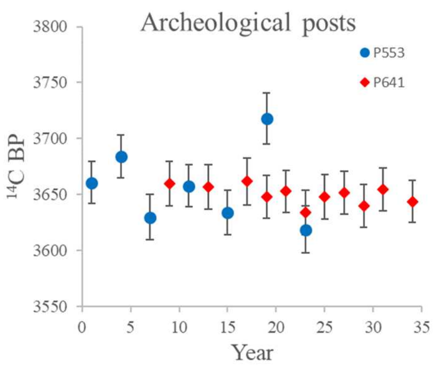

Figure 7. ^{14}C results of random rings sampled from posts 553 and 641 from the Lucone D pile dwelling confirm their dendrochronological synchronization, despite post 553 showing more dispersed values. For this reason, rings 19 and 23 of the M912Q subchronology, which presented the highest dispersion, were also measured in post 641. The results of the two measurements for ring are in agreement (at 2σ range for ring 19 and 1σ range for ring 23; indeed, the values were averaged for each year and the series of posts 553 and 641 were combined for the calibration (LucD ^{14}C sequence, 34-years long). ^{14}C results of this series are positioned along a "plateau"; thus suggesting difficulties in the high-precision calibration purpose. Errors are at 1σ range.

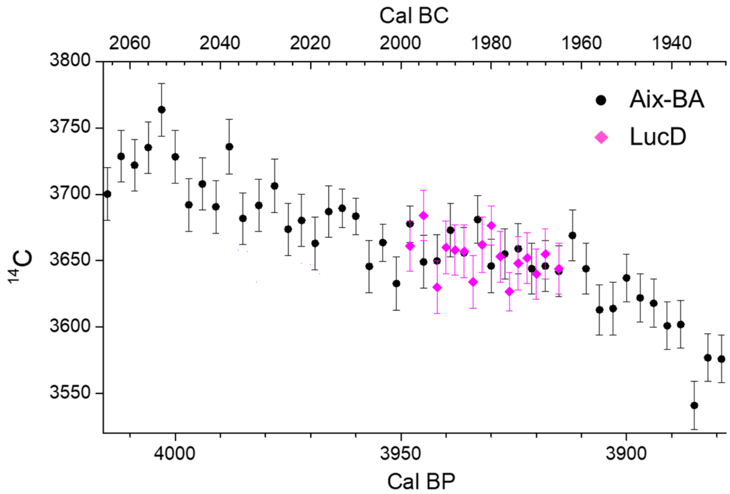

Figure 8. Results of the wiggle-matching dating of the LucD series against the Aix-BA curve. Errors are at 1σ range. When comparing the LucD ^{14}C sequence with Aix-BA, the last ring of the series is dated to 3936-3894 cal BP (-1986 to -1944) at 95.4% probability, which dates the LucD ^{14}C series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

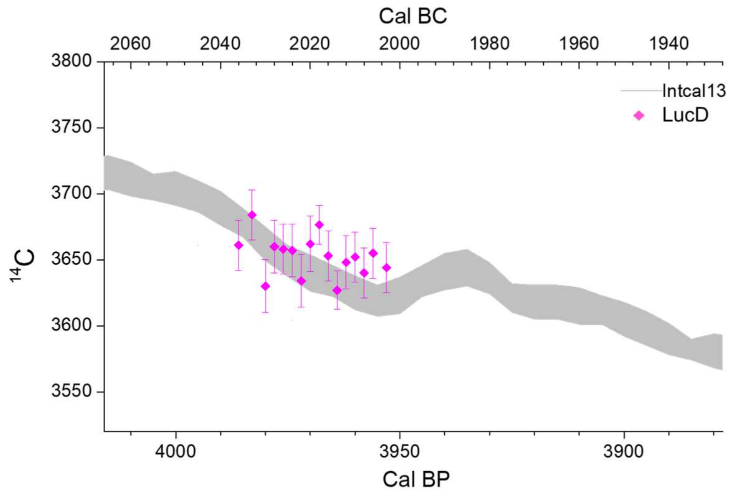

Figure 9. Results of the wiggle-matching dating of the LucD series against the IntCal13 curve. Errors are at 1σ range. The results of calibration against IntCal13 curve date, at 95.4% probability, the series to 3978-3927 cal BP (-2028 to -1977) for the last ring of the LucD ^{14}C sequence, enabling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

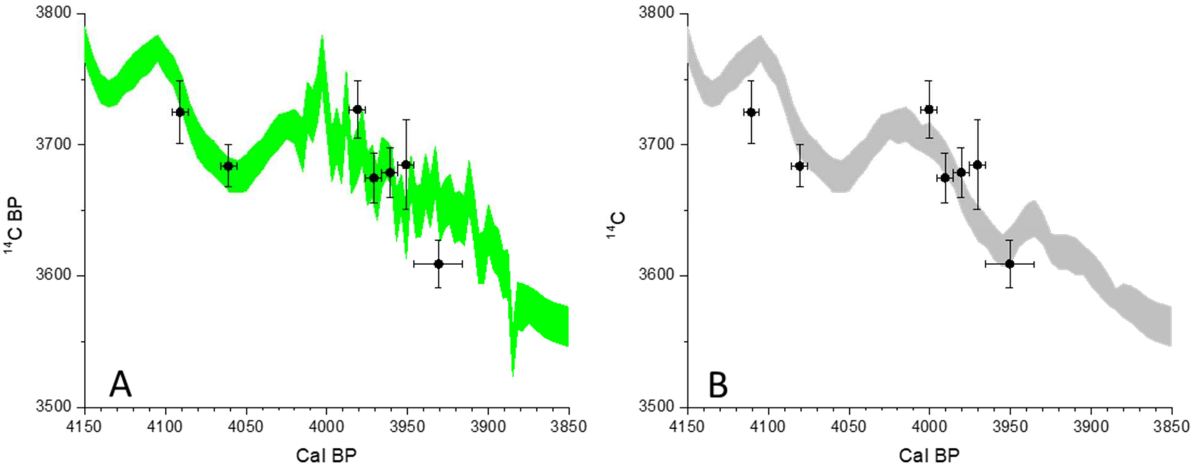

Figure 10. Calibration of the GARDA1-I chronology against A) the Aix-BA calibration curve, completed in the missing portion by IntCal13 (Aix-BA+IntCal13) and B) against the IntCal13 calibration curve. The highest agreement is obtained when comparing GARDA1-I against Aix-BA+IntCal13, which enables to date the last ring of the ^{14}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).

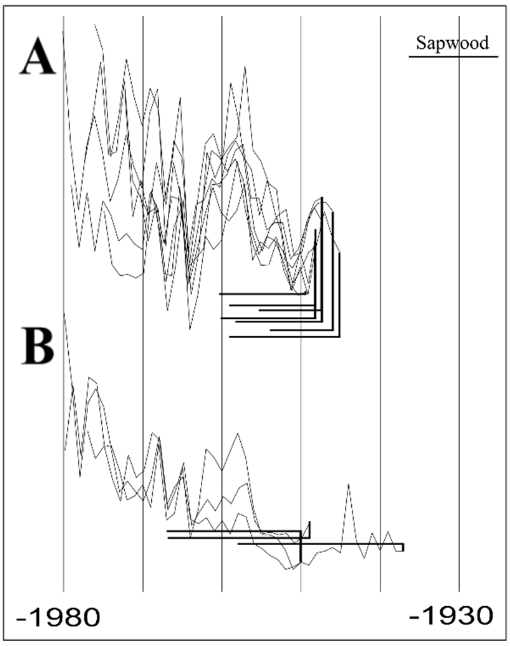

Figure 11. Two groups highlighted by preliminary dendrotypological analysis: A) high growth-rate series with small number of sapwood rings, indicating young trees with low competition; B)

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

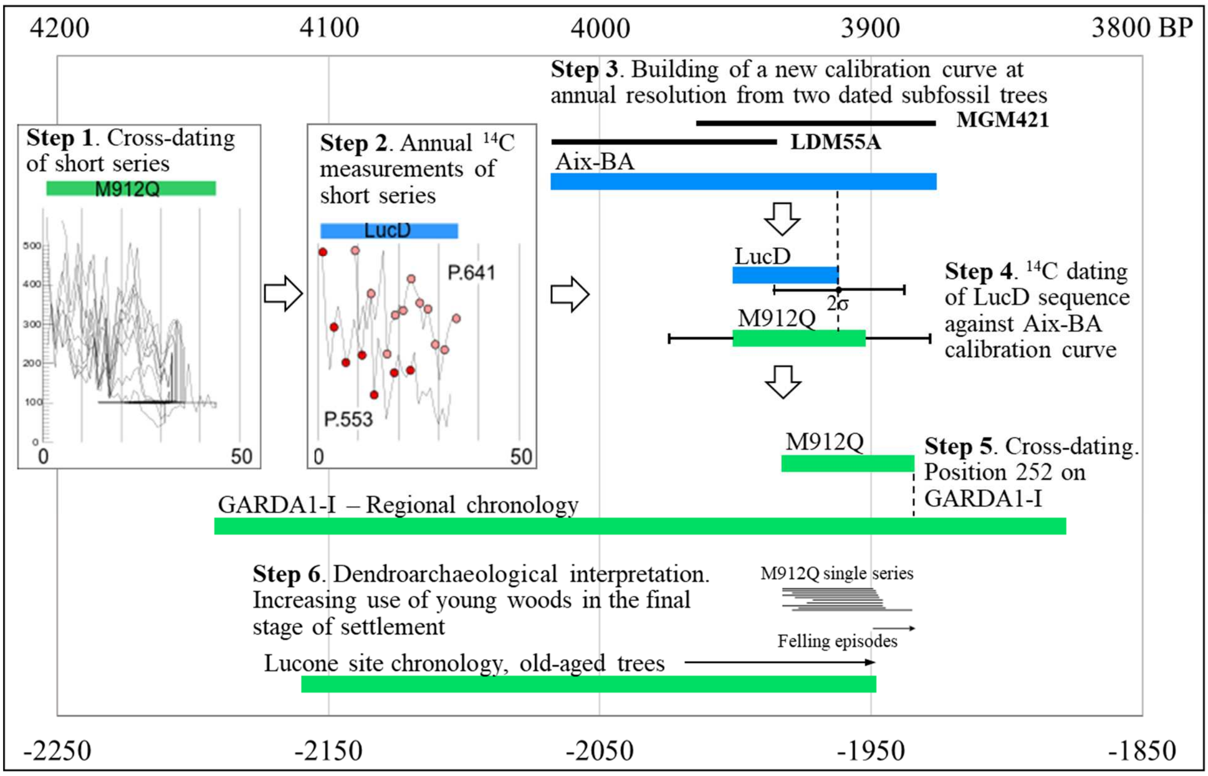

Figure 12. Schematic summary of the methodological and interpretative steps of the research. In blue ^{14}C sequences and in green dendrochronological series. With the exception of step 1 and 2, with their own relative scale, all the other steps are on the same chronological scale. It should be noted that GARDA1-I chronology and the related Lucone and M912Q chronologies are dated by ^{14}C wiggle-matching with an uncertainty of ±23 years (2σ).