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Scientific Dating

Bourn Mill, Caxton End, Bourn, Cambridgeshire

Ring-width Dendrochronology, Radiocarbon Wiggle-matching, and Oxygen Isotope Analysis of Elm and Oak Timbers

Martin Bridge, Cathy Tyers, Alex Bayliss, Silvia Bollhalder, Lukas Wacker, Neil J Loader, and Danny McCarroll

Discovery, Innovation and Science in the Historic Environment

Research Report Series no. 12-2022

Front Cover: Bourn Mill in Cambridgeshire during restoration. Photo: Domenico D'Alessandro.

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NGR: TL 31187 58004

ISSN 2059-4453 (Online)

SUMMARY

Samples were taken from 21 of the various timber elements of the mill, including both oak and elm timbers. Conventional ring-width dendrochronology established that the main post was most likely felled in the first half of the sixteenth century, making this the earliest main post of a post mill yet dated. Felling dates for the sheers and front sheer spacer of spring AD 1703 and spring AD 1707 also indicated a previously unknown rebuilding phase, which is earlier than the known partial-destruction of the mill during a storm in AD 1741.

Other weak statistical matches between the ring-width series of oak and elm timbers were explored using other scientific dating techniques. The combined analysis confirmed that these other surviving timbers in the trestle probably date from repairs undertaken in AD 1874 and AD 1931 but suggested that many other timbers in the buck are eighteenth-century survivals.

CONTRIBUTORS
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ACKNOWLEDGEMENTS
We are grateful to all at Cambridge Past, Present, and Future and in particular CEO James Littlewood, for arranging the on-site logistics and to Kate Armstrong and Graham Bruce too for their help and kindness. We would also like to thank architect Tim Buxbaum for advice and arrangements for site access, Martin Davies and Dave Pearce of Cambridgeshire Windmills Consultancy for their advice, support and research input, and Stuart Armitage of The Morton Partnership, the project civil and structural engineers with specialist experience in conservation, repairs and adaption of historic buildings and structures. Thanks also to R H Partnership Architects for their kind permission to reproduce Figure 2 in this report, and finally, we would like to thank Shahina Farid (Historic England Scientific Dating Coordinator) for commissioning and facilitating this programme of tree-ring analysis, Alison Arnold and Robert Howard (Nottingham Tree-Ring Dating Laboratory) for dissection of the samples for radiocarbon dating, and Gareth James (Swansea University) for technical support.

ARCHIVE LOCATION
Historic England Archive
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HISTORIC ENVIRONMENT RECORD OFFICE
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DATE OF INVESTIGATION
2020–2

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INTRODUCTION

The timber-framed and weather-boarded Bourn postmill is a Grade I Listed (List Entry Number 1162375 here) Scheduled Ancient Monument (List Entry Number 1002935 here), situated to the north-west of the village of Bourn, approximately half-way between Bourn and Caxton (Fig 1).

The earliest documented record of the mill is from AD 1636, but it has long been considered as one of the earliest post mills surviving, largely because of its shape, which resembles early manuscript illustrations, and the use of vertical posts at the end of the crown-tree, which is identified as a more primitive form than horizontal side girts (Bridge *et al* in prep). It is known to have undergone restorations in AD 1874, AD 1933, AD 1961, and AD 1984, and contains some reused elements. A stud bears the inscription 'E. Bismur 1758', and the cross-trees have inscribed dates of '1874' and '1875'.

Scientific dating was requested by Domenico D'Alessandro, Historic England Architect, to inform current restoration activities and, if possible, to reveal more of the history of the structure.

RING-WIDTH DENDROCHRONOLOGY

Sampling

An assessment of the potential of surviving timbers in the trestle and buck for dendrochronology and radiocarbon wiggle-matching was undertaken in October 2020. It was found at this time that in a past restoration programme many of the timbers from the trestle had been treated by infilling with some form of resin/concrete, which was surrounded by a thin veneer of the original wood. As most of the structure was covered in bitumen, apart from areas uncovered during the present investigations, it was difficult to judge the number of rings available in the timberwork for dating.

Sampling was undertaken in October 2020, with duplicate cores taken for radiocarbon dating and oxygen isotope analysis in February and October 2021. Details of the samples taken are given in Table 1. Figure 2 shows, where possible, the positions of the timbers sampled for scientific dating. Some timbers are not shown, ie bourn06, the south quarter bar, which is opposite bourn05, and bourn08, the left sheer which is adjacent to bourn10 (the right sheer), with bourn09, the front sheer spacer sitting between the two. The left-side front and rear corner posts (bourn14 and bourn20) are opposite their counterparts on the right-hand side (eg bourn20 is the equivalent of bourn15, which is illustrated). The top rail is largely obscured in Figure 2 but sits at the base of the roof rafters, at the top of the buck frame, and bourn16 is on the left-hand side. Other timbers are illustrated in Figures 3 to 5.

Much of the buck was found to be of elm (*Ulmus* sp.), but samples were taken for subsequent radiocarbon or oxygen isotope analysis. Although it is clear from inscriptions on the timbers that most of the trestle was replaced in AD 1874/5, these timbers were still of interest, especially the main post, which had the potential to be an early survival. The ring-width series from the first sample taken from the elm crown-tree proved very difficult to resolve, but a second sample, taken for radiocarbon analysis had much clearer rings, and retained complete sapwood. In total, 21 timbers were sampled, 14 oak (*Quercus* sp.) and 7 elm (*Ulmus* sp.).

Methodology

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

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

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

The sapwood estimate for oaks in this area is that for the North and Midlands provided by Miles (1997, fig 5). The equivalent values for elm are as yet unknown. One problem that has been encountered in considering elm is that it has often proven very difficult to determine the position of the heartwood/sapwood boundary, even when it is known that the complete sapwood is present on a timber. Out of 129 measured series considered by Bridge (2020), 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 and so the North and Midlands sapwood estimate for oaks provided by Miles (1997, fig 5) has also been used for elm timbers in this report.

Results

Seven, of the 21 timbers sampled, were of elm, one of which was not measured as it contained fewer than 20 rings (bourn15). Three oak timbers also had fewer than 20 rings and were not measured (Table 1).

Three samples were taken from the main post (bourn01) in order to establish its date and in the hope of getting some sapwood that was not visible because of the tar covering. Bourn01a matched 01b (t=7.0 with 27 years overlap); 01a matched 01c (t = 9.7 with 30 years overlap); and a t-value of 2.8 is obtained for the 18-year overlap between 01b and 01c.

Samples 03i and 03ii are the inner and outer rings of bourn03, but with a break between them, and similarly 05i and 05ii are the inner and outer rings of bourn05. Although the breaks look clean, with no loss of rings, this can only be confirmed if the series are cross-matched with other timbers, which was not possible in these cases. The inner and outer ring sections of sample bourn09 are separated by a clean break (confirmed by subsequent cross-dating of the series), and these were combined to form a single series bourn09.

A t-value of 2.7 is produced when bourn12a and bourn12b cross-match with bourn12a at relative years 2–43 (Table 1). This, low t-value is mostly the result of the disparity between the early rings of these two sequences as the rest of the two sequences match very well visually (Fig 6). Given the good visual matching and the fact that bourn12a retains the heartwood/sapwood boundary, and bourn12b has complete sapwood, this relative dating was thought likely to be correct. This was confirmed by the removal of the inner seven rings of bourn12a and the inner eight rings of bourn12b, the resulting series then matching with a t-value of 6.8, with 35 years overlap. A truncated mean series, bourn12short, was used in further analysis (Table 1).

The ring-width series of bourn13a and bourn13b cross-match at the relative positions given in Table 1 with a t-value of 15.2 for this 40-year overlap.

The ring-width series for the oak samples representing 11 of the sampled timbers were then compared with each other and, where they did not cross-match, with the full corpus of reference chronologies for oak.

This process suggested that the main post of the trestle (bourn01) dated as spanning AD 1402–1503 (Table 2a). This timber did not retain any sapwood, but examination of the timber suggested that the outer rings are likely to be close to the heartwood/sapwood boundary. This conclusion is based on the irregular roundness of the outer layer and presence of knots, but weathering and tar covering prevent positive identification of any sapwood. All three cores taken had similar dates for the outermost measured ring, suggesting few heartwood rings had been lost.

Tenuous cross-matching was identified between the east quarter bar (bourn04) and the west quarter bar (bourn07) (t=3.2 with 52 years overlap and good visual matching) when bourn04 spans relative years 1–58 and bourn07 spans relative years 7–62 (Table 1), although this was insufficiently strong to be considered secure. This potential match was explored further with radiocarbon dating.

The ring-width series from the right sheer (bourn10) cross-matched the connecting beam (bourn09) with a t-value of 10.3, with 74 years overlap, suggesting the possibility that they are derived from the same parent tree, and a composite series bourn109 was formed. The combined series bourn109 matches bourn08 with a t-value of 4.9 with 84 years overlap, and a new series bourn1098 was made, the dating evidence for which is given in Table 2b. Both bourn09 and bourn10 retained complete sapwood and are thus from a tree felled in spring AD 1703. The left sheer (bourn08) is from a tree felled a few years later, in spring AD 1707.

When the ring-width series from the six measured elm samples were compared, potential cross-matching was found between bourn11b and bourn12short (t=5.1 with 33 years overlap) when bourn11b spans relative years 1–95 and bourn12short spans relative years 63–105, and this again was not considered secure because of the short overlap and previous problems matching elm samples. This potential match was explored further with radiocarbon dating and oxygen isotope analysis.

Comparison with the oak reference chronologies also highlighted some potential cross-dating, with bourn11b giving some potentially statistically significant matches with the outer ring positioned at AD 1729 (Table 2c). The tentative dating of bourn11b as ending in AD 1729, implies that the last ring of bourn12short may have formed in AD 1739, if the tentative cross-matching between these samples is correct. Some potentially significant cross-matching was also found for bourn20, with its outer ring at AD 1732 (Table 2d). At this possible matching position, the ring-width series for bourn20 matches bourn 11b (t=3.4 with 35 years overlap; Fig 7) and bourn12short (t=3.0 with 36 years overlap).

One of the elm vertical posts that are jointed to the end of the crown-tree, bourn13a, also produced a possible cross-match with the oak main post from the trestle (bourn01) at an end date of AD 1456 (t=4.7 with 47 years overlap). This would be particularly important for dating the earliest surviving fabric in the mill as this timber retained its heartwood/sapwood boundary (Table 1).

Previous work on elm however (Bridge 2020) has shown that elm matches to the oak database at these *t*-values are often unreliable, and a much higher threshold *t*-value is likely to be required before elm series are considered securely dated against oak chronologies. These cross-matching positions and suggested dates are therefore not considered secure without other supporting evidence.

The ring-width data for the measured samples are given in Appendix 1.

RADIOCARBON DATING

In order to test the potential survival of early fabric in the trestle beyond the main post, two single rings were selected for radiocarbon dating from each of the oak quarter bars that had produced tenuous cross-matching (bourn04 and bourn07) through ring-width tree-ring analysis. This dating would inform the significance of the extant timberwork in the trestle and decisions on repair.

Two single-ring samples were also selected for dating from the elm timbers forming the crown-tree and the left vertical wall post at the end of the crown-tree (bourn11b and bourn 12a), which again produced tentative cross-matching. As bourn11b was the only timber that retained bark edge, the middle of the core was deliberately preserved intact to allow oxygen isotope analysis should the radiocarbon dating prove its antiquity.

Three single-ring samples were selected for radiocarbon dating from bourn13a, an elm timber forming the right vertical wall post at the end of the crown-tree, to test the very tentative cross-dating hinted at by the ring-width dendrochronology.

Radiocarbon dating is based on the radioactive decay of ^{14}C, which trees absorb from the atmosphere during photosynthesis and store in their growth-rings. The radiocarbon from each year is stored in a separate annual ring. Once a ring has formed, no more ^{14}C is added to it, and so the proportion of ^{14}C versus other carbon isotopes reduces in the ring through time as the radiocarbon decays. Radiocarbon ages, like those in Table 3, 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).

Eleven radiocarbon measurements have been obtained from single annual tree-rings from five timbers (Table 3). Dissection was undertaken by Alison Arnold and Robert Howard at the Nottingham Tree-Ring Dating Laboratory. Prior to sub-sampling, the core was checked against the tree-ring width data. Then each annual growth ring was split from the rest of the tree-ring sample using a chisel or scalpel blade. Each radiocarbon sample consisted of a complete annual growth ring, including both earlywood and latewood. Each annual ring was then weighed and placed in a labelled bag. Rings not selected for radiocarbon dating as part of this study have been archived by Historic England.

Radiocarbon dating was undertaken by the Laboratory of Ion Beam Physics, ETH Zürich, Switzerland in 2021. Cellulose was extracted from each ring using the base-acid-base-acid-bleaching (BABAB) method described by Němec *et al* (2010), combusted and graphitised as outlined in Wacker *et al* (2010a), and dated by Accelerator Mass Spectrometry (AMS) (Synal *et al* 2007; Wacker *et al* 2010b). Data reduction was undertaken as described by Wacker *et al* (2010c). The facility maintains a continual programme of quality assurance procedures (Sookdeo *et al* 2020), in addition to participation in international inter-comparison exercises (Scott *et al* 2017; Wacker *et al* 2020). These tests demonstrate the reproducibility and accuracy of these measurements.

The results are conventional radiocarbon ages, corrected for fractionation using $\delta^{13}C$ values measured by AMS (Stuiver and Polach 1977; Table 3). These $\delta^{13}C$ values may deviate from the natural $\delta^{13}C$ of the sample by a few per mille, because sample preparation and the ion source of the AMS may lead to fractionation during the dating process, but this value is most appropriate for correcting for $^{14}C/^{12}C$ fractionation in dating.

WIGGLE-MATCHING

Radiocarbon ages are not the same as calendar dates because the concentration of ^{14}C in the atmosphere has fluctuated over time. A radiocarbon measurement has thus to be calibrated against an independent scale to arrive at the corresponding calendar date. That independent scale is the IntCal20 calibration curve (Reimer *et al* 2020). For the period covered by this study, this is constructed from radiocarbon measurements on tree-ring samples dated absolutely by dendrochronology. The probability distributions of the calibrated radiocarbon dates from bourn04, bourn07, bourn11b, bourn12a, and bourn13a, derived from the probability method (Stuiver and Reimer 1993), are shown in outline in Figures 8, 10, and 12–14.

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

The approach to wiggle-matching adopted here employs Bayesian chronological modelling to combine the relative dating information provided by the tree-ring analysis with the calibrated radiocarbon dates (Christen and Litton 1995). It has been implemented using the program OxCal v4.4 (http://c14.arch.ox.ac.uk/oxcal.html; Bronk Ramsey *et al* 2001; Bronk Ramsey 2009). The modelled dates are shown in black in Figures 8, 10, and 12–14, and quoted in italics in the text. The Acomb statistic shows how closely the assemblage of calibrated radiocarbon dates as a whole agree with the relative dating provided by the tree-ring analysis that has been incorporated in the model; an acceptable threshold is reached when it is equal to or greater than An (a value based on the number of dates in the model). The A statistic shows how closely an individual calibrated radiocarbon date agrees its position in the sequence (most values in a model should be equal to or greater than 60).

Figure 8 illustrates the chronological model for the mean sequence from bourn04 and bourn07, the quarter bars from the trestle. This model incorporates the gaps between each dated annual ring on the basis of the tentative cross-matching suggested by the ring-width dendrochronology (eg that the carbon in ring 5 of bourn04 (ETH-113041) was laid down eleven years before the carbon in ring 10 of bourn 07 (ETH-113043); Fig 9). It also incorporates the radiocarbon measurements from both cores (Table 3) calibrated using the internationally agreed radiocarbon calibration data for the northern hemisphere, IntCal20 (Reimer *et al* 2020).

The model has good overall agreement (Acomb: 115.0, An: 35.4, n: 4), and all the dates on the single rings have good individual agreement (A > 60) with their positions in the sequence. It suggests that the final surviving ring of bourn04 formed in *cal AD 1736–1751 (40% probability; bourn04 last ring*; Fig 8*)* or *cal AD 1853–1868 (15% probability)* or *cal AD 1922–1944 (40% probability)*, probably in *cal AD 1738–1748 (34% probability)* or *cal AD 1925–1941 (34% probability)*. The last surviving ring of bourn07 formed in *cal AD 1740–1755 (39% probability; bourn07 last ring*; Fig 8*)* or *cal AD 1857–1872 (15% probability)* or *cal AD 1926–1948 (40% probability)*, probably in *cal AD 1742–1752 (34% probability)* or *cal AD 1929–1945 (34% probability)*.

The radiocarbon wiggle-matching confirms the relative positions of bourn04 and bourn07 suggested by the cross-matching of the ring-width series.

Figure 10 illustrates the chronological model for bourn11b and bourn12a, the crown-tree and the left vertical wall post at the end of the crown-tree. This model incorporates the gaps between each dated annual ring on the basis of the tentative cross-matching suggested by the ring-width dendrochronology (eg that the carbon in ring 3 of bourn11b (ETH-114594) was laid down 57 years before the carbon in ring 5 of bourn 12a (ETH-114596); Fig 11). It also incorporates the radiocarbon measurements from both cores (Table 3) calibrated using the internationally agreed radiocarbon calibration data for the northern hemisphere, IntCal20 (Reimer *et al* 2020).

The model has good overall agreement (Acomb: 50.7, An: 35.4, n: 4), but both dates from core bourn11b have poor individual agreement (A: 53 and A: 31 respectively) with their positions in the sequence. It suggests that the final ring of bourn11b formed in *cal AD 1714–1719 (3% probability; bourn11b felling*; Fig 10*)* or *cal AD 1721–1737 (92% probability)*, probably in *cal AD 1726–1733 (68% probability)*. The heartwood/sapwood boundary of bourn12a formed in *cal AD 1716–1721 (3% probability; bourn12a h/s*; Fig 10*)* or *cal AD 1723–1739 (92% probability*, probably in *cal AD 1728–1735 (68% probability)*. When this sequence is constrained to end in AD 1731, the model again has good overall agreement

(Acomb: 46.2, An: 31.6, n: 5; model not shown), but both dates from bourn11b again have poor individual agreement (A: 43 and A:21 respectively).

The radiocarbon wiggle-matching thus suggests that the tentative cross-matching and dating of bourn11b and bourn12a suggested by ring-width dendrochronology is possible, but does not confirm that it is correct.

Separate models were therefore constructed for the dating of these timbers, which include only the relative sequences provided by the ring counting in each timber and the radiocarbon dates (Fig 11).

The model for bourn11b has good overall agreement (Amodel: 69.0, An: 50.0, n:2; Fig. 12 (lower)), and both radiocarbon dates have good individual agreement (A: 69 and A: 86 respectively). This model suggests that bourn11b was felled in *cal AD 1673–1704 (90% probability; bourn11b felling*; Fig 12 (lower)*)* or *cal AD 1726–1735 (5% probability)*, probably in *cal AD 1677–1693 (68% probability)*. When this sequence is constrained to end in AD 1729, the overall model has poor agreement (Amodel: 25.3, An: 40.8, n: 3; model not shown) and both radiocarbon dates again have poor individual agreement (A: 43 and A: 21 respectively).

The model for bourn12a also has good overall agreement (Amodel: 114.2, An: 50.0, n: 2; Fig 12 (upper)), and suggests that the heartwood/sapwood transition of this timber formed in *cal AD 1716–1740 (30% probability; bourn12a h/s*; Fig 12 (upper)) or *cal AD 1836–1853 (22% probability)* or *cal AD 1873–1891 (5% probability)* or *cal AD 1893–1928 (38% probability)*, probably in *cal AD 1722–1736 (24% probability)* or *cal AD 1840–1851 (18% probability)* or *cal AD 1899–1902 (2% probability)* or *cal AD 1907–1923 (24% probability)*. When this sequence is constrained to end in AD 1731, the overall model has good agreement (Acomb: 146.1, An: 40.8, n: 3; model not shown) and both radiocarbon dates have good individual agreement (A: 135 and A: 143 respectively).

This analysis suggests that the tentative dating suggested for bourn11b from the ring-width dendrochronology as ending in AD 1729 is possible, but not probable. The tentative dating of bourn12a, as ending in AD 1731, however, is supported by the radiocarbon wiggle-matching.

Figure 13 illustrates the chronological model for the sequence of dates from bourn13a, a core from the right vertical post at the end of the crown-tree in the buck. This model incorporates the gaps between each dated annual ring (eg that the carbon in ring 5 (ETH-113045) was laid down 20 years before the carbon in ring 25 (ETH-113046); Fig 11). It also incorporates the radiocarbon measurements (Table 3) calibrated using the internationally agreed radiocarbon calibration data for the northern hemisphere, IntCal20 (Reimer *et al* 2020).

This model has good overall agreement (Amodel: 114.7, An: 40.8, n: 3; Fig 13), and suggests that the heartwood/sapwood boundary ring of bourn13a formed in *cal AD 1704–1723 (66% probability; bourn13a h/s*; Fig 13) or *cal AD 1820–1834 (29% probability)*, probably in *cal AD 1708–1719 (54% probability)* or *cal AD 1822–1827 (14% probability)*. The date of AD 1456 tentatively suggested by the ring-width dendrochronology is clearly erroneous. When this sequence is constrained to end in AD 1711, as suggested by the oxygen isotope analysis (*see* below), the overall model has good agreement (Acomb: 131.6, An: 40.8, n: 3; model not shown) and all three radiocarbon dates have good individual agreement (A: 141, A: 169, and A: 73 respectively).

Finally, we test the relative positions of the elm ring sequences tentatively suggested by the ring-width and oxygen isotope dendrochronology by combining the radiocarbon dates from all three cores (Table 3) with this sequence (Fig 11). This model has good overall agreement (Amodel: 71.3, An: 26.7, n: 7; Fig 14), and suggests that the final ring of the elm sequence formed in *cal AD 1735–1745 (95% probability; elm_final_ring*; Fig 14), probably in *cal AD 1737–1743 (68% probability)*. When this sequence is constrained to end in AD 1739, as suggested by the oxygen isotope dendrochronology (*see* below), the overall model has good agreement (Acomb: 66.0, An: 25.0, n: 8; model not shown), but again the two dates from bourn11b have poor individual agreement (*ETH-114594*, A: 43 and *ETH-111459*, A: 21). It is clear, however, that the radiocarbon wiggle-matching independently confirms the dating of these timbers suggested by the ring-width and oxygen isotope dendrochronology.

OXYGEN ISOTOPE ANALYSIS

Following the ring-width dendrochronology and radiocarbon wiggle-matching, it was clear that the main post is the earliest surviving element in the mill, with a last dated ring of AD 1503 (Tables 1 and 2a). Other elements of the trestle appear to date to the mid eighteenth-century at the earliest, and may relate to timbers inserted during repairs in the AD 1870s or AD 1930s (*see* below, Fig 17). Given the poor state of repair of the existing timbers in the trestle, the decision has been made to replace this element of the mill during current renovations.

Ring-width dendrochronology has dated the felling of three timbers used in the buck to the first decade of the eighteenth century. Radiocarbon wiggle-matching has not been able to confirm a date of AD 1729 tentatively suggested by the ring-width analysis for the felling of the crown-tree (bourn11b), but suggests that a similarly tentative date of AD 1731 for the last surviving ring of bourn12a, the left vertical wall post at the end of the crown-tree, may be correct (Figs 10 and 12). Wiggle-matching has demonstrated that the other vertical post at the end of the crown-tree, bourn13a, is not coeval with the main post, but rather dates either to the first quarter of the eighteenth century or to the AD 1820s or early AD 1830s (Fig 13).

Potentially, therefore, the existing fabric in the buck may represent largely intact early eighteenth-century timberwork. The middle section of core bourn11b (rings 6–86) from the crown-tree and duplicate cores from the two vertical posts at the end of the crown-tree (bourn12b and bourn13b), were therefore submitted for oxygen isotope analysis in an attempt to refine our understanding of this important survival.

The three samples from Bourn Mill selected for oxygen isotope analysis (bourn11b, bourn12b, and bourn13b) were all from elm timbers. Sample bourn11b comprised 95 measured rings with complete sapwood and bark edge, sample bourn12b had 51 measured rings and bark edge, and sample bourn13b had 50 measured rings, plus an additional 8–11 unmeasured rings to bark edge (Table 1). Oxygen isotope ratios were obtained from a total of 78, 42, and 41 rings from samples bourn11b, bourn12b, and bourn13b respectively (Fig 11; Table 4; Appendix 2). Samples bourn12b and bourn13b had latewood or additional rings visible at the start of the core (pith end), not included in the initial ring-width measurements. These rings were excised and prepared for isotopic analysis (ring 0 in bourn12b and rings −2–0 in bourn13b). Where rings exhibited no latewood, or where the sample was degraded or showed signs of possible contamination, isotopic analyses were not attempted. For bourn11b rings 49 and 31 there was insufficient latewood for an isotope measurement.

Methodology

Oxygen isotope dendrochronology relies upon the same fundamental principles, limitations, and assumptions as conventional (ring-width-based) dendrochronology. However, rather than using ring-width measurements it uses the ratio of heavy to light oxygen isotopes (McCarroll and Loader 2004) in the latewood cellulose ($\delta^{18}O$). The isotopes can have a higher signal to noise ratio than ring-width measurements and strong signals do not require the trees to be growing under any environmental stress (Young *et al* 2015).

The method relies on a regional master chronology (Loader *et al* 2019) constructed using dendrochronologically-dated oak timbers sourced from across a c 45,200km^2 (20,000 mile^2) region centred on Oxfordshire, in south-central England. The chronology was developed as part of a Leverhulme Trust funded project (RPG-2014-327) and currently covers a period from AD 1200–2000 with annual replication (sample depth) of 10 trees throughout the chronology period. A thin slice (4mm) is removed from the base of the sample cores selected for isotopic analysis to retain the original measured surface and ensure its preservation for future dendrochronology and archiving.

Several physiological studies of oak trees have shown that the earlywood is partially formed from carbohydrates fixed in previous years (Richardson *et al* 2013; McCarroll *et al* 2017). To avoid this chemical carry-over effect in oak, only the latewood of each tree-ring is prepared for chemical analysis and dating. Elm is also a ring porous species and likely also exhibits a carry-over of carbohydrate from latewood to earlywood (Loader *et al* 2021). For consistency of approach, latewood only was analysed isotopically. Each latewood ring is carefully removed as thin slivers (approximately 40µm thick) using a scalpel and dissecting microscope.

Wood samples are converted to α-cellulose using an acidified sodium chlorite solution with removal of hemicelluloses by sodium hydroxide (Loader *et al* 1997). Samples are homogenised using an ultrasonic probe and vacuum-dried at −50˚C for 48 hours. 0.30–0.35mg of dry α-cellulose are weighed into individual silver foil capsules for pyrolysis to carbon monoxide (CO) at 1400°C (Woodley *et al* 2012). The resulting carbon monoxide is analysed using a Delta V isotope-ratio mass spectrometer. Data are expressed as per mille (‰) deviations relative to the Vienna Standard Mean Ocean Water (VSMOW) international standard. Analytical precision is typically 0.30‰ (σ_{n-1}, n=10) (Loader *et al* 2015). The master chronology was prepared as two independent pools of five trees to ensure quality control and the resulting data combined to form the ten-tree master chronology. Individual samples for dating are prepared and analysed separately, using identical preparation protocols. The resulting stable isotopic data are presented as chronologies (time series).

Tree-ring oxygen isotope data have statistical properties that are quite different from ring-widths, requiring different pre-treatment. The Baillie-Pilcher filter that works well for ring width dating (Baillie and Pilcher 1973) is not appropriate for isotope data and would result in unrealistically high *t*-values (Loader *et al* 2019). The isotope data are filtered using a simple nine-year rectangular filter, with indices derived by subtraction. Degrees of freedom are corrected for autocorrelation and filtering resulting in *t*-values that conform to a Student's *t*-distribution and can be used to calculate one-tail probabilities of error. The probabilities are corrected for multiple testing by division by the number of possible matches against the master chronology (a 'Bonferroni' correction) (Dunn 1959; 1961). The ratio of probabilities for the first and second highest *t*-values provides an 'isolation factor'. Potential dates are only considered for acceptance when the corrected probability of error is less than one in a hundred and the probability for the best match is more than an order of magnitude less likely to be in error than the next best match. All *t*-values pertaining to isotope data in this report are Student's *t*-values.

Cross-matching between isotope samples is achieved using the same approach, with the number of possible matches determined by setting a minimum size of overlap. Student's *t*-values, corrected one-tail probabilities and the isolation factor are reported as well as the highest correlation coefficient, offset in ring number, and size of overlap.

In isotope dendrochronology it is not always necessary or possible to measure isotopically each tree-ring, in which case the last ring measured isotopically must be placed within the context of the entire sample. This may require addition of years identifiable in the sample, but not measured isotopically. Once a date for the last ring has been calculated, a felling date or sapwood estimate may be assigned using identical methods to those in ring-width dendrochronology (*see* above).

Results

The oxygen isotope series from bourn11b comprises isotopic measurements from 78 rings (ring 6 to ring 85). Rings 31 and 49 did not yield enough latewood for isotope analysis. The series from bourn12b comprises isotopic measurements from 42 rings (ring 0 to ring 41). The series from bourn13b comprises measurements from 41 rings (ring –2 to ring 38). Inter-series cross-matching is relatively low, but consistent with one another (Table 5).

The *t*-value thresholds required for secure cross-matching of isotopic series from elm timbers, however, are currently uncertain but it is unlikely that the isotopic match between bourn11b and bourn12b (Student's *t*=2.85), at least, could be considered secure in the absence of supporting evidence. In this case, the relative position of bourn11b and bourn12b suggested by the oxygen isotope analysis is supported by the ring-width cross-matching between bourn11b and bourn12short (Baillie-Pilcher *t*=5.1) at the same relative offset, and also by the radiocarbon wiggle-matching of the combined series (Fig 10). The relative position of bourn13b against the other two timbers is also supported by radiocarbon wiggle-matching (Fig 14).

Table 6 shows the cross-dating statistics for the individual isotopic series from each of the three sampled timbers from Bourn Mill, and also the cross-dating statistics for the three two-timber isotopic mean series, and the three-timber isotopic mean series. Individually, only timbers bourn11b and bourn12b produce dates that independently pass the thresholds for consideration as dated suggested by Loader *et al* (2019), although in this case these thresholds are considered indicative given the species and relative short length of the isotope series. Although isotopic series of bourn13b does not pass this threshold individually, it does cross-match securely against the isotopic mean series of bourn11b and bourn12b (r=0.709, df=33, Student's *t*=5.78, 1/p > 1 million, IF > 1000; Table 5; Fig 15).

A mean oxygen isotope series (bourn-x) covering 90 years (89 measurements) was compiled, which dated securely against the south-central England oxygen isotope master chronology (r=0.622, df=75, Student's *t*=6.88, 1/p > 1 million, IF > 1000; Table 6; Fig 16) when it spans AD 1640–1729.

INTERPRETATION

Three oak timbers have been dated from the Trestle (Table 1; Fig 17). Ring-width dendrochronology has determined that the last sampled ring of the main post formed in AD 1503. The samples did not retain any sapwood, but examination of the timber suggested that the outer rings are likely to be close to the heartwood/sapwood boundary. The *terminus post quem* for felling provided by adding the probability distribution of sapwood rings observed on historic oak timbers in the North and Midlands of England (Miles 1997, fig 5) to the date of the last measured ring is thus likely to be close to the time of felling of this tree. This is after AD 1513–44 (94% probability) or AD 1546–9 (1% probability). Radiocarbon wiggle-matching confirmed the tentative cross-matching of the east and west quarter bars, but was only able to suggest that these dated to either the later eighteenth century or to the later nineteenth century or to the mid-twentieth century (Table 1; Figs 8 and 17). There are records of the trestle being renewed in oak in AD 1874 and additional work by Hunts of Soham in AD 1931 (Davies and Pearce 2020), and so it is possible that these timbers derive from one of these episodes.

Using a combination of techniques, seven timbers have been dated from the Buck (Table 1; Fig 17). Ring-width dendrochronology has determined the felling dates of three oak timbers: the left sheer (bourn08) in the spring of AD 1707, and that the right sheer (bourn10) and sheer space (bourn09) in the spring of AD 1703. The cross-matching of the ring-width series from bourn11b (the crown-tree) against the oak master chronologies (Table 2c) would have been accepted as evidence of secure dating if this timber had been oak, but experience of the statistical thresholds required for secure dating of elm timbers, such as this, urges caution (Bridge *et al* 2019; Bridge 2020). Table 2d shows the matches for the short sequence for bourn20, which must be regarded as tentative because of the shortness of the sequence.

The suggested dating for bourn11b, and bourn12short with which it cross-matches, is supported, however, by oxygen isotope dendrochronology (Table 6), and that for bourn12 by radiocarbon wiggle-matching as well (Fig 12). We can therefore accept the dating of bourn11 as an oxygen isotope-supported ring-width date as felled in winter AD 1729/30$_{\mathrm{DI}}$, and the dating of bourn12 as and oxygen isotope and radiocarbon-supported ring-width date as felled in winter AD 1739/40$_{\mathrm{DIR}}$. This leads us to accept the ring-width dendrochronology for bourn20 (the left rear corner post), which cross-matches with both these ring-series at the relevant offsets (bourn11b, t=3.4 and bourn12short, t=3.0) and provides good matches against the oak reference chronologies (Table 2d). A *terminus post quem* for the felling of bourn20 is provided by adding the probability distribution of sapwood rings observed on historic oak timbers in the North and Midlands of England (Miles 1997, fig 5) to the date of the last measured ring (AD 1732). This is after AD 1741–72 (94% probability) or AD 1774–7 (1% probability). The oxygen isotope dendrochronology of bourn13 provides conclusive dating of this timber (Table 6), but only if the cross-matching of bourn11b and bourn12 is accepted. As we have seen, this cross-matching requires the support of ring-width dendrochronology. The isotopic dating of bourn13 is, however, supported by radiocarbon wiggle-matching (Fig 13), and so can be accepted as a radiocarbon-supported isotope date. The date of AD 1709 for bourn13b relates to ring 38, which is 12 rings from the end of the ring-width sequence (Fig 11). There follows between 8 and 11 unmeasured rings before the waney edge, so the timber was felled in the winter of AD 1729–32$_{\mathrm{IR}}$.

DISCUSSION

Allowing for the minimum likely number of sapwood rings and assuming that the outer rings on the timber are likely to be close to the heartwood/sapwood boundary, a felling date for the main post in the first half of the sixteenth century is most likely (Table 2a; Fig 17), suggesting that the mill could be somewhat earlier than suggested by the record of the mill being present in AD 1636. It is also of interest that the main post has proved to be much older than other timbers in a number of post mills previously investigated, as at Pitstone Mill (Miles *et al* 2004), Nutley Mill (Bridge 2006), and Drinkstone Mill (Bridge 2001a). Although several mills claim to be the oldest in the country, Bourn has often been thought to have the best claim for this title, although it is a slightly faulty concept, in that nearly all mills dated so far have proved to be assemblages of timbers of several dates (Bridge *et al* in prep).

The felling dates for the sheers and sheer-spacer are of particular interest, as it is known that the mill was blown down in AD 1741 and it was thought the buck might post-date this event, but these dates in the first decade of the eighteenth century highlight a previously unrecognised phase.

Combined results from ring-width dendrochronology, radiocarbon dating, and oxygen isotope dendrochronology enable precise dates to be assigned to the elm timbers bourn11, bourn12, and bourn13. The combined oxygen isotope and radiocarbon dating of bourn13 confirms that a tentative early date of AD 1456 suggested by ring-width dendrochronology is erroneous.

The sites giving the strongest ring-width matches with the Bourn timbers (Tables 2a-d) suggest a likely local origin for the dated material.

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TABLES

Table 1: Details of samples taken from Bourn windmill for scientific dating

Sample No	Location	No rings	Date of measured sequence AD	Sapwood	Mean ring width (mm)	Mean sensitivity	Felling date range (AD/*cal AD*)
Trestle							
bourn01a	Main post	98	1402–99	-	2.14	0.22	
bourn01b	*ditto*	31	1473–1503	-	2.26	0.24	
bourn01c	*ditto*	30	1461–1490	-	2.24	0.22	
bourn01	Mean of 01a, 01b, and 01c	102	1402–1503	-	2.13	0.22	after 1513–44 (94%) or 1546–9 (1%)
bourn02	North-south cross-tree	<20	-	-	NM	-	-
bourn03i	West-east cross-tree (inner)	18	-	-	5.16	0.15	-
bourn03ii	*ditto* (outer)	24	-	11	3.94	0.22	-
bourn04	East quarter bar	58	Rel yrs 1–58[0407]	-	3.81	0.17	after *1749–89 (40%)* or *1868–1900 (15%)* or *1936–1978 (40%)*
bourn05i	North quarter bar (inner)	20	-	-	4.04	0.23	
bourn05ii	*ditto* (outer)	13	-	7	4.55	0.12	-
bourn06	South quarter bar	58	-	-	2.98	0.24	-
bourn07	West quarter bar	56	Rel yrs 7–62[0407]	11	2.83	0.18	*1744–83 (40%)* or *1863–94 (15%)* or *1931–72 (40%)*
Buck							
bourn08	Left sheer	93	1614–1706	17¼C	1.63	0.27	spring 1707
bourn09i	Front sheer spacer (inner rings)	53	1619–71		1.45	0.17	
bourn09ii	*ditto* (outer rings)	31	1672–1702	16¼C	0.85	0.22	
bourn09	Front sheer spacer	84	1619–1702	16¼C	1.23	0.19	spring 1703
bourn10	Right sheer	74	1629–1702	21¼C	1.24	0.28	spring 1703
bourn11a	Crown-tree (ELM)	*c* 102	-	*c* 25C	NM	-	-

bourn11b	*ditto*	95	1635–1729$_{\mathrm{DI}}$	*c* 25C	2.04	0.31	winter 1729/30$_{\mathrm{DI}}$
bourn12a	Left vertical wall post (at end of crown tree) (ELM)	42	1690–1731$_{\mathrm{DIR}}$	h/s	2.58	0.21	-
bourn12b	*ditto*	51	1689–1739$_{\mathrm{DIR}}$	C	2.51	0.22	-
bourn12short	Mean of 12a-short and 12b-short	43	1697–1731$_{\mathrm{DIR}}$	C	2.48	0.21	winter 1739/40$_{\mathrm{DIR}}$
bourn13a	Right vertical wall post (at end of crown tree) (ELM)	47	1665–1711$_{\mathrm{IR}}$	h/s	2.02	0.27	-
bourn13b	*ditto*	50	1672–1721$_{\mathrm{IR}}$	(+8–11NMC)	1.88	0.26	-
bourn13	Mean of 13a and 13b	57	1665–1721$_{\mathrm{IR}}$	(+8–11NMC)	1.86	0.26	winter 1729–32$_{\mathrm{IR}}$
bourn14	Front left corner post (ELM)	30	-	h/s	2.62	0.26	-
bourn15	Right rear corner post (ELM)	< 20	-	-	NM	-	-
bourn16	Left top rail	< 20	-	-	NM	-	-
bourn17	Windshaft	70	-	?h/s	1.67	0.30	-
bourn18	Rear beam supporting end of windshaft (ELM)	36	-	-	1.91	0.33	-
bourn19	Patch on main post	< 15		-	NM	-	-
bourn20	Left rear corner post (ELM)	38	1695–1732	(+2NM)	2.17	0.22	after 1741–72 (94%) or 1774–7 (1%)
bourn21	Left front diagonal brace (re-used timber)	27	-	-	2.90	0.27	-

Key: ¼C = complete sapwood, felled the following spring; C = complete sapwood, felled the following winter; h/s = heartwood/sapwood boundary; NM = not measured; 0407 = relative years within mean series bourn0407; $_{\mathit{DI}}$ *= oxygen isotope-supported ring-width date;* $_{\mathit{DIR}}$ *= radiocarbon and oxygen isotope-supported ring-width date;* $_{\mathit{IR}}$ *= radiocarbon-supported oxygen isotope date; date ranges* in italics *derive from radiocarbon wiggle-matching alone*

Table 2a: Dating evidence for the site series bourn01 (main post) as spanning AD 1402–1503

Source region:	Chronology name:	Publication reference:	File name:	Span of chronology (AD)	Overlap (years)	*t*-value
Bedfordshire	Chicksands Priory	Howard *et al* 1998	CHKSPQ01	1200–1541	102	9.9
Cambridgeshire	Jesus College, Cambridge	Tyers 2006	JESUSC1	1379–1509	102	9.1
Northants	Apethorpe Hall, Apethorpe	Arnold *et al* 2008	APTASQ01	1292–1639	102	9.0
Essex	Thaxted Church	Tyers 1990	THAXTED2	1345–1526	102	7.6
Cambridgeshire	Peterborough Cathedral presbytery	Tyers 2004b	PCF6	1208–1500	99	7.3
Oxfordshire	Christ Church porters' lodge	Miles *et al* 2014	CHCHPL	1323–1525	102	6.9
Kent	Walmer Castle, Deal	Arnold and Howard 2015	WLMCSQ01	1396–1523	102	6.8
Somerset	Muchelney Abbey	Bridge 2002	MUCHNEY	1148–1498	97	6.8
Devon	Sydenham House panelling	Arnold *et al* 2015	SYDPSQ01	1266–1629	102	6.8
Suffolk	Crow's Hall panelling	Miles *et al* 2007	CROWSHL2	1404–1551	100	6.6

Table 2b: Dating evidence for the site series bourn1098 as spanning AD 1614–1706

Source region:	Chronology name:	Publication reference:	File name:	Span of chronology (AD)	Overlap (years)	*t*-value
Rutland	Oakham Castle	Arnold and Howard 2013	OKMCSQ03	1598–1737	93	8.9
Berkshire	Maidenhead Bridge	Miles *et al* 2003	MDNHEAD2	1605–1750	93	8.8
Bedfordshire	De Grey Mausoleum, Flitton	Howard *et al* 2003	FLTASQ01	1510–1726	93	8.6
Northants	Apethorpe Hall, Apethorpe	Arnold *et al* 2008	APTASQ02	1574–1749	93	8.5
Shropshire	Buildwas Abbey	Miles 2002	BUILDWS3	1563–1687	74	7.2
Oxfordshire	Old Clarendon Building, Oxford	Worthington and Miles 2006	CLRNDNOX	1539–1711	93	6.9
Leicestershire	Kibworth Harcourt mill	Arnold *et al* 2004	KIBASQ01	1582–1773	93	6.9
Nottinghamshire	Old House, Norwell	Hurford *et al* 2010	NRWCSQ02	1653–1742	54	6.7
Worcestershire	The Commandery, Worcester	Arnold *et al* 2006	WORDSQ02	1608–1708	93	6.7
Essex	Cressing Temple Barns	Tyers and Hibberd 1993	CRBCR2	1661–1737	46	6.7

Table 2c: Dating evidence for bourn11b as spanning AD 1635–1729

Source region:	Chronology name:	Publication reference:	File name:	Span of chronology (AD)	Overlap (years)	*t*-value
South Yorkshire	Barnburgh Hall, nr Doncaster	Tyers 2000	BRNBGHST	1663–1734	67	6.3
Oxfordshire	Old Clarendon Building, Oxford	Worthington and Miles 2006	CLRNDNOX	1539–1711	77	5.7
Suffolk	Ballingdon Bridge	Cooper *et al* 2012	BALLNGDN	1484–1790	95	5.3
Buckinghamshire	West Lake Pavilion, Stowe	Miles *et al* 2003	STOWE6	1610–1762	95	5.3
Suffolk	Ballingdon Bridge, Sudbury	Tyers 2002	BCBT12	1484–1790	95	5.3
Northamptonshire	Apethorpe Hall, Apethorpe	Arnold *et al* 2008	APTASQ02	1574–1749	95	5.1
Wiltshire	Salisbury Cathedral	Miles 2005	SARUM12	1556–1703	69	5.1
Cambridgeshire	Jesus College, Cambridge	Tyers 2006	JESUSC2	1625–1738	95	5.0
Rutland	Oakham Castle	Arnold and Howard 2013	OKMCSQ03	1598–1737	95	5.0
Bedfordshire	Chicksands Priory	Howard *et al* 1998	CHKSPQ02	1611–1814	95	4.8

Table 2d: Dating evidence for bourn20 as spanning AD 1695–1732

Source region:	Chronology name:	Publication reference:	File name:	Span of chronology (AD)	Overlap (years)	*t*-value
Cambridgeshire	St Andrew's Church, Wimpole	Bridge 1998	WIMPOLE2	1667–1729	38	5.7
Kent	Longport Farmhouse	Tyers 1996	LPH2T7	1617–1760	38	5.3
Norfolk	Thrigby Post Mill	Fletcher 1984	THRIGBY	1674–1790	38	5.2
Cambridgeshire	Ely Cathedral	Arnold *et al* 2005	ELYCSQ05	1592–1794	38	5.1
Cambridgeshire	Houghton Mill	Loader pers comm	HGHTNMLL	1683–1764	38	4.8
Essex	St Mary's Church, Saffron Walden	Bridge 2001b	SAFFRON2	1701–89	32	4.7
London	White Tower, Tower of London	Miles 2007	WHTOWR9	1629–1782	38	4.5
London	Dovecote, Breakspear House	Arnold and Howard 2011	HFDCSQ01	1695–1769	38	4.5
Oxfordshire	Chazey Court	Miles *et al* 2004	CHAZEY2	1674–1737	38	4.5
Hampshire	Parsonage Farm, Kings Somborne	Miles *et al* 2006	PARSNFB2	1684–1761	38	4.3

Table 3: Radiocarbon measurements and associated δ13C values from samples bourn04, bourn07, bourn11b, bourn12a, and bourn13a

Laboratory Number	Sample	Radiocarbon Age (BP)	$\delta^{13}C_{AMS}$ (‰)
ETH-113041	bourn04, ring 5 (*Quercus* sp., heartwood)	145±14	−26.7
ETH-113042	bourn04, ring 40 (*Quercus* sp., heartwood)	129±14	−24.7
ETH-113043	bourn07, ring 10 (*Quercus* sp., heartwood)	101±14	−26.5
ETH-113044	bourn07, ring 50 (*Quercus* sp., sapwood)	157±14	−24.0
ETH-114594	bourn11b, ring 3 (*Ulmus* sp., heartwood)	325±15	−23.3
ETH-114595	bourn11b, ring 89 (*Ulmus* sp., heartwood)	154±15	−21.8
ETH-114596	bourn12a, ring 5 (*Ulmus* sp., heartwood)	138±15	−21.9
ETH-114597	bourn12a, ring 25 (*Ulmus* sp., heartwood)	92±15	−22.7
ETH-113045	bourn13a, ring 5 (*Ulmus* sp., heartwood)	189±14	−23.9
ETH-113046	bourn13a, ring 25 (*Ulmus* sp., heartwood)	145±14	−21.0
ETH-113047	bourn13a, ring 43 (*Ulmus* sp., heartwood)	85±14	−20.9

Table 4: Sample description: timber type and position, material analysed, number of complete tree rings (N), number (N_i) and range of rings for which $\delta^{18}O$ measurements were undertaken, and laboratory code. The presence of a zero/negative ring number indicates that latewood or additional rings were preserved at the pith-end of the sample, these were measured isotopically but not included in the ring-width analyses

Sample	Timber and Position	Species	N	N_i	$\delta^{18}O$ (Measured rings)	Code
bourn11b	Crown-tree (*c* 25C)	Latewood α-cellulose *Ulmus* spp	95	78	6–85	SWAN-70a
bourn12b	Left vertical wall post (at end of crown tree) (C)	Latewood α-cellulose *Ulmus* spp	51	42	0–41	SWAN-70b
bourn13b	Right vertical wall post (at end of crown tree) (+8–11NMC)	Latewood α-cellulose *Ulmus* spp	50	41	−2–38	SWAN-70c

Key: h/s=heartwood/sapwood boundary; (7) = number of sapwood rings preserved; C =bark edge preserved; NM = ring-widths not measured

Table 5: Cross-matching matrix for samples bourn11b, bourn12b and bourn13b identifying number of rings [N_i] for which $\delta^{18}O$ measurements have been undertaken. Upper right: Student's t*-value and position (offset; the bourn12b isotopic series ends 10 years after that of bourn11b and 20 years after bourn13b). Lower left (shaded cell): Pearson's correlation coefficient and degrees of freedom for position of best match (series compared column versus row). Right hand side shows the Students-t values obtained with two sample means of the isotope series aligned by their internal matching*

	bourn11b [78]	bourn12b [42]	bourn13b [41]	bourn11b12b [88]	bourn11b13b [79]	bourn12b13b [61]
bourn11b	-	2.85 10	3.92 –10	-	-	5.03 –10
bourn12b	0.495 16	-	3.68 –20	-	4.10 10	-
bourn13b	0.570 24	0.666 16	-	5.78 –20	-	-

Table 6: Stable oxygen isotope dating of the composite and individual elm samples from Bourn Mill against the south-central England master chronology (Loader et al *2019) over the period AD 1200–AD 2000. Number of whole rings present in core sample (N), number of rings on which $\delta^{18}O$ measurements were undertaken (N_i), Pearson's correlation coefficient (r), degrees of freedom (adjusted for autocorrelation and multiple sampling), Student's* t*-value, probability (1/p), isolation factor (IF), and date*

Sample	Description	N	N_i	R	df	*T*	1/p	IF	Date
bourn11b	Crown-tree	95	78	0.583	65	5.78	11,926	>1000	AD 1719
bourn12b	Left vertical wall post	51	42	0.675	34	5.33	410	718	AD 1729
bourn13b	Right vertical wall post	50	41	-	-	-	-	-	FAIL
bourn11b12b	Mean of bourn11b & bourn12b		88	0.633	74	7.03	>1 million	>1000	AD 1729
bourn11b13b	Mean of bourn 11b & bourn 13b		79	0.580	66	5.78	12,700	>1000	AD 1719
bourn12b13b	Mean of bourn12b & bourn13b		61	0.667	51	6.40	55,670	>1000	AD 1729
bourn-x	Mean of bourn11b, bourn12b & bourn13b		89	0.622	75	6.88	>1 million	>1000	AD 1729

FIGURES

Figure 1: Maps to show the location of Bourn Mill (marked in red dot). Scale: top right 1:25000; bottom 1:1250. © Crown Copyright and database right 2021. All rights reserved. Ordnance Survey Licence number 100024900

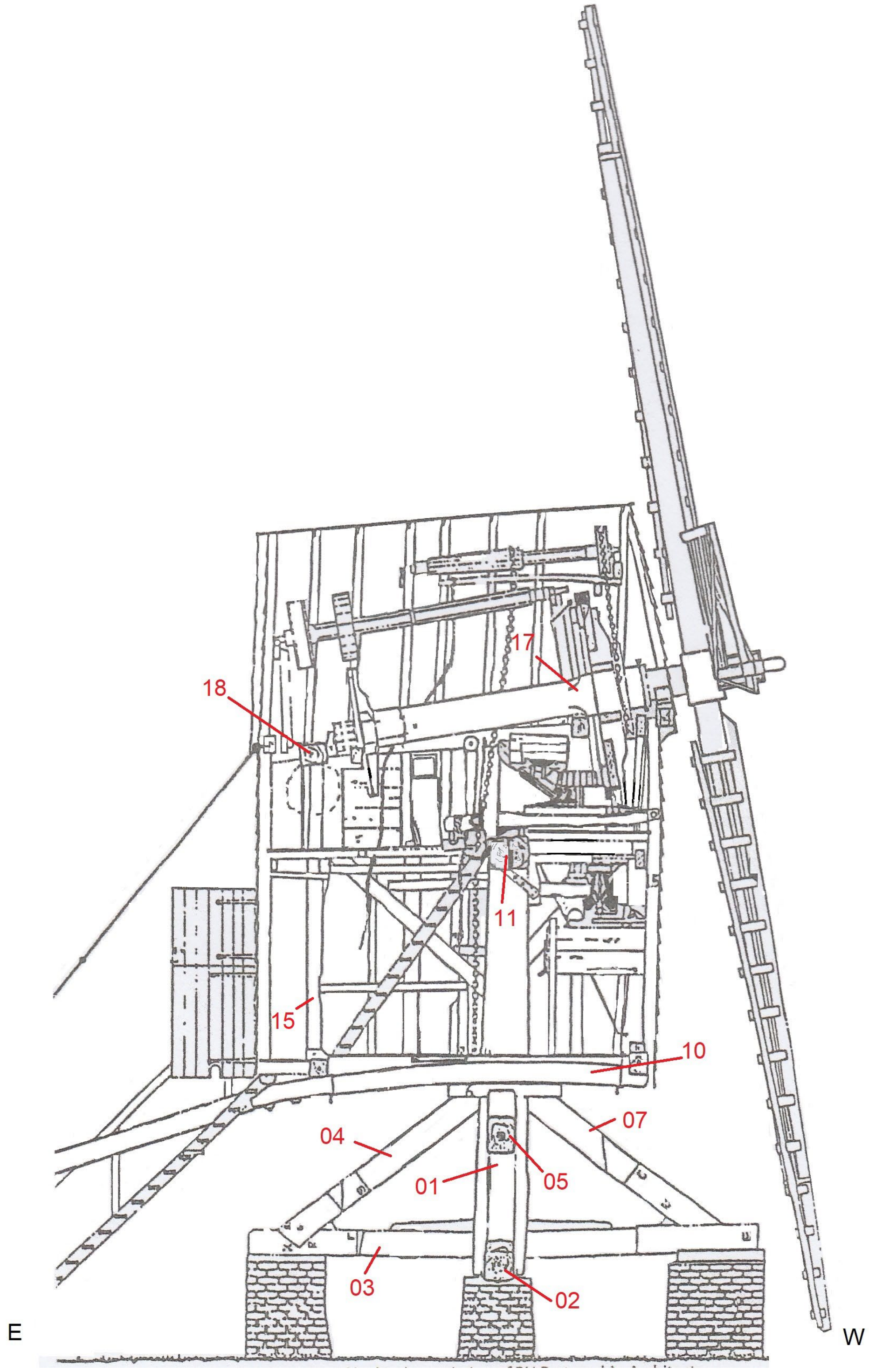


Figure 2: Drawing of the mill supplied by Cambridge Past, Present, and Future and reproduced by kind permission of RH Partnership Architects, indicating some of the timbers sampled for dendrochronology. Presently, the mill is immobile, facing west

Figure 3: Photograph looking at the left centre of the buck, indicating the left vertical post (bourn12) with the crown-tree (bourn11) and front diagonal brace (bourn21, photograph by Martin Bridge)

Figure 4: The right vertical post, sample bourn13 (photograph by Martin Bridge)

Figure 5: View of the main post (bourn01), looking towards the rear of the mill (currently east, with the mill immobile) and indicating the patch at the base of the main post (bourn19)(photograph by Martin Bridge)

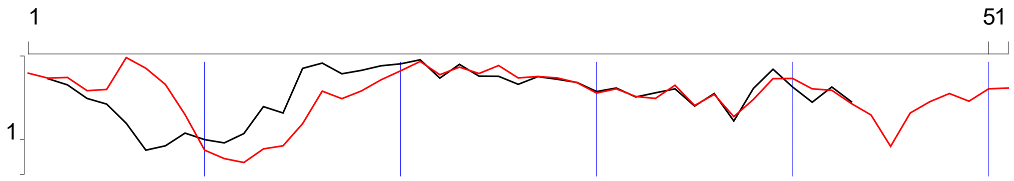


Figure 6: Plots of the two elm series bourn12a (black) and bourn12b (red) showing the similarity in growth of the outer rings, but distinct differences between the early rings. The y-axis is ring width (mm) on a logarithmic scale, the x-axis is relative years

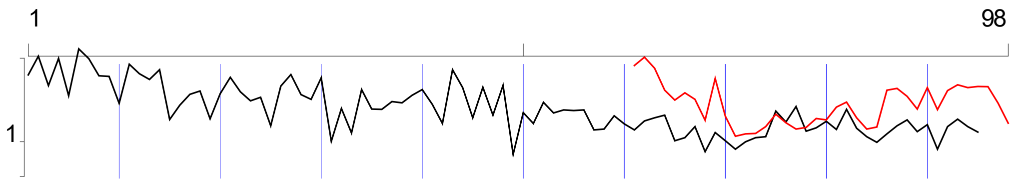


Figure 7: Plots of the two elm series bourn11b (black) and bourn20 (red) showing a potential matching position originally highlighted by matches against the oak database. The y-axis is ring width (mm) on a logarithmic scale, the x-axis is relative years.

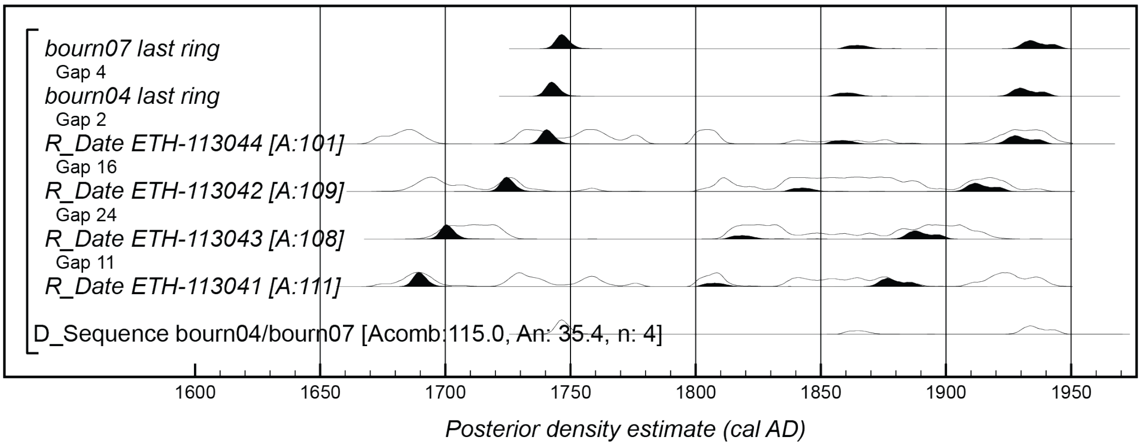


Figure 8: Probability distributions of dates from mean sequence bourn0407, from the timbers forming the quarter bars in the trestle. Each distribution represents the relative probability that an event occurs at a particular time. For each of the dates two distributions have been plotted: one in outline, which is the simple radiocarbon calibration, and a solid one, based on the wiggle-match sequence. Distributions other than those relating to particular samples correspond to aspects of the model. For example, the distribution 'bourn04 last ring' is the estimated date when the last surviving ring of sample bourn04 formed. The large square brackets down the left-hand side along with the OxCal keywords define the overall model exactly

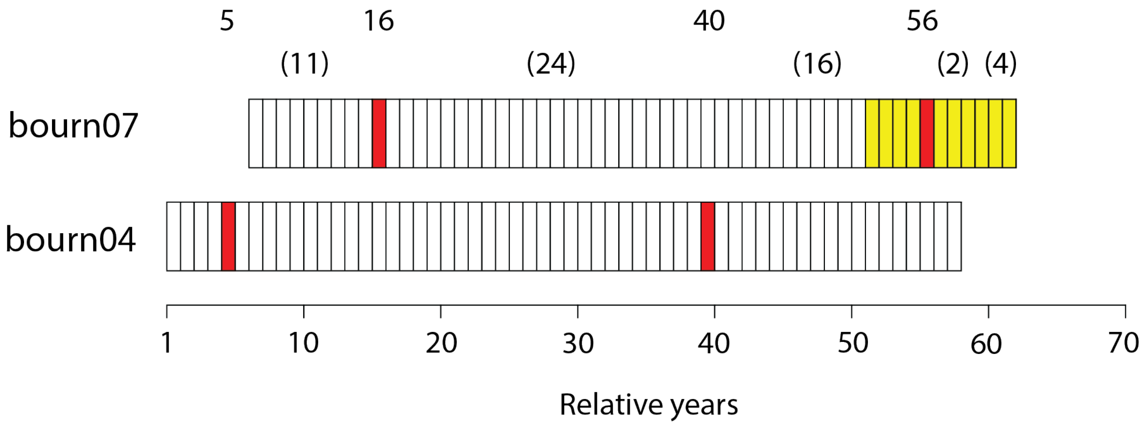


Figure 9: Schematic illustration of timbers from mean sequence bourn0407, showing the relative positions of the single-ring sub-samples from timbers bourn04 and bourn07 submitted for radiocarbon dating and the gaps between these samples (white: heartwood rings; yellow: sapwood rings; red: rings sampled for radiocarbon dating)

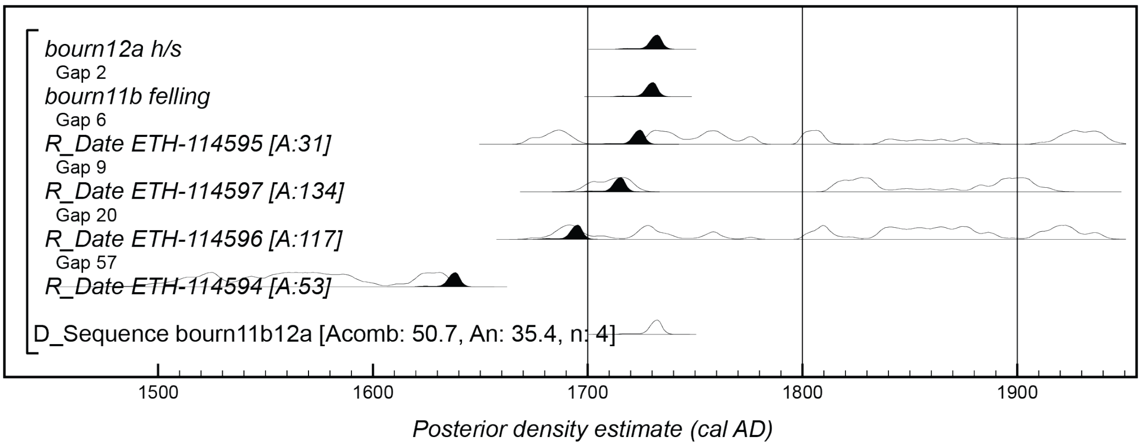


Figure 10: Probability distributions of dates from mean sequence bourn11b12a, from the crown-tree and left vertical wall post at the end of the crown-tree. The format is identical to that of Figure 8. The large square brackets down the left-hand side along with the OxCal keywords define the overall model exactly

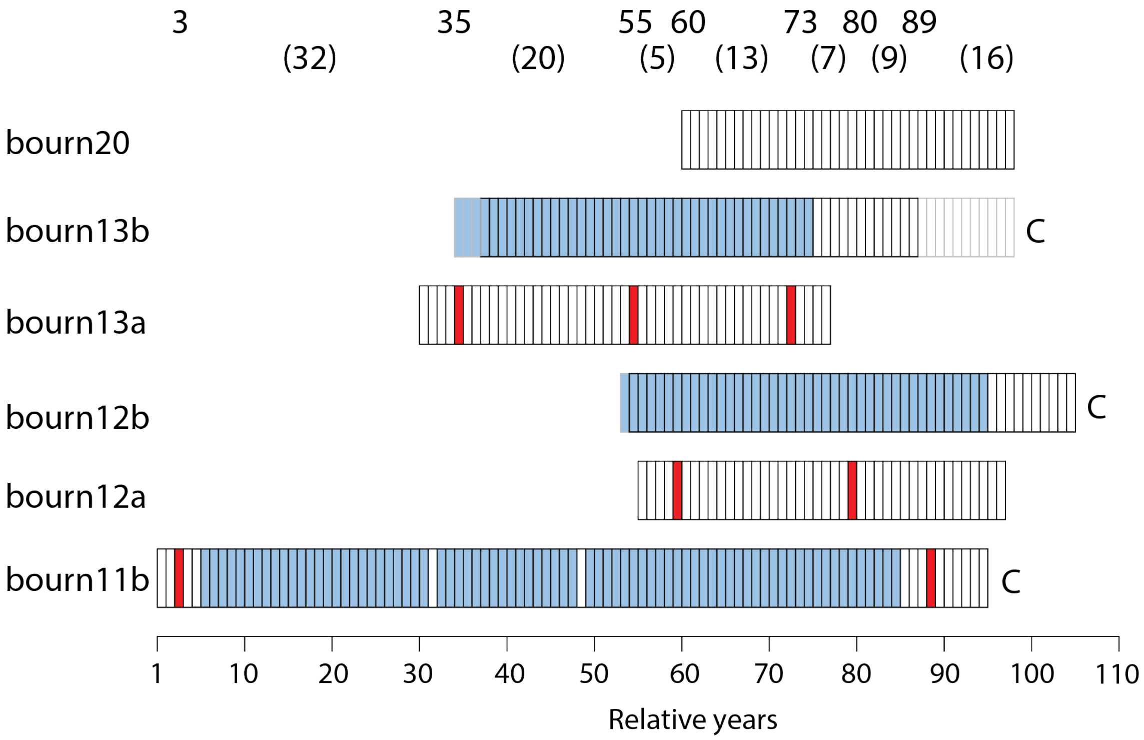


Figure 11: Schematic illustration of the relative positions of the elm timbers from Bourn Windmill suggested by the combined programme of scientific dating, showing the single-ring sub-samples from cores bourn11b, bourn12a, and bourn13a submitted for radiocarbon dating and the gaps between these samples (red), and the rings sub-sampled for oxygen isotope analysis from bourn11b, bourn12b, and bourn13b (blue)

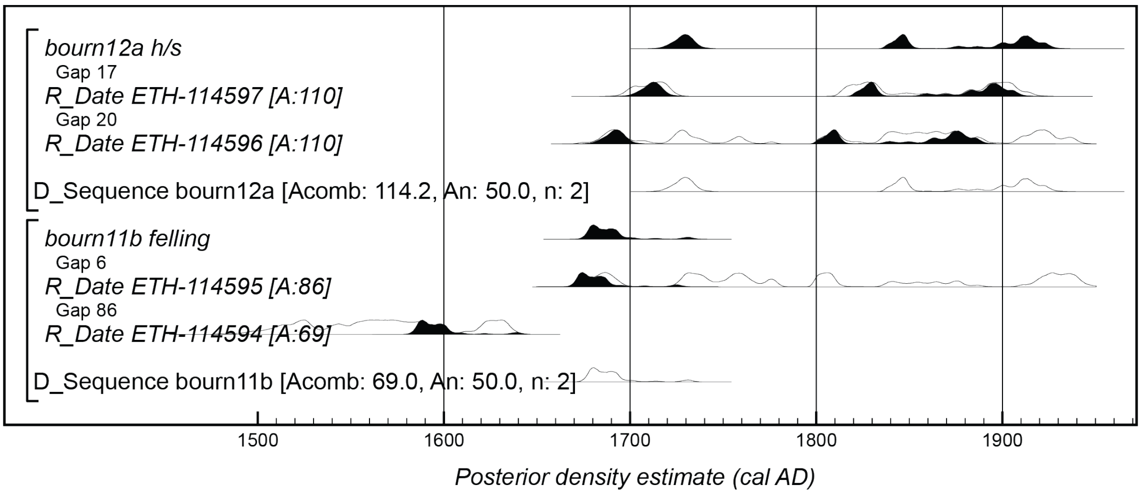


Figure 12: Probability distributions of dates from bourn11b (lower) and bourn12a (upper). The format is identical to that of Figure 8. The large square brackets down the left-hand side along with the OxCal keywords define the models exactly

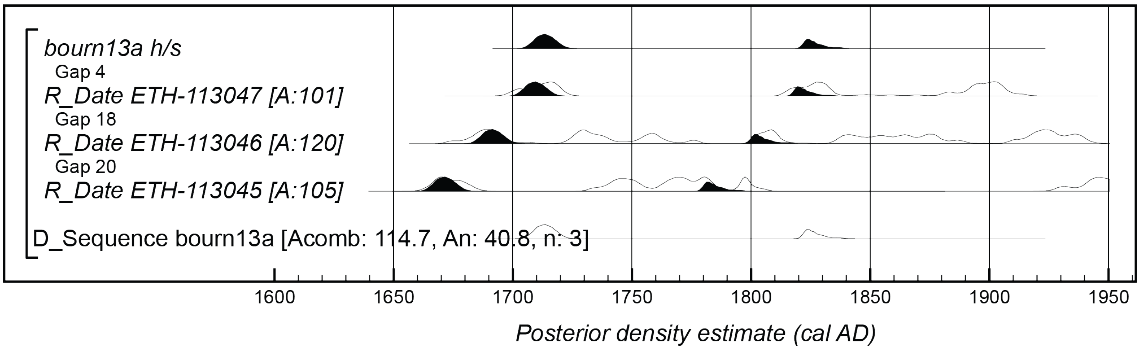


Figure 13: Probability distributions of dates from bourn13a, the right vertical post at the end of the crown-tree. The format is identical to that of Figure 8. The large square brackets down the left-hand side along with the OxCal keywords defines the model exactly

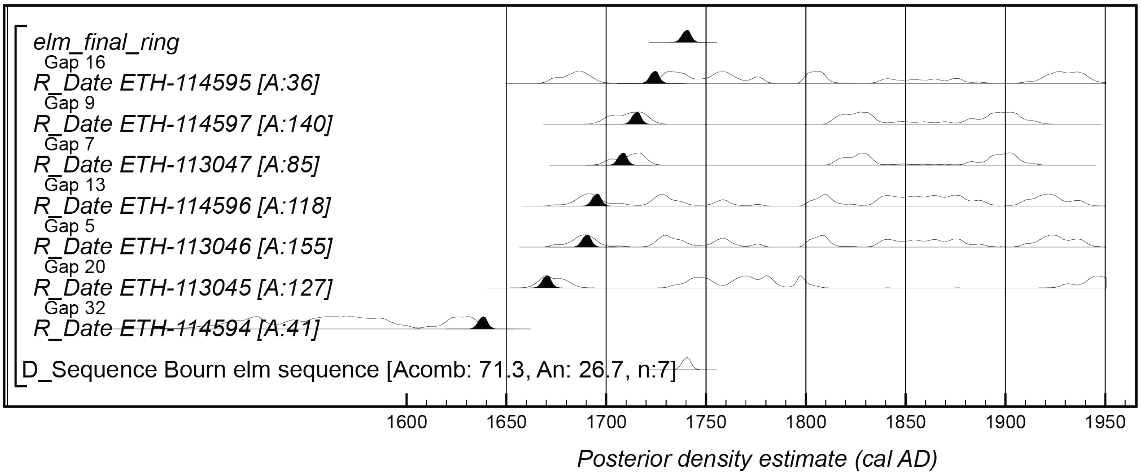


Figure 14: Probability distributions of dates from bourn11b, bourn12a, and bourn13a in the relative positions suggested by the combined scientific dating programme (as illustrated in Fig 11). The format is identical to that of Figure 8. The large square brackets down the left-hand side along with the OxCal keywords defines the model exactly

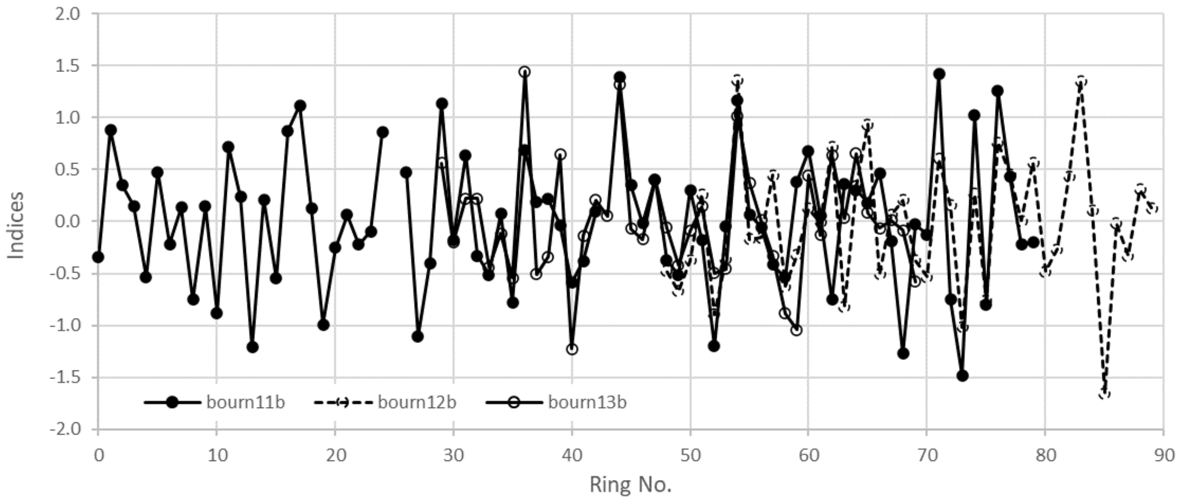


Figure 15: Time series of the filtered and indexed $\delta^{18}O$ values from the three samples plotted at the position of strongest match

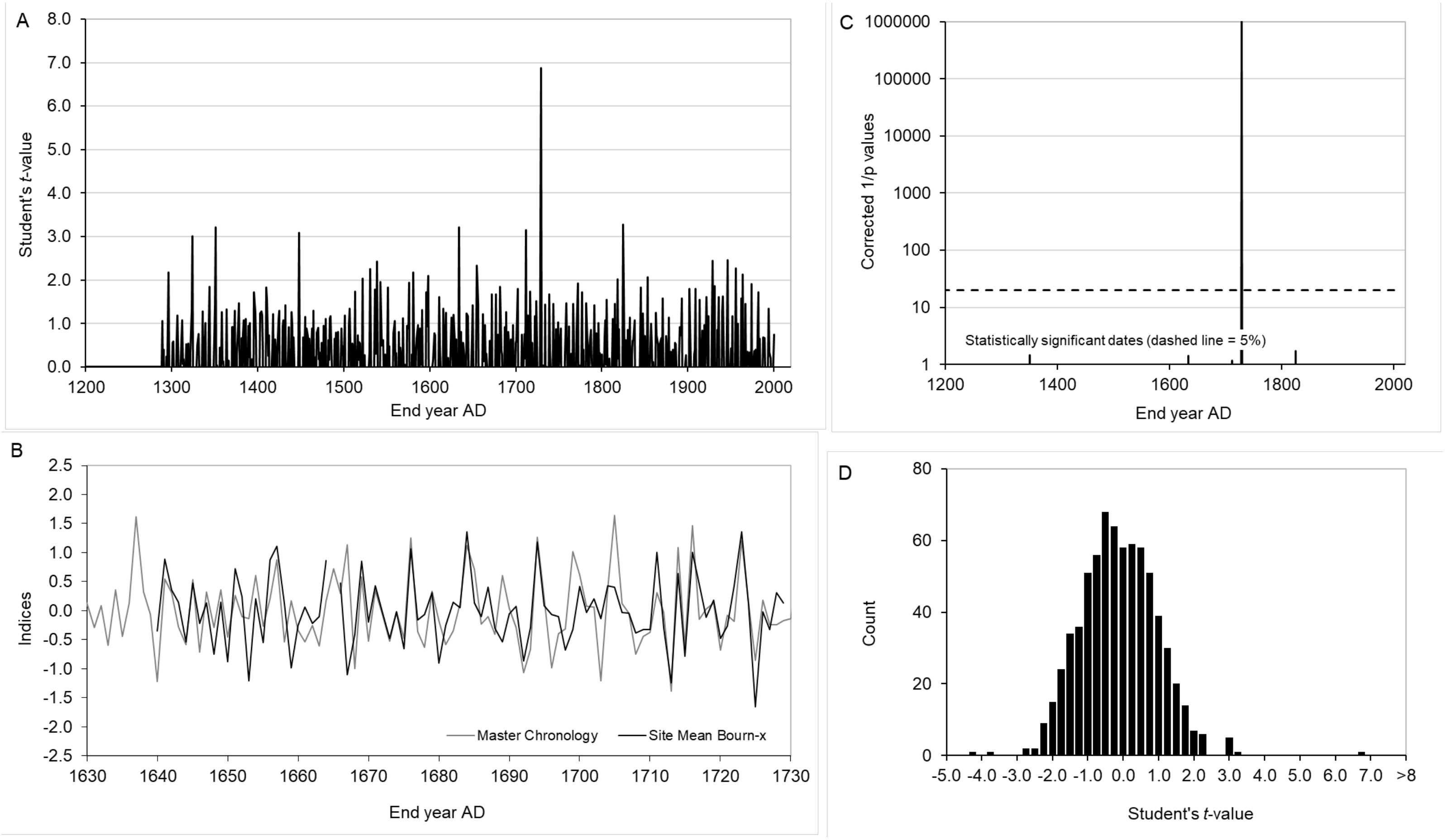


Figure 16: Dating results for the 90-year mean isotope chronology (bourn-x). A: Student's t-values for all possible end dates with full overlap against the master chronology. B: Time series of the site isotopic mean plotted against the master chronology. C: End dates with corrected probabilities (1/p) of more than one. Those below the dashed line (1/p = 20) are not statistically significant. D: Distribution of Student's t-values for all possible matches

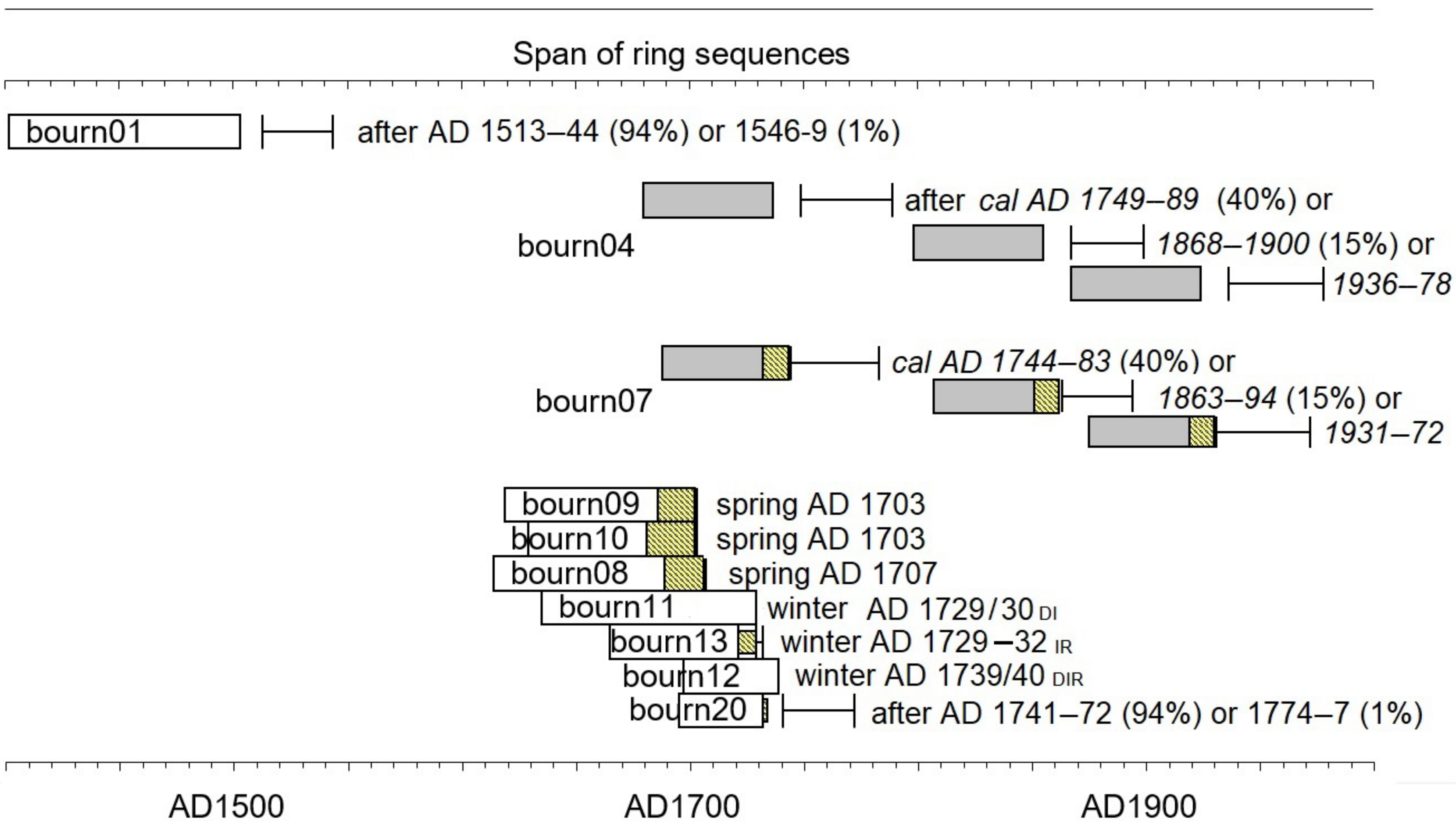


Figure 17: Bar diagram showing the relative positions of overlap (or potential ovelaps) of the dated timbers, with their actual, or derived, felling dates or date ranges. White bars represent measured heartwood rings, yellow hatched sections are measured sapwood rings, with narrow sections representing additional unmeasured rings. Grey bars represent potential positions of radiocarbon dated timbers

APPENDIX 1

Ring width values (0.01mm) for the sequences measured

Oak

bourn01a

544	308	273	157	154	127	177	171	160	104
141	158	122	111	157	150	171	142	196	175
170	310	221	155	127	291	287	210	144	160
306	195	154	205	177	218	190	198	187	198
168	264	226	197	225	186	168	184	150	150
203	315	372	285	361	275	248	191	259	204
212	225	123	240	257	255	324	305	324	162
184	185	176	219	160	219	191	257	332	348
287	239	225	200	195	297	265	331	259	192
132	142	120	121	236	236	156	231		

bourn01b

159	172	239	185	253	272	384	363	411	285
192	168	132	163	247	265	372	293	182	114
147	155	169	294	228	147	227	210	182	168
216									

bourn01c

200	203	248	134	224	269	335	378	378	431
178	181	160	146	184	155	233	180	260	322
358	282	248	171	123	111	136	127	167	208

bourn03i

365	456	614	401	501	471	662	524	508	511
485	416	582	617	623	583	477	497		

bourn03ii

356	478	441	266	366	355	335	426	208	377
326	306	386	255	367	405	430	396	397	546
577	688	404	370						

bourn04

319	263	317	280	243	338	375	416	287	235
352	353	424	339	373	410	397	349	515	602
343	244	338	481	474	411	547	489	437	377
339	351	416	414	425	337	405	406	439	301
392	262	408	391	363	397	339	351	471	289
270	332	437	472	460	472	440	399		

bourn05i

476	507	487	372	391	393	629	339	297	268
235	366	346	501	607	327	271	263	370	626

bourn05ii

626	512	476	458	377	449	413	483	441	382
407	476	421							

bourn06

283	428	342	255	212	231	342	180	229	213
146	205	283	146	314	196	293	332	277	397
389	376	380	349	202	172	224	283	261	223
220	200	279	352	329	362	344	335	340	210
281	451	272	386	286	305	372	210	162	197
365	443	457	447	445	432	304	350		

bourn07

252	252	154	130	142	297	326	339	291	255
314	420	374	474	348	362	397	411	344	369
307	314	341	407	298	275	331	256	260	203
242	298	220	172	213	198	265	347	289	293
278	250	316	171	242	208	258	238	197	252
300	248	230	236	299	326				

bourn08

128	135	234	174	143	140	123	183	178	266
226	152	127	113	114	137	96	93	115	116
67	56	60	72	107	95	208	350	358	330
253	214	383	715	629	268	180	156	80	65
64	89	96	108	137	94	101	123	102	140
132	95	70	114	157	180	161	232	173	229
133	114	100	180	191	139	202	112	238	183
120	111	213	169	173	112	83	173	203	184
141	133	188	234	179	91	67	101	84	144
139	122	153							

bourn09i

162	172	223	275	243	212	229	216	189	258
299	220	223	238	234	226	183	129	163	203
192	150	140	138	165	188	198	196	162	159
123	129	124	71	66	65	79	86	77	133
74	89	69	73	58	54	46	35	56	44
39	49	71							

bourn09ii

50	67	66	59	45	82	66	71	94	62
103	78	75	65	97	112	202	108	91	102
86	78	76	59	65	120	92	87	87	93
90									

bourn10

294	197	166	176	138	122	127	108	177	262
299	204	165	135	148	194	237	279	217	256
169	149	110	51	46	55	97	99	89	147
76	97	75	91	66	50	59	43	85	71
86	65	133	101	131	84	67	61	107	105
79	118	85	142	152	93	84	127	102	218
113	59	76	101	105	73	72	71	187	187
117	81	76	71						

bourn17

331	342	337	430	250	141	198	104	229	279
142	174	131	109	139	109	195	168	224	174
223	221	238	244	152	196	171	219	123	160
96	151	346	293	304	341	185	87	58	129
85	97	147	148	251	168	122	93	101	77
107	240	214	79	126	101	65	64	82	70
94	92	111	125	114	103	84	109	122	121

bourn21

569	800	638	379	425	673	441	663	182	151
233	274	267	219	210	168	196	201	117	99
102	102	215	157	114	127	108			

Elm

bourn11b

352	500	288	479	238	574	477	346	342	206
430	360	323	388	152	199	244	260	154	247
336	256	216	231	135	285	354	243	222	333
101	187	118	267	185	184	213	208	240	267
202	141	388	277	157	279	165	289	79	173
141	210	172	182	180	182	125	127	163	140
125	148	157	165	102	108	133	83	119	102
87	100	108	110	178	145	194	122	130	147
126	184	129	110	99	116	135	151	121	138
87	133	153	133	120					

bourn12a

315	280	217	195	136	82	89	113	100	94
112	186	165	382	422	345	368	401	416	449
318	412	330	329	283	327	311	293	247	264
223	241	260	188	238	142	262	376	269	202
269	204								

bourn12b

349	318	322	251	257	468	383	282	160	82
70	65	84	89	135	249	216	250	308	365
435	339	391	347	403	319	328	319	292	240
260	225	217	278	190	234	154	213	315	316
260	253	197	159	88	165	204	238	206	260
264									

bourn13a

144	111	315	142	177	142	153	215	159	240
714	622	450	421	264	115	124	326	448	435
202	264	370	227	190	179	135	123	134	110
120	130	121	135	119	84	83	101	82	103
99	77	79	97	104	152	145			

bourn13b

224	172	211	745	681	417	517	202	110	74
297	546	427	191	201	276	200	166	184	139
127	146	139	141	134	140	127	95	85	74

84	81	105	98	71	83	88	104	152	137
113	112	125	129	118	151	150	102	78	126

bourn14

305	398	317	488	461	161	115	167	212	230
195	148	175	209	280	200	371	362	357	191
234	390	341	335	245	206	140	158	223	256

bourn18

121	36	36	60	97	93	212	229	277	82
84	113	278	350	377	491	405	585	593	190
108	110	142	191	174	145	240	301	202	103
81	85	55	65	69	78				

bourn20

420	491	399	264	219	251	222	150	329	162
111	116	117	133	168	143	127	131	155	151
192	211	157	127	132	264	273	235	185	277
183	262	292	277	283	282	207	142		

APPENDIX 2

Oxygen isotope ratios (δ18O) for the measured tree ring series. Data are reported as per mille (‰) deviations relative to the VSMOW standard (Coplen 1995).

Sample bourn11b

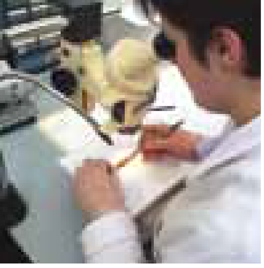
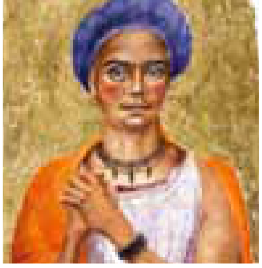
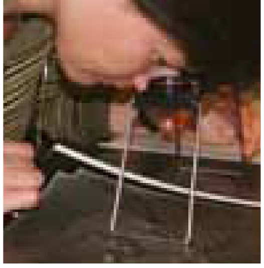
Ring	δ18O	Ring	δ18O	Ring	δ18O
95	-	59	28.98	23	30.69
94	-	58	27.84	22	30.43
93	-	57	28.97	21	29.05
92	-	56	29.51	20	29.76
91	-	55	28.66	19	28.29
90	-	54	29.05	18	29.46
89	-	53	29.98	17	29.81
88	-	52	29.65	16	28.20
87	-	51	30.00	15	29.23
86	-	50	31.09	14	28.33
85	**29.13**	49	-	13	29.23
84	29.19	48	29.80	12	28.87
83	29.66	47	29.31	11	29.81
82	30.34	46	29.10	10	28.78
81	28.36	45	29.38	9	29.57
80	30.13	44	29.65	8	29.79
79	27.56	43	29.54	7	30.36
78	28.05	42	30.02	6	29.08
77	30.05	41	28.65	5	-
76	28.61	40	29.49	4	-
75	28.59	39	29.00	3	-
74	27.54	38	29.14	2	-
73	28.80	37	29.94	1	-
72	29.28	36	29.27		
71	29.06	35	30.57		
70	29.33	34	29.18		
69	29.61	33	28.49		
68	28.49	32	30.00		
67	29.25	31	-		
66	29.88	30	30.30		
65	29.56	29	29.28		
64	28.70	28	29.30		
63	28.87	27	29.66		
62	29.08	26	29.47		
61	29.10	25	28.59		
60	30.19	24	29.76		

Sample bourn12b

Ring	$\delta^{18}O$	Ring	$\delta^{18}O$
51	-	20	29.52
50	-	19	29.25
49	-	18	28.67
48	-	17	30.17
47	-	16	29.59
46	-	15	28.31
45	-	14	29.74
44	-	13	29.06
43	-	12	28.99
42	-	11	28.39
41	29.12	10	28.25
40	29.36	9	29.13
39	28.93	8	28.33
38	29.36	7	28.26
37	27.77	6	29.75
36	29.59	5	27.96
35	30.98	4	27.30
34	30.17	3	28.54
33	29.56	2	28.00
32	29.64	1	27.63
31	30.62	0	27.95
30	29.93		
29	30.17		
28	30.47		
27	28.96		
26	29.76		
25	28.35		
24	29.45		
23	29.76		
22	28.60		
21	28.80		

Sample bourn13b

Ring	δ¹⁸O	Ring	δ¹⁸O
50	-	20	28.66
48	-	18	28.16
47	-	17	28.82
46	-	16	29.44
45	-	15	28.94
44	-	14	29.09
43	-	13	30.46
42	-	12	29.28
41	-	11	29.34
40	-	10	28.92
39	-	9	27.97
38	27.98	8	29.61
37	28.55	7	28.57
36	28.63	6	28.31
35	28.59	5	30.29
34	28.67	4	28.42
33	29.30	3	28.74
32	28.51	2	28.50
31	28.96	1	29.20
30	28.08	0	29.02
29	28.58	−1	28.62
28	27.01	−2	29.38
27	27.20		
26	27.62		
25	27.94		
24	28.31		
23	29.12		
22	27.76		
21	27.85		

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ISSN 2059-4453 (Online)