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Tree ring dating using oxygen isotopes: a master chronology for central England

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ABSTRACT: Ring-width dendrochronology, based on matching patterns of ring width variability, works best when trees are growing under significant environmental (climatic) stress. In the UK, and elsewhere in the temperate mid-latitudes, trees generally experience low stress, so dating is more difficult and often fails. Oxygen isotopes in tree rings passively record changes in the isotopic ratios of summer precipitation, so they carry a strong common signal, which offers potential for cross-dating. A master chronology covering the period 1200–2000 CE was constructed using the oxygen isotope ratios of the latewood cellulose of oak samples from central England. Two independent chronologies, developed to verify the isotopic signal, were combined ($n = 10$ trees) and the method was evaluated by dating timbers of known age and historical timbers that could not be dated by ring-width dendrochronology, from both within and beyond the central England region. The agreement between samples and the master chronology is exceptionally strong, allowing the dating of timbers with far fewer rings than is normally the case for ring-width dendrochronology. Tree-ring oxygen isotope values are more suited to correlation analysis than tree-ring widths, so it is possible to provide t-values that conform to Student's t-distribution and can be converted into probabilities of error. A protocol for assigning dates using 'stable-isotope dendrochronology' is proposed, which has the potential to revolutionize the dating of wooden structures and artefacts, allowing the dating of short and invariant ring sequences from young, fast-grown trees. Such samples are commonplace throughout the historical building and archaeological records and were, until now, considered impossible to date.
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Introduction

Dendrochronology, matching the annual growth pattern of tree-ring widths in a wood sample of unknown age with the patterns in samples of known age, is among the most precise dating methods in Quaternary research (Walker, 2013). It allows the growth of an individual tree ring to be assigned to a single calendar year and, where wood samples retain the bark-edge, it is possible to determine the season and the year in which the tree died, or was felled.

In the UK, Ireland and across continental Europe, dendrochronology is an established and reliable dating technique that is routinely used to date the timbers in historical buildings (Alcock, 2017), and wooden artefacts unearthed during archaeological excavations (Fletcher, 1978; Hillam *et al.*, 1990; Čufar, 2007; Haneca *et al.*, 2009; Nayling and Jones, 2014; Bonde and Stylegar, 2016). The dating procedure relies upon the multitude of regional and local ring-width chronologies that have been developed over many years (English Heritage, 1998; Alcock, 2017). The longest UK 'master chronology' based on the ring widths of many overlapping trees is the 'Irish Long Chronology' (Pilcher *et al.*, 1984; Brown *et al.*, 1986), covering the period 5289 BCE to 1981 CE and compiled by linking together living oak trees, building timbers and subfossil 'bog-oak' from Northern Ireland and elsewhere across the British Isles (Baillie, 1982, 1992).

Although ring-width dendrochronology has proven extremely useful, it has several limitations which mean that the technique is not always able to return a 'robust' date. Fast or unconstrained growth may result in 'complacent' (invariant) time-series that do not reliably cross-correlate and thus do not date dendrochronologically (Fig. 1). By contrast, some timbers can display abrupt changes in ring widths, typically due to disturbances such as disease, defoliation or forest management practices, including pollarding and thinning. Such patterns may render samples impossible to date using ring widths (English Heritage, 1998; Haneca *et al.*, 2009). For most trees across the British Isles (and those growing elsewhere in less climatically stressed regions), tree-ring width is not strongly influenced by climate (Kelly *et al.*, 2002; Loader *et al.*, 2008; García-Suárez *et al.*, 2009; Haneca *et al.*, 2009; Cooper *et al.*, 2013; Wilson *et al.*, 2013). For such regions, secure dating usually requires samples that have continuous sequences of at least 80 and often greater than 100 rings, which is more than is found in many timber structures and artefacts. Structures built from fast-grown timbers, with short invariant ring width sequences, are usually considered unsuitable for dendrochronology, so samples are rarely taken and their chronology remains unknown (English Heritage, 1998; Alcock, 2017; Bayliss *et al.*, 2017).

Furthermore, regional differences, both in the pattern of ring-width variations and in the strength of the common growth signal, make dating much more problematic in some locations than in others. Even in areas where dendrochronology works well, many structures cannot be dated because

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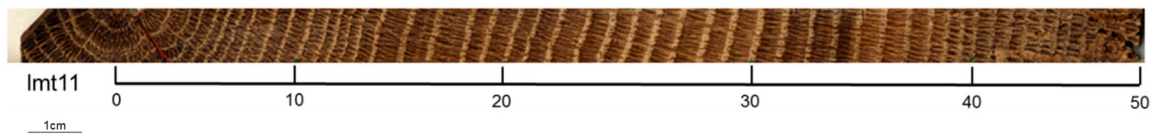E-mail: d.mccarroll@swansea.ac.uk

Figure 1. An example of a 'complacent' (largely invariant) sample core from Llwyn Celyn (lmt11), Monmouthshire, UK. This timber is fast growing, exhibits limited inter-annual variability and comprises only 50 rings. Considered not dateable using ring-width dendrochronology, the isotope results indicate the tree was felled in 1418 CE. [Color figure can be viewed at wileyonlinelibrary.com].

there may be no chronologies available for that region, species or period of time. In Radnorshire, for example, a Welsh county where ring-width dendrochronology is often successful, 60% of timber buildings either failed to date or were judged unsuitable and not sampled (Suggett, 2005).

Dendrochronological dates are based on correlation coefficients, and the strength of individual matches is normally reported as 't-values' (Baillie and Pilcher, 1973; Hollstein, 1980). These 't-values' do not actually conform to a Student's t-distribution, so it is not possible to furnish individual dates with statistically defined probabilities of error, or to meaningfully compare results based on large differences in the number of rings.

It has long been recognized that the stable (carbon, oxygen and hydrogen) isotope ratios of tree rings generally exhibit much stronger correlations between trees than is the case with ring widths (e.g. Robertson et al., 1997; McCarroll and Pawellek, 2001; Treydte et al., 2007; Saurer et al., 2008; Baker et al., 2015) and it has been noted several times that this might allow stable isotopes to be used for cross-dating, in a similar manner to ring-width-based dendrochronology (Leavitt et al. 1985). Loader and Switsur (1996) used carbon isotopes to date a growth disturbance event in Scots pines trees and Roden (2008) demonstrated that both oxygen and carbon isotopes could support dendrochronology by using the tree ring program COFECHA to explore correlation strength in living trees. Subsequent studies have further demonstrated strong inter-tree correlation or have utilized inter-tree isotopic coherence to support chronology-building in palaeoclimate reconstructions (Hangartner et al., 2012; Xu et al., 2013; Baker et al., 2015) with varying degrees of success. More recently, Yamada et al. (2018) were successful in cross-correlating oxygen isotopes from conifer samples buried by landslides in Japan with a chronology developed from long-lived trees of known age. Similarly, Rebenack et al. (2018) were able to cross-correlate living coastal sub-tropical trees and Sakamoto et al. (2017) used an isotopic approach in association with high-resolution radiocarbon dating to assign a date for samples recovered from a Japanese temple.

This paper describes the development and evaluation of the oxygen isotope dating method for the south central UK. The environmental and physiological controls on the oxygen isotopic signal in UK oak tree rings are outlined, followed by the process of developing the isotopic reference chronology. The statistical properties of the reference chronology are described within the context of the dating procedure and protocol for assigning an isotopic date with objectively defined probabilities of error. The method is then evaluated using samples of known age and samples for which a robust date cannot be obtained by ring-width dendrochronology. Finally, we explore the ability of the method for dating short (30–50-year) tree ring sequences and consider its wider potential.

Development and evaluation of the isotopic dating method

Oxygen isotopes in tree rings

The ratio of the stable (non-radioactive) isotope ^{18}O to the more common ^{16}O, expressed as per mil deviations relative to a standard (Vienna Standard Mean Ocean Water) using the delta notation ($\delta^{18}O‰$ VSMOW) is a common palaeoenvironmental proxy in Quaternary science (Coplen, 1995; Waelbroeck et al., 2002; Leng and Marshall, 2004; McDermott, 2004). When trees draw water through their roots, the isotopic signal of the source water, antecedent precipitation, is unaltered. Water is transferred, via the xylem, to the leaf, where it is subject to fractionation due to evaporation. There is a near constant biochemical fractionation during photosynthesis and sugar formation, followed by the potential for isotopic exchange with xylem water prior to wood synthesis; this exchange enhances the source water signal (Hill et al., 1995; Saurer et al., 2000; Waterhouse et al., 2013; Treydte et al., 2014).

In the UK the oxygen isotopic values of summer rainfall are strongly influenced by atmospheric circulation, with wet summers dominated by westerly air-flow and frontal rainfall resulting in much lower isotope values than dry anticyclonic dominated summers with more convective rainfall (Darling and Talbot, 2003; Dong et al., 2013; Young et al., 2015; Trouet et al., 2018). The more positive isotopic ratios of 'dry-summer' rainfall are potentially increased by evaporation in the leaf, where fractionation is largely a function of the vapour pressure difference inside and outside of the leaf, and therefore of air humidity (McCarroll and Loader, 2004). The oxygen isotopic record in the latewood cellulose of UK oaks thus reflects past changes in the isotopic signature of summer rainfall and in summer relative humidity, both of which are strongly correlated with the amount of summer rainfall.

Importantly, the trees passively record the isotopic signal of precipitation and unlike tree ring-width dating, there is no requirement for trees to be growing under any environmental stress to record a strong common isotopic signal. Indeed, trees that are growing under near optimal conditions, and thus are likely to produce very complacent ring-width sequences, are likely to record the isotope signals most closely related to that of precipitation. The strong common climate signal in oxygen isotope ratios of UK oaks, which has been shown in the UK to faithfully preserve both high- and low-frequency (decadal and greater) variability without prolonged juvenile or age-related trends, appears to be as strong as that in conifers growing under extreme environmental stress at the northern timberline of Europe (Young et al., 2015; Duffy et al., 2017, 2019).

Master chronology construction

To produce a continuous master chronology spanning 1200–2000 CE, precisely dated (by ring-width dendrochronology) living oak [Quercus robur L., Q. petraea (Matt.) Liebl.] and oak (Q. spp.) building timber samples, sourced principally through the Oxford Dendrochronology Laboratory archive, were used. The southern central England region was selected for this investigation, because the area has been demonstrated to have a very strong climate-sensitive common signal, preserved within oak tree ring stable isotopes (Young et al., 2012a, 2015). It is also a region where there are both abundant dated timbers for construction of a master chronology and a growing need for new approaches to science-based dating of historical buildings, which have proved undateable by

ring-width dendrochronology. For each calendar year the rings of ten individual samples were drawn from across the central England region (a *c.* 33 600-km^2 area centred *c.* 51.488°N, −1.035°E) (Fig. 2). Samples were of known origin or cross-dated against local chronologies to confirm provenance.

The early- or spring-wood of each ring was removed, as in oak this is formed prior to bud burst and comprises photosynthate from previous years (Switsur *et al.*, 1995; Richardson *et al.*, 2013; Kimak and Leuenberger, 2015; McCarroll *et al.*, 2017). The late- or summer-wood for each year, which carries a clearer annual isotopic signal, was then manually subdivided as fine slivers (*c.* 40 μm thick), under magnification using a scalpel. In this case, resource constraints precluded the analysis of individual series to construct the isotopic reference chronology, and consequently samples were combined to develop two independent parallel pools, with the sample for each year containing wood from five different trees. Pooling is an established approach in isotopic dendroclimatology and has been demonstrated to yield comparable results to the analysis and combination of single timbers (e.g. Loader *et al.*, 2013). To reduce the risk of local signals which could dominate the master chronology or influence dating success, samples of dendrochronologically dated wood were sampled from across the study region, as evenly as possible, for each year of the chronology.

The pooled samples were purified to α-cellulose using standard methods (Loader *et al.*, 1997), homogenized and then freeze dried for 48 h at −50°C and <50 mbar. Between 0.30 and 0.35 mg of α-cellulose was weighed into silver capsules for pyrolysis to carbon monoxide over glassy carbon at 1400 °C. Oxygen isotope ratios were measured on-line using a Flash HT elemental analyser interfaced with a Thermo Delta V isotope ratio mass spectrometer. Analytical precision determined from a standard laboratory α-cellulose [Sigma Aldrich UK (No. C-8002 Lot. 92F-0243)] was 0.3‰ (σ_{n-1} $n = 10$) (Loader *et al.* 2015).

Due to the nature of the sample material available, multiple relatively short-lived timbers were required to attain the replication target of ten trees per year [1800–1200 CE: 96 timbers, with mean (isotope) segment length of 100 (62) rings]. Development of the master chronology as two independent pools (after Laxton and Litton, 1988) enabled confirmation that the isotopic chronologies were coherent and free from temporal dating, processing or analytical errors between the two pools. Over the historical period the two pools exhibit a high degree of coherence (1200–1800 CE: $r = 0.74$), supporting their combination, by simple averaging to produce a single master chronology with a constant ten-tree replication (Fig. 3). The master chronology is currently being extended and strengthened further, in order to reconstruct the summer precipitation of England and Wales over the last millennium, after which the data will be publicly archived under non-commercial licence.

Chronology properties and data pretreatment

Dendrochronology uses correlation coefficients to compare an undated sample with a securely dated master chronology. However, the raw ring-width data need first to be pretreated, so that they are suitable for correlation analysis (Baillie and Pilcher 1973; Hollstein 1980). Tree-ring width measurements tend to be strongly skewed, as rings cannot be narrower than zero, and exhibit very strong positive autocorrelation. The autocorrelation is due to a combination of strong age trends and biological memory effects, including the use of stored photosynthates (Richardson *et al.* 2013; McCarroll *et al.* 2017). A variety of filters can be used to make the data more suitable for correlation analysis, the most common being that proposed by Baillie and Pilcher (1973), which involves taking each value as a percentage of the mean of the 5 years, of which it is the central value and then transforming that value using the natural logarithm. The 5-year running mean acts as a low-pass filter, removing trends and thus reducing positive autocorrelation. Taking a percentage captures the higher frequency information, and the logarithmic transformation is designed
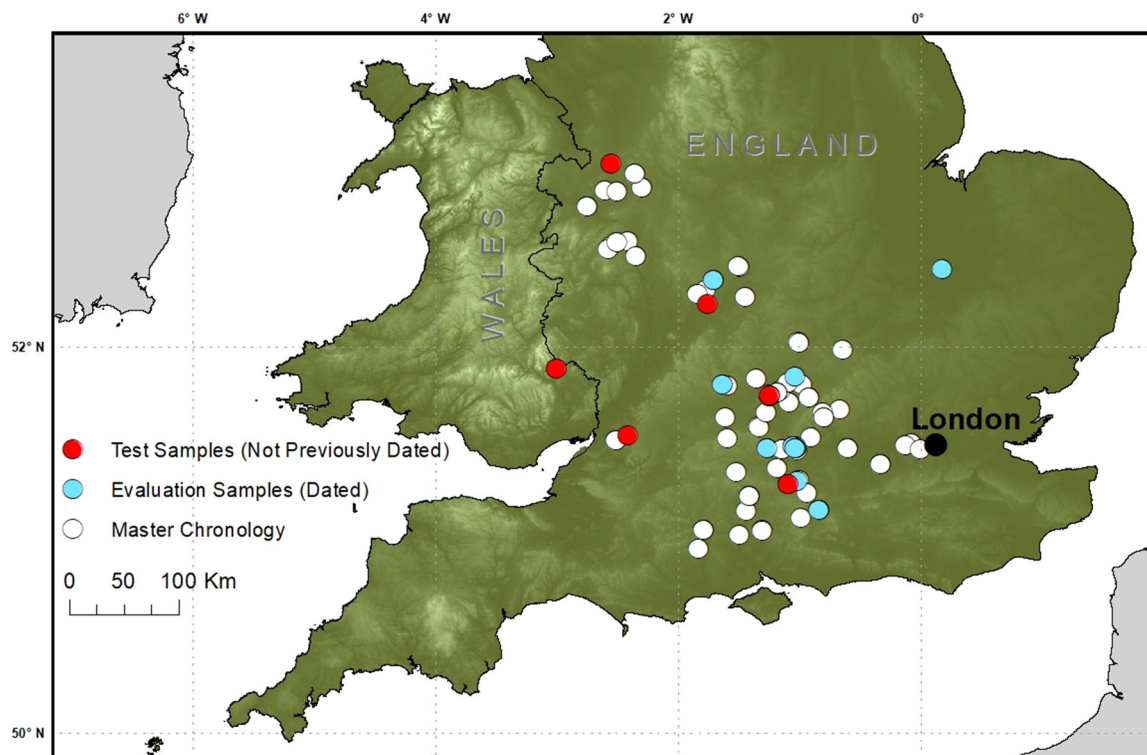

Figure 2. Location map indicating the region from which modern and historical samples were sourced. [Color figure can be viewed at wileyonlinelibrary.com].
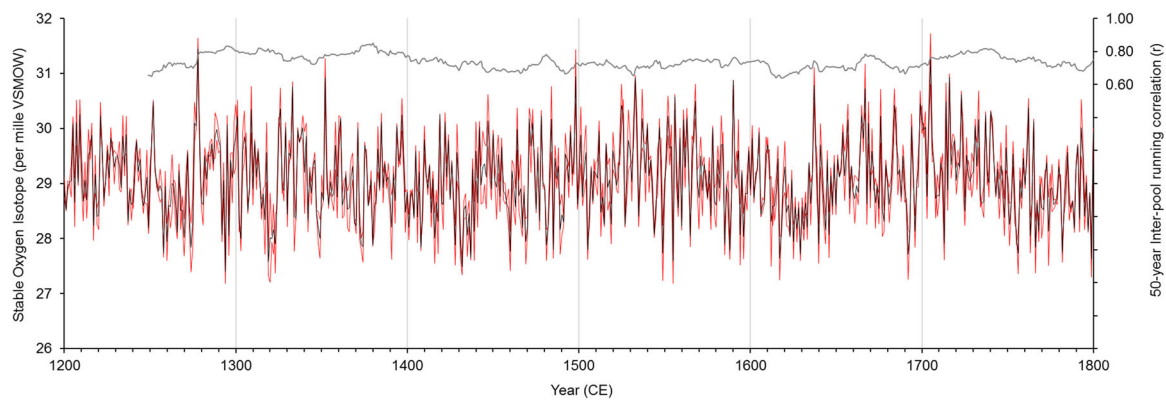
Figure 3. Comparison of the two individual data pools sourced from historical timbers 1800–1200 CE. Red lines indicate individual pools (five trees), and the black line the mean master chronology (ten trees). The grey line (secondary axis) shows the 50-year inter-pool running correlation. [Color figure can be viewed at wileyonlinelibrary.com].

to reduce the skew and push the data closer to a normal (Gaussian) distribution. After 'filtering' the data in this manner, correlation coefficients are calculated and then transformed into t-values, by assuming that the degrees of freedom are equal to the length of the overlap minus two. The t-values calculated by following this procedure are commonly referred to as Baillie–Pilcher t-values or 'BPt-values.' Soon after publication it was recognized that BPt-values do not follow Student's t-distribution and thus cannot be easily translated into probabilities (Munro, 1984; Wigley *et al.*, 1987; Monserud, 1989; Fowler and Bridge, 2017), the main reason being the unrealistic treatment of degrees of freedom (see section below).

The statistical properties of tree ring oxygen isotope time-series are very different from those of ring widths. The oxygen isotope master chronology is near normally distributed, with almost identical mean and median (29.13 and 29.11‰), low skew (0.27) and low excess Kurtosis (−0.07) values. Most importantly, the isotope series exhibit only very low positive first-order autocorrelation (0.15). The logic that was used to design the Baillie–Pilcher 5-year filter (BP5) clearly does not apply to oxygen isotope values, and this filter is unlikely to be suitable for stable isotope dating.

Given that the oxygen isotope data are near normally distributed, one option would be to date timbers using the raw, unfiltered isotope data. However, although this approach does tend to produce the correct dates, the low-frequency variability in the time-series, which reflects real low-frequency variability in climate, means that the correlation coefficients for adjacent time windows are not independent. This will inflate correlation coefficients for those time periods when trends in the sample and master chronology happen to coincide. Correlation analysis assumes that the series being compared are stationary (have no trend) so the lower frequency variability should be removed.

A total of 30 filters, falling into five broad classes, were considered. Dating results proved remarkably insensitive to the choice of filter, so the aim was to find a filter that is easy to apply, minimizes loss of independent degrees of freedom, removes low-frequency trends and retains low absolute autocorrelation. The effect on autocorrelation is particularly important, because significant autocorrelation, irrespective of sign, violates the assumptions of correlation analysis and strongly reduces the independent degrees of freedom. Full results for all filters are tabulated in the supplementary files (Table S1).

Two-year filters, commonly used in dendrochronology, perform very poorly. The low positive autocorrelation in the raw master chronology (0.15) is replaced with extremely high

negative autocorrelation (−0.49). Two-year filters also reduce the number of independent degrees of freedom by at least 50%, because there is no independence between adjacent values. Gaussian kernel filters, commonly used in dendroclimatology, are centrally weighted, so the values close to the centre are strongly dependent on each other, resulting in very strong negative first-order autocorrelation. Using a 5-year filter the autocorrelation is −0.64, and even a 15-year filter has much higher absolute autocorrelation (−0.21) than the raw data. The shortest filter that results in lower absolute autocorrelation than the raw data is 31 years. However, such a long filter is very difficult to apply to short time-series.

A more flexible approach to time-series filtering, with a clearer definition of the frequencies that are being excluded (the cut-off frequency) and more control over the length of the filter, is termed 'sinc' or 'Lanczos' filtering (Duchon, 1979). In terms of clearly defining the effects of a filter and avoiding distortion of the time-series properties of the original data, they are probably superior to the other options explored here but they are also centrally weighted and thus result in the same inflation of absolute autocorrelation as Gaussian kernel filters. A filter length of at least 19 years would be required to remove autocorrelation, which would be difficult to apply to short series.

Rectangular filters, in which each year has the same weight, have the advantage of simplicity and they do not inflate absolute autocorrelation as much as the centrally weighted filters. Five-year rectangular filters, with indices derived by division or subtraction, result in much less autocorrelation (−0.28) than Gaussian filters of the same length (0.64) but they are still much worse than the raw data (0.15). The BP5 filter behaves in almost the same way as a simple 5-year rectangular filter, with identical autocorrelation and only slightly reduced skew. A 7-year rectangular filter replaces positive autocorrelation with negative autocorrelation of the same magnitude, but a 9-year rectangular filter reduces it to less than 0.1 (−0.09).

In terms of the effect on the autocorrelation in the full master chronology, and ease of use, the 9-year rectangular filter seems a reasonable solution. However, it is not the autocorrelation of the full master chronology that influences dating results, but the autocorrelation in segments of the master that are similar in length to the target to be dated. In a master chronology of 801 years there are 721 segments that could be used to match a typical sample of 80 rings with full overlap. In a perfectly random data set one would expect 1% of these segments to exhibit significant autocorrelation at $p < 0.01$. In the raw isotope data, 6.2% of the segments exhibit significant autocorrelation, reflecting the influence of low-frequency trends. If the BP5 filter is applied almost half of the segments show significant autocorrelation (49% at $p < 0.01$, 12% at

$p < 0.001$). Using a 7-year rectangular filter 7.5% are significant but with the 9-year rectangular filter it falls to less than 1% (0.7%). We conclude that the shortest and simplest filter that adequately deals with autocorrelation is a rectangular 9-year filter (each year having equal weight) with indices calculated by subtraction.

Dating procedure

Dating experiments were conducted to test the ability of oxygen isotopes to date samples that had already been securely dated by ring-width dendrochronology and undated samples where ring-width dendrochronology failed. Samples were obtained from both within and beyond the central England region.

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 (indices). The ends of the sample and master chronologies were 'mirrored', so that the filter effectively covered the full sequence length. Pearson's correlation coefficients were calculated at each position and converted into Student's t-values. The degrees of freedom were adjusted for any remaining first-order autocorrelation, in both the sample and the relevant section of the master, and then for the statistical 'cost' of the filter. The use of filters reduces the degrees of freedom, with short filters having a stronger effect. For a rectangular 9-year filter the statistical 'cost' on the degrees of freedom is $1/9^{th}$ of the total sample size ($1/5^{th}$ for a 5-year filter). Autocorrelation (irrespective of sign) was dealt with by translating the sample size (N) into a 'corrected sample size' (N_{cor}) using the absolute magnitude of the first-order autocorrelation in the sample and in the master chronology at each possible dating position using the Equation 1:

$$N_{cor} = N\frac{1-r1_s\,r1_m}{1+r1_s\,r1_m} \qquad (1)$$

where $r1_s$ is the absolute first-order autocorrelation in the sample and $r1_m$ is the absolute first-order autocorrelation of the master section to which it will be compared (Dawdy and Matalas, 1964). The degrees of freedom used to calculate Student's t-values and probabilities therefore represent the corrected sample size, minus the cost of the filter, minus two, conservatively rounded down to the nearest integer. The t-values calculated using this procedure are more conservative (lower) than the Baillie–Pilcher t-values, normally reported for ring widths, and should 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. Where multiple correlations are calculated for the same sample, as in this case where there is one for each possible position of full overlap, probabilities need to be corrected for multiple testing (McCarroll, 2016). The simple, and deliberately severe, 'Bonferroni correction' is applied here, where the probability is multiplied by the number of tests conducted (Dunn, 1959, 1961). Using this methodology the probability of the chance occurrence of an r-value as high as that recorded at any position of full overlap on the master chronology can be calculated. The probabilities are reported as $1/p$, up to a limit of one million. Although it would be logical to objectively restrict the search to parts of the master chronology where a date would be considered reasonable, in this pilot phase of method development the stricter test of running all samples against the full master chronology is preferred.

Because the search area for the dating tests does not vary (all positions of full overlap, 1200–2000 CE), the number of possible matches is constant for each sample size so that the $1/p$ values, after Bonferroni correction, effectively represent the predicted return interval of spuriously high t-values in units of number of dates. In ring-width dendrochronology the decision on whether to accept or reject a date requires expert judgement, but to test this new method it is preferable to define some critical thresholds, below which potential dates are rejected.

To define potential dates, we propose the following thresholds:

1. The Bonferroni-corrected probability should be at least one in one hundred ($1/p \geq 100$).
2. The corrected probability for the strongest match should be at least an order of magnitude higher than that of the next highest ['isolation factor' (IF) ≥ 10].

These criteria are essentially the same as those proposed by Wigley *et al.* (1987), but applied more stringently. Wigley *et al.* (1987) used a corrected probability of $1/p \geq 10$ and IF ≥ 5. When a match passes the thresholds, it is not necessarily accepted as a date. Fortuitously high correlation coefficients are not impossible and it is necessary to consider the other lines of evidence that are available (English Heritage, 1998). Where a date is assigned to the final isotopically measured ring, it must finally be placed into the context of the entire timber sample, taking into account any rings not measured isotopically and the presence or absence of sapwood and waney (bark) edge, following identical criteria to ring-width dendrochronology (English Heritage, 1998; Miles, 2006).

Results
Evaluation of the method
Dating samples of known age

The isotope dating method was evaluated using 17 individual samples, including four living trees and 13 felled trees or historical building timbers, with end dates spanning 1384–2000 CE and with between 41 and 123 rings (Supporting Information, Table S2). Sample ring widths were measured prior to subdivision, cellulose extraction and isotopic analysis using an identical approach to that described above. None of the samples in this evaluation are included in the master chronology, but all have already been independently dated using ring-width dendrochronology (Table 1).

In all cases, the established date yielded the highest r-value and t-value, using both the raw and filtered oxygen isotopes. Even the lowest t-value of 5.41, on a sample with just 50 rings, gives a corrected $1/p$ value of > 700 with an isolation factor of 400. In 12 of the 17 cases, the corrected probability is more than one million to one, and in 15 it is more than one in 10 000. In 16 cases the correct match gave a probability more than 1000 times less likely to occur by chance than the next best match (IF > 1000). Due to the step-wise correlation at all possible positions against the master chronology, each test results in a large number of t-values. If they conform to Student's t-distribution one would predict that 1% of them should fall beyond the critical threshold of $p = 0.01$ for the appropriate degrees of freedom. For each run the false match percentages were recorded and the overall average is 1.0% as predicted by the t-distribution (Table 1).

Dating samples of unknown age

The most exacting test of the new method was to date timbers that, for a variety of reasons, could not be dated using ring-width dendrochronology. Where more than one timber from a

Table 1. Dating results for samples of known age and unknown age not dateable by ring-width dendrochronology.

Sample	N	No data	Strongest match	r	d.f.	t	1/p	IF	>1%
Samples of known age, dated by ring-width dendrochronology									
ahf16	100	0	2000	0.706	86	9.25	>1 M	>1k	1.7
ahf18	101	2	2000	0.830	84	13.64	>1 M	>1k	1.1
ahf21	100	0	2000	0.743	85	10.23	>1 M	>1k	1.6
ahf28	100	0	2000	0.629	85	7.46	>1 M	>1k	1.4
wen	115	0	1983	0.706	98	9.85	>1 M	>1k	0.4
hwk110	123	0	1960	0.725	106	10.83	>1 M	>1k	1.2
map78	64	1	1887	0.725	53	7.67	>1 M	>1k	0.7
mapt1	60	0	1820	0.670	49	6.32	>35k	>1k	0.7
mm51	61	0	1800	0.656	49	6.08	>15k	>1k	1.2
hvl3	51	0	1770	0.683	40	5.92	>4k	>1k	0.7
bad83	61	0	1770	0.788	50	9.04	>1 M	>1k	1.1
hn10a	41	0	1766	0.840	34	9.03	>1 M	>1k	1.1
bad32	50	0	1687	0.655	39	5.41	779	400	0.9
mdmh7	87	1	1587	0.777	73	10.55	>1 M	>1k	1.3
bfdd9	100	0	1518	0.654	84	7.92	>1 M	>1k	1.4
nc16	68	0	1386	0.647	58	6.46	>113k	>1k	1.0
sher2	94	0	1384	0.641	80	7.46	>1 M	>1k	0.8
Central England samples that could not be dated by ring-width dendrochronology									
vyne x	86	0	1655	0.663	71	7.47	>1 M	>1k	1.3
vyne11	73	0	1655	0.635	61	6.42	>121k	71	1.2
vyne12	86	0	1655	0.573	70	5.84	>18k	>1k	0.8
linc3	98	0	1626	0.691	83	8.70	>1 M	>1k	1.6
wilm4	62	0	1371	0.684	53	6.83	>300k	>1k	1.6
ggfh3	52	0	1592	0.765	41	7.61	>1 M	>1k	1.2
Samples from beyond central England that could not be dated by ring-width dendrochronology									
lmt x	50	0	1420	0.704	41	6.35	>19k	>1k	0.5
lmt3	57	0	1420	0.564	48	4.73	136	239	1.2
lmt3(-5)	52	0	1420	0.675	43	5.99	>7k	>1k	1.5
lmt11	50	0	1418	0.550	41	4.21	20	49	1.3
of2	100	0	1368	0.608	86	7.10	>1 M	>1k	1.4

Notes: Number of rings (N) and number of years within each sequence for which no isotopic data were available (no data), year of best match (Strongest match), Pearson's correlation coefficient (r), degrees of freedom (d.f.), Students t-value (t) and the one-tailed 1/p value corrected for multiple testing (1/p), isolation factor (IF), percentage of false matches with t-values beyond the threshold for p = 0.01 (>1%). Samples vyne x and lmt x are the average values from two timbers for The Vyne (vyne11 and vyne12) and for Llwyn Celyn (lmt3 and lmt11).

single building phase was available, the isotope series were combined using cross-correlation and simple averaging of the filtered series, as is the normal convention in dendrochronology. The method was applied to four structures within the central England region, two of which have supporting chronological information known from other evidence, and to two located further to the west (Welsh border) and northwest (Shropshire) outside of the chronology region (Fig. 2).

The Vyne, Sherborne St John, Hampshire

The Vyne (Fig. 4) is a 17th century (UK Grade I listed) country house in Hampshire, in the care of the National Trust (Howard and Wilson, 2003). In 1654 CE John Webb, a student of the architect Inigo Jones, was commissioned to design a Classical portico, reputed to be the first of its kind in England (Bold, 1989). Samples from the two main principal rafters, comprising 86 (vyne11) and 73 (vyne12) rings respectively, both with complete sapwood and bark, failed to cross-match and date using ring-width dendrochronology, due to complacent ring widths. However, timbers used in the reconstruction of the south front immediately behind the portico were dated to 1645 CE (Miles and Worthington, 1998). Using $\delta^{18}O$, the two samples correlate with each other extremely well (r = 0.74, n = 73, p < 0.0001) with no temporal offset. When compared

to the master chronology, the combined series gives an unequivocal felling date of winter 1655/6 CE (r = 0.66, Student's t = 7.47, 1/p > 1 million, IF > 1000). The two individual timbers give the same date and pass all thresholds (n = 73, r = 0.64, Student's t = 6.42, 1/p > 120 000, IF = 71 and n = 86, r = 0.57, Student's t = 5.8, 1/p > 18 000, IF > 1000). This demonstrates that the timbers sampled are part of Webb's original portico, confirming it as the oldest example on an English country house (Fig. 5).

Lincoln College Chapel, Oxford, Oxfordshire

The chapel of Lincoln College, Oxford (Fig. 6), was completed in 1631 CE and the roof timbers have been successfully dated, using ring-width dendrochronology, to between spring 1627 and spring 1629 CE (Miles and Bridge, 2017). Of the ten samples collected for dendrochronological dating, a single sample from a principal rafter on the west side (linc3) failed to date, despite having 98 rings, possibly because the ring widths are complacent. Using oxygen isotopes, however, there is a very strong match for the final ring of 1626 CE, with earlywood vessels of 1627 present (but not measured), giving a felling date of spring 1627 CE (r = 0.69, Student's t = 8.70, 1/p > 1 million, IF > 1000) (Fig. 7). This sample, together with those from The Vyne, confirms that complacency in ring widths is

Figure 4. The Vyne Portico, Hampshire. (A) External view showing Webb's original portico, the first and oldest example on an English country house. (B) Internal view of portico showing sampled rafters. © The National Trust. [Color figure can be viewed at wileyonlinelibrary.com].
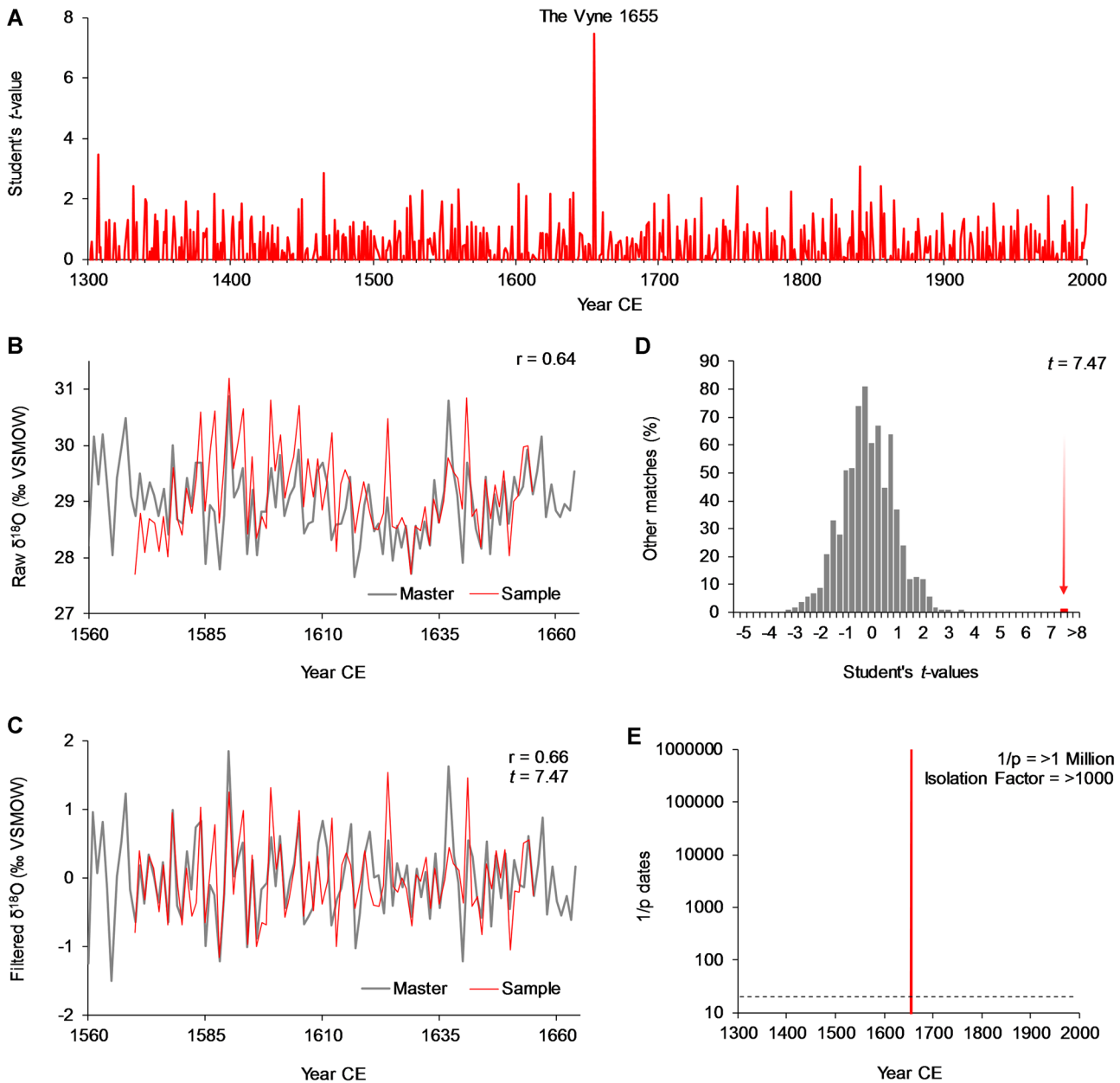

Figure 5. Composite figure presenting the dating profile and match statistics for vyne x (a composite of vyne11 and vyne12). (A) Distribution of Student's t-values through time with best match clearly identifiable as the highest t-value calculated with full-sequence overlap. (B) Raw oxygen isotope data versus time for the sample and master chronology (Pearson's correlation coefficient r presented). (C) Filtered isotope data (indices) versus time for the sample and master chronologies [Pearson's correlation coefficient (r) and Student's t presented]. (D) Histogram showing the distribution of all annual matches derived from the dating procedure with the best match and Student's t-value identified. (E) All corrected probabilities for dates with $1/p > 10$. The dashed horizontal line represents $1/p = 20$ significance threshold. The length of the bar corresponds to the significance of the match. The isolation factor (IF), the ratio of probabilities for the first and second best matches, is presented. [Color figure can be viewed at wileyonlinelibrary.com].

Figure 6. Lincoln College Chapel, Oxford. (A) External view. (B) Internal view of roof structure showing sampled rafters. © D. Miles. [Color figure can be viewed at wileyonlinelibrary.com].
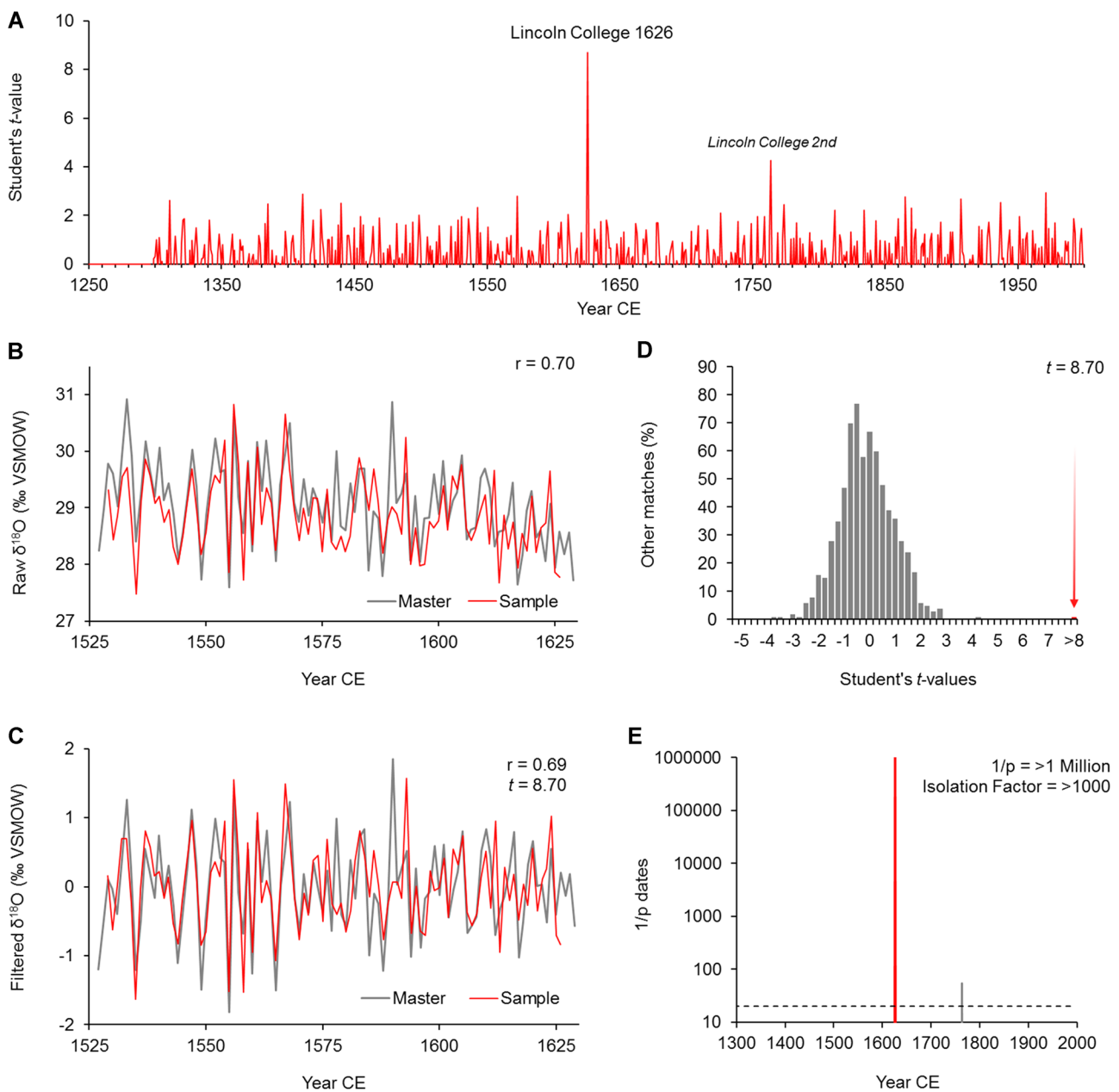

Figure 7. Same as Fig. 5 presenting the dating profile and match statistics for linc3. [Color figure can be viewed at wileyonlinelibrary.com].

not a barrier to successful dating using oxygen isotopes; indeed, wide and complacent ring widths are a practical advantage.

Wilmcote Cruck, Wilmcote, Warwickshire

The added cross-wing of a cruck-framed house (2–6 Church Lane, Wilmcote) in Warwickshire (Fig. 8) has been dated, using ring-width dendrochronology, to the 16th century. However, the original structure failed to date using ring-width dendrochronology (Bridge and Miles, 2017). A single sample from one of the cruck trusses, of unusual design, gave a clear isotopic match for the final measured ring of 1371 CE (62 rings, $r = 0.68$, Student's $t = 6.83$, $1/p > 300\,000$, IF > 1000), with no other statistically significant matches. There are earlywood cells beyond the last measured latewood band, and as these are abraded, a felling date of spring–summer 1372 CE is established. The new isotope date clearly positions this as the oldest full cruck-framed house in Warwickshire (Alcock and Miles, 2013) (Fig. 9).

Goosegreen Farmhouse, Yate, Gloucestershire

Goosegreen Farmhouse in Yate, Gloucestershire, contains rare and well-preserved examples of vernacular wall painting, comprising remarkable and colourful mock panelling, which has been dated stylistically to the late 16th to early 17th century (Fig. 10). The paintings are associated with the original structural timbers, which have not proved dateable by dendrochronology, due to short and complacent ring sequences. The oxygen isotopes of a single sample ggfh3, with 52 rings, gives a single clear match for the final ring measured isotopically of 1592 CE ($r = 0.77$, Student's $t = 7.61$, $1/p > 1$ million, IF > 1000). This sample had c. 16 additional (degraded and very narrow/distorted) sapwood rings with bark edge preserved, allowing a felling date of winter c. 1607/8 CE to be determined (Fig. 11).

Llwyn Celyn, Cwmyoy, Monmouthshire

Llwyn Celyn, in Monmouthshire, is an exceptionally rare and important medieval hall house rescued from dereliction by the Landmark Trust (Stanford, 2018) (Fig. 12). It was constructed using fast-growing oaks (Fig. 1), so the ring width sequences are both short and complacent and it could not be dated by ring-width dendrochronology. The $\delta^{18}O$ values of two timbers (lmt3 from the open hall with 57 rings and lmt11 from the solar cross-wing with 50 rings), both with complete sapwood and bark edge, were measured. Although this house lies well beyond the central England region used to build the master chronology, the longer timber gave a single clear match of 1420 CE and passed the thresholds (Student's $t = 4.73$), but the correlation with the master chronology is considerably stronger if the first five juvenile rings (Duffy *et al.* 2017) are excluded (Student's $t = 5.99$). The shorter timber from the cross-wing gives a best match at 1418 CE, but it does not pass all the thresholds, with or without excluding the first five juvenile rings. The strongest correlation between the two timbers is with a 2-year offset, which is consistent with the dating results. The average of the two aligned timbers over the 50 years of common overlap (lmt x) gives an unequivocal date of 1418 CE for the final ring of lmt11 ($r = 0.70$, Student's $t = 6.35$, $1/p > 19\,000$, IF > 1000) with no other statistically significant matches (Fig. 13).

The results for Llwyn Celyn suggest that the timbers were felled in winter 1418/19 CE for the cross-wing (lmt11) and winter 1420/21 CE for the open hall (lmt3); the custom of using timber 'in the green' (unseasoned) means that the house is likely to have been built shortly after 1420 CE, or possibly the cross-wing a year or two earlier as it is not uncommon to find timbers felled over one or two years used in the same structure (Miles, 2006). This date is unusually early for a high-status Welsh hall house. The date has also been verified using wiggle-match radiocarbon dating for both of the timber samples. The ring assigned to 1417 CE dates radiometrically to 1407–1428 CE [2σ agreement factor (A_{COMB}) 161.15%, $n = 4$].

Oldfields Farm, Moreton Say, Shropshire

Oldfields Farm in Moreton Say, Shropshire (Fig. 14), is a two-bay base-cruck hall (Moran, 2003) and the upper parts of the base-cruck structure have as much as 8 mm of soot encrustation. It is suspected to be one of the oldest base-cruck-framed houses in Shropshire but despite strong internal matches with timbers from the same construction phase, they did not date through dendrochronology, despite having over 100 clear growth rings (17 sapwood present but incomplete) (Miles and Haddon-Reece 1994). A probable reason for its failure to date using dendrochronology is the growth complacency of trees across the flat north Shropshire landscape. The isotope results yield a single unequivocal date of 1368 CE for the last ring measured for of1 ($n = 100$, $r = 0.61$, Student's $t = 7.10$, $1/p > 1$ million, IF > 1000). Whilst this timber did not have bark edge on the sample, it did match unequivocally (by dendrochronology) with another arcade post of2, which did retain bark edge, thus allowing a precise felling date to be assigned of winter 1393/4 CE), confirming its considerable age and significance. As with Llwyn Celyn, this date demonstrates that the method works well even beyond the central England region where the master chronology was developed (Fig. 15).

The number of rings required for dating

Given the strong correlations between the individual samples and the master chronology it seems likely that it will be possible to use oxygen isotopes to date samples with fewer rings than is the case with ring-width dendrochronology. To test this each of the 18 timber samples from the central England region (including those dated using the stable isotope method) were isotopically dated using just the innermost rings, beginning with 50 and reducing the number in 5-year steps as far as 30, to mimic the dating of young trees. The living trees were not used because they were not cored close to the pith.

All samples give the correct dates and pass the selection criteria with the first 50 rings (Table S3) and with 35 rings or more all dates are correct but the proportion passing the criteria drops from 94% with 45 rings to 72% with 40 rings and 50% with 35 rings. Only when sample size drops to 30 do three samples exhibit the highest correlation with the wrong date, although in all cases the erroneous dates fail the selection criteria and the correct date is ranked second. Even with just 30 rings c. 28% of samples date correctly and pass all the selection criteria. For all sample sizes there is no overlap in t-values between false matches and correct dates that pass the selection criteria (Fig. 16).

The samples from beyond central England perform less well with short ring sequences. The two individual timbers from Llwyn Celyn require 50 and 40 rings to obtain the correct date and only one passes the thresholds, requiring 45 rings. The sample from Oldfields Farm captures the correct date with 30 rings but requires 50 rings to pass the thresholds (Supporting Information Table S3).

Figure 8. 2–6 Church Lane, Wilmcote, Warwickshire. (A) External view. (B) Internal view showing the head of a spere post. © N. Alcock. [Color figure can be viewed at wileyonlinelibrary.com].
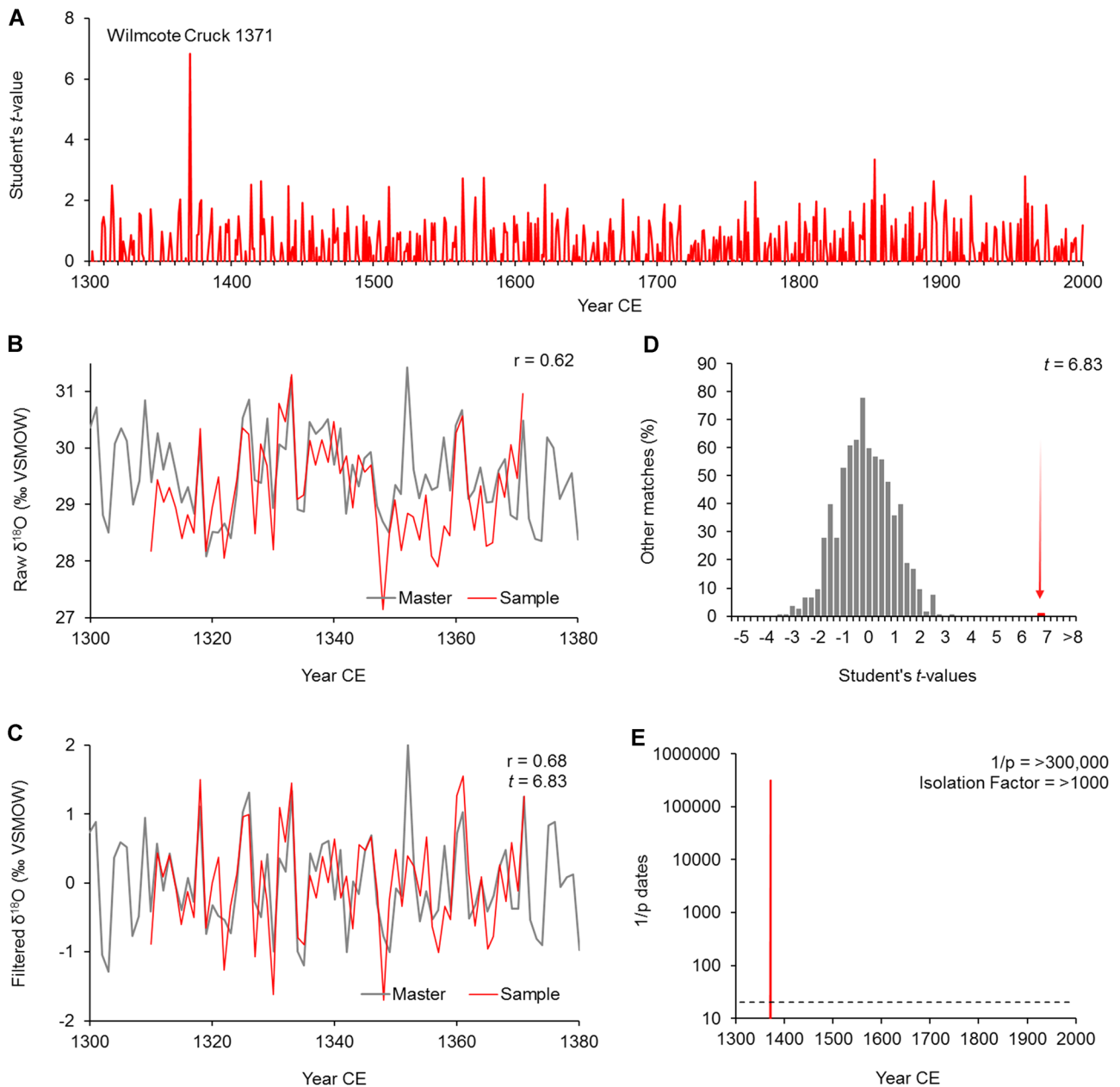

Figure 9. Same as Fig. 5 presenting the dating profile and match statistics for wilm4. [Color figure can be viewed at wileyonlinelibrary.com].

Figure 10. Goosegreen Farmhouse, Yate, Gloucestershire. (A) External view. (B) Internal view of mock panel paintings. © L. Hall. [Color figure can be viewed at wileyonlinelibrary.com].
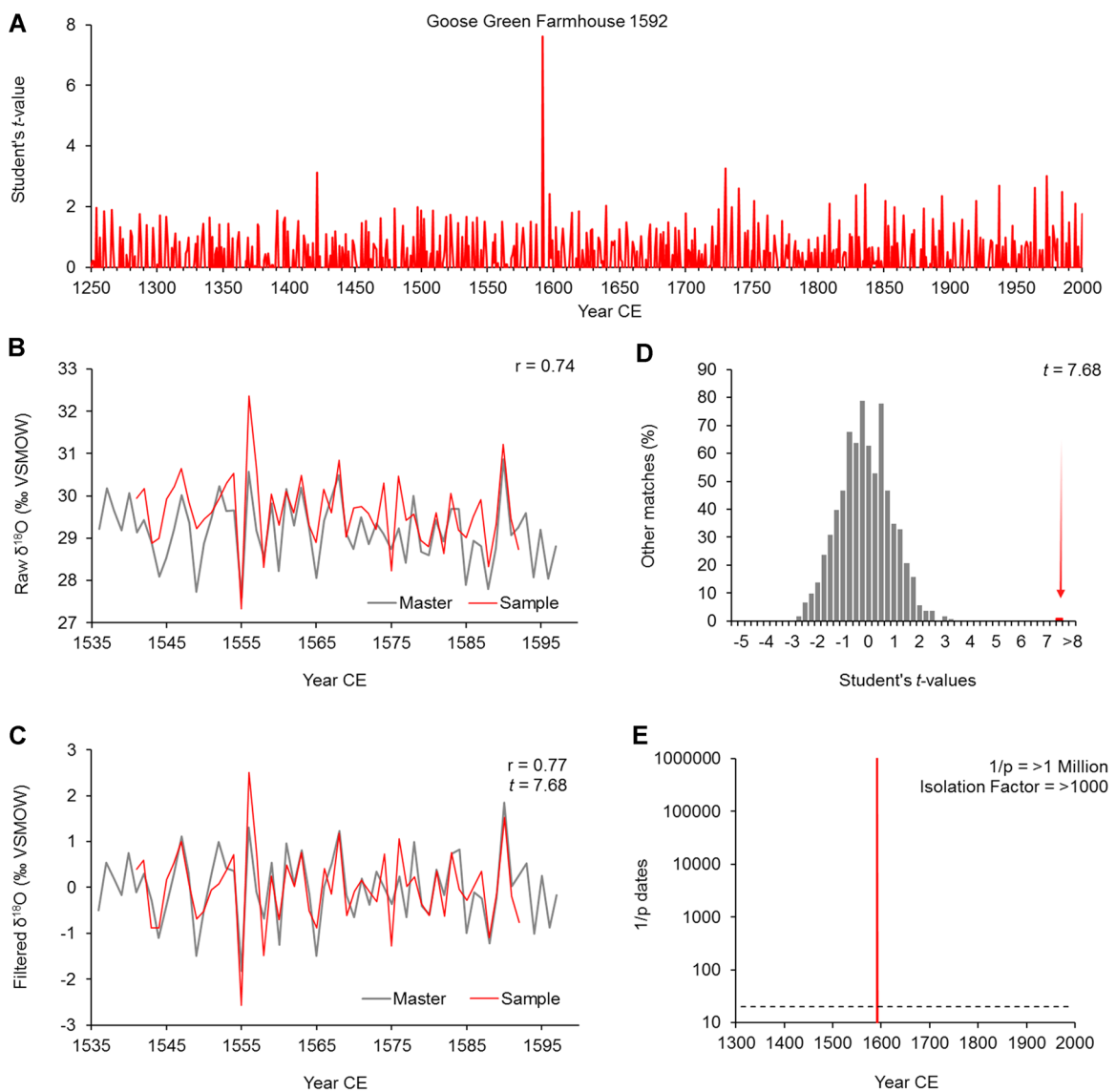

Figure 11. Same as Fig. 5 presenting the dating profile and match statistics for ggfh3. [Color figure can be viewed at wileyonlinelibrary.com].

Figure 12. Llwyn Celyn, Monmouthshire. (A) External view. (B) Internal view of roof structure in main hall. © John Miller, by kind permission of the Landmark Trust. [Color figure can be viewed at wileyonlinelibrary.com].
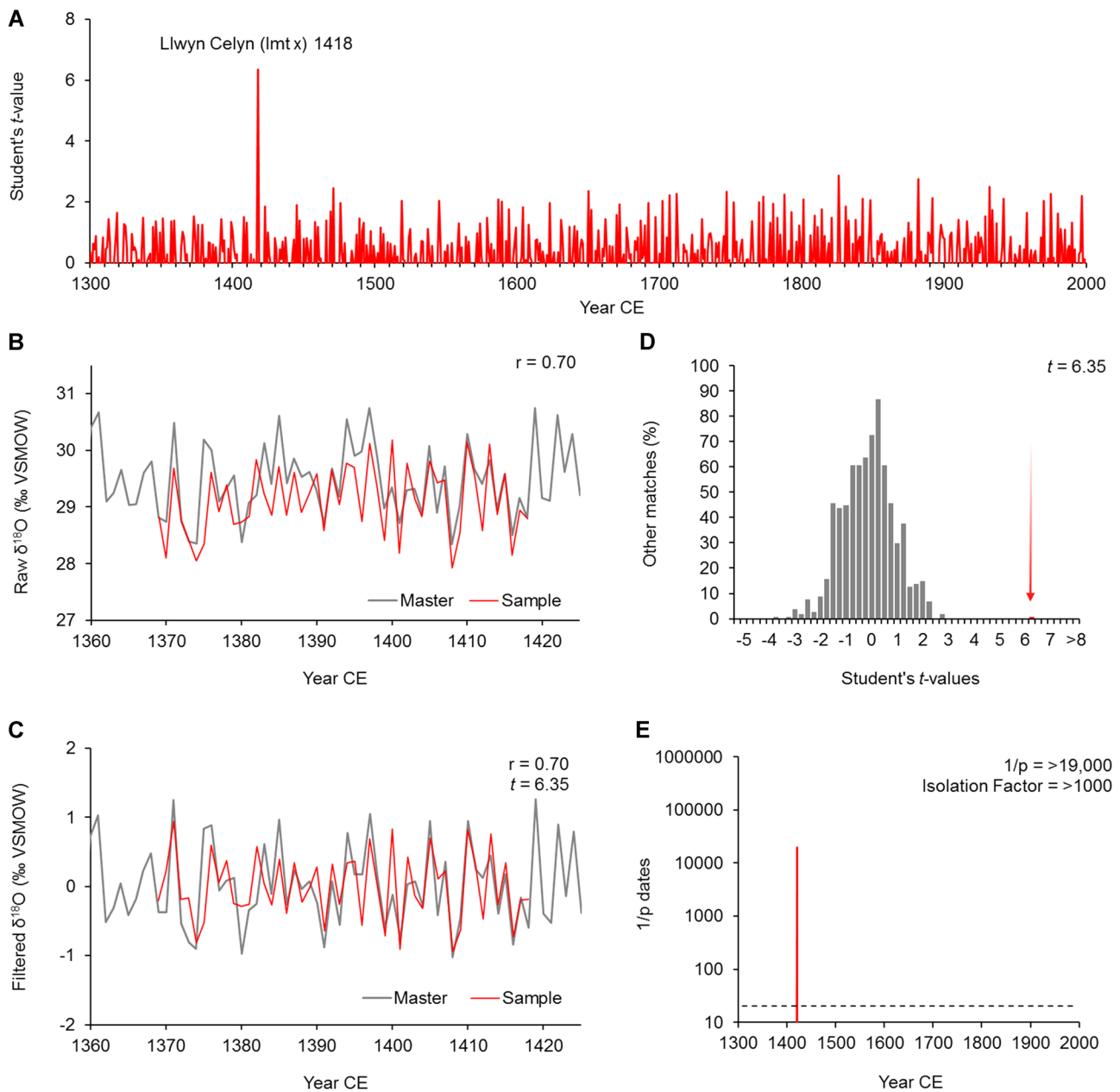

Figure 13. Same as Fig. 5 presenting the dating profile and match statistics for lmt x (a composite of lmt3 and lmt11). [Color figure can be viewed at wileyonlinelibrary.com].

Figure 14. Oldfields Farm, Shropshire. (A) External view. (B) Internal view of roof structure showing king strut. © Madge Moran. [Color figure can be viewed at wileyonlinelibrary.com].
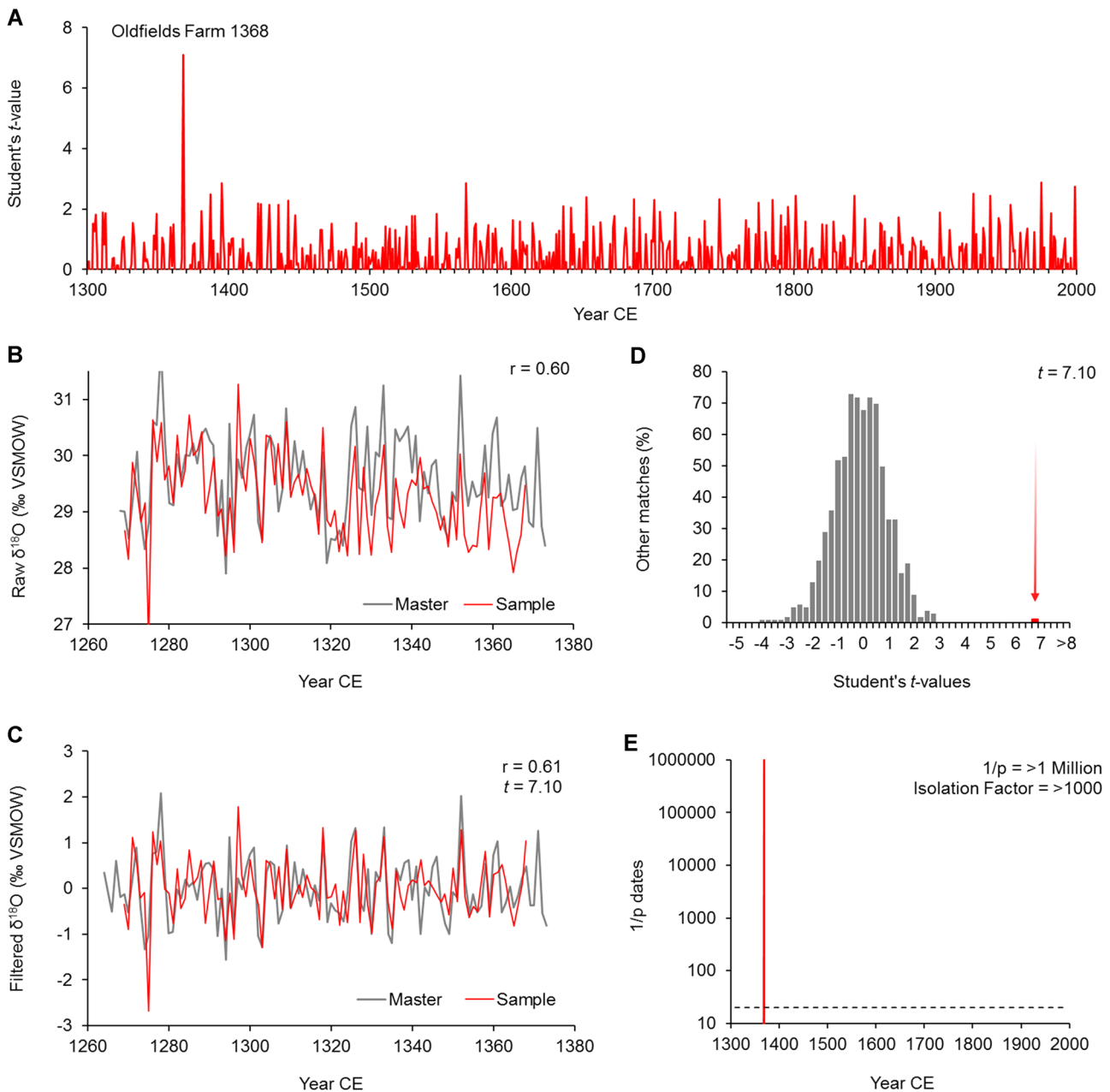

Figure 15. Same as Fig. 5 presenting the dating profile and match statistics for of2. [Color figure can be viewed at wileyonlinelibrary.com].
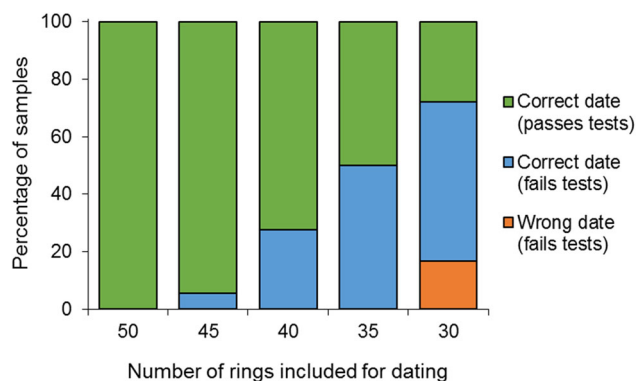
Figure 16. Dating results for the 18 central England timbers using only the first (innermost) 30–50 rings. [Color figure can be viewed at wileyonlinelibrary.com].

Discussion and conclusions

Tree ring dating using oxygen isotopes in the UK works extremely well. Even though the master chronology is based on only ten tree replication, it has been possible to date timbers of known age, and timbers that could not be dated by ring-width dendrochronology. Secure dates were also obtained with much smaller numbers of rings than is normally possible using traditional dendrochronology. The reason the method works so well is the presence of strong between-tree isotopic correlation. The ring widths of UK oak trees do not correlate so strongly with each other because their growth is not strongly constrained by climate. The oxygen isotope signal, by contrast, does not rely on any climatic limitation to growth, it is dominated by the isotopic ratios of the oxygen in summer precipitation and the trees act largely as passive monitors of that signal.

The statistical properties of tree ring widths make them poorly suited to correlation analysis because they are strongly skewed and characteristically display very strong positive autocorrelation, and therefore require rather harsh data pretreatment. Although the resulting correlations are usually expressed as *BPt*-values, those values do not actually follow Student's *t*-distribution and cannot therefore be used to estimate probabilities of error (Munro, 1984; Fowler & Bridge, 2017). The statistical properties of oxygen isotopes from tree rings are much less problematic and even in their raw, unfiltered form are better suited to correlation analysis. They are not strongly skewed and most importantly they do not show strong positive autocorrelation. The result is that correct dates are routinely obtained by comparing the raw oxygen isotope data of a sample with the raw master chronology. However, trends in the oxygen isotope values, which reflect real changes in climate, may lead to inflated correlation values for false matches, where the trends in the sample parallel those in the master chronology. Serial autocorrelation in the errors is undesirable when dating, so it is preferable to use some form of filtering to remove most of the trends in both sample and master chronologies. A wide range of filters was tested and found to make little difference to the dating results. A 9-year rectangular filter, with indices calculated by subtraction, is the simplest and shortest effective filter. After applying this filter, and making appropriate corrections for the loss of degrees of freedom caused by filtering and autocorrelation, the resulting *t*-values follow Student's *t*-distribution. It is thus possible to calculate the probability that the correlation coefficient, on which a potential date is based, could have arisen purely by chance. When calculating this probability the number of

possible matches against the master chronology is also taken into account.

It is important to recognize that the calculated probabilities are based on the standard assumptions of correlation analysis. The 'null hypothesis' that is being tested assumes that the isotope values have been drawn from a random normal (Gaussian) distribution. However, oxygen isotope ratios in tree rings are not of course random numbers; they reflect real changes in the climate of the past, so the assumptions are not exactly met. The probability values should therefore not be used in isolation to determine whether a date should be accepted, and the other available evidence should also be considered.

One consequence of the very strong isotopic correlation between trees is that it is possible to obtain reliable dates using far fewer rings than is the case for ring-width dendrochronology. Within the central England region it seems likely that it will be possible to date many samples using just the first 35 rings. Complacency in the ring widths (lack of variability) seems to have no effect on the isotopic signal and it is likely that many timbers cut from young, fast grown oaks will be suitable for isotopic dating. It may also be possible to date timbers that cannot be dated by ring-width dendrochronology due to strong disturbance in the ring widths, caused by thinning and pollarding for example, although it would probably be necessary to date series leaving gaps where rings are too thin to cut and perhaps to use a shorter filter.

Although the master chronology was compiled using trees and timbers from central southern England, it has been possible to date structures outside the chronology region in both Wales and Shropshire. Preliminary results from living trees and a few building timbers (not presented) suggest that it will be possible to expand the range of dating. Given that the source of the oxygen isotope signal is summer precipitation, a chronology dating range that follows the summer storm tracks and variability in oxygen isotopes in rainfall (from W/SW to E/NE) seems logical. More work is required to determine the true range of the method using this master chronology, but based upon isotope climatology one would not expect to be able to routinely date material from northern Scotland. Additional regional master chronologies are likely to be required if the geographical range of the method is to be extended to areas that currently experience limited ring-width dating success (e.g. south-west Wales, Kent, Scotland, East Anglia). Wider applications of the isotopic approach, such as timber provenancing and the reliable dating of short sequences or non-oak timbers, are still to be explored.

Conventional dendrochronology, based on ring widths, was a huge advance in science-based archaeology, allowing the precise dating of many historical and Holocene oak timbers and logs. However, the method often fails, or is not applied because there are insufficient rings or ring widths are either too complacent or too disturbed. Stable isotope dendrochronology has the potential to revolutionize the dating of timber structures and artefacts. An oxygen isotope master chronology, with replication as low as ten trees, is routinely capable of dating ring sequences that are short and/or complacent and can furnish those dates with statistically defined probabilities of error.

Stable isotope dendrochronology is too resource-intensive to replace ring-width dendrochronology but offers an attractive alternative to radiocarbon dating because, at similar cost, it can return an exact (felling) date with an objectively defined probability of error. It is particularly suited to dating material from the highly populated moist mid-latitudes, where tree growth is not strongly controlled by climate.

Supporting information

Additional supporting information can be found in the online version of this article.

Table S1. Properties of the oxygen isotope master series before (raw) and after filtering with a variety of different types of filters. AC1 is first order autocorrelation.

Table S2. Sample code, description and location for dated and undated timbers used to evaluate the isotope dating method.

Table S3. Dating results for the innermost rings 30–50 rings.

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