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Dendroarchaeological dating of Renaissance Mudejar artefacts in western Spain

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ABSTRACT

The absence of precise dates in Extremadura's Renaissance heritage can generate ambiguities that hinder the cultural interpretation of regional history. The analysis of the duration of the art styles, the date of construction of buildings and artefacts or the exact determination of restoration periods are severely affected by the absence of specific chronological information. Dendrochronology can help to resolve these unknowns. We analysed historical woods from timbers, painting panelings, ceilings, furniture and art objects, all from two Renaissance monumental buildings: the San Vicente Ferrer church in the city of Plasencia and the Las Veletas palace in Cáceres, both in Spain. We used a local chronology of living trees as reference. This living chronology was developed with tree-ring data hosted in the International Tree Ring Data Bank (ITRDB) but reinforced with recent wood samplings from the Sierra de Gredos, a mountainous area close to the historic sites. After a step-by-step crossdating process, the historical timbers were dated and a floating chronology was built. The comparison between this floating chronology and that obtained from living trees reached a Pearson-r correlation of 0.65 with a temporal overlap of 106 years. Thus the living tree-ring chronology was extended 253 years into the past (from 1769 CE to 1516 CE), allowing the dating of new historical materials that may arise in the future for this period and confirming that tree-ring dating is a feasible technique to use in the dating of historic buildings and artefacts in western Spain. The results indicate that it is feasible to admit that Mudejar art, a mixture of Arab and Christian styles, remained in active development in Extremadura for much longer than in any other regions of Spain.

1. Introduction

The Renaissance was a cultural and artistic movement originated in Italy during the 15th century (Rabil, 1988). This cultural expression spreads to the rest of Europe in a non-uniform and slow process (Mayhew, 2001). In Spain, the first evidence of the Renaissance dates from the late 15th century (Sánchez, 1988) and began to disappear slowly towards the beginning of the 17th century (Rabil, 1988). However, in the Extremadura region (western Spain), presence of this cultural heritage appears to have decreased more slowly than in the rest of the country. This characteristic in the speed of incorporation of new cultural styles in Extremadura is associated with the secular historical, cultural, political and intellectual isolation of this region. This may explain the irruption of the Gothic style from the Late Middle Ages without transition stages (Sánchez, 1988). The Renaissance period in Extremadura has two moments of expansion linked to population growth: the first one between 1500 and 1515 and the second one between 1545 and 1560. During both periods there was intense military, civil and religious activity that brought an increase in the construction of houses and monumental buildings (Sánchez, 1988). Simultaneously, the Muslim influence continued in the Mudejar art style. The term *Mudejar* (adaptation of the Arabic word *Mudajjan* مدجن), refers to the Muslims who obeyed to the Christian kings, but conserved their cultural heritage. Mudejar art partially coexisted during the period between the 13th and 17th centuries with combinations of Romanesque, Gothic and Renaissance styles (Mogollón-Cano, 2006). The style combines elements of Islamic art with different construction techniques linked to Christian culture, a synthesis that is evident in the Iberian Peninsula (Sarasa, 2006). Within this cultural crucible, an exact time period delimitation of each style is of great importance for understanding this phase of the Iberian history. In this sense, different dating methods could be used such as radiocarbon, identification of styles, determination of craftsmanship periods, analysis of documentary sources and dendrochronology. These methods have, however, different levels of dating accuracy that can influence the historical reconstruction of the human society development. Radiocarbon permits dating around 50 ka

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years BP, but with relative low and variable resolution. Art and documentary methods are appropriate but could be erroneous in certain areas with less or complex historical information, as the Extremadura region. Dendrochronology is the only technique that yields an annual resolution dating of historic pieces of wood (Fritts, 1976). In this sense, this method is a powerful tool to solve dating related to archaeological and art history studies (Baillie, 1995; Grabner et al., 2007; Szántó et al., 2007). In fact, dendrochronology has been widely used to date the origin of different art objects, architectural wood pieces, panel paintings (Fraiture, 2009), musical instruments (Topham and McCormick, 2000), roof constructions (Haneca and Debonne, 2012) or trunks (Thuna and Alsvikb, 2009). Dendrochronology can also help infer the geographic origin of historic wood objects (Fraiture, 2009; Romagnoli et al., 2016). Furthermore, dendrochronology has also served for calibrating radiocarbon method (Leavitt and Bannister, 2009), which in turn helps in dating dendroarchaeological wood samples that are so far beyond the living chronologies. The dendrochronological dating potential in the Iberian Peninsula has been evaluated in detail by Domínguez-Delmás et al. (2015).

The aim of this study is to date wood pieces from two historical buildings related to the Mudejar style in Extremadura (western Spain), by applying dendrochronological methods. Additionally, the possible geographic origin of the wood samples and the historic implications of this origin is suggested. Moreover, the results will allow a better understanding of the Mudejar cultural influence and the duration of this historical period in western Spain. Since this region has not been previously studied from a dendroarchaeological perspective, and given that long tree-ring records of reference in the area are relatively scarce (Patón et al., 2009; Roig et al., 2009), we highlight the importance of the results found here and their potential to extend dendroarchaeological studies in this region of Spain.

2. Material and methods

2.1. Sampling

Two types of wood sample data were used: 1) tree-ring widths from living trees collected for the purpose of this study (Fig. 1) and a complementary set of living tree-ring width data housed in the International Tree Ring Data Bank (ITRDB), and 2) ring width measurements from historical woods (Figs. 2–5, Table 1). Samples from living trees were obtained in two pine populations from the south face of the Sierra de Gredos (Fig. 1), a mountainous area 60 km away from San Vicente Ferrer church (Plasencia) and 115 km away from Las Veletas palace in Cáceres, the other two main sources of historical wood samples. Consequently, living trees and local historic woods can be considered as belonging to the same macro-climatic region.

In the Sierra de Gredos, there are two pine tree species, *Pinus sylvestris* L. and *Pinus nigra* Arnold, which are difficult to differentiate anatomically from their xylem characteristics (Akkemik and Yaman, 2012; Martin-Benito et al., 2013; Schoch et al., 2004). The first species is clearly dominant in the area and grows in acidic soils whereas the second grows as isolated patches on calcareous soils (López-Sáez et al., 2016). Both species present similar response to climate and can be treated as a unique group for crossdating purposes (Richter et al., 1991). As indicated in Table 1 and Fig. 1, living trees from both pine species were collected from standing individuals, and between two to three transverse wood cores were taken from each tree (with increment borer of $\varnothing = 5$ mm) at breast height to capture potential variability in tree growth around the stem. These samples have served to update the tree-ring width series of *P. sylvestris* and *P. nigra* hosted in the ITRDB and originally derived from trees growing in the south face of the Sierra de Gredos.

The historical woods considered in this study were recovered from Las Veletas palace and San Vicente Ferrer church. These samples are stored in the Cáceres Museum (Spain) and consist of pine wood samples from different sources: timbers, furniture, picture frames, upper sides of doors, benches, looms, Mudejar ceilings, polychrome panels and a codex (Figs. 2–5). Because most of these samples cannot be intervened (e.g. polished or cut) due to their historical value, images of cross sections with sufficient quality to distinguish the growth rings were obtained according to procedures described by Bridge and Miles (2011). Sequential high-resolution photographs (1 px = 100 µm) were taken at a short distance (10 cm), through a scan of the surface on a horizontal plane with a metric scale as reference. We used a Canon SX-30 camera with 15 megapixels of resolution. Similar digital techniques have been used with historic pieces of wood that cannot be physically altered (Bernabei et al., 2010; Thuna and Alsvikb, 2009). Wood material with a minor historical value, such as church roofs extracted after refurbishing or upper sides of doors, was carefully polished using belt sanders in a grit sequence from 40 to 1500. Sapwood was not a problem because the analysed living trees were not too old, not exceeding 300 years in any case. All the photographs and the polishing of wood material were made in the facilities of the Cáceres Museum Laboratory.

2.2. Crossdating and measuring

Crossdating is the most important principle of dendrochronology (Fritts, 1976). It establishes that the matching patterns in ring widths or any other tree ring characteristic between samples allows the identification of the exact year in which each tree-ring was formed. This technique helps to identify false or missing rings and any other possible errors during both the ring boundary recognition and the measuring stage of the ring widths. In an initial dating control stage it is advisable to make a visual crossdating. This procedure allows us to easily detect missing or false rings prior to performing the correct ring width measurements. Consequently, we followed the Yamaguchi method that consists of classifying the rings according to their relative characteristics in their widths, tracheid diameter and/or any type of anomaly present in the wood (Yamaguchi, 1991). Thus, we built an initial calendar plot taking advantage of the coincidences of the ring characteristics from different wood samples. Subsequently, we measured the ring widths at a resolution of 0.01 mm using ImageJ (http://rsbweb.nih.gov/ij/) image analysis software in a Slackware (http://www.slackware.com) Linux environment. The pixels were converted to millimetres using the metric scale included in each image.

In the case of historic woods, the innermost growth rings were dated at a relative age, waiting for a later correction by comparison with the living tree-ring chronology. Each historical wood sample/photograph was classified individually according to their archaeological origin and measurement data was transferred to a spreadsheet (LibreCalc) using the sample code in columns. A second crossdating procedure through visual inspection was conducted by simple comparisons of the measurement profiles transformed in figures, following Stokes and Smiley (1968). This procedure helps to detect more accurately dating problems not previously discriminated by the Yamaguchi method. Once an error is detected, it is resolved by re-examination of the wood samples, identifying the possible mistakes and making a new measurement of the corresponding wood portion. When missing rings were detected they were assigned a value of 0.001 in order to avoid mathematical artefacts during the final statistical phase of crossdating (Leland et al., 2016).

Once all samples (living and historic woods) were visually controlled, the statistical crossdating performance was verified with the facilities of the free computer COFECHA routine (DPL suite, Holmes, 1983). The primary function of COFECHA is to verify the crossdating of the tree-ring series, assessing the quality of the cross-match procedure and measuring accuracy of the tree-ring series. Basically, the dated and measured ring series were filtered by a 32-year cubic spline, and then each data set was divided by its corresponding value of the spline curve. The procedure transforms raw data in normalized indexes facilitating the subsequent correlation between single series and the master chronology. Thus, COFECHA provides information of segments having

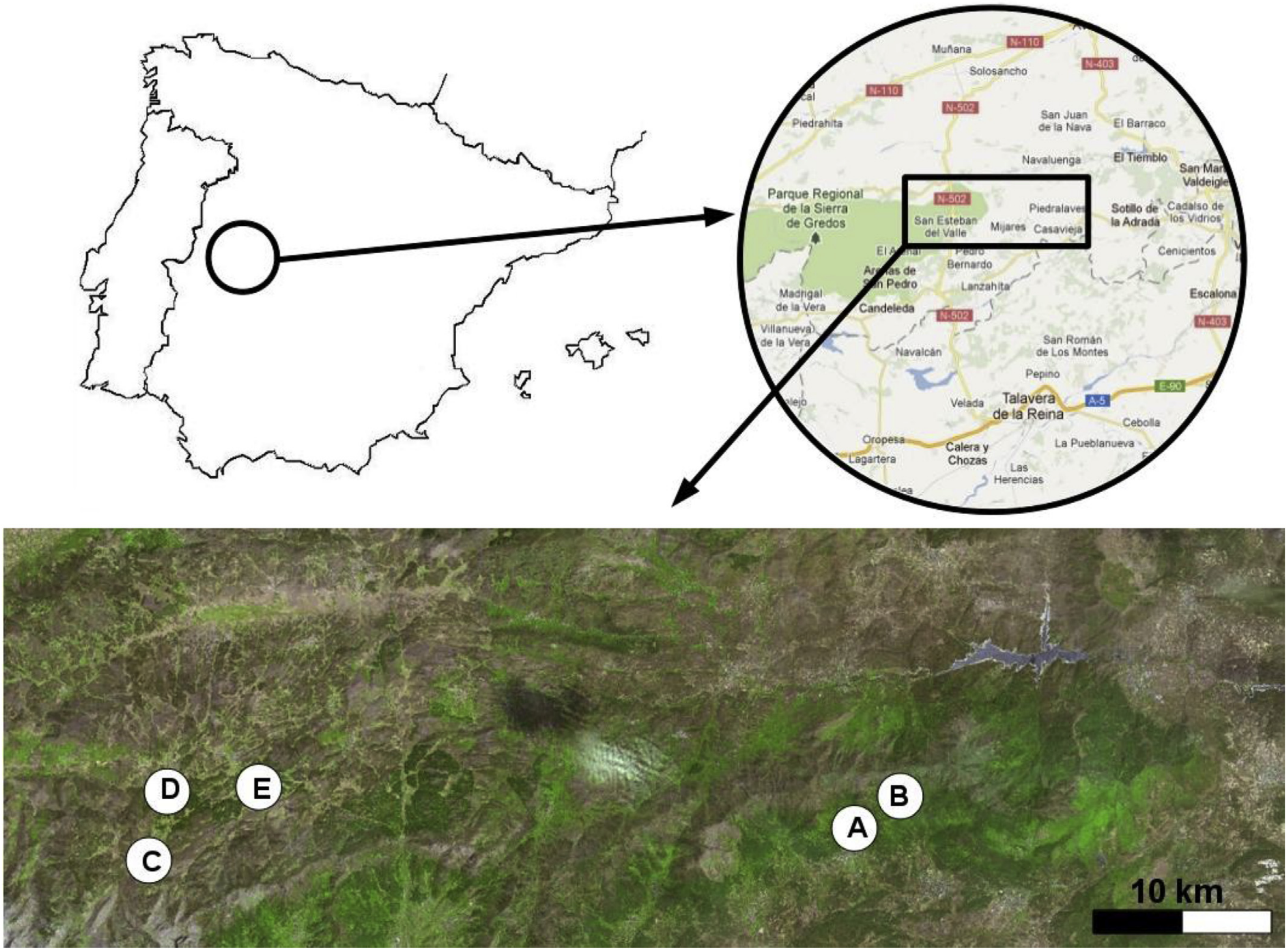

Fig. 1. Sampling areas of living trees in the Sierra de Gredos mountains (western Spain).

possible dating errors, natural low correlation, divergent year-to-year changes, absent rings or outliers (Grissino-Mayer, 2001). Only when COFECHA produces zero errors (and with as high as possible correlation coefficients) we can consider that the control process via crossdating has been successfully concluded. In consequence, COFECHA is mainly used to determine the quality of measurements by mathematical crossdating. Finally, visual and mathematical crossdating must coincide to consider a group of measurements perfectly assigned to their calendar years (Fritts, 1976).

2.3. Building the floating and living tree-ring chronologies

Prior to the construction of both floating and living tree-ring chronologies it is necessary to reduce the age influence in the shape of the tree-ring series by the process named detrending (Fritts, 1976). Consequently, we use an accepted method to filter dendrochronological data which corresponds to a spline function (Cook, 1981), through the dplR library of R statistical environment (Bunn, 2008). The strength of this spline value corresponds to 65% of the series length. Then, we constructed two separated chronologies: one using the living trees from both the recent collections and the data hosted in the ITRDB (namely the calendar reference chronology), and a second, floating chronology, which is the result of the combination of all floating dated historical woods. For the construction of the living tree-ring chronology we use three data sets: one corresponding to data hosted in ITRDB and two other collections obtained from recent field samplings (Fig. 1 and Table 1). The floating (or archaeological) chronology was developed sequentially. First, we crossdated all the samples to others, preferably those older than 50 years, belonging to the same wood object. In this way partial floating chronologies were obtained. Subsequently, these partial floating chronologies were progressively crossdated each to the other until they constituted a global floating chronology. The utility of using this sequential crossdating helps to avoids possible errors in the assignment of ages in wood pieces with low numbers of tree rings. This method has been extensively applied in archaeo-dendrochronology (Grissino-Mayer, 2009a, 2009b). The global floating archaeological chronology was referred to calendar years by crossmatching with the living tree-ring chronology. In consequence, each historic piece was placed in the real time of its formation by a simple comparison (correlation) with the living chronology (Table 1). Finally, all crossdated samples were used to construct a floating indexed tree-ring chronology using the same statistical techniques with which the chronology of living trees was constructed.

The common signal strength of both chronologies was determined by RBAR (Wigley et al., 1984). RBAR is defined as the average correlation between all series, which is an expression of the percentage of variance in common. We estimated another statistic, the expressed population signal (EPS), that indicates the relationships between a finite sample chronology and the theoretical population chronology (Wigley et al., 1984). EPS is very dependent of the number of samples used in the chronology and according to Wigley et al. (1984) is arbitrarily placed above 0.85 value. Both indexes (EPS and RBAR) are

Fig. 2. Photographic method of historic woods from Las Veletas palace (Cáceres, Spain). Loom (LO), plow (PW), prisoner's bank (PB) and front door (FD) are shown.

shown to identify the quality of the chronology along different historical periods. Additionally, we determined the percentage of variance (PV) and t-values of each historic wood according to its fitting with master chronology. This is an additional indicator of the quality of crossdating that complement the COFECHA output (Maxwell et al., 2011). Construction of chronologies and associated statistics were determined using the library dplR (Bunn, 2008).

2.4. Homogeneity of the origin of historical woods through multivariate analysis

In tree-ring research, the initial sampling strategy is focused on the analysis of many individuals of the same population until enough interseries correlation is established (Fritts, 1976). Then, to increase robustness of a regional tree-ring chronology, it is necessary to sample a high number of local populations. The main problem with historic wood samples is the undetermined origin. Therefore, we need statistical methods to analyze the data homogeneity. If historic samples belong to the same population, then different groups will not emerge from the multivariate analysis. In contrast, if groups are separated by the multivariate analyses, they should be considered different for ulterior dendrochronological studies (Shah and Bhattacharyya, 2012). To solve this dilemma we applied the Non Metric Multidimensional Scaling (NMMS) method in order to identify homogeneity between samples (Borg and Groenen, 2005). An NMMS algorithm starts with a matrix of mathematical indexes (distances or similarities/dissimilarities) that are calculated with the original tree-ring data. The method can use different metrics such as Euclidean, Mahalanobis or Bray-Curtis (Borg and Groenen, 2005). Then the algorithm assigns a location to each item in *N*-dimensional space. The appropriate *N* is determined by the goodness of fit, which in NMMS is called stress and can be defined in different ways. One of the most common is Kruskal's Stress that is the sum of squared differences between ordination-based distances and observed metrics of original data (Borg and Groenen, 2005). In this way, the NMMS method complements the interseries correlation produced by COFECHA, giving additional information on the homogeneity of the samples. In consequence, we applied both COFECHA and NMMS ordination to the historic data in order to analyze the existence of possible grouping patterns that could indicate a different geographic origin of historic wood samples.

3. Results

Living data from *Pinus* trees (*P. sylvestris* and *P. nigra*) collected from five sites in the Sierra de Gredos constitute the basic material used for the construction of a reference chronology that allowed the dating of historical woods. All wood material crossdated perfectly because trees are subjected to the same climate characteristics. This allowed the construction of a chronology of living trees covering the period between 1769 and 2011 (242 years). This chronology was based on 144 trees, selected by its high correlations. Using the precepts of the crossdating technique, both the chronology of living trees and the floating chronology derived from historical woods, were confronted to achieve the chronological dating of the latter material. Thus, a correlation of 0.65 was obtained for the overmatch period between 1769 and 1875 (106 years), indicating a good level of synchronization and quality reference to resolve the historical wood dating (Fig. 6).

Besides, by applying a COFECHA run to the combined set of series from both living trees and historical woods, we achieved a mean interseries correlation of 0.696 and an average mean sensitivity of 0.256 (Table 3), confirming the robustness of the obtained dates.

Having already achieved the dating of the archaeological woods (Figs. 2–5), it was possible to recognize their historical context (Table 2). A total of 55 samples from San Vicente Ferrer church in Plasencia city and 101 samples from Las Veletas palace in Cáceres were analysed (Table 2). The wood samples recovered from San Vicente Ferrer church, originally a convent, were linked to three different structures (Table 2). The first one is made up of 31 samples of ceiling

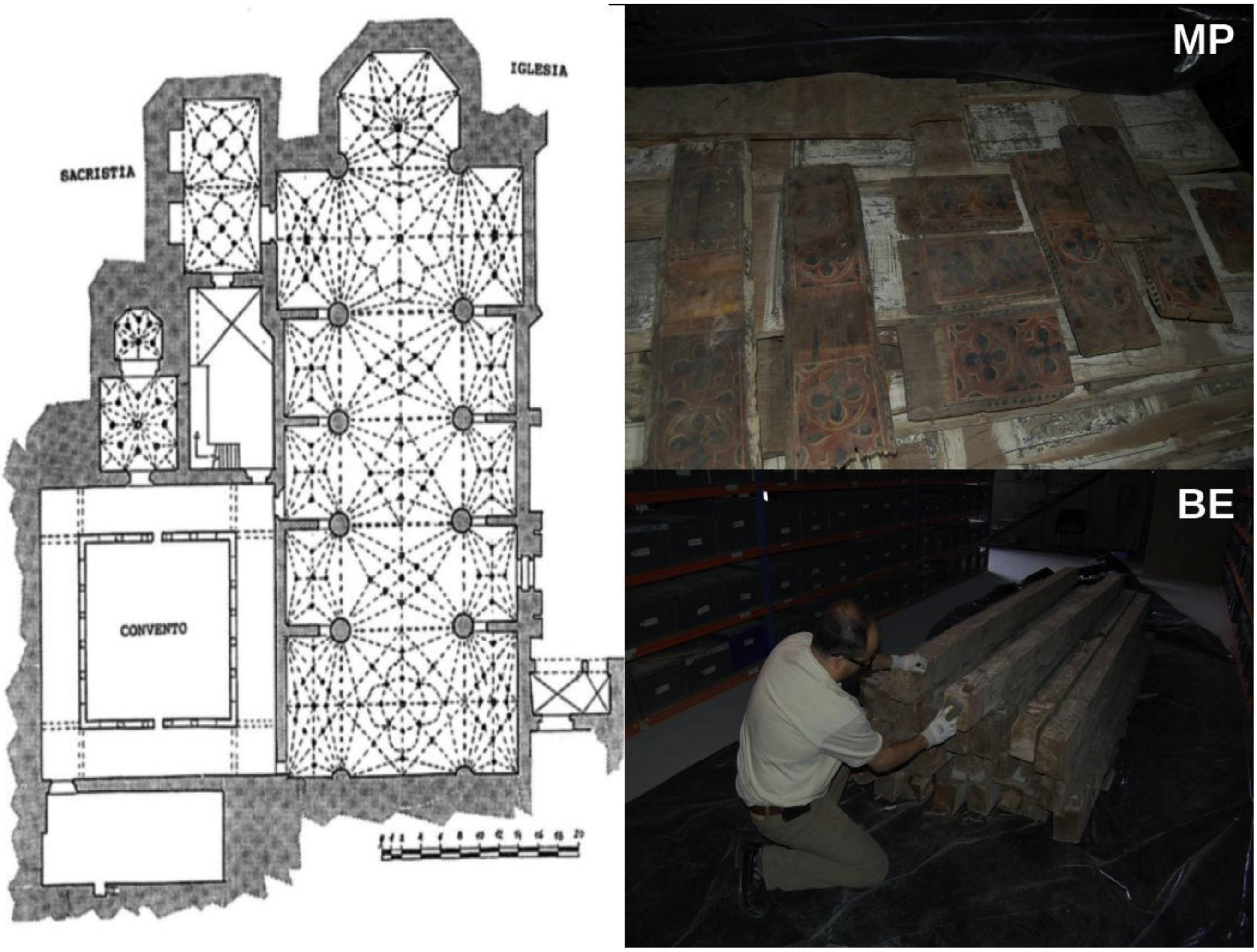

Fig. 3. Map of San Vicente Ferrer church (Plasencia, Spain), modified by Sendín (2006). Mudejar panelling (MP) and polishing beams (BE) by hand at the San Vicente Ferrer building.

Fig. 4. The front door (FD) from the Las Veletas palace (Cáceres, Spain) constructed with the original wood pieces dated to the period 1562–1717. The arrow indicates the latest restoration of the lower part in 1872, showing the replacement of the wood material. The medieval city of Cáceres can be seen in the upper right part of the image. A Mudejar panelling (MP) covering the period 1658–1698 (r = 0.71) is shown.

Fig. 5. Codex (CO) from the Cáceres Museum. The covers are mainly from the period 1628–1696 and do not coincide with the Gothic art style of the manuscript, indicating three possibilities: restoration, imitation or a larger duration of the style.

timbers (CT) grouped in a single period from 1594 to 1851. Another group of samples corresponds to a Mudejar paneling (MP), where 10 samples were dated to the period 1574–1735. Finally, the third structure was a Mudejar polychrome (PL), represented by 14 samples divided in two historic periods: 1636–1760 (n = 11) and 1810–1875 (n = 3).

From the Las Veletas palace, 68 wood samples were obtained from beams (BE) which were dated to a long period between 1516 and 1875, indicating an intense structural remodelling. Also, in this palace 11 samples of a front door (FD), a plow (PW) and three looms (LO) were analysed. The FD door shows two different periods of construction. The majority of the samples (n = 10) are from 1562 to 1717 (FD1). These samples are mainly from the upper part of the door (Fig. 4). A sample of the cover at the base of the door was dated to 1872 (FD2), indicating a later restoration (Fig. 4). Unpublished information provided by archaeologists at the Cáceres Museum indicates that the beginning of the construction of this front door (FD) began in 1606, indicating a delay between the cutting of the trees and the beginning of the works. This situation occurs in many historical buildings due to the need to dry the wood (Hillam, 1979). The plow (PW) is the oldest piece of the palace and was dated to 1696. A loom (LO) dated to 1728 and a chest (CH) dated to 1698 completed the pieces analysed.

The codex (CO) from the Las Veletas palace represents a special piece. It was built with a *Pinus pinea* L. wood, a Mediterranean tree with a different ecology with respect to the species that are usually found in the Sierra de Gredos and surroundings (Tenorio et al., 1998). However, these woods could be crossdated with the chronologies derived from *P. sylvestris* and *P. nigra*, an association between tree species that has been previously observed by Richter et al. (1991). The CO indicates that it was built with wood related to two periods: CO1 (1628–1696, n = 4) and CO2 (1791–1829, n = 1). Finally, a prisoner bench (PB), formed by 12 overlapped wood samples, indicating a construction period between 1592 and 1742. This piece of wood is part of the objects found in the Las Veletas palace, but it is from Granadilla, a village located 89 km away from the city of Cáceres.

The stress function of NMMS with Euclidean distance, showed that

Table 1
Samples analysed for the construction of the chronology of living trees, population of origin, species, time period and data bank. Between brackets are shown the samples finally selected by their better correlation.

Code	Authors	Population (Province)	Species	Years	Trees	Mean length of series	Data Bank (File)
A	D. Patón	Piedralaves (Avila)	*P. nigra*	1836–2011	37 (31)	71.2	this paper
B	D. Patón	Piedralaves (Avila)	*P. sylvestris*	1793–2011	223 (42)	117.4	this paper
C	F. Schweingruber	Calvero de Gredos (Avila)	*P. sylvestris*	1923–1977	20	49.2	ITRDB (spai058w.rwl)
D	K. Richter	Hoyos del Espino (Avila)	*P. sylvestris*	1812–1985	25	131.3	ITRDB (spai033.rwl)
E	K. Richter	Navarredonda de Gredos (Avila)	*P. sylvestris*	1769–1985	26	146.5	ITRDB (spai034.rwl)

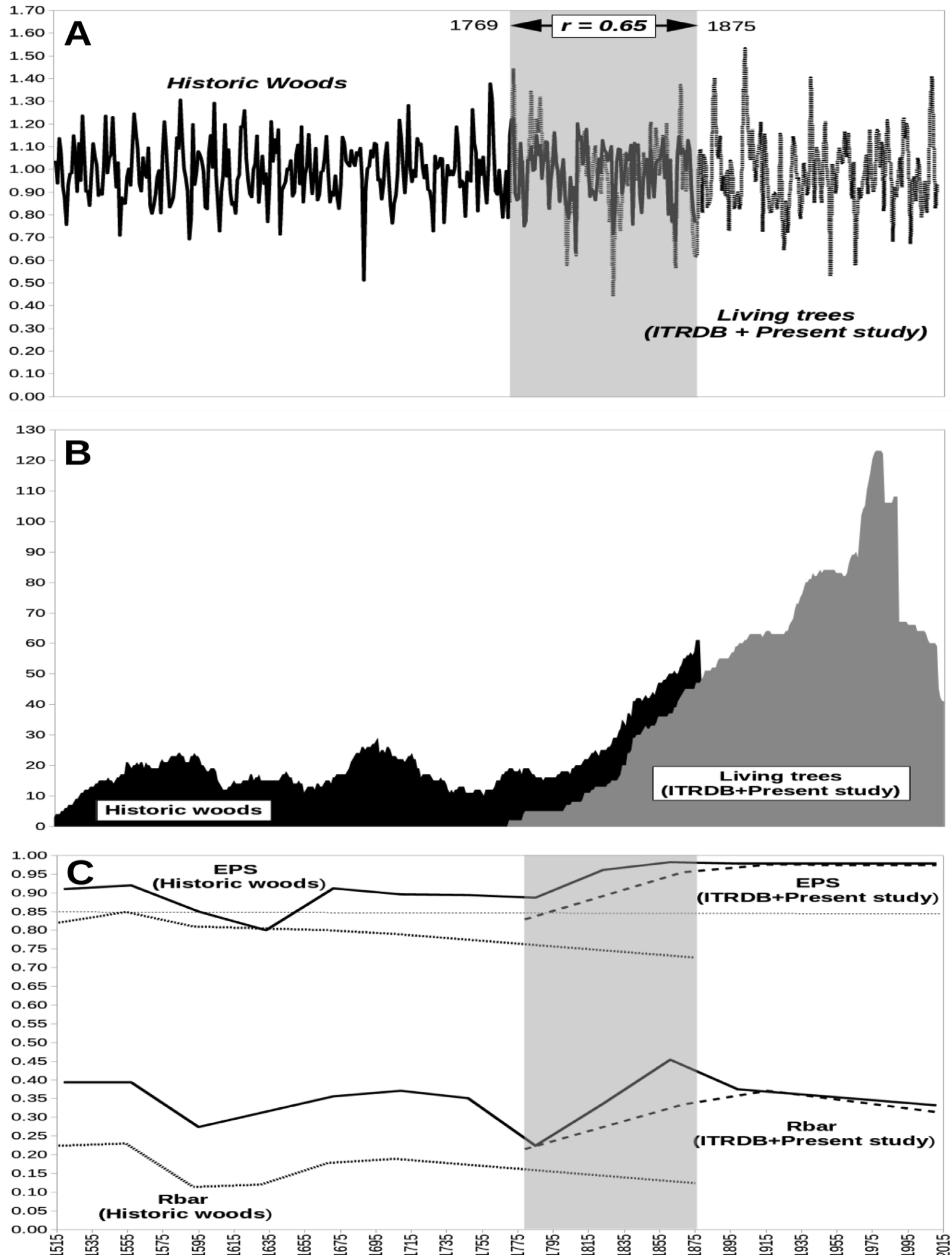

Fig. 6. A: Coupling of chronologies based on archaeological woods and living trees (ITRDB + Present study). Correlation in the overlapping period (grey area) is shown. B: Number of samples from historic woods and living trees. C: EPS and RBAR statistics along the interval of chronology in historic woods (finned dotted), living trees (sparse dotted) and all data (continuous line). The extremes of chronology have been suppressed by the process of averaging. The fine broken line indicates the critical value of EPS = 0.85.

Table 2
Historic wood samples, origin, time period and correlation with the reference chronology. The buildings studied were Las Veletas palace (1) and San Vicente Ferrer church (2).

Source of historical wood	Code	Locality	Sample number	Period	Correlation	t-values	PV%
Beams (1)	BE	Cáceres	68	1516–1875	0.636	6.69	22.23
Chest (1)	CH	Cáceres	1	1658–1698	0.617	4.83	29.60
Ceiling timber (2)	CT	Plasencia	31	1594–1851	0.569	11.05	26.28
Codex 1 (1)	CO1	Cáceres	4	1628–1696	0.620	6.42	16.38
Codex 2 (1)	CO2	Cáceres	1	1791–1829	0.599	4.49	27.72
Front door 1 (1)	FD1	Cáceres	10	1562–1717	0.650	10.58	13.59
Front door 2 (1)	FD2	Cáceres	1	1847–1872	0.652	4.12	28.62
Loom (1)	LO	Cáceres	3	1631–1728	0.622	7.74	14.39
Mudejar panelling (2)	MP	Plasencia	10	1574–1735	0.736	13.71	22.02
Mudejar polychrome 1 (2)	PL1	Plasencia	11	1636–1760	0.643	9.27	26.54
Mudejar polychrome 2 (2)	PL2	Plasencia	3	1810–1875	0.661	6.99	10.61
Plow (1)	PW	Cáceres	1	1651–1696	0.683	6.13	22.95
Prisoner's bench (1)	PB	Granadilla	12	1592–1742	0.629	9.84	21.56

three axes are enough to describe the multivariate information (Fig. 7). According to mathematical theory that support the method of NMMS, the addition of more axes only reduces statistical noise but does not provide more multivariate information (Borg and Groenen, 2005). Therefore, with these three axes we detected that only MP and PB samples were slightly different from the rest (Fig. 8). In conclusion, all the multivariate mathematical structure of the data indicates a high homogeneity among samples.

4. Discussion

Our results show that the historic woods belonging to two Renaissance buildings from Extremadura crossdated perfectly with living trees from the same climatic area. This could indicate that during the Renaissance, the Gredos mountains was the area predominantly used for wood provisioning in northern Extremadura region. The different *Quercus* species, dominant in the area, are not appropriate for construction and consequently do not appear in the samples. In fact, *Quercus ilex* L. wood broke easily during manipulation and *Quercus pyrenaica Willd.* presents turned and short trunks that can not be used for trails. In contrast, *P. sylvestris* and *P. nigra* tree species from the Sierra de Gredos were widely used for construction, because they provided straight and long stems of better quality for different constructive purposes (Kúdela et al., 2006). Even when these two species can be hardly distinguished by their wood anatomy (Schoch et al., 2004), their annual growth ring variability presents a similar response to the Mediterranean climate, and therefore the information extracted from their growth rings can be combined in dendroclimatic studies. In fact, Richter et al. (1991) recommend the combination of different *Pinus* species to improve dendroarchaeological dating in southern Spain.

The presence of *P. nigra* in the Gredos area is, however, very scarce (Richter et al., 1991; Patón et al., 2010) implying that most of the historical timbers considered in this study may be from *P. sylvestris*. The only different wooden object was the codex, built with *P. pinea* wood. The use of this species in large buildings is not very common, being more frequently used in the structure of small houses, furniture or art objects. However, in other Mediterranean areas, where trees suitable for various construction uses are scarce, *P. pinea* can supply this fault. In this sense, this pine was extensively used during the Roman period (Giachi et al., 2016).

Richter et al. (1991) demonstrated that it is possible to combine the tree-ring information from different *Pinus* species in the same chronology for dating purposes. Multi-specific dendroclimatic approach has also been demonstrated by Roig et al. (2009) considering chesnut (*Castanea sativa* L.) and Pyrenean oak (*Quercus pyrenaica* L.) forests distributed in the same region, which can facilitate a regional approach to the variability of tree growth. This brings two benefits for historical and palaeoenvironmental reconstructions. First, it increases the number of interspecific interactions, allowing to incorporate a greater number of trees with different ages and integrating ecological conditions that result in a reference chronology with a regional imprint. Second, it facilitates the dating of historical pieces built with wood from different tree species but that grew under similar climatic and geographical conditions. In consequence, for the objectives of this study the taxonomical identification of wood samples was irrelevant for both the process of the construction of the living tree-ring chronology and the archaeological dating.

As a consequence of the calendar date of the historical material it was possible to extend the chronology of living trees back to the year 1516. This opens new possibilities for dating monuments in western Spain built since the early expansion of the Renaissance period. This allows interesting discussion about the history of wooden objects, such as the codex constructed with *P. pinea* wood, whose manuscript is associated with earlier Gothic art style but whose wood covers were dated for the period 1628–1696, indicating restoration, imitation or a large duration of the style (Table 2, Fig. 5).

In dendroarchaeological studies, a correlation higher than 0.5 between historical woody objects and a reference chronology is enough to confirm calendar dates and in the help to consolidate contextualization with other historical or constructive information (Pickard et al., 2011). Few cases in our study showed minor correlations when compared with the reference chronology, as in the case of bench (BN), Mudejar ceiling (MC) and Mudejar polychrome (PL1). This could be linked to very marked differences in the ecological situation of the trees used or by the

Table 3
Crossdating results based on COFECHA output of historical woods, living trees (own data + ITRDB) and total data.

Parameters	Historical Woods	Living trees	Total
Number of dated series	156	144	300
Master Series	1516-1875 (359 years)	1769-2011 (242 years)	1516-2011 (495 years)
Total rings	6765	12,416	19,181
Series intercorrelation	0.635	0.771	0.696
Average mean sensitivity	0.251	0.258	0.256

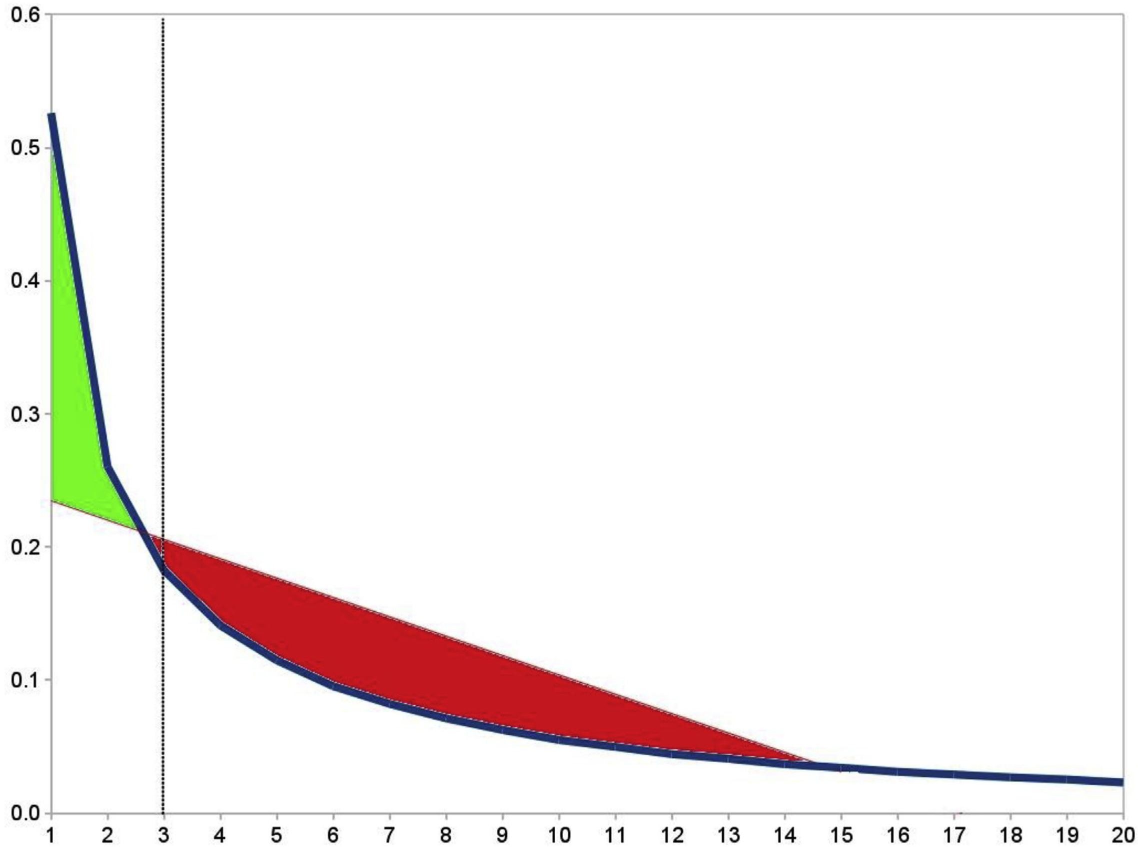

Fig. 7. Stress function of Non Metric Multidimensional Scaling (NMMS) on tree ring measurements.

distance of provisioning these woods with respect to the rest of the woods analysed. However, and according to the NMMS multivariate analysis, low correlations are not strictly produced by differences in the geographic origin. It is well accepted in dendroarchaeological studies, that the exact origin of each wood piece is uncertain, but strong correlations with a reference chronology may indicate a geographic proximity in obtaining the wood for construction. Moreover, for dating purposes it is also relevant to consider that usually there is no exact match between the cut-off date of a tree and its use (Hillam, 1979). This is the case of the historic data of the Las Veletas front door, which indicates a time lag of a few years in relation to the dendrochronological dating, suggesting that the wood was left drying for some time before use.

Our results confirm that the Extremadura region presents certain archaeological particularities. First, the intense remodelling to which the Renaissance monumental buildings have been subjected. In that sense, it is known that the Las Veletas Palace was built at the end of the 15th century by Diego Gómez de Torres but it underwent intense refurbishing in the 17th century by Lorenzo de Ulloa (Mogollón-Cano, 1996). The abundance of wood samples in this period confirms this fact. Another period of intense remodelling took place during the War of Independence against Napoleon's army (1808–1814) and our wood samples confirm it again. These periods of refurbishing are specially indicated through certain structures such as PL, codex (CO) or front door (FD). CO is the only sample that presents a Gothic art style but the cover underwent subsequent renovation according to the dendrochronological dating. This means that CO is either a copy of the original or it has been restored multiple times due to its use. With regards to the Mudejar art style our results prompt two hypotheses: a longer permanence of the styles,or an imitation of the style during restoration processes. Experts in art history have supported the first option as the most probable explanation (Mogollón-Cano, 2006; Sarasa, 2006). In this sense, our results not only confirm this hypothesis but they also provide more precise data as to the chronological span of the Mudejar art style in Extremadura.

To respond with more arguments to these issues concerning dating, dendroarchaeological methods must be complemented with other techniques, in order to reach a multidisciplinary point of view of the history of Extremadura for the past centuries. The present results pose new challenges in archaeological studies and in the recovery of old woods that allow the extension to the past of the living tree-ring chronologies in Spain. This has implications for paleoclimate and paleoenvironmental studies.

5. Conclusions

Our study has demonstrated that precise dating of historic woods from different *Pinus* tree species through dendroarchaeological methods is possible in western Spain. The majority of the historic woods originated from the south face of the Sierra de Gredos, indicating an intense use of this area for wood material destined for construction in Extremadura. In addition to determining periods of refurbishing or destruction caused by reforms or wars, we demonstrate that the creation of art in Mudejar style lasted longer in Extremadura than in other regions of Spain.

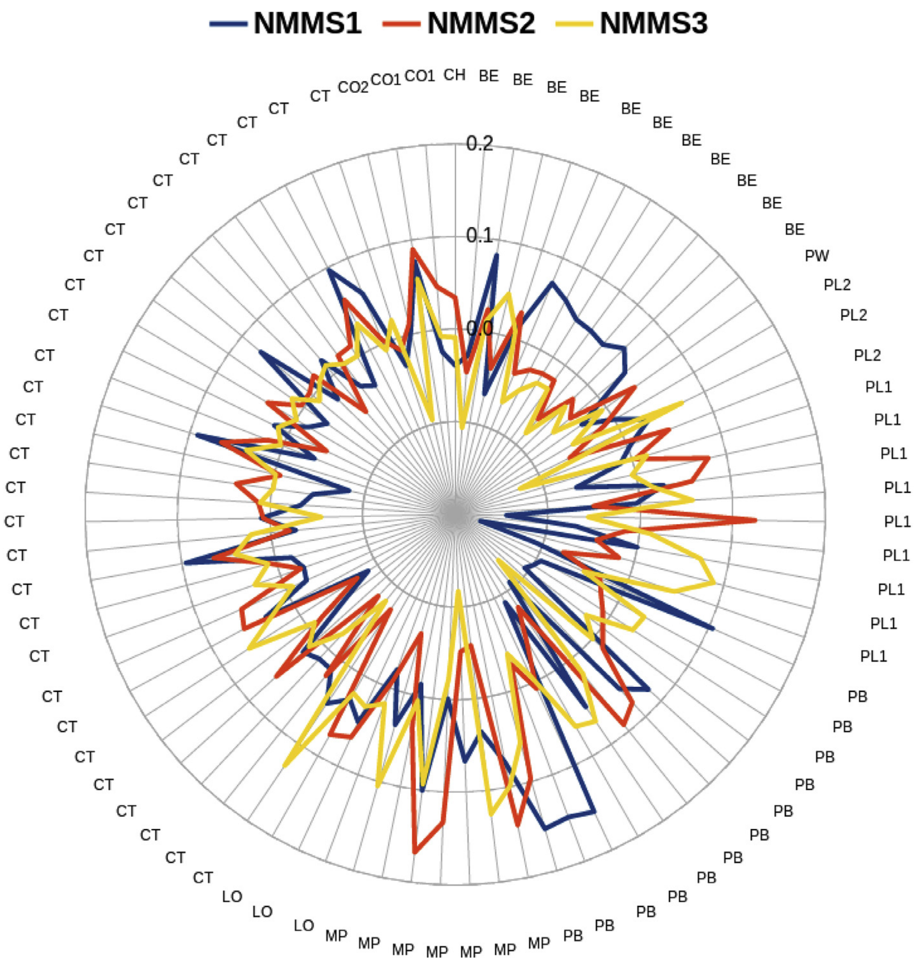

Fig. 8. Star plot of the three axes of Non Metric Multidimensional Scaling (NMMS1-3). The relative positions between samples along the three axes indicate the multivariate homogeneity.

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