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Tree-ring Analysis and Radiocarbon Wiggle-matching of Elm and Oak Timbers from the Hall Roof

Martin Bridge, Cathy Tyers, Alex Bayliss, Silvia Bollhalder, Michael Dee, Sanne Palstra, and Lukas Wacker

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SUMMARY
Elm samples were taken from the hall roof, from which oak timbers had been previously dated, along with some additional oak samples. One oak sample was dated to the period AD 1362–1480, having a likely felling date range compatible with the tree-ring date previously determined for the roof (spring AD 1493). Three elm samples matched each other, and their combined series gave some consistent matches at a position corresponding to the period AD 1381–1480, but against oak reference data, not the oak at this site. The statistical evidence was not considered strong enough, particularly against a different species, and would, if it had been accepted, imply that the elm trees were felled more than ten years before the oak timbers used in the construction of the roof.

Elm samples were submitted for radiocarbon wiggle-matching to confirm, or refute, this tenuous dendrochronological match. In fact the wiggle-matching shows that the tentative dating of the mean elm series suggested by the ring-width dendrochronology is not correct, and the elm was most likely felled at a similar time to the oak. Unusually for a building of this date, the hall roof at Fulham Palace appears to be constructed from timbers felled over a number of years.

CONTRIBUTORS
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INTRODUCTION

The investigation of the elm timbers from the roof of the Great Hall at Fulham Palace, contributes to a research programme, funded by Historic England through its Heritage Protection Commissions programme, and led by Martin Bridge from the Institute of Archaeology, University College London.

Developing the dendrochronology of elm in historic buildings

Ring-width dendrochronology of oak timbers from historic buildings in England is well established, with dating having been obtained on more than 3000 buildings (or parts thereof), with nearly one third of these having been funded by Historic England (and its predecessors). Dendrochronological evidence is a valuable component underpinning the discovery and identification of assets in the historic environment, aiding decisions relating to protection, management, and conservation, and enhancing appreciation and enjoyment of these buildings.

During this work on oak timbers, a significant amount of historic fabric constructed from timbers other than oak, most notably elm, has been identified, but this has previously been rejected as unsuitable for dendrochronological investigation. Elm in buildings has been identified in counties from Cornwall to Kent and up into the Midlands and beyond, but formal records of the presence of elm are scant as such buildings were generally dismissed for dating purposes and thus the presence of elm in the published record is rare. The inability to date historic buildings (or sections of buildings) constructed of elm by ring-width dendrochronology is seen as problematic in some areas of the country which have a comparatively high proportion of such buildings; buildings which nevertheless form a significant part of the historic environment but could not be afforded the same level of understanding in comparison to their oak counterparts.

Prior to the start of this project, only four instances of dating elm by ring-width dendrochronology have been successful (Groves and Hillam 1997; Haddon-Reece *et al* 1989, 1990; Bridge and Miles 2015). Each of these studies involved matching elm with oak from the same site, although the Ashdon, Essex example matched oak chronologies over a wide area (Bridge and Miles 2015). This project aimed to establish whether the use of standard ring-width dendrochronology could be extended to the dating of historic buildings in England where elm (*Ulmus* sp.) is the sole, or predominant species used rather than oak (*Quercus* sp.). A systematic approach was adopted concentrating on elm in the geographical areas where it is most commonly found. Buildings were thus sought that contained a significant number of elm timbers with sufficient numbers of rings that might be matched against either oak timbers in the same building or oak chronologies from the surrounding area (Fig 1).

An article will summarise the overall outcomes of the project (Bridge forthcoming). However, each building sampled for dendrochronology has an associated building survey report or similar publication, whilst the primary archive of the dendrochronological analysis is reported in the Historic England Research Report Series.

Fulham Palace Hall Roof

Fulham Palace, a former palace of the bishops of London, is Grade I listed (LEN 1286903) and sits on the north bank of the Thames (Fig 2). The building is aligned north-west to south-east (Fig 3), but these have been nominally referred to as west to east throughout this report, with the main gateway being the west gate. The Great Hall and service rooms were thought to have been built between AD 1506 and AD 1522 for Bishop Fitzjames, but a previous study (Bridge and Miles 2004) showed an oak timber in the roof to be from a tree felled in spring AD 1493, with a second oak timber having sapwood consistent with this felling date. The hall roof is of four bays, and originally extended to at least one further bay. The purlins have tenons with soffit spurs and there is a double row of windbraces. The elbowed canting struts were secured by free tenons. The tiebeams and principal rafters of this roof are of elm, with other elements such as the queen-posts and many purlins being of oak.

RING-WIDTH DENDROCHRONOLOGY

Sampling

Fieldwork for the present study was carried out in April 2017, following an initial assessment of the potential for elm dendrochronology some weeks beforehand. In the initial assessment, based on the general criteria used for oak timbers, accessible elm timbers with more than 50 rings and where possible traces of sapwood were sought, although slightly shorter sequences may be sampled if little other material is available. Those timbers judged to be potentially useful were cored using a 16mm auger attached to an electric drill. The cores were labelled, and stored for subsequent analysis. Additional oak timbers with complete sapwood were also sampled to provide same-site comparative material to increase the chances of producing dating evidence for the elm samples, and to provide further support for the dating of the roof previously obtained by ring-width dendrochronology of the oak timbers used in its construction.

Methodology

The cores were polished on a belt sander using 80 to 400 grit abrasive paper to allow the ring boundaries to be clearly distinguished. The samples had their tree-ring sequences measured to an accuracy of 0.01mm, using a specially constructed system utilising a binocular microscope with the sample mounted on a travelling stage with a linear transducer linked to a PC, which recorded the ring widths into a dataset. The software used in measuring and subsequent analysis was written by Ian Tyers (2004). Cross-matching was attempted by a combination of visual matching and a process of qualified statistical comparison by computer. The ring-width series were compared for statistical cross-matching, using a variant of the Belfast CROS program (Baillie and Pilcher 1973). Ring sequences were plotted on the computer monitor to allow visual comparisons to be made between sequences. This method provides a measure of quality control in identifying any potential errors in the measurements when the samples cross-match.

In comparing one oak sample or site master against other samples or chronologies, *t*-values over 3.5 are considered significant, although in reality it is common to find demonstrably spurious *t*-values of 4 and 5 because more than one matching position is indicated. For this reason, dendrochronologists prefer to see some *t*-value ranges of 5, 6, and higher, and for these to be well replicated from different, independent chronologies with both local and regional chronologies well represented, except where imported timbers are identified. Where two individual oak samples match together with a *t*-value of 10 or above, and visually exhibit exceptionally similar ring patterns, they may have originated from the same parent tree. Same-tree matches can also be identified through the external characteristics of the timber itself, such as knots and shake patterns. Lower *t*-values however do not preclude same tree derivation. Threshold values for elm samples are as yet unknown, but are likely to be of similar value.

Once a tree-ring sequence has been firmly dated in time, a felling date, or date range, is ascribed where possible. With samples which have sapwood complete to the underside of, or including bark, this process is relatively straightforward. Depending on the completeness of the final ring, ie if it has only the spring vessels or early wood formed, or the latewood or summer growth, a precise felling date and season can be given. If the sapwood is partially missing, or if only a heartwood/sapwood transition boundary survives, then an estimated felling date range can be given for each sample. In oak, the number of sapwood rings can be estimated by using an empirically derived sapwood estimate with a given confidence limit. If no sapwood or heartwood/sapwood boundary survives then the minimum number of sapwood rings from the appropriate sapwood estimate is added to the last measured ring to give a *terminus post quem* (*tpq*) or felled-after date.

A review of the geographical distribution of dated sapwood data from historic oak timbers has shown that a sapwood estimate relevant to the region of origin should be used in interpretation, which in this area is 9–41 rings (Miles 1997). The equivalent values for elm are as yet unknown, but the results of this project suggest that the range of the number of sapwood rings in elm timbers is likely to be much lower. One problem that has been encountered in considering elm is that it has often proved very difficult to determine the position of the heartwood/sapwood boundary, even when it is known that the complete sapwood is present on a timber. It must be emphasised that dendrochronology can only date when a tree has been felled, not when the timber was used to construct the structure or object under study.

Results

Details of the eleven timbers sampled as part of this study are given in Table 1, and their locations are illustrated in Figures 4–6. Samples FP01, FPoak02, and FPoak03 are not shown in the figures, as they are from the east side of the roof, but their locations can be deduced from the others shown on the west side, except for FPoak03, whose location was not properly noted at the time of sampling, but is thought to be from a wallplate. The ring-width measurements made as part of this study are given in the Appendix. Three of the elm samples, and one oak sample had too few rings for dendrochronological analysis and were not measured. A further oak sample had only 45 rings, and its ring-width series did not match the remaining oak sample, and only gave a weak potential match (t = 3.6) against the oak master, FULHAM1, from the first investigation (Bridge and Miles 2004) which could not be confirmed by comparison with the wider oak reference database. The third oak series taken, of unrecorded origin, matched this existing oak site chronology at a position corresponding to the years AD 1362–1480 with a value of t = 3.9 with 119 years overlap. This is again a rather weak match, but it was confirmed by comparison with the wider oak reference database, the strongest matches being shown in Table 2. With five sapwood rings, this sample has a likely felling date range of AD 1484–1516, in agreement with the precise felling date of AD 1493 previously obtained by dendrochronology.

Comparisons between the individual elm ring-width series did not show matches with the oak from the site, but did show consistent matches between three of the elm ring-width series (Table 3; Figs 7–8), which were combined into a single site series FPELMt3. This series, and the remaining long elm series, FP04, were compared with the extensive oak database. It was found that FPELMt3 did give some relatively low but consistent statistical matches at a position corresponding to the period AD 1381–1480, but these were against sites quite widely geographically spread (Table 4) and were considered inconclusive . If these matches were to be considered acceptable, it would also mean that the trees had been felled more than ten years before the oak used in the roof and, while possible, overall this seems unlikely.

RADIOCARBON DATING

The ring-width dendrochronology has provided apparent relative dating for the three elm samples that cross-match to form site master chronology, FPELMt3 (Table 3), and tentative, but not conclusive, cross-dating for this elm site master chronology when it spans AD 1381–AD 1480 (Table 4). The programme of radiocarbon wiggle-matching was designed to validate both elements of this tree-ring analysis: the cross-matching of the three elm samples to form the relative sequence, FPELMt3 (Figs 7 and 8), and the tentative dating of this mean sequence (Table 4). Twelve single-ring samples were selected for radiocarbon dating, six from FP07 and six from FP08 (Table 5; Fig 9).

Radiocarbon dating is based on the radioactive decay of ^{14}C, which trees absorb from the atmosphere during photosynthesis and store in their growth-rings. The radiocarbon from each year is stored in a separate annual ring. Once a ring has formed, no more ^{14}C is added to it, and so the proportion of ^{14}C versus other carbon isotopes reduces in the ring through time as the radiocarbon decays. Radiocarbon ages, like those in Table 5, measure the proportion of ^{14}C in a sample and are expressed in radiocarbon years BP (before present, 'present' being a constant, conventional date of AD 1950).

A total of 14 radiocarbon measurements have been obtained from the annual tree-rings from timbers FP07 and FP08 (Table 5). Dissection was undertaken by Alison Arnold and Robert Howard at the Nottingham Tree-Ring Dating Laboratory. Prior to sub-sampling, the core was checked against the tree-ring width data. Then each annual growth ring was split from the rest of the tree-ring sample using a chisel or scalpel blade. Each radiocarbon sample consisted of a complete annual growth ring, including both early-wood and late-wood. Each annual ring was then weighed and placed in a labelled bag. Rings not selected for radiocarbon dating as part of this study have been archived by Historic England.

Radiocarbon dating was undertaken by the Centre for Isotope Research, University of Groningen, the Netherlands in 2019–20 and at the Laboratory of Ion Beam Physics, ETH Zürich in 2020. In Groningen, each ring was converted to α-cellulose using an intensified aqueous pretreatment (Dee *et al* 2020) and combusted in an elemental analyser (IsotopeCube NCS), coupled to an Isotope Ratio Mass Spectrometer (Isoprime 100). The resultant CO_2 was graphitised by hydrogen reduction in the presence of an iron catalyst (Wijma *et al* 1996; Aerts-Bijma *et al* 1997). The graphite was then pressed into aluminium cathodes and dated by AMS (Synal *et al* 2007; Salehpour *et al* 2016). In Zürich, cellulose was extracted from each ring using the base-acid-base-acid-bleaching (BABAB) method described by Němec *et al* (2010), combusted and graphitised as outlined in Wacker *et al* (2010a), and dated by Accelerator Mass Spectrometry (Synal *et al* 2007; Wacker *et al* 2010b). At both laboratories data reduction was undertaken as described by Wacker *et al* (2010c). The facilities maintains a continual programme of quality assurance procedures (Aerts-Bijma *et al* forthcoming; Sookdeo *et al* 2020), in addition to participation in international inter-comparison exercises (Scott *et al* 2017; Wacker *et al* 2020). These tests demonstrate the reproducibility and accuracy of these measurements.

The results are conventional radiocarbon ages, corrected for fractionation using $\delta^{13}C$ values measured by Accelerator Mass Spectrometry (Stuiver and Polach 1977; Table 5). The quoted $\delta^{13}C$ values provided by Groningen were measured by Isotope Ratio Mass Spectrometry, and more accurately reflect the natural isotopic composition of the sampled wood.

Two single-ring samples from FP07 were dated by both laboratories. Both pairs of replicate measurements are statistically indistinguishable at the 5% significance level and have been combined by taking a weighted mean before further analysis (Table 5; Ward and Wilson 1978).

WIGGLE-MATCHING

Radiocarbon ages are not the same as calendar dates because the concentration of ^{14}C in the atmosphere has fluctuated over time. A radiocarbon measurement has thus to be calibrated against an independent scale to arrive at the corresponding calendar date. That independent scale is the IntCal20 calibration curve (Reimer *et al* 2020). For the period covered by this study, this is constructed from radiocarbon measurements on tree-ring samples dated absolutely by dendrochronology. The probability distributions of the calibrated radiocarbon dates, derived from the probability method (Stuiver and Reimer 1993), are shown in outline in Figures 10–11.

Wiggle-matching is the process of matching a series of calibrated radiocarbon dates which are separated by a known number of years to the shape of the radiocarbon calibration curve. At its simplest, this can be done visually, although statistical methods are usually employed. Floating tree-ring sequences are particularly suited to this approach as the calendar age separation of tree-rings submitted for dating is known precisely by counting the rings in the timber. A review of the method is presented by Galimberti *et al* (2004).

The approach to wiggle-matching adopted here employs Bayesian chronological modelling to combine the relative dating information provided by the tree-ring analysis with the calibrated radiocarbon dates (Christen and Litton 1995). It has been implemented using the program OxCal v4.3 (http://c14.arch.ox.ac.uk/oxcal.html; Bronk Ramsey *et al* 2001; Bronk Ramsey 2009). The modelled dates are shown in black in Figures 10–11 and quoted in italics in the text. The Acomb statistic shows how closely the assemblage of calibrated radiocarbon dates as a whole agree with the relative dating provided by the tree-ring analysis that has been incorporated in the model; an acceptable threshold is reached when it is equal to or greater than An (a value based on the number of dates in the model). The A statistic shows how closely an individual calibrated radiocarbon date agrees its position in the sequence (most values in a model should be equal to or greater than 60).

Figure 10 illustrates the chronological model for FPELMt3. This model incorporates the gaps between each dated annual ring suggested by the cross-matching statistics used to form the elm site chronology (eg that the carbon in FP08, ring 1 (GrM-19922) was laid down 10 years before the carbon in FP07, ring 9 (ETH-104556 & GrM-21040); Fig 9), with all the radiocarbon measurements (Table 5), calibrated using the internationally agreed radiocarbon calibration data for the northern hemisphere, IntCal20 (Reimer *et al* 2020).

This model also has good overall agreement (Acomb: 174.7, An: 20.4, n: 12), and all 12 dated rings have good individual agreement (A: > 60.0). This suggests that the relative dating produced by the ring-width cross-matching of the three elm series (Tables 1–2; Fig 7) is correct.

The model suggests that the final ring of FPELMt3 formed in *cal AD 1485–1494 (95% probability; FP08 felling*; Fig 10), probably in *cal AD 1486–1492 (68%*

probability). This does not support the end date of AD 1480 for this ring tentatively suggested by the ring-width dendrochronology (Table 4). Furthermore, when the wiggle-match is constrained to end in AD 1480, it has poor overall agreement (Acomb: 17.0, An: 19.6, n: 13: Fig 11), with three dated rings having poor individual agreement (*ring 9*, A: 6; *ring 38*, A: 6; *GrM-21017*, A: 35). This also suggests that the tenuous cross-dating of the mean ring-width series as ending in AD 1480 is incorrect.

As the final ring of FPELMt3 is also the final ring of timber FP08, on which complete sapwood was retained (Table 1), the model suggests that FP08 was felled in *cal AD 1485–1494 (95% probability; FP08 felling*; Fig 10), probably in *cal AD 1486–1492 (68% probability)*.

The tree that produced sample FP01 was probably felled a year earlier: the final measured ring being relative year 90 of FPELMt3, but with eight unmeasured rings and 1mm lost on coring. As the last 10 rings of FP01 have a mean ring-width of 1.59 mm on a declining trend, this 1mm is likely to represent the loss of a single additional ring. On this basis the model estimates that FP01 was felled in *cal AD 1484–1493 (95% probability; FP01 felling*; Fig 10), probably in *cal AD 1485–1491 (68% probability)*.

The tree that produced sample FP07 was felled four years before FP08, in relative year 96 of FPELMt3, which is estimated to have formed in *cal AD 1481–1490 (95% probability; FP07 felling*; Fig 10), probably in *cal AD 1482–1488 (68% probability)*.

DISCUSSION

The Hall roof at Fulham Palace is thought, on the basis of the tree-ring dates produced for oak timbers used in its construction, to have occurred shortly after the felling of the tree which produced the collar of truss 4 (FPH05) in spring AD 1493 (Bridge and Miles 2004). Another sample from the original analysis, FPH01 from the collar of truss 2, and an unprovenanced oak sample from the present study (FPoak3), which may have been from a wallplate, produced estimated felling dates that are consistent with felling in AD 1493.

The relative dating of the three elm timbers in site chronology FPELMt3 clearly shows that the roof timbers in the hall of Fulham Palace come from trees felled over a number of years, radiocarbon wiggle-matching, suggesting that this was in the mid-to-late AD 1480s or early AD 1490s (Fig 12). It seems that the hall roof of Fulham Palace was constructed from oddments of timber residing in the diocesan timber-yard. This is unusual as evidence suggests that, with the exception of reused timbers, in most historical periods construction took place within a very few years of felling (Miles 2006).

The three ring-width series in elm site master chronology FPELMt3 gave consistent, but rather weak, matches against the oak database (Table 4). The radiocarbon wiggle-matching shows, however, that this matching position is erroneous, and that felling of the elms was later than AD 1480 in each case. Much stronger statistical matches were found to be erroneous when elm was matched against oak in a case in Oxfordshire (Bridge *et al* 2019), so this case again underlines the caution needed when attempting to date ring widths against master chronologies of a different species.

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TABLES

Table 1:. Details of the samples taken from the roof of the Hall, Fulham Palace

Sample number	Timber and position	No of rings	Dates spanning	h/s boundary	Mean ring width	Sapwood rings	Mean sensitivity	Felling date ranges
Elm samples								
FP01	East principal rafter, truss 1	90+8NM+1mm	1–90FPELMt3	-	2.23	nearly complete	0.21	c 99FPELMt3
FP02	Tiebeam, truss 1	<35	-	-	NM	-	-	-
FP03	Tiebeam, truss 2	40+20NM	-	-	3.95	present	0.30	-
FP04	West principal rafter, truss 3	80	-	-	1.89	21C	0.16	-
FP05	Tiebeam, truss 3	<35	-	-	NM	present	-	-
FP06	West principal rafter, truss 4	<35	-	-	NM	-	-	-
FP07	East principal rafter, truss 2	82	15–96FPELMt3	-	2.52	C	0.21	96FPELMt3
FP08	West principal rafter, truss 2	88	13–100FPELMt3	-	2.91	?¼C	0.24	100FPELMt3
Additional oak samples								
FPoak01	West queen post, truss 2	<40	-	-	NM	h/s	-	-
FPoak02	East lower purlin, bay 2	45	-	-	2.62	-	0.24	-
FPoako3	Wallplate?	119	AD 1362–1480	AD 1475	1.07	5	0.24	AD 1484–1516

FPELMt3 = relative date within site master chronology FPELMt3

Table 2: Dating evidence for the site sequence FPoak03, AD 1362–1480

Source region	Chronology:	Publication reference:	Filename:	Span of chronology (AD)	Overlap (years)	t-value
Somerset	Manor Court House, Chard	Arnold *et al* 2004	SMCASQ01	1409–1517	72	6.9
Hampshire	Street House Farm, Lower Farringdon	Miles *et al* 2009	STRHOFM2	1379–1492	102	6.7
Hampshire	Church Cottage, Basingstoke	Miles *et al* 2007	BSNGSTK1	1364–1541	117	5.9
London	Westminster School	Miles *et al* 2007	LIDDELLS	1346–1540	119	5.8
East Sussex	Hempstead House, Framfield	Bridge and Miles 2016	HMPSTDHO	1373–1501	108	5.7
London	Wolsey Buttery Roof, Hampton Court	Miles and Bridge 2013	HMPTNCT4	1340–1516	119	5.7
West Sussex	Field Place Barn	Bridge 1993	FIELDPB	1309–1465	104	5.6
Hampshire	Abbotstone Farmhouse	Miles *et al* 2006	ABBOTSTN	1367–1561	114	5.4
Hampshire	Swan Inn, Kingsclere	Miles and Worthington 1997	SWANINN	1363–1447	85	5.4
Hampshire	Parsonage Farm, Overton	Miles *et al* 2005	OVERTON7	1326–1545	119	5.3

Table 3: Crossmatching between elm elements

t-values	*t*-values	
Sample No	FP07	FP08
FP01	4.0	3.6
FP07		4.2

Table 4: Statistical matching of the elm sequence FPELMt3 at a position corresponding to AD 1381–1480

Source region	Chronology:	Publication reference:	Filename:	Span of chronology (AD)	Overlap (years)	t-value
Norfolk	St Nicholas' Church, Potter Heigham	Arnold and Howard 2013	PTHASQ01	1356–1479	99	5.9
Oxfordshire	Magdalen College, Oxford	Miles *et al* 2018	MAGDLN10	1277–1480	100	5.1
London	Sutton House, Hackney	Tyers and Hibberd 1993	SUT91	1319–1534	100	4.8
Buckinghamshire	Burrow Farm, Hambleden	Miles and Haddon-Reece 1995	BURROWFM	1350–1494	100	4.8
Essex	Park Farm Barn, Liston	Bridge and Miles 2017	LISTON	1340–1464	84	4.8
Surrey	Home Farm, Newdigate	Bridge 1998	NEWDIG1	1261–1483	100	4.3
Essex	Eastbury	Tyers 1997	EASTBURY	1250–1565	100	4.3
Oxfordshire	Stonor Park, tower	Bridge and Miles 2015	STONOR4	1391–1480	90	4.2
Hampshire	2 Park Lane	Miles *et al* 2007	LFROYLE	1386–1506	95	4.2
Sussex	Warhams, Rudgwick	Miles *et al* 2009	WARHAM3	1342–1606	100	4.2

Table 5: Radiocarbon measurements and associated δ¹³C values from fp07 and fp08 (replicate measurements have been tested for statistical consistency and combined before calibration as described by Ward and Wilson (1978))

Laboratory Number	Sample	Relative year	Radiocarbon Age (BP)	Weighted mean (BP)	δ13CIRMS (‰)	δ13CAMS (‰)
ETH-104556	FP07, ring 9	23FPELMt3	518±14	525±11; T′=0.6, T′(5%)=3.8, ν=1		−23.4
GrM-21040	replicate of ETH-104556		534±16		−22.09±0.15	
ETH-104557	FP 07, ring 26	40FPELMt3	497±14			−22.7
ETH-104558	FP 07, ring 38	52FPELMt3	444±14	443±11; T′=0.0, T′(5%)=3.8, ν=1		−24.8
GrM-21041	replicate of ETH-104558		442±16		−23.32±0.15	
ETH-104559	FP07, ring 52	66FPELMt3	409±14			−22.6
ETH-104560	FP07, ring 65	79FPELMt3	371±14			−24.6
ETH-104561	FP07, ring 75	89FPELMt3	371±14			−24.2
GrM-19922	FP08, ring 1	13FPELMt3	585±13		−22.15±0.15	
GrM-21016	FP08, ring 13	25FPELMt3	545±18		−22.58±0.15	
GrM-21328	FP08, ring 23	35FPELMt3	513±14		−23.07±0.15	
GrM-19923	FP08, ring 32	44FPELMt3	498±18		−23.17±0.15	
GrM-21017	FP08, ring 45	57FPELMt3	431±18		−22.92±0.15	
GrM-19896	FP08, ring 58	70FPELMt3	405±16		−22.11±0.15	

FPELMt3 = relative date within site master chronology FPELMt

FIGURES

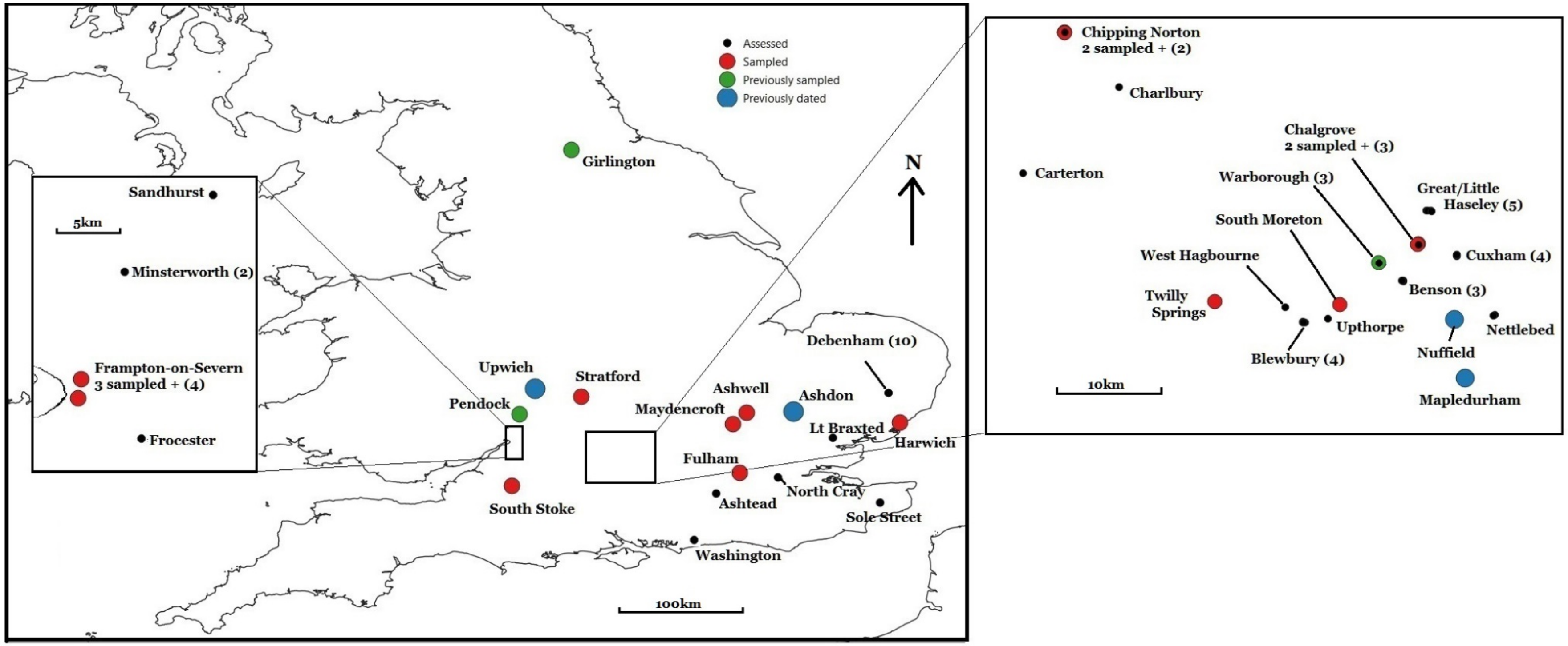

Figure 1: Map showing the distribution of sites sampled, some of which were dated, prior to the start of this project, and sites assessed and sampled properties for this project. Numbers in brackets after a place name represent the number of properties assessed in that location

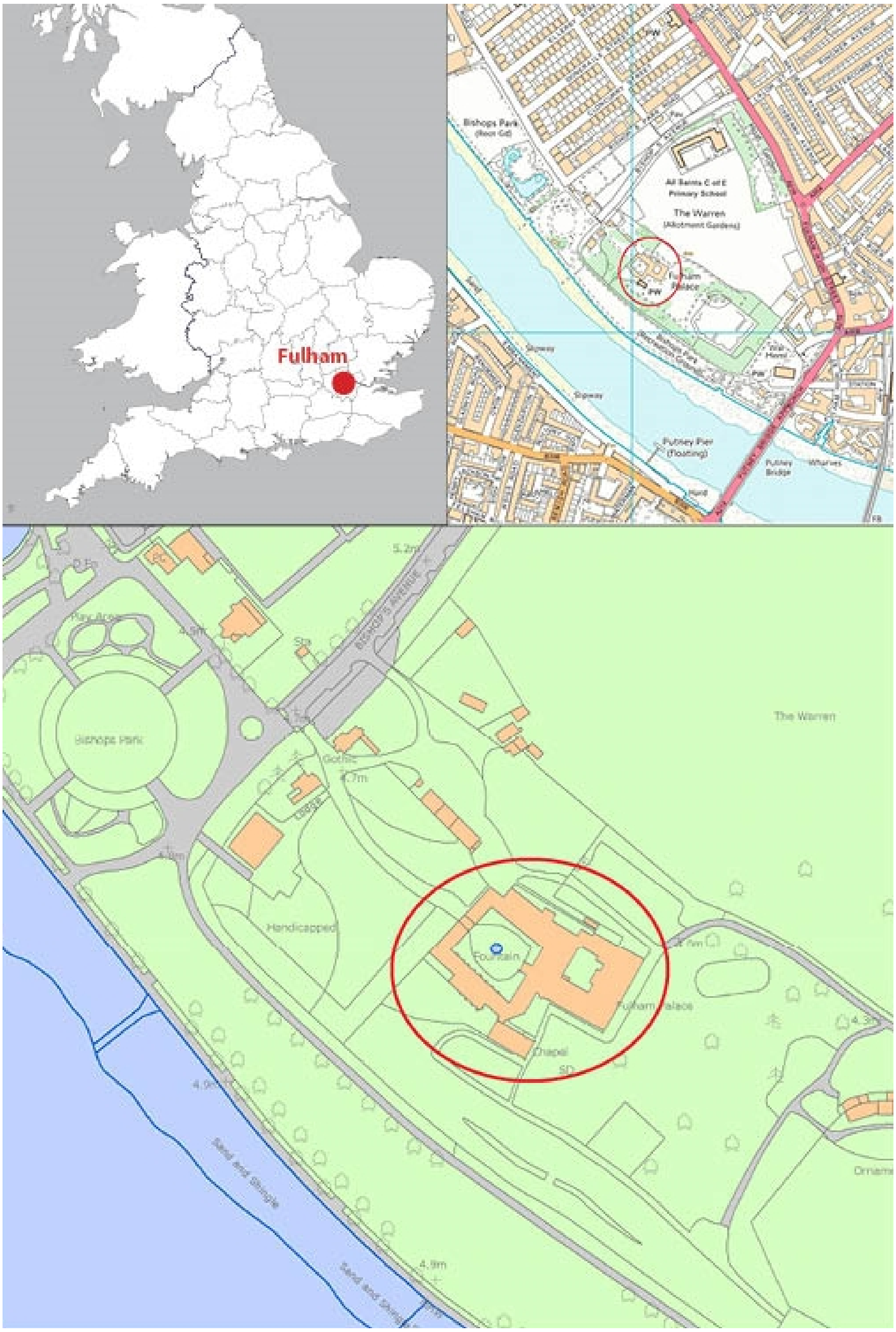

Figure 2: Maps to show the location of Fulham Palace, London, circled.Scale: top right 1:7500; bottom 1:2000 © Crown Copyright and database right 2020. All rights reserved. Ordnance Survey Licence number 100024900. © British Crown and SeaZone Solutions Ltd 2020. All rights reserved. Licence number 102006.006. © Historic England

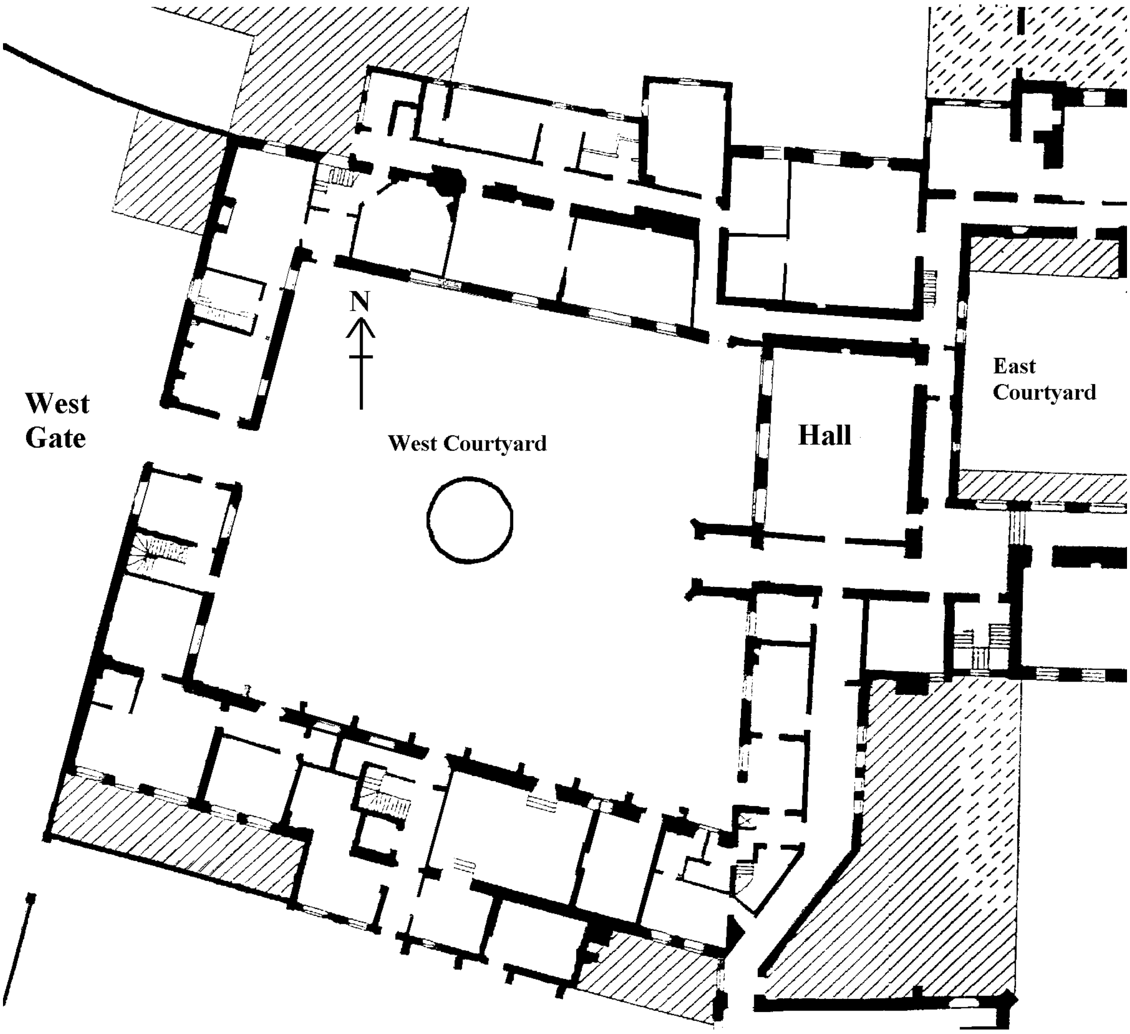

Figure 3: Plan of the layout of Fulham Palace indicating the position of the Hall within the complex

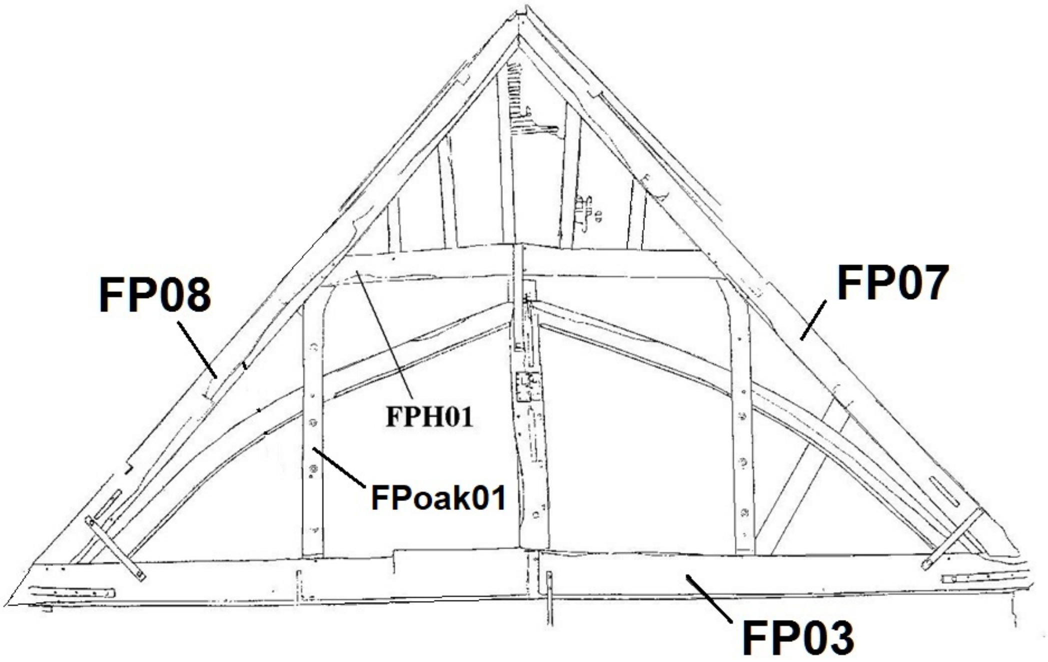

Figure 4: Drawing of truss 2 showing elm timbers sampled (FP) and previous samples from 2004 (FPH).

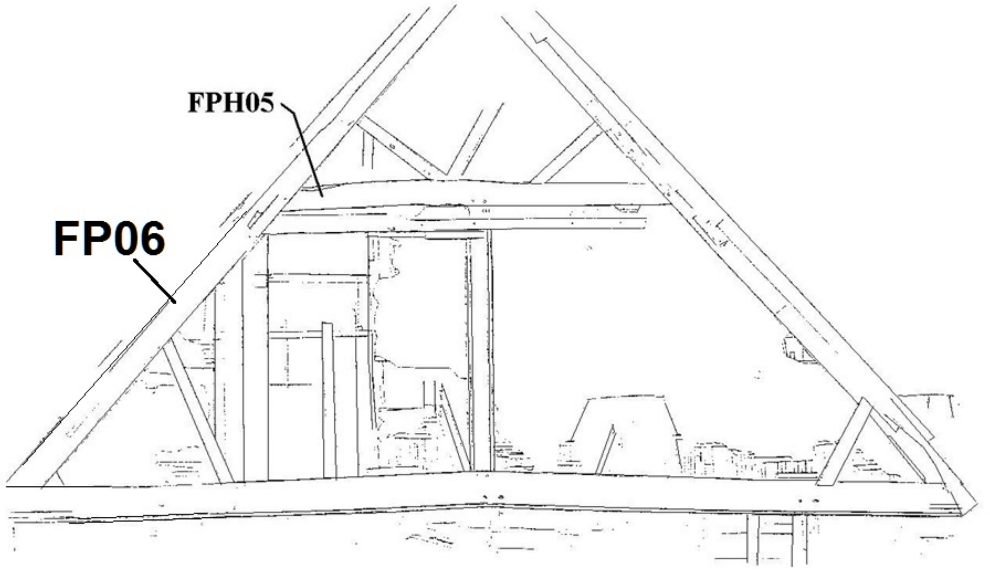

Figure 5: Drawing of truss 4 showing elm timbers sampled (FP) and previous samples from 2004 (FPH).

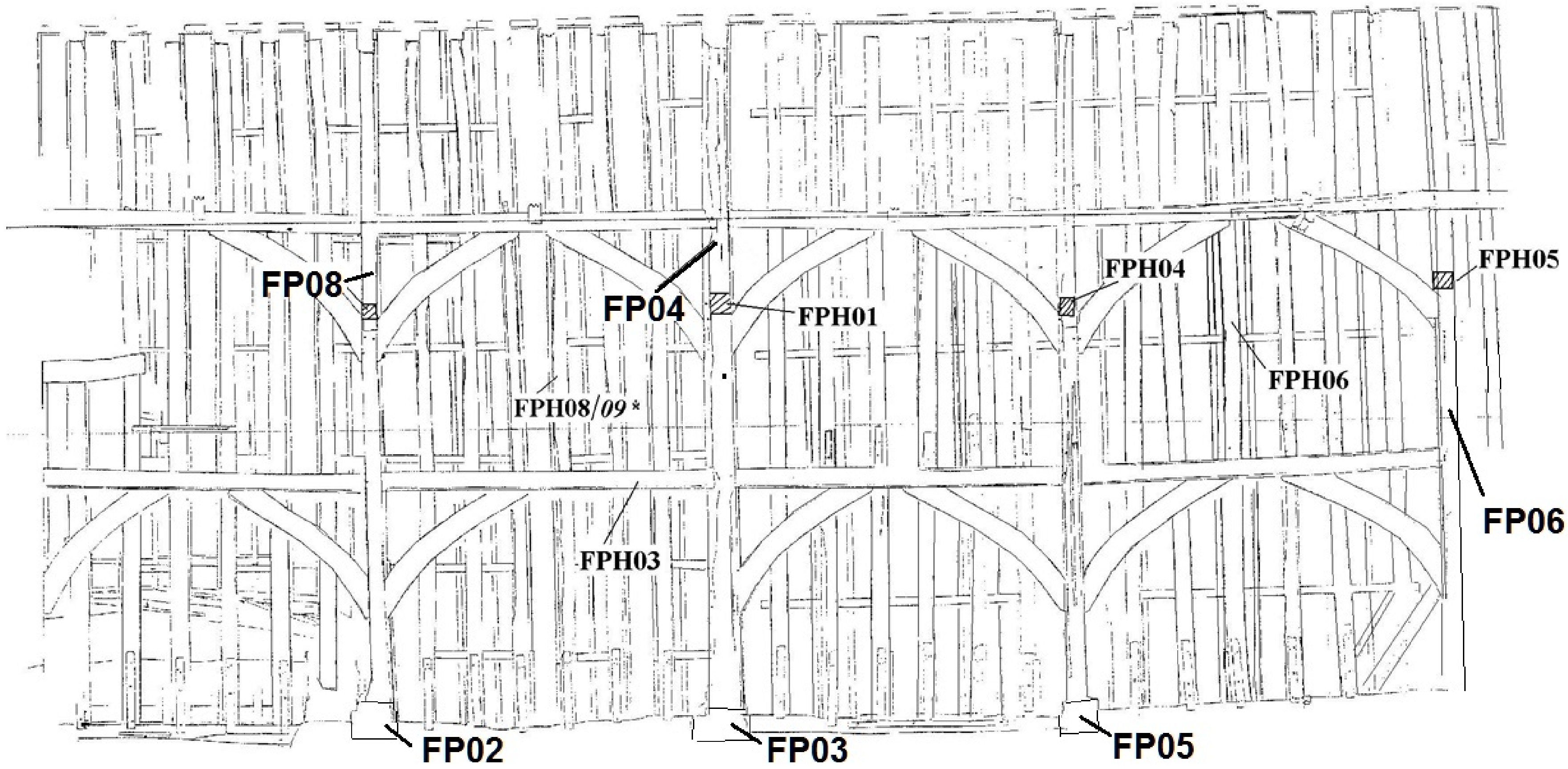

Figure 6: Drawing of the west side of the Hall roof, showing the locations of some of the elm timbers sampled (FP), and other timbers sampled in 2004 (FPH). Adapted from an original drawing by Engineering Surveys Ltd

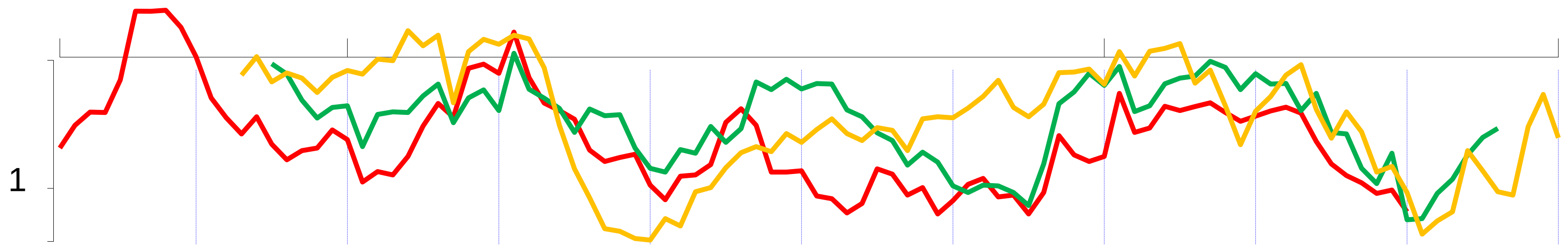

Figure 7: Plots of the three elm samples that potentially match each other and give some statistical matches against oak reference chronologies. Red line =FP 01, orange line=FP 08, green line = FP 07. The y-axis is ring width (mm) on a logarithmic scale

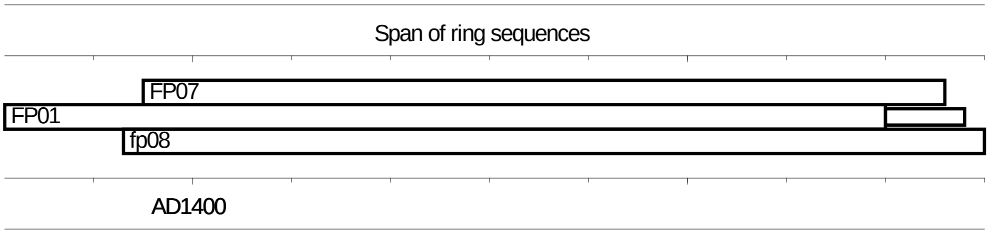

Figure 8. Bar diagram showing the relative positions of overlap of the cross-matched ring-series in elm site master chronology FPELMt3 using the radiocarbon supported dendrochronological date spans identified and individual felling dates/date ranges. White bars represent heartwood rings

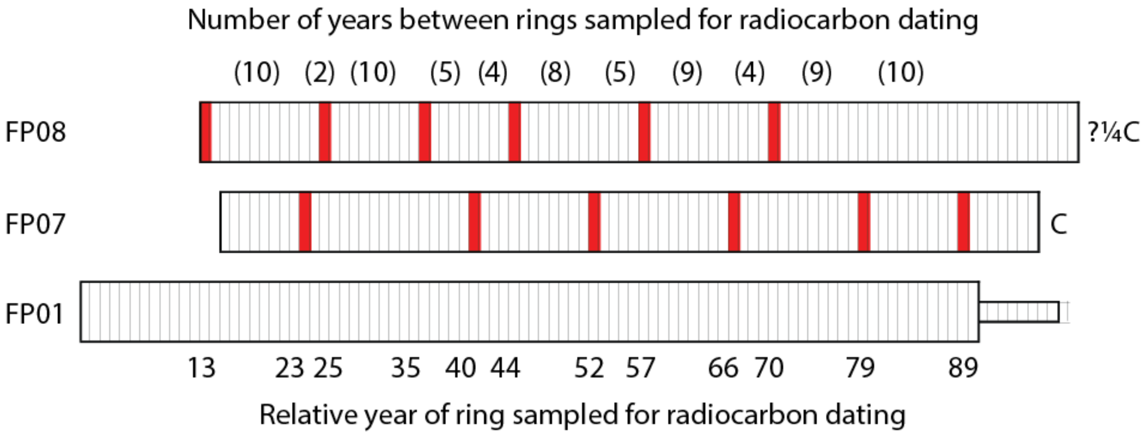

Figure 9. Schematic illustration of the samples in elm site master sequence FPELM53, locating the single-ring sub-samples submitted for radiocarbon dating (?¼C = complete sapwood, probably spring felled; C = complete sapwood, winter felled)

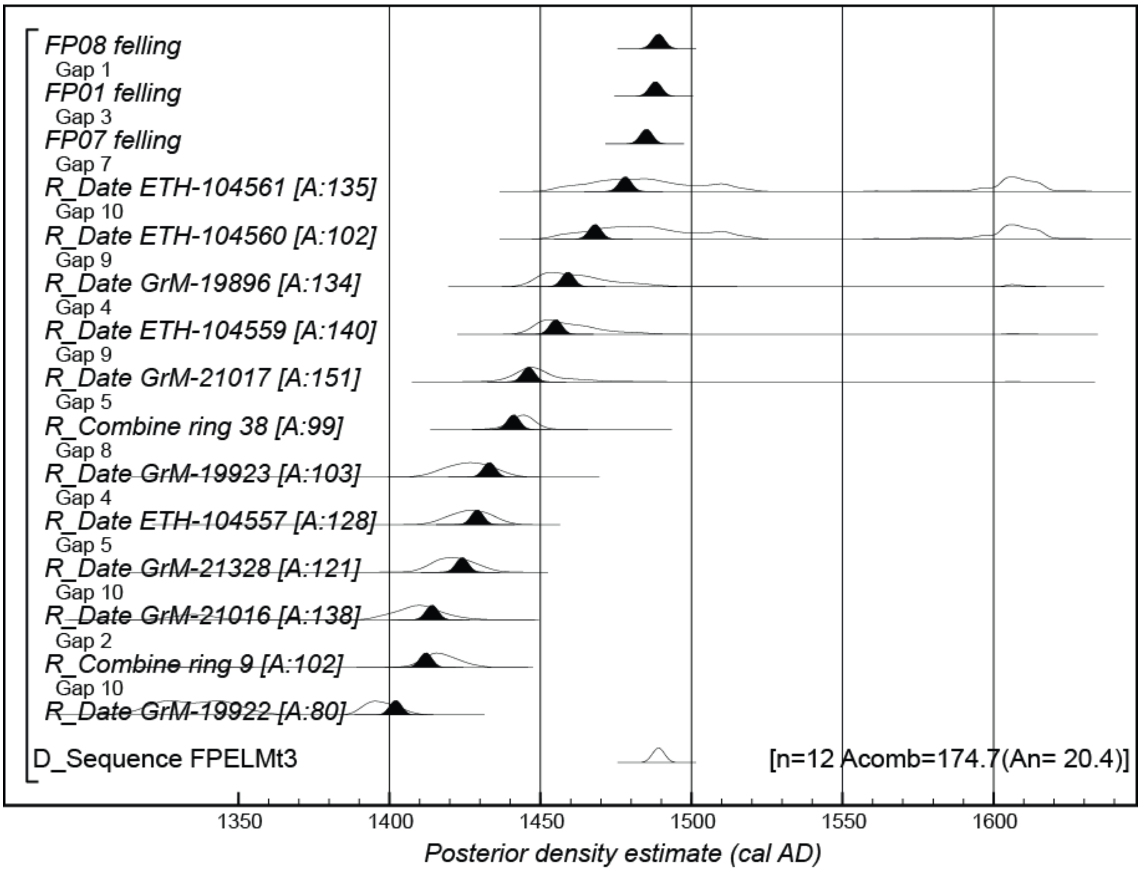

Figure 10. Probability distributions of dates from site elm chronology, FPELMt3. Each distribution represents the relative probability that an event occurs at a particular time. For each of the dates two distributions have been plotted: one in outline, which is the simple radiocarbon calibration, and a solid one, based on the wiggle-match sequence. Distributions other than those relating to particular samples correspond to aspects of the model. For example, the distribution ''FP07 felling' is the estimated date when the tree which produced the timber FP07 was felled. The large square brackets down the left-hand side along with the OxCal keywords and the description of the sapwood estimates in the text defines the overall model exactly

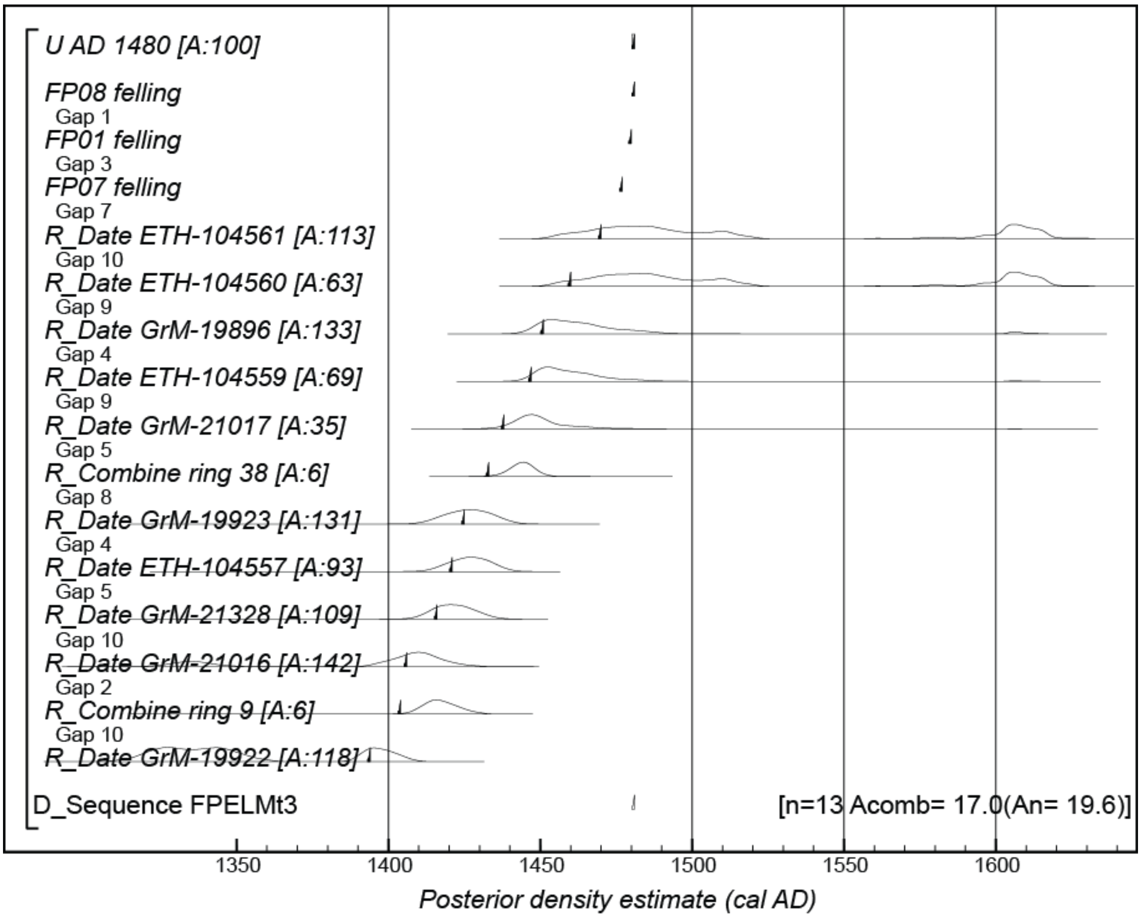

Figure 11. Probability distributions of dates from site elm chronology, FPELMt3, when its last ring is constrained to have formed in AD 1480. The format is identical to that of Figure 10. The large square brackets down the left-hand side along with the OxCal keywords define the overall model exactly

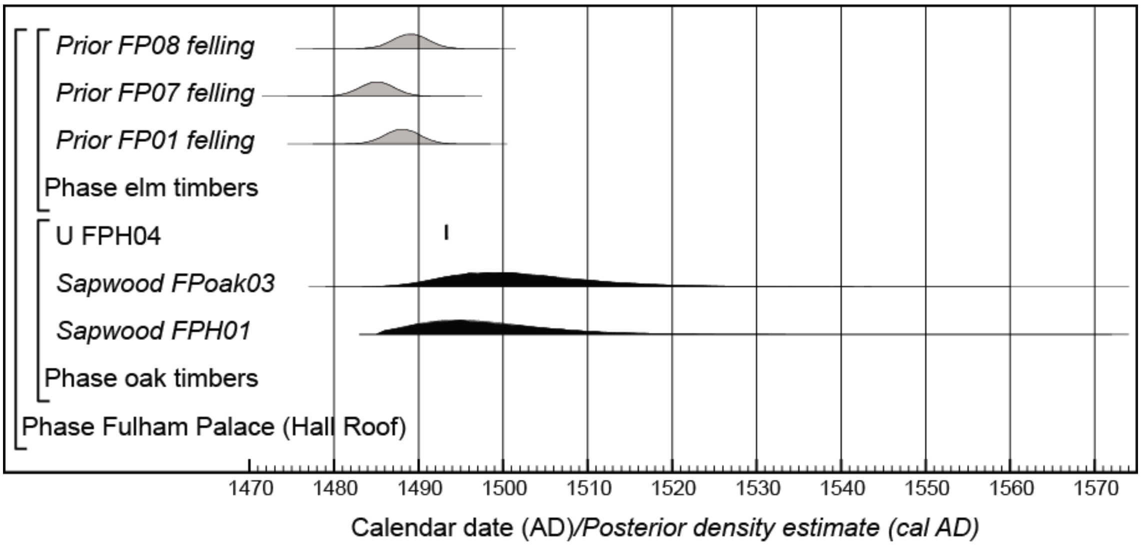

Figure 12. Estimated felling dates for the parent trees of timbers utilised in the hall roof at Fulham Palace (black = derived from ring-width dendrochronology, estimated felling dates calculated as described by Miles (2005); grey = derived from radiocarbon wiggle-matching)

APPENDIX

Ring width values (0.01mm) for the sequences measured

Elm

FP01

164	217	255	254	379	882	881	891	723	503
304	238	195	241	172	142	159	164	205	182
108	123	118	148	215	284	240	437	460	411
682	390	285	260	234	160	139	146	152	104
87	116	118	134	225	266	217	122	122	124
91	88	74	83	127	119	92	101	73	86
105	113	90	92	73	95	191	151	139	148
321	199	210	274	260	273	286	254	228	243
259	271	252	178	135	117	107	94	98	75

FP03

815	859	662	143	145	445	697	537	136	148
344	320	341	390	343	180	232	306	411	564
404	436	329	306	281	460	545	359	380	383
489	776	748	499	391	356	148	157	179	165

FP04

549	542	561	525	485	446	307	228	190	199
249	275	298	187	192	174	158	137	136	106
97	148	124	148	175	170	188	189	199	191
178	124	164	157	144	132	173	135	118	120
118	141	136	160	167	139	130	163	206	196
141	189	234	220	262	259	310	320	521	298
203	166	180	140	117	94	85	72	67	53
58	58	47	70	56	65	56	64	65	82

FP07

462	407	295	237	270	276	167	248	256	254
311	360	224	304	335	260	525	338	303	267
199	265	244	247	164	128	122	161	154	214
176	208	369	336	382	339	362	360	262	241
198	180	133	156	138	103	95	104	103	95
81	135	283	327	411	354	447	257	276	361
387	397	476	442	336	409	360	363	260	321
199	195	128	106	154	68	69	94	112	151
187	209								

FP08

402	504	370	413	387	325	391	425	407	489
480	693	576	656	286	536	624	587	656	627
440	217	127	89	61	59	54	53	69	63
96	101	129	155	167	157	196	176	206	235
196	180	211	204	159	235	241	238	268	309
377	270	241	281	414	417	433	359	536	397
539	558	592	364	427	276	171	258	309	402
457	264	185	256	200	122	131	95	57	67
75	159	124	96	92	213	317	186		

Oak

FPoak02

179	221	283	249	302	347	252	311	107	233
347	272	226	233	218	161	225	331	263	298
436	331	286	293	258	401	262	280	407	418
360	276	325	284	218	243	249	221	153	143
229	152	155	149	215					

FPoak03

275	155	145	134	139	61	97	179	143	112
131	107	159	130	191	149	159	146	137	109
130	218	198	120	235	313	337	189	152	113
69	44	45	45	63	55	95	90	87	71
52	91	137	106	106	84	71	55	102	131
89	70	100	56	41	70	83	81	80	85
76	87	93	60	47	50	35	29	24	43
51	50	54	47	43	60	50	61	71	86
84	127	110	96	94	93	57	82	74	88
87	75	90	83	87	58	65	58	45	58
60	101	73	73	135	137	128	85	121	117
116	98	222	296	238	142	189	242	217	

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