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Dating of non-oak species in the United Kingdom historical buildings archive using stable oxygen isotopes

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ABSTRACT

Stable oxygen isotope dendrochronology is an effective precision-dating method for fast grown, invariant (complacent) tree-rings and for trees growing in moist, temperate climatic regions where growth may not be strongly controlled by climate. The method works because trees preserve a strong common isotopic signal, from summer precipitation, and therefore do not need to be physiologically stressed to record a dating signal. This study explores the working hypothesis that whilst tree species may differ in their eco-physiology, leaf morphology and wood anatomy they will record an isotopic signal in their growth rings that is sufficiently similar to enable their precise dating against isotopic reference chronologies developed using dated oak tree rings from the same region. Modern and historical samples from six species (sweet chestnut, English elm, ash, alder, European beech and black poplar) were analysed and their oxygen isotopic variability was compared against an oak master chronology previously developed for central southern England. Whilst differences in the relative strength of the agreement between the different species and the master chronology are apparent, the potential for interspecies dating is demonstrated convincingly. The ability to date non-oak species using stable oxygen isotopes opens-up new opportunities for science-based archaeology and will improve understanding of a largely-unexplored, but significant part of the European historical buildings archive.

1. Introduction

Across the United Kingdom, Ireland and large areas of continental Europe, oak (*Quercus petraea/Q. robur*) is the dominant species used in the construction of historic buildings. The longevity of oak, the reliability of annual ring formation, its resistance to decay and relative abundance throughout the Common Era and late pre-history has enabled the development of ring-width chronologies covering decades to millennia (Hollstein, 1980; Pilcher et al., 1984; Brown et al., 1986; Baillie, 1990; Crone and Mills, 2002; Friedrich et al., 2004; Wilson et al., 2013). Where suitable sample material is available, these reference chronologies have been successfully applied to precisely-date historic timbers and wooden artefacts by ring-width dendrochronology (Historic England 1988, Baillie, 1990, Čufar, 2007; Haneca et al., 2009). Furthermore, the abundance and wide spatial distribution of oak timbers throughout much of the last millennium has enabled networks of chronologies to be developed that allow, through spatial correlation, an exploration of the trade, transportation and geographic origin of construction timbers; a process termed dendro provenancing (Bridge, 2000, 2012; Wazny, 2002; Domínguez-Delmás et al., 2013).

In addition to oak, secondary species may occur sporadically in the historic building archive. These typically include material from the genera *Castanea* (chestnut), *Pinus* (pine), *Populus* (poplar), *Alnus* (alder), *Ulmus* (elm), *Fraxinus* (ash) and *Fagus* (beech). Some of these secondary species cluster in time or geographically within the historical record. Whilst for others, their targeted use may reflect preferences in local building style, advantageous timber properties, socio-economic constraints or material availability through time.

In regions of central continental Europe where the range of species used for building timbers is both more diverse and more abundant, some exceptional, non-oak, historic chronologies have been developed (Heussner, 2018, Pers. Comm) which permit ring-width dating of less-common species across this region. In Britain, Ireland and parts of northwest maritime Europe where oak is the dominant construction

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timber, few such long chronologies for secondary species exist (Groves and Hillam, 1988). The presence of non-oak timbers therefore represents a significant problem for dendrochronologists as non-oak master chronologies of sufficient length, replication and geographic coverage are rare, making secure dating difficult. As a consequence, structures or sites comprising a large proportion of non-oak material may simply not be sampled due to commercial constraints or the high risk of failure when dating between species. The result is that a significant and important part of the UK and NW European historic buildings archive remains largely unstudied and only partially understood.

In an attempt to provide chronology for less-represented species across this region, a small number of UK and Irish studies have reported successful inter-species dating by ring-width dendrochronology. Results are often considered indicative or tentative because the species-specific chronologies required for more conclusive dendro-dating are simply not available (Historic England, 1998). Reported successful dating of secondary species has typically been obtained by cross-matching against oak (or local reference) timbers from the same location or construction phase within a building (Haddon-Reece et al., 1989, 1990,Groves, 1997; Hillam et al., 1990; Čufar, 2007; Čufar et al., 2008; Billamboz, 2008; Daly, 1998). In some cases inter-species dating has been supported through wiggle-match radiocarbon dating (Bridge et al., 2019), or confirmed using Miyake events (Barrett et al., 2019).

Field studies conducted on living trees have also provided evidence for inter-species coherence. Jarman et al. (2018) were able to demonstrate cross dating between chestnut and oak in southern England, whilst García-Suárez et al. (2009) compared six species growing at the same site in the north of Ireland. They reported significant differences in tree response related to climate that would make secure inter-species dating difficult, but identified potential for combining species to strengthen environmental signals. Crone and Mills (2002) highlighted the importance of inter-species dating, especially for areas of northern Britain (Scotland) where many structures are constructed from pine.

A recently developed dating technique using stable isotopes has demonstrated the potential for dating short, complacent (invariant) or disturbed ring-width sequences of oak from across the United Kingdom (Loader et al., 2019a). The technique is based upon the measurement of stable oxygen isotope ratios in the latewood cellulose of oak tree rings and their objective comparison against a reference oxygen isotope chronology of known age. The method has already been used to date timbers that failed to date by ring-width dendrochronology or were previously considered unsuitable for tree-ring dating (McCarroll et al., 2019).

The inter-annual signal in latewood oxygen isotopes used for dating primarily reflects changes in the oxygen isotope ratios of the precipitation sampled by the tree during the (summer) growing season (Darling and Talbot, 2003; Danis et al., 2006; Labuhn et al., 2013; Treydte et al., 2014; Young et al., 2015; Loader et al., 2020a). Trees do not need to be physiologically stressed to record an isotopic dating signal. This means that the isotope dating method will work even where trees are fast growing and exhibit complacent (invariant) ring width patterns. Such fast growing wide-ringed oak timbers are common across much of NW Europe, particularly in the vernacular structures of everyday life.

Mechanistic models for isotope fractionation indicate that where trees share a common water source and grow together in the same environment, they will record a similar isotopic signal in their rings (Roden et al., 2000, 2000). Differences in phenology, leaf morphology, wood anatomy, rooting depth, physiology and climate response will however modify the isotopic signal preserved in the cellulose of a tree ring (McCarroll and Loader, 2004). Where these factors are sufficiently similar between species the resulting tree-ring chemistry should exhibit a high degree of inter-annual isotopic coherence and it should be possible to precisely-date non-oak timbers using a dated oak oxygen isotopic reference chronology.

The ability to date secondary (non-oak) species in this way would represent an advance for dendrochronology across the UK and similar climatic regions. It would provide a means for independent inter-species dating, and support for existing inter-species dates or in situations where inter-species ring-width dating is tentative and bespoke species-specific chronologies are not yet available.

Isotopic coherence between species is relatively well-established and has primarily been described and discussed within the plant physiological/palaeoclimatological literature (for example: Hemming et al., 1998; Li et al., 2015; Zhang et al., 2018; Ponton et al., 2001; Saurer et al., 2008; Fu et al., 2017; Tsuji et al., 2006; Treydte et al., 2007). Daux et al. (2018) concluded that inter-species coherence was not always strong enough to enable their direct combination for dendroclimatology. The degree to which a common (dating) signal is preserved in tree genera remains largely unexplored. Recent studies in Japan have also demonstrated strong inter-species coherence for chronology and climate research (Yamada et al., 2018; Sakamoto et al., 2017; Nakatsuka et al., 2004, 2020; Li et al., 2015).

This paper explores inter-species isotope coherence with a specific focus on its application for the isotopic dating of non-oak species commonly found in the structures, artefacts and historic timber buildings of NW Europe. Samples of living and historic wood of known and unknown age are compared against the south-central UK oak reference chronology and their coherence and dating potential assessed against the reference isotope chronology.

2. Materials and method

Samples from six non-oak species (alder, ash, beech, black poplar, chestnut, elm) were selected for this study. Samples were collected from living trees and from historic timber samples from across the south and west United Kingdom (Table 1, Fig. 1).

Annual rings were removed manually as thin slivers (c. 40 μm thick) using a scalpel under magnification. For the ring-porous species (ash, elm, chestnut) latewood was sampled. It was assumed that as observed in oak, the earlywood will incorporate stored photosynthates (Switsur et al., 1995; Kimak and Leuenberger 2015; McCarroll et al., 2017). For the diffuse porous species (alder, beech and black poplar) the whole ring was sampled (Fig. 2). All samples were chemically treated to α-cellulose using an acidified sodium chlorite solution (Loader et al., 1997). Samples were homogenised and freeze-dried (−40°C 48 h 1 Pa), then 0.30−0.35 mg weighed into silver foil capsules for stable isotope analysis. Samples were pyrolised at 1400°C over glassy carbon and analysis of the resulting carbon monoxide gas conducted using a Flash HT elemental analyser and Delta V isotope ratio mass spectrometer. Results are reported using the delta notation relative to the VSMOW standard. Typical analytical precision is better than 0.3 per mille ($n = 10$) on replicate analysis of cellulose (Loader et al., 2015).

2.1. Isotope dendrochronology

The isotope dendrochronology method is outlined here and detailed in Loader et al. (2019a) (available with open access online).

Dating was carried out by a step-wise comparison of the filtered sample isotope series (indices) against all possible positions of full overlap on the filtered master chronology. Pearson's correlation coefficients were calculated at each position with degrees of freedom adjusted for autocorrelation and the effect of the filter. The resulting *t*-values, which are more conservative (lower) than the Baillie-Pilcher *t*-values normally reported for ring widths (Baillie and Pilcher, 1973), conform to Student's *t*-distribution, allowing them to be converted into one-tailed probabilities.

Probabilities calculated directly from Student's *t*-distribution are based upon the assumption that only one single correlation coefficient has been calculated. Dendrochronology relies upon multiple comparisons as the sample is compared with all possible positions on the reference series so probabilities need to be adjusted for multiple testing using a "Bonferroni correction" (McCarroll, 2016; Dunn, 1959, 1961). Using this methodology, the probability of the chance occurrence of an

Table 1
Species and location details of the samples tested, with results obtained from the oxygen isotope dating of the six common secondary species against the oak stable isotope chronology for south central England. Match statistics are presented for individual and mean series (after Loader et al., 2019a).

Sample / Species	N_i	Pearson's r	Student's *t*	df	1/p	IF	End Date	Result	Notes
Fraxinus sp.	67	0.591	5.5	56	2565	255	2016	Pass	Fineshades Forest, Bedfordshire. Increment core from living tree.
C. sativa 1	57	0.617	5.4	48	1479	651	2005	Pass	Crowthorne Woods, Berkshire. Increment core from living tree.
C. sativa 2	83	0.752	9.6	71	>1Million	>1000	2011	Pass	Crowthorne Woods, Berkshire. Increment core from living tree.
C. sativa 3	74	0.612	6.0	61	>27k	>1000	2015	Pass	Crowthorne Woods, Berkshire. Increment core from living tree.
C. sativa x	90	0.758	10.2	77	>1Million	>1000	2015	Pass	Crowthorne Woods, Berkshire. Mean of 3 increment cores.
Ulmus sp. 1	83	0.612	6.5	71	>315k	>1000	1802	Pass	West Hendred, Oxfordshire. Building timber.
Ulmus sp. 2	79	0.545	5.3	67	2139	513	1792	Pass	West Hendred, Oxfordshire. Building timber.
Ulmus sp. x	90	0.620	6.9	76	>1Million	>1000	1802	Pass	West Hendred, Oxfordshire. Building timber. Mean of 2 timbers.
F. sylvatica 1	100	0.565	6.3	84	>197k	>1000	2010	Pass	Mapledurham, Oxfordshire. Slice from dead tree.
F. sylvatica 2	60	0.722	7.0	45	>270k	>1000	1804	Pass	Mapledurham, Oxfordshire. Building timber.
A. glutinosa 1	49	0.582	4.5	40	50	11	2016	Fail*	Clyne Valley, Swansea, Wales. Increment core from living tree.
A. glutinosa 2	48	0.480	3.5	40	2	2	2016	Fail*	Clyne Valley, Swansea, Wales. Increment core from living tree.
A. glutinosa x	49	0.600	4.8	41	124	28	2016	Pass	Clyne Valley, Swansea, Wales. Mean of 2 increment cores.
P. nigra 1	74	0.524	4.9	63	361	114	1375	Pass	Cuppernham, Hampshire. Building timber.
P. nigra 2	51	0.723	6.9	43	>130k	>1000	1352	Pass	Cuppernham, Hampshire. Building timber.
P. nigra x	74	0.613	6.2	63	>48k	>1000	1375	Pass	Cuppernham, Hampshire. Mean of 2 timbers.

N_i, Number of isotope measurements; df, degrees of freedom adjusted for filtering and autocorrelation, 1/p, the probability of error (how likely it is that an equivalent match could occur by chance in the wrong position); IF, Isolation Factor (a measure of the uniqueness of the match); PASS/FAIL, Denotes whether the sample date passes the objective criteria for consideration proposed by Loader et al. (2019a); FAIL*,Denotes that the correct end date is returned, but that match statistics are too weak to PASS the objective criteria.

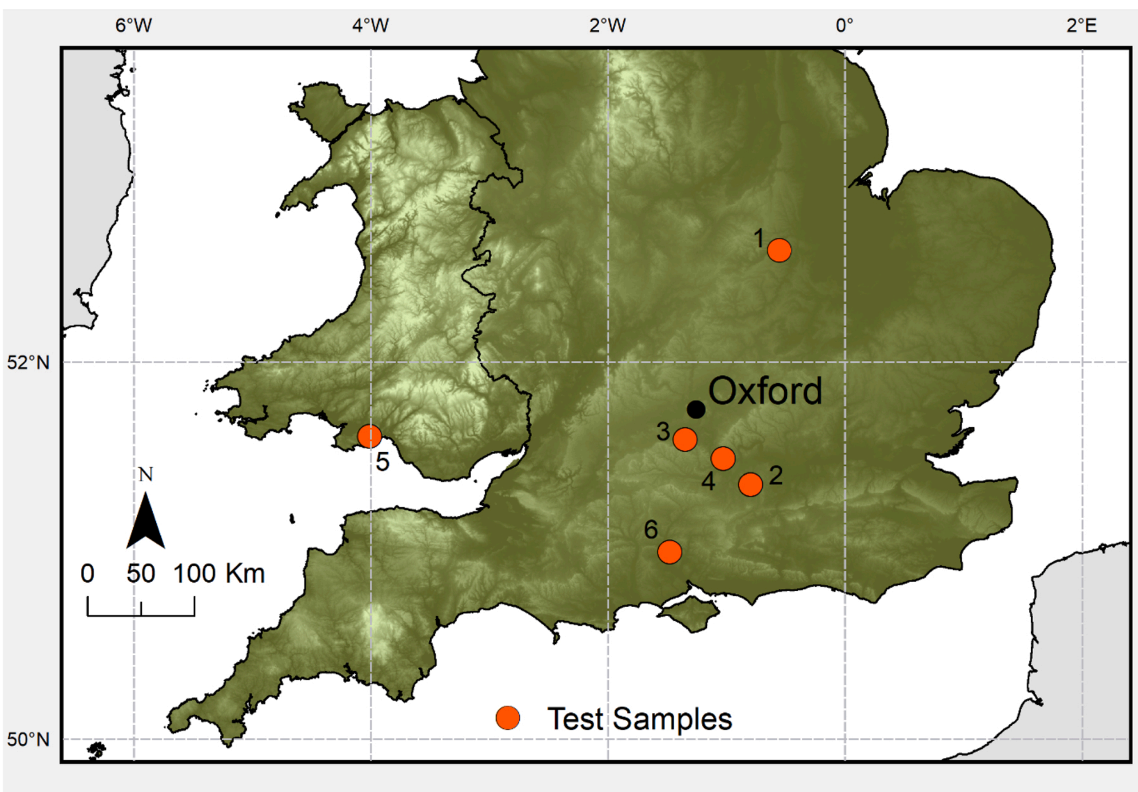

Fig. 1. The location of the samples analysed in this study (red circles). 1. Fineshades (ash); 2. Crowthorne (chestnut); 3. West Hendred (elm); 4. Mapledurham (beech); 5. Clyne (alder); 6. Cuppernham (black poplar). The south central England isotope chronology used as a reference chronology in this study contains samples sourced from across a *c.* 33 600-km^2 area roughly centred on Oxfordshire.

r-value as high as that recorded at any position of full overlap on the master chronology can be calculated. It is this probability that is used to identify the position of best match.

In ring-width dendrochronology the decision on whether to accept or reject a date requires expert judgement. Loader et al. (2019a) proposed critical thresholds for assessing dates, below which potential dates are rejected. First, the Bonferroni-corrected probability should be at least one in one hundred ($1/p \geq 100$) and second, the corrected probability for the strongest match should be at least an order of magnitude greater than that of the next highest match. This "Isolation Factor", a ratio of the best to next best probability, provides a very useful measure of the uniqueness of the match ($IF \geq 10$). These criteria are similar to those proposed by Wigley et al. (1987), but applied more stringently.

Isotope timeseries were dated against the Loader et al. (2019a) oxygen isotope master series (1200−2000CE), however, to accommodate modern cores that were sampled more recently and post-date the end of

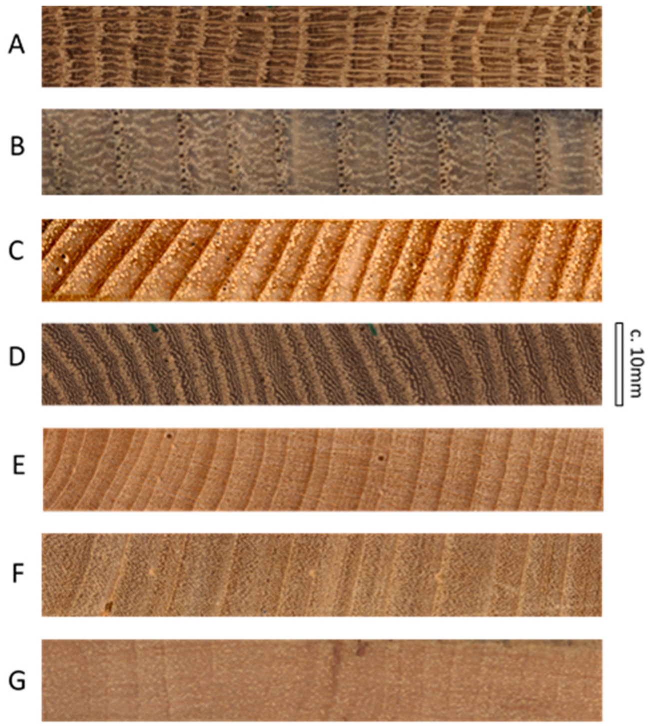

Fig. 2. Test species investigated in this study: A, oak; B, chestnut; C, ash; D, elm; E, beech; F, black poplar; G, alder. Details of timber origin and sample location are listed in Table 1.

the published master chronology, the chronology was extended using living trees from the region to enable a more meaningful comparison and calculation of match statistics from these relatively short contemporary series.

3. Results and discussion

Results from the dating comparisons for each species are summarised in Table 1. Where multiple samples of the same species have been analysed, dating results for both the individual and mean series are presented. Information on the strength of the match between the filtered sample and reference series (indices) as well as the probability (1/p) and isolation factor (IF) are also reported.

As a general guide, samples that do not pass the objective criteria are considered not to date. For those that pass these thresholds, the isotope date is expressed as a Student's *t* value with an associated probability (reported up to $1/p > 1$ Million). This is the probability of achieving a match of equivalent magnitude in error. The Isolation Factor (IF), is a measure of the uniqueness of match (reported up to $IF > 1000$), and represents the ratio of the probability (1/p) of the best match to the next highest value.

Adopting the objective thresholds proposed by Loader et al. (2019a) for this study facilitates comparison between sites, samples and species. Further examples of isotope dating from oak series across the study region (reported in McCarroll et al., 2019; Loader et al., 2019a, b, 2020c, 2021) may be used to place these results within the context of a diverse assemblage of isotopically-dated oak timbers.

3.1. Chestnut (Castanea sativa)

Three modern isotope records were developed covering a combined period of 90 years (1926–2015CE). The three individual series date successfully against the oak master chronology with the correct (year sampled) end date, confirming a high similarity in signal preservation between this species and UK oaks. The individual series also cross-correlate with one another returning an expressed population signal of 0.83 (rbar = 0.62, 3 trees). The signal is further enhanced when the three sequences are combined into a single site chronology. This approach is common practice in ring-width dendrochronology once inter-sample matching is assured (Historic England, 1998). The strength of the match of individual series against the reference chronology is similar to that observed in oak samples from across the region.

This result is not entirely unexpected. Jarman et al. (2018) found that it was possible to cross-date chestnut (Baillie-Pilcher *t* value >3.5) in the UK to develop a ring-width chronology for this species, which could then be dated against oak tree ring series. The very similar wood anatomy of chestnut and oak (both ring porous) may also contribute to the similarities observed. These findings indicate that where chestnut is found in the archaeological or historic building archive, stable isotopic analysis offers potential for dating. Unlike other parts of Europe, chestnut is only rarely found in historic buildings, and does not appear to have been a popular choice as a UK building timber (Wright, 2020).

3.2. Ash (Fraxinus excelsior)

Ash is highly prized for many specialist applications, but for building its durability does not compare with oak or elm. It is not likely to be found except, perhaps, occasionally for rafters and small internal parts of a building (Rackham, 2014). An exception to this is in limestone areas of the UK such as the Yorkshire Dales and some parts of Scotland, where soil chemistry favours ash over oak (Wright, 2020; Armstrong, 1998, Mills Pers. Comm.). Ash is more commonly reported as artefacts, such as tool handles and has been identified in early Neolithic trackways (Hillam et al., 1990; Hart et al., 2015).

The prevalence of ash die-back (Hymenoscyphus fraxineus) in the UK precluded collection of multiple cores from this species. However the successful dating of a 67-year isotopic record against the oak reference chronology (Table 1) confirms a similarity in isotopic response that may be useful for dating. Ash is ring porous and like the chestnut exhibits a broadly similar growth response to that of oak. Analysis of cambial dynamics and leaf phenology would however indicate subtle differences in the controls and timing of the growing season for oak and ash which may contribute to some of the differences observed (Sass-Klaassen et al., 2011).

3.3. Elm (Ulmus spp.)

Elm is of great interest in UK dendrochronology, due to its widespread occurrence and difficulty to precisely date. Elm trees were once abundant, and south of the Scottish border, elm is the principal secondary timber species. Elm is common in the historic buildings record, but its use, distribution and chronology remain poorly understood (Bridge, 2020). Elm is commonly found in historic buildings across England, but is also present in the keels of boats and wet environments such as piers, conduits and piping. Elm is the timber, after oak, that is most often found in vernacular buildings. Wych elm (*Ulmus glabra)* and English elm (*Ulmus procera*) timber is strong and durable, and when kept dry, or permanently wet, has good qualities as a constructional material. Its characteristically twisted grain makes it prone to warping, but resistant to cracking (Wright, 2020). In his 2020 review, which included results from a survey of c.70 buildings in England where elm was preserved, Bridge reported that by 2015 only four instances of dendro-dated elm were recorded, two of those involving a single timber. Since then only six elm timbers have been reported as precisely-dated by ring-width dendrochronology (Groves and Hillam, 1988; Haddon-Reece et al., 1989, 1990; Bridge and Miles, 2015). All but one of these studies involved matching elm with oak from the same site. This is in contrast to many tens of thousands of oak tree cores successfully dated by ring-width dendrochronology during the last c.40 years.

In this study, two samples of elm were analysed from Twilly Springs House, West Hendred, Oxfordshire. Both dated securely against the oak chronology (Table 1). This date strengthens further when the two series, which independently cross-date, are combined into a mean series of 90 rings. The successful independent dating of two samples of elm from Twilly Springs reported here forms part of multi-method study conducted at the site which included independent verification by wiggle-match radiocarbon dating and co-located oak ring-width dating (Bridge et al., 2019).

There is little doubt that development of an elm chronology for the UK would make a significant contribution to dendrochronology in this region. The two elm samples calendar dated from Twilly Springs together with additional elm samples from the Tower of London (Loader et al., 2020b) and Mill Farm, Mapledurham, Oxfordshire (unpublished), represent a small, but growing proof of concept for developing this approach for the more widespread dating of elm.

Unfortunately, the outbreak of Dutch Elm disease (*Ophiostoma novo-ulmi*) in the 1970's devastated the living English elm population making the development of modern chronologies virtually impossible and rendering dendrochronology of elm reliant upon matches with oak ring-width data. An exciting opportunity arising from these results is to use the stable isotope dated series to "anchor" elm ring-width series in time so that future elm sequences collected for ring-width dendrochronology or isotopic analysis can be compared against these using isotopes, and if successfully dated, added to the chronology providing a means for developing regional elm (ring-width and isotope) chronologies (Bridge et al., 2019).

3.4. Beech (Fagus sylvatica)

Beech is diffuse porous and differs from oak in its wood anatomy, growth preference and form, often favouring shallow well-drained soils. Beech has a shallow root system capable of sampling near-surface water from precipitation over deeper-sourced groundwater. Wright (2020) reports that beech has no natural resistance to decay and is unlikely to be found in exposed timbers, but that it may occur in the UK, in interior situations, particularly where the timber was common in the wild. The known-age sample from a recently felled 175 year-old tree from Mapledurham House (100 rings measured isotopically) dates well (Table 1), confirming that this tree species preserves in its rings a signal sufficiently similar to oak latewood to enable dating. Although not often found in the UK building record, being rare outside southern England prior to the nineteenth century, beech is often found in household items (e.g. rolling pins, spoons) and furniture. It is more common as a construction timber across continental Europe (Čufar et al., 2014). A second sample of beech comprising 60 rings from a mantel beam in Well Cottage, Mapledurham, Oxfordshire also dates securely using the isotope approach (Table 1). This sample could not be dated using ring-widths.

3.5. Black poplar (Populus nigra)

Black poplar is not common in the historic buildings archive but was believed to once have been common in the English landscape. Examples of poplar in cruck frames have been recorded in a cottage at Cuppernham, Hampshire, as well as in Avon, Herefordshire and Worcestershire (Harris, 1974; Wright, 2020). Two samples of black poplar from the cruck frame at Cuppernham, comprising 81 and 73 rings were processed for isotope dating. Both samples had bark edge present. The samples exhibited some eccentricity in the annual growth rings and juvenile (near pith) growth, there was also some discolouration of the rings at the end of the longer core, which were not processed. The isotopic dating results based upon 74 and 51 isotope measurements confirmed a common isotopic pattern between the two poplar samples ($t = 7.86$).

Having dated both series independently, and with firm between-series alignment, the two series were combined into a mean series (74 rings). The combined series returned a date of 1375CE. This date is the same as a tentative match obtained by ring-width dating of the cruck blades against local oak ring-width chronologies and serves to demonstrate how isotopic dating may be used to independently-support inter-species dating.

3.6. Alder (Alnus glutinosa)

Alder is a relatively short-lived tree and grows frequently in wet and near-waterlogged conditions. Alder is found often as short segments in wet environments such as crannogs and trackways which can be very challenging to date dendrochronologically (Crone, 2014; Hillam et al., 1990; Hart et al., 2015; Barrett et al., 2019). Alder is also found as small roundwood or the product of coppicing, where timbers are often used as whole trunks with bark left on for rafters or studs in more primitive buildings (Wright, 2020). Two living trees from the Clyne Valley, Swansea UK, were sampled as part of a student project. The site is located in the west of the UK, outside the source region of the reference chronology. Both trees failed to date independently, but did return their best match at the correct (sampling) date (Table 1). When combined, the mean series passed the objective criteria, although the strength of the date remained relatively low. This probably reflects the westerly location and the growth preference of this species towards wet and waterlogged environments. In such conditions a year to year summer precipitation signal may be more muted than in more freely drained locations. This result offers some encouragement for the development of site chronologies from relatively short-lived alder samples.

4. Conclusions and future scope

Oxygen isotope dating has successfully been applied to non-oak species in the UK and has been shown to provide an additional tool for developing chronology and supporting ring-width dendrochronology where tentative associations may previously have been identified. The method works because the water sampled by the tree during photosynthesis and its resulting signal in tree-ring cellulose, is broadly similar to that of the oak trees used to develop the reference chronology.

In this study, samples of chestnut, ash, elm, alder, beech and poplar all dated with differing levels of success against the master chronology. The variability observed, most likely reflects physical differences and micro-environment as well as location relative to the chronology. Comparison of the relationship both within and between species identifies the potential for cross-matching, and potentially combining non-oak species to facilitate dating where agreement is strong, unambiguous, and supported by context. Some of the comparisons made between cores of the same species were at least equivalent in *t*-value to those obtained when cross-dating oak timbers. As in ring-width dendrochronology, there is a significant benefit to be gained by series replication and the development of site chronologies to support the dating process. This is particularly so when working with a mix of species.

Of special interest to the UK dendrochronological community is the ability to isotopically date samples of elm. In the absence of established, region-specific well-replicated elm chronologies the isotope approach appears capable of dating this species to a standard equivalent to that of oak. This does not mean that all elm samples will date. Abrupt growth decreases in ring-width, which may reflect defoliation or woodland management (e.g. pollarding) appear common in many of elm samples and these, along with local environmental factors, could have an impact upon dating success.

Work is ongoing to further investigate and to develop the wider application of stable isotope dating of non-oak species. Although at an early-stage, this study demonstrates significant potential. Where in the past a dendrochronologist conducting an assessment of the dating potential of a building might reject it as unsuitable based upon the presence of fast-grown invariant oak or non-oak timber, it is now possible that in both cases, stable isotope dendrochronology may be able to provide support for ring-width dendrochronology and a solution to these problems.

Declaration of Competing Interest

The authors declare no conflict of interest.

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