Elm Dendrochronology

Martin Bridge

UCL Institute of Archaeology, London, U.K.

31-34 Gordon Square, London WC1H 0PY. martin.bridge@ucl.ac.uk

Elm Dendrochronology

Elm is generally considered to be unsuitable for dendrochronology, usually having too few rings, or having abrupt growth rate changes that do not result from the external weather conditions. Samples rarely match each other in the same structure. A further difficulty is that even where it is known that the sequence is complete (the bark is still present), it is often not possible to distinguish sapwood rings by their appearance, even under a microscope. This is a significant problem as elm has been an important structural component of many British vernacular buildings over many centuries, but whereas dendrochronological dating of oak has transformed our understanding of thousands of buildings, by 2015 only four instances of dating elm had been made, two of those involving a single timber. When elm has been encountered, it has generally been dismissed from further dendrochronological study as a result of these known issues, but no systematic study has been undertaken to see whether these prejudices are justified.

In order to get some evidence-based information about how elm might behave dendrochronologically, Historic England initiated a study: Developing the dendrochronology of elm in historic buildings, Project 7350, funded through its Heritage Protection Commissions. This resulted in over seventy buildings being looked at, with several being sampled, and the results are discussed here.

At some sites an elm site master sequence could be derived, but potential matches with local oak chronologies were generally not strong enough to be considered dated. In one instance good matches with local oak sites were found, but subsequent radiocarbon analysis found these matches to be erroneous. At another site, five trees gave an 89-year ring sequence, but no acceptable matches were found with oak chronologies. Radiocarbon dating and oxygen isotope dating both gave the same dating results at this site however, showing that these two methods appear to give the best hope of dating elm in the future.

Keywords: dendrochronology; elm; *Ulmus* spp; standing buildings

Background

Throughout the extensive dendrochronological studies in standing buildings and other artefacts carried out in the UK over the last four to five decades based on oak (*Quercus* spp.), it has been common practice to dismiss elm (*Ulmus* spp.) as unsuitable for dating because of its known limitations. It has been observed as often having too few rings for statistically meaningful cross-matching, and it often exhibits uneven growth around the circumference, meaning that one radius of the tree may be quite different to another. The lack of dating, with only four known sites where elm has been successfully dated against oak at the same site from all UK studies (see below) has also meant that when elm is found, financial constraints have deemed it non-commercially viable to sample. Nevertheless, it is the second most common structural timber in medieval and immediately post-medieval buildings, being found in perhaps 10% of buildings (though this has never been systematically recorded), and obviously being chosen over and above ash (*Fraxinus* spp) which was always more common in the countryside throughout this period.[1]

It has been observed that elm is found in buildings throughout the UK, but that it is more common in certain geographical areas than others, for example up to 20% of buildings assessed in a project in Debenham, Suffolk in 2008 were noted as having substantial amounts of elm in them,[2] and it has been noted as more common in Gloucestershire and south Worcestershire, as well as Oxfordshire and Warwickshire,[3] whilst rarely being encountered in some areas, e.g. Hampshire,[4] where elm was anyway never common in the landscape.

One problem with elm is that it has been described as one of the most complex genera of British trees, especially in woodlands, where it is extremely variable.[5] It is however, generally considered to be a light-demanding tree, more common in hedgerows and woodland edges than in woods. Rackham says that the genus has largely abandoned sexual reproduction, mostly reproducing by suckering to produce clones, with the result that some types may be unique to a particular village. Others however say that it hybridizes readily, which would seem to be a contradiction. All agree that the classification of elms is difficult. The so-called English Elm (often *U. procera*, but Richens refers to it as *U. minor* var *vulgaris*) is the most common in southern counties. Richens recognises five varieties of *U.* minor, one being an 'East Anglian Elm' found in both hedges and woods in Essex, and elsewhere in East Anglia, which is less common but more variable. Wych Elm (*U. glabra*) is rare, but also present in these areas.[6] Richens describes elm groves in the valleys of south-west Cambridgeshire and says that elm is common in buildings in Cambridgeshire, and in the coastal plain of Sussex.[7] The Wych Elm is generally regarded as more common in the northern counties and the Welsh borders. With such complexity, and the fact that the different species cannot readily be distinguished on the basis of their wood anatomy, it is perhaps not surprising that elm ring-width sequences, on the rare occasions when they have been looked at, rarely match the available long tree-ring width data for oak, with which they have been compared.

Of the four successful dating studies, three were over twenty-five years ago. The first was a short (54-year) combined sequence comprising four timbers, UPWICHELM, matched ($t = 5.8$, 54 years overlap) with an oak sequence (UPWICH4) from the same site, dating the sequence to 1692–1745,[8] and it matches very well against oak data from a wide geographical area, with at least 12 sites matching at $t < 6.0$. A 103-year sequence from an elm wallplate at Upper House Farm, Nuffield, Oxfordshire dated against oak in the same building,[9] and it was noted that although complete sapwood was present, it was not possible to distinguish the sapwood rings. This sequence does not match oak sequences outside the site itself. A 43-year long sequence was dated from a cruck blade in Mill Farm Cottage, Mapledurham, Oxfordshire, matching oak from the same property,[10] the visual ring-width plots being particularly good, but this short sequence gives only two matches with a *t*-value between 4 and 5 at the proposed date against oak chronologies from outside Mapledurham, and stronger matches at different dates. More recently, Ashdon Street Farm, Ashdon, Essex (within 1km of the boundary with Cambridgeshire) yielded three elm timbers which gave a combined sequence of 91-years that matched weakly against oak from the same site ($t = 3.9$ with 91 years overlap) but, importantly gave stronger matches to other oak site chronologies from the area (5 sites with $t < 6.0$), dating felling to 1446 and 1447,[11] agreeing well with the dated oak phases in the same building. Other than that, the only published successful elm work appears to be on living cultivated elms from London parks carried out by Brett in the 1970s.[12]

Recognising the importance of elm in the built environment and the potential for an improved understanding of the significance and character of this second most common timber in our buildings, Historic England initiated a project (Project 7350 Developing the dendrochronology of elm in historic buildings) to improve the understanding of these buildings and support decision-making with respect to protection, management and conservation.

The Historic England Project

The project design for the Historic England project that went out to tender suggested concentrating on three geographical areas and assessing up to 60 buildings spread over these areas, plus any other buildings encountered within usual dendrochronological studies elsewhere, and sampling at least fifteen of the best prospects. One of the best ways to undertake a fundamental review of the prospects for dating a different species by comparison with the oak tree-ring width database as a first step would be to use living trees, where the date and origin of growth is known, but this was ruled out from the start because of the danger of spreading disease within the very limited elm population remaining after the Dutch Elm epidemic of the late twentieth century. Although the primary aim of the project was to try and develop elm dendrochronology for use with vernacular buildings, the development of the oak chronology over recent decades has shown that initially it can be useful to look at more polite buildings, which often have the best quality timbers, to establish growth patterns for different geographical areas. With this in mind, one building that was proposed as a good candidate for sampling from the outset was the Great Hall roof at Fulham Palace, where previous work had dated the oak in this largely elm roof to having been felled in 1493.[13]

In all, over 70 buildings were assessed, mostly in Oxfordshire, Suffolk and Gloucestershire, but also more widely across southern England (see Appendix 1, and Fig 1). The reason for assessing a greater number of buildings was simply that little promising timber was found in the majority of the buildings looked at – the elm seen generally had too few rings – it is desirable to have a minimum of 50-60 rings, and when starting out in a new area, or with a new species, longer sequences are preferable. It was also noted that many elm timbers looked to have a good number of relatively narrow rings in the outer 20-30 years of growth, but had few much wider rings towards the centre of the tree.

Methods

Standard Ring Width Dendrochronology

The widely used and now standard methods for dendrochronology, in line with the English Heritage Guidelines (EH 1998)[14] were employed. Cores (16mm diameter) were extracted using an electric drill, and these were then returned to the laboratory and sanded with progressively finer grit abrasive belts to make the ring boundaries clearly visible. The ring width sequences were then measured to an accuracy of 0.01mm under a binocular microscope on standard dendrochronological equipment, storing the measurements on a computer for subsequent analysis. Cross-matching was undertaken both statistically and visually, and where possible, individual sequences were combined to make site master sequences. These site masters, as well as longer individual sequences, were compared with the available oak reference material.

Radiocarbon Wiggle Matching

Radiocarbon dating is based on the radioactive decay of ^{14}C, which all living things absorb from the atmosphere during their life. Trees store this in their growth-rings, the radiocarbon from each year being stored in each 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 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). The methodology employed is detailed in the Historic England Research Report Series report (HE RRS) for each site investigated in this way. This project was able to make use of the new IntCal20 calibration, itself based on dendrochronologically dated wood samples.[15]

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 sample.

The modelled dates are quoted in italics in the text to distinguish them from conventional dates.

Oxygen Isotope Dendrochronology

Oxygen isotope dendrochronology relies upon the same fundamental principles, limitations, and assumptions as conventional (ring-width-based) dendrochronology. Rather than using ring-width measurements however, it uses the ratio of heavy to light oxygen isotopes in the late-wood cellulose ($\delta^{18}O$).[16] Whereas ring-width dendrochronology relies on limitations to growth by external climatic factors, and can be also be upset by things like human management of the trees, the oxygen isotope ratios directly reflect the external conditions in each year. A master oxygen isotope chronology was constructed using dendrochronologically-dated oak timbers,[17] largely from the archives of dendrochronological laboratories, particularly the Oxford Dendrochronology Laboratory. The latewood of each tree-ring is prepared for chemical analysis and dating, the methodology again being described in the individual HE RRS reports.

Findings

The initial 60 buildings assessed for this project yielded too few sites that looked as if they might be worth investigating further, largely because the timbers had too few rings. Also, several timbers showed very abrupt growth rate changes, a result in line with the accumulated anecdotal evidence from dendrochronologists over several decades. In the end over 70 sites were assessed, at which point it was decided to investigate the most promising looking sites further. These were the sites where the assessment of the outside of the timbers suggested there might be 50 or more rings and several timbers had the heartwood/sapwood boundary or traces of sapwood present.

Fourteen buildings were sampled specifically for this project (see Appendix 1), along with another site sampled in Oxfordshire before the start of the project. Three other sites that contained elm encountered during normal case-work studies by the Nottingham Tree-Ring Dating Laboratory (NTRDL) were also looked at (Girlington, Treludick and Charterhouse, Coventry). Each is the subject of an individual HE RRS report which will give details of the timbers sampled, so just a summary will be given here. Several sampled sites were found to have elm timbers with fewer rings then expected, the result of the observation that the inner rings are often much wider than the outer rings (see for example Fig 2). It is known that elms where pollarded and 'shredded' (where side branches are removed up the trunk, sometimes leaving a 'tuft' of branches at the top),[18] and this would be expected to be reflected in the ring-width series by sudden reductions in growth rate, followed by a slow recovery. In many cases however (Fig 3), the growth rate was seen to not only decline rapidly, but also to increase dramatically in the space of a year, making even long series unlikely to date. This is because these sudden changes are unlikely to be reflecting variations in the weather between years, but are more likely due to changes in the immediate environment of individual trees. Dendrochronologists have a measure of this year-to-year variation called 'mean sensitivity' which for oak series usually falls within the range 0.18 – 0.28.

In the elm series measured in this study, also including the NTRDL sites and 233-235 Thame Road, Warborough (see below), 36% had mean sensitivity values of 0.29 or higher. A number of samples went out to the bark edge, but few had readily distinguishable sapwood (Fig 2), so the number of sapwood rings could rarely be determined. Out of 129 measured series, 19 had complete sapwood where the number of sapwood rings could not be determined, but in 18 cases where sapwood numbers were counted, the mean number of rings was 24, with a range of 9 to 51. With relatively few examples, it is probably wise not to make generalisations about elm sapwood numbers at this stage.

One interesting observation, given Brunskill's assertion that elm 'was not commonly used until the eighteenth century'[19] is the distribution of the likely ages of the elm in buildings looked at through the course of this study. Although in many cases the dating is subjective, based on stylistic features, a couple of phases were dated to the fourteenth century. More than 10% of sites were attributed to the fifteenth century, and more than a quarter to the sixteenth century, the most common period seen. Around 16% were attributed to each of the seventeenth and eighteenth centuries. Earlier, Stenning found several early small aisled halls in Essex contained elm.[20] Brunskill also passes on the well-known assertion that elm is used either when it is kept constantly wet, or constantly dry. It is interesting that buildings like the Wool Barn, and Frampton Manor (both in Frampton on Severn, Gloucestershire) have the exposed framing of oak, but the roof that should be dry is of elm on an estate that had a lot of elm, 1300 elms being lost in the Dutch Elm epidemic, according to the estate owner.

Given that the most promising looking sites were the only ones sampled (excluding NTRDL sites which were sampled opportunistically), only 54% of the elm samples obtained had 60 or more rings in them, the longest series being 119 years long. With these short ring series and the high mean sensitivity, it is not surprising that little cross-matching was found between the samples, the first step in any dating process.

Girlington Hall (Co Durham)[21] – a NTRDL site – had some of the longest sequences, including the longest at 145 rings, each with relatively low mean sensitivity values (0.17 to 0.30), perhaps, given its northern location, indicating that these were from *U. glabra* or one of the varieties of *U. minor* not encountered elsewhere. Six timbers matched together to form a 158-year long sequence, but this did not match against local oak chronologies.

Pairs of matching timbers were found at Treludick, Cornwall[22] (an NTRDL site with three pairs of matching timbers, 73, 74 and 77 years long, but not matching each other); 1 Middle Row, Chipping Norton, Oxfordshire (two pairs with weak visual matches between the plots of 62 and 93 years length); Great Barn, Chalgrove, Oxfordshire, 105 years long; The Packhorse, South Stoke, Somerset – 71 years long. In addition, two groups of three timbers, and a pair of elm timbers were found from 233-235 Thame Road, Warborough, Oxfordshire, investigated before the HE project.[23] All of these had rapid growth rate changes, and were not dated.

Four matching elm timbers were found at 11 St Austin's Lane, Harwich, Essex, resulting in a 62-year long sequence, but this did not date against reference oak sequences, although a potential matching position in the early sixteenth century with very weak matches was considered. Subsequently, radiocarbon wiggle matching was carried out, resulting in a date range of *cal AD 1425–36* (95% probability) being derived, thus ruling out the weak ring-width dendrochronology matching.

At Fulham Palace, three elm cores from timbers in the Great Hall roof matched each other, and the combined site master gave some weak statistical matches with oak reference material at a position corresponding to the felling of one timber in 1480. This seemed a little unlikely, as it would have meant the elms having been felled over ten years previously to dated oak in the roof, but it was nevertheless considered worthy of further analysis by radiocarbon wiggle matching. The result of analysing two elm series gave a range of *cal AD 1485–94* (95% probability) for the end dates, strongly suggesting that the ring-width match is erroneous.

One result that is more troubling is that obtained for 1 Middle Row in Chipping Norton, Oxfordshire. Here, standard ring width dendrochronology identified three pairs of elm samples that matched each other well, two samples matching with t = 7.1 with 54 years overlap, a second pair with t = 6.7 with 45 years overlap, and the third pair with t = 8.2 with 74 years overlap. Similarities in the curves suggested the three pairs might match each other, and they were tentatively combined into a single sequence, which gave consistent good statistical matches with local oak chronologies at a position equating to the early sixteenth century (t <6.0 against at least 6 oak chronologies) . Although not strong enough to be considered a date in this case, where there was no matching with oak from the same site as had been found in the earlier dated sequences, radiocarbon wiggle matching was undertaken to see if this position might be confirmed. The results however show the final ring of the samples tested was formed in *cal AD 1669–1676* (95% probability), meaning that the ring-width chronology derived potential match was erroneous. These results clearly show the good dendrochronological match of elm against the oak database was, in this case, not a date, and it suggests that a higher t-value threshold may be needed for accepting elm matches against oak chronologies for the results to be accepted as dates.

Three elm timbers at Twilly Springs House, West Hendred, Oxfordshire, resulted in a 96-year long sequence. This gave no consistent acceptable statistical matches against the oak database. Two methods were however used to analyse elm material from this site, radiocarbon wiggle matching, and oxygen isotope dating. The radiocarbon analysis gave a likely felling date range for a timber with complete sapwood of *cal AD 1801–1808* (95% probability) or the likely *cal AD 1802-1806* (68%

probability). The oxygen isotope analysis, initiated independently by Dan Miles, gave a felling date in winter 1806/07. These all agree very well with oak dating in the same phase of spring 1807 derived previously by Dan Miles (pers comm.).

The conclusions from the study have to be at this stage that the likelihood of obtaining a date from elm timbers by standard ring-width dendrochronology remains extremely low, with just a few sites having been successfully dated in the past, and only two of those (Upwich and Ashdon Street) yielding elm ring-width sequences that could be confidently matched with oak sequences outside the structures they were found in. The parent trees from which these timbers had been converted were perhaps odd elm varieties that happened to respond to external stimuli in a similar way to oak trees. The sites with the most potential from over 70 sites investigated failed to date, even though in some cases it was possible to form a site master from more than one timber. It is useful at this point to re-assess the four previous elm dates reported, where it seems that each can be supported by oak at the same site, and two of them give extensive good matches with local oak chronologies, though the Chipping Norton example shows that this is not always a reliable guide. The recent Ashdon Street Farm elm dating against oak is supported by early results from oxygen isotope dating.

There is however some prospect for the future dating of elm, coming from two different ways of investigating the timber – oxygen isotope analysis and radiocarbon wiggle matching, and the results obtained so far are summarised in Appendix 2. Oxygen isotope analysis for dating is currently being developed at Swansea University.[24]

Although in its early stages, this project has already proved useful in deriving dates for previously undated samples of oak, and analysis of the dated elm from Ashdon Street Farm, and a barn in Pendock, Gloucestershire, both sampled prior to the Historic England project, showed that it has the potential to be able to date elm as well. The analysis, carried out at an early stage in the isotope project, examined material from the whole annual ring, and gave the best result at the dendrochronologically derived date in the case of Ashdon Street Farm, but neither were considered strong enough on their own to be considered as a date by oxygen isotope analysis. Further samples may now be analysed using just the summer growth. A more recent study[25] has dated an elm element of the portcullis windlass in the Byward Tower at the Tower of London to be of similar age to the oak components, also dated by oxygen isotope dating, with none of the timbers having been dated by conventional dendrochronology.

Radiocarbon has long proved useful in dating oak samples that could not be dated by dendrochronology, and improvements in the calibration of the radiocarbon curve and better Bayesian modelling are allowing more sites to be dated, and this includes elm sites. It is hoped that samples from some of the sites in the HE Elm Project will be submitted for analysis at a future date as part of further research combining both radiocarbon dating and oxygen isotope analysis.

ACKNOWLEDGEMENTS

I am grateful to both Cathy Tyers and Alex Bayliss (both of Historic England) for their helpful comments on earlier drafts of this paper.

Very many people have assisted in carrying out this project for Historic England, not least all the property owners too many to list individually, but without whom none of this work would have been possible. The Oxfordshire Buildings Record (OBR) introduced me to many buildings and gave background information, and I am particularly grateful to David Clark for the OBR's involvement, Victoria Hubbard (Chipping Norton), Sally Stradling (many of the Oxfordshire villages), Rachel Jacques (Chalgrove) and Marianne Suhr (Blewbury). Rose Hewlett (Frampton on Severn), Lesley Grant-Adamson (Debenham) and Dan Miles (Oxfordshire) were also instrumental in my gaining access to several properties. Additional tree-ring information on elm was supplied by Dan Miles (Oxford Dendrochronology Laboratory) and Robert Howard and Alison Arnold of the Nottingham Tree Ring Dating Laboratory. Alex Bayliss and Peter Marshall (Historic England) were responsible for modelling the best samples for radiocarbon analysis, submitting samples, and interpreting the results. Shahina Farid (Historic England

commissioned some of the sites and assisted in the production of the RRS reports. Neil Loader of Swansea University led the work on oxygen isotopes.

NOTES

1. Rackham, *Trees and Woodland in the British Landscape* and *Ancient Woodland*, 267.
2. Martin Bridge, project for the Debenham History Society, Suffolk.
3. Personal observation, reinforced by comments from other dendrochronologists such as Cathy Tyers, Dan Miles and Robert Howard.
4. Observation by Edward Roberts.
5. Rackham *The Woods of South East Essex* and Richens *Elm*.
6. Richens, *Elm.*
7. Ibid.
8. Groves in Hurst (ed) *A multi-period salt production site at Droitwich: excavations at Upwich*.
9. Haddon-Reece et al., “Tree ring Dating List 32.”
10. Haddon-Reece et al., “Tree Ring Dating List 38.” Dan Miles informs me that oxygen isotope work has confirmed the likelihood of this result, but this is unpublished as yet.
11. Bridge, Oxford Dendrochronology Laboratory report 2015/03.
12. Brett “Dendroclimatology of Elm in London.”.
13. Bridge and Miles Centre for Archaeology Report 79/2004.
14. English Heritage, “*Dendrochronology: Guidelines on producing and interpreting dendrochronological dates*.”.
15. Reimer *et al* 2020.
16. McCarroll and Loader 2004.
17. Loader *et al* 2019.
18. Richens, *Elm.*
19. Brunskill *Timber Building in Britain*.
20. Stenning, “Small Aisled Halls in Essex”
21. Arnold et al., Historic England Research Report Series, forthcoming.
22. Arnold and Howard, *English Heritage Research Department Report* 63/2007.
23. Bridge, Oxford Dendrochronology Laboratory Report 2015/09.
24. A Leverhulme Trust grant (RPG-2014-327) awarded to Swansea University Geography Department is developing a chronology for oak oxygen isotopes from dated wood in collaboration with The Research Laboratory for Archaeology and the History of Art, Oxford University.
25. Loader et al., “Oxygen isotope dating of oak and elm timbers from the portcullis windlass, Byward Tower, Tower of London.”

BIBLIOGRAPHY

Arnold, A. and R. Howard. *Tree-ring analysis of timbers from Treludick House, Egloskerry, Cornwall*. English Heritage Research Department Report 63/2007, 2007

Arnold, A., R. Howard, C. Tyers, P. Marshall, S. Bollhalder, C. Bronk Ramsey, M. Dee, E. Dunbar, S. Palstra, and L. Wacker. *Girlington Hall Farmhouse, Ovington, County Durham: tree-ring analysis of oak and elm timbers and radiocarbon wiggle-matching of elm timbers*. English Heritage Research Department Report 79/2019, 2019.

Arnold, A., R. Howard and C. Tyers. *The Charterhouse, Priory of St Anne, London Road, Coventry, Warwickshire: tree-ring analysis of oak and elm timbers*. Historic England Research Report Series: forthcoming.

Brett, D. "Dendroclimatology of Elm in London." *Tree-Ring Bulletin* 38 (1978): 35-44.

Bridge, M. *The tree-ring dating of Ashdon Street Farmhouse, Ashdon, Essex*. Unpublished Oxford Dendrochronology Laboratory Report, 2015/03, 2015.

Bridge, M. *The Dendrochronological Investigation of 233-235 Thame Road, Warborough, Oxfordshire*. Unpublished Oxford Dendrochronology Laboratory Report 2015/09, 2015.

Bridge, M. C. and D. W. H. Miles. *Tree-Ring Analysis of Timbers from the Hall Roof, West Gateway, and Gates at Fulham Palace, London Borough of Hammersmith and Fulham*. Centre for Archaeology Report 79/2004, 2004.

Bridge, M., C. Tyers, A. Bayliss, S. Bollhadler, L. Wacker, N. Loader, D. McCarroll, D. Davies, G. Young and D. Miles. *Twilly Springs, Manor Lane, West Hendred, Oxfordshire: tree-ring analysis, radiocarbon wiggle matching, and oxygen isotope dendrochronology of elm and oak timbers*. Historic England Research Report Series 2019-97, 2019.

Bridge, M., C. Tyers, A. Bayliss, S. Bollhadler, M. Dee, S. Palstra and L. Wacker. *'Bitter and Twisted', 1 Middle Row, Chipping Norton, Oxfordshire: tree-ring analysis and radiocarbon wiggle-matching of elm timbers*. Historic England Research Report Series 2019-98, 2019.

Bridge, M., C. Tyers, A. Bayliss, M. Dee and S. Palstra. *11 King's Quay Street/11 St Austin's Lane, Harwich, Essex: tree-ring analysis and radiocarbon wiggle-matching of elm and oak timbers.* Historic England Research Report Series 2019-99, 2019.

Bridge, M., C. Tyers, A. Bayliss, S. Bollhadler, M. Dee, S. Palstra and L. Wacker. *Fulham Palace, Bishop's Avenue, London Borough of Hammersmith and Fulham: tree-ring analysis and radiocarbon wiggle matching of elm and oak timbers from the hall roof.* Historic England Research Report Series 2019-100, 2019.

Bridge, M. and C. Tyers. *Manor Farm Barn, 'The Wool Barn', The Green, Frampton on Severn, Gloucestershire: tree-ring analysis of further oak timbers, and elm timbers*. Historic England Research Report Series 2019-101, 2019.

Bridge, M. and C. Tyers. *College Barn, Mill Lane, Chalgrove, Oxfordshire: tree-ring analysis of elm timbers.* Historic England Research Report Series 2019-102, 2019.

Bridge, M. and C. Tyers. *Great Barn, Mill Lane, Chalgrove, Oxfordshire: tree-ring analysis of elm timbers*. Historic England Research Report Series 2019-103, 2019.

Bridge, M. and C. Tyers. *9 Market Street, Chipping Norton, Oxfordshire: tree-ring analysis of elm and oak timbers*. Historic England Research Report Series 2019-104, 2019.

Bridge, M. and C. Tyers. *The Packhorse, Old School Hill, South Stoke, Somerset: tree-ring analysis of elm and oak timbers*. Historic England Research Report Series 2019-105, 2019.

Bridge, M. and C. Tyers. *Falcon Hotel, Chapel Street, Stratford-upon-Avon, Warwickshire: tree-ring analysis of elm timbers*. Historic England Research Report Series 2019-106, 2019.

Bridge, M. and C. Tyers. *Manor Farm Barn, 'Bunyans Barn', Maydencroft, St Ippolyts, Hertfordshire: tree-ring analysis of elm*. Historic England Research Report Series 2019-107, 2019.

Bridge, M. and C. Tyers. *59 High Street, Ashwell, Hertfordshire: tree-ring analysis of elm and oak timbers*. Historic England Research Report Series 2019-108, 2019.

Bridge, M. and C. Tyers. *The Manor House, The Green, Frampton on Severn, Gloucestershire: tree-ring analysis of oak and elm timbers*. Historic England Research Report Series 2019-109, 2019.

Bridge, M. and C. Tyers. *Ye Olde Cruck House and De Lacy Hall, The Street, Frampton on Severn, Gloucestershire: tree-ring analysis of elm timbers*. Historic England Research Report Series 2019-110, 2019.

Bridge, M. and C. Tyers. *9 West Street, Chipping Norton, Oxfordshire: tree-ring dating of oak and elm timbers*. Historic England Research Report Series 2020-165, 2020.

Brunskill, R. W. *Timber Building in Britain.* London: Orion Publishing, 1985.

English Heritage, "Dendrochronology: Guidelines on producing and interpreting dendrochronological dates." (1998) London: English Heritage

Haddon-Reece, D., D. H. Miles and J. T. Munby. Tree-ring dates, *Vernacular Architecture* 20 (1989): 46-49.

Haddon-Reece, D., D. H. Miles and J. T. Munby. Tree-ring dates, *Vernacular Architecture* 21 (1990): 46-50.

Hurst, J. D. (ed) '*A multi-period salt production site at Droitwich: excavations at Upwich*' Council for British Archaeology Research Report, (1997): 107.

Loader, N., D. Miles, D. McCarroll, G. Young, D. Davies, C. Bronk Ramsey and G. James, "Oxygen isotope dating of oak and elm timbers from the portcullis windlass, Byward Tower, Tower of London." *Journal of Archaeological Science* (2020): doi.org/10.1016/j.jas.2020.105103

McCarroll, D. and N. J. Loader. "Stable isotopes in tree rings." *Quaternary Science Reviews* (2004): 23, 771–801. doi.org/10.1016/j.quascirev.2003.06.017.

Miles, D., M. Bridge and C. Tyers. *Manor House, Paper Mill Lane, South Moreton, Oxfordshire: tree-ring analysis of timbers*. Historic England Research Report Series 2019-112, 2019

Rackham, O. *Trees and Woodland in the British Landscape*. London: Orion, 1976.

Rackham, O. *Ancient Woodland.* London: Edward Arnold, 1980.

Rackham, O. *The Woods of South-East Essex*. Rochford: Rochford District Council, 1986.

Reimer, P., W. Austin, E. Bard, A. Bayliss, P. Blackwell, C. Bronk Ramsey, M. Butzin, H. Cheng, R. Edwards, M. Friedrich *et al*, "The IntCal20 Northern Hemispheric radiocarbon calibration curve (0–55 kcal BP)." *Radiocarbon*, (2020) 62.

Richens, R. H. *Elm.* Cambridge: Cambridge University Press, 1983.

Stenning, D. F. "Small Aisled Halls in Essex", *Vernacular Architecture* 34 (2003): 1-19.

APPENDIX 1

List of the buildings assessed as part of this project set out geographically:

COUNTY	TOWN/VILLAGE	BUILDING	Sampled (Y/N)
ESSEX	Harwich	11King's Quay St/11 St Austin's Lane	Y
	Little Braxted	'kitchen' at Little Braxted Hall	N
GLOUCESTERSHIRE	Frampton on Severn	De Lacy Cottage, The Street	N
		De Lacy cruck (Ye Olde Cruck House)	Y
		Falfield Cottage, The Street	N
		Frampton Manor (including flat), The Green	Y
		Manor Farm Barn 'Wool Barn', The Green	Y
		Red House, The Green	N
		The Laurels, The Street	N
		Oegrove Farmhouse, The Street	N
		Wildgoose Cottage, The Street	N
	Frocester	34 Bath Road	N
	Minsterworth	Lyn Paddock, Church Lane	N
		Minsterworth Court, Church Lane	N
	Sandhurst	Singleton Cottage, Mussell End	N
HERTFORDSHIRE	Ashwell	59 & 60 High Street	Y
	St Ippolyts	Manor Farm Barn, 'Bunyan's Barn', Maydencroft	Y
LONDON	Hammersmith and Fulham	Great Hall Roof, Fulham Palace	Y
OXFORDSHIRE	Aston Upthorpe	Old Church Barn, Thorpe Street	N
	Benson	10 High Street	N
		28 High street	N
		9 Castle Street	N
	Blewbury	Cotterills, London Road	N
		Chapmans, Watery Lane	N
		Laurences, Nottingham Fee	N
		Stocks, Chapel Lane	N
	Carterton	St Joseph's RC Church	
	Chalgrove	Chalgrove Manor, Mill Lane	N
		Chalgrove Mill, Mill Lane	N
		College Barn, Mill Lane	Y
		Great Barn, Mill Lane	Y
		Little Barn, Mill Lane	N
	Charlbury	The Thatched Cottage, The Slade	N
	Chipping Norton	9 Market Street	Y
		'Bitter and Twisted' 1 Middle Row	Y
		Corner Chase, Middle Row	N
		32 Spring Street	N
	Cuxham	Brook Cottage	N
		College Farmhouse	N
		Old Rectory Cottage	N
		The Thatch	N
	Great Haseley	Crown House, Thame Road	N

		8 Mill Lane	N
		The Crucks, Rectory Road	N
		Walnut Tree Cottage, Mill Lane	N
	Little Haseley	Beehive Cottage	N
	Nettlebed	23 High Street	N
		8 Watlington Street	N
	Thame	The Bird Cage, High Street	N
	Warborough	Ash Cottage, 119 Thame Road	N
		139 Thame Road	N
		Lavender Cottage, 31 The Green North	N
	West Hagbourne	Wycherts, Main Street	N
	West Hendred	Twilly Springs House, Manor Lane	Y
SOMERSET	South Stoke	The Packhorse Inn, Old School Hill	Y
SUFFOLK	Debenham	6 Aspall Road	N
		8 Aspall Road	N
		12 Aspall Raod	N
		50 Aspall Raod	N
		4 Cross Green	N
		9 Cross Green	N
		37 Gracechurch Street	N
		44 Gracechurch Street	N
		9 High Street	N
		74 High Street	N
WARWICKSHIRE	Clifford Chambers	Clifford Cottage	N
	Stratford-upon-Avon	Falcon Inn, Chapel Street	Y
Buildings at the Weald and Downland Museum, West Sussex		Building from North Cray	N
		Poplars	N
		Sole Street	N
		Whittakers	N

Appendix 2: Table showing the sites reported in the HE Elm Project along with some earlier sites with derived dates from various methods. ^{14}C dates are modelled *cal AD* at the 95% level. VA = Vernacular Architecture, ODL = Oxford Dendrochronology Laboratory Report, CfA = Centre for Archaeology Report, RRS = Historic England Research Report Series, RDR = English Heritage Research Department Report, JArchSci = Journal of Archaeological Science paper.

Name of Site	Dendro Dates of Oak	Dendro date of elm	^{14}C date of elm	^{18}O date of elm	Short report reference
Sites investigated prior to the Historic England project					
Upwich, Cheshire	1745	1745	-	-	Hurst 1997
Nuffield, Oxon	1600–1603	1632			VA 1989
Mapledurham, Oxon	1334	1334			VA 1990
Ashdon St Farmhouse, Essex (Hall and Service)	1446	1446 &1447	-	1446	ODL 2015/03
Barn at Pendock, Gloucs.	-	-	-	?	unpublished
Warborough, Oxon	-	-	-	-	ODL 2015/09
Sites investigated during the Historic England project					
Fulham Palace, London	1493	1480?	*1485–94*	-	CfA 79/2004; RRS 2019-100
Harwich, Essex	-	-	*1425–36*	-	RRS 2019-99
Manor House, Frampton on Severn, Gloucs	1547	-	-	-	RRS 2019-109
Wool Barn, Frampton on Severn, Gloucs	1563/64	-	-	-	RRS 2019-101
Ye Olde Cruck House, Frampton on Severn, Gloucs	-	-	-	-	RRS 2019-110
Bunyans Barn, Herts	-	-	-	-	RRS 2019-107
59 High St, Ashwell, Herts	*c*1460	-	-	-	RRS 2019-108
Twilly Springs House, West Hendred, Oxon	1807		*1801–08*	1806/7	RRS 2019-97
9 Market St, CN, Oxon	-	-	-	-	RRS 2019-104
1 Middle Row, CN, Oxon	-	1519?	*1669–76*		RRS 2019-98
College Barn, Chalgrove, Oxon	-	-	-	-	RRS 2019-102
Great Barn, Chalgrove, Oxon	-	-	-	-	RRS 2019-103
South Moreton Mnr, Oxon	1315; 1398; 1631	-	-	-	RRS 2019-112
Packhorse Inn, South Stoke, Somerset	1633/34	-	-	-	RRS 2019-105
Falcon Hotel, Stratford-upon-Avon, Warwicks	Other ranges 1622	-	-	-	RRS 2019-106
Girlington Hall, Co Durham	1436; 1439/40; 1579; 1594–1616	-	*c 1700*	-	RRS 2019-79
Treludick House, Cornwall	Various in range 1623–48	-	-	-	RDR 63/2007
Charterhouse, Coventry, Warwicks	1450–75; early 1560s				RRS forthcoming
Site investigated outside the Historic England project					
Windlass, Tower of London	-	-	-	After 1648	JArchSci 2020

Figure captions

Figure 1. Map showing elm sites discussed in this paper

Figure 2. Photographs of two elm samples, both of which retain complete sapwood (the lower sample having bark present), but there is no clear distinction of sapwood and heartwood. Note also the sudden decline in growth rate in both samples towards the outer (right hand) end.

Figure 3. Two ring-width series from College Barn, Chalgrove, Oxfordshire. The y-axis is ring width (mm) on a logarithmic scale which helps to visualise the variation. Both show great year-to-year variations in growth rate, sometimes with a very wide ring immediately following a very narrow ring.