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Supplementary information

Eleven-year solar cycles over the last millennium revealed by radiocarbon in tree rings

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11-year solar cycles over the last millennium revealed by radiocarbon in tree rings

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Supplementary Information

S1 Dendrochronology

Radiocarbon measurements were obtained from 13 timbers that had been sampled for ring-width dendrochronology from 11 standing buildings, and from one tree that had been recently felled (Figure S1.1).

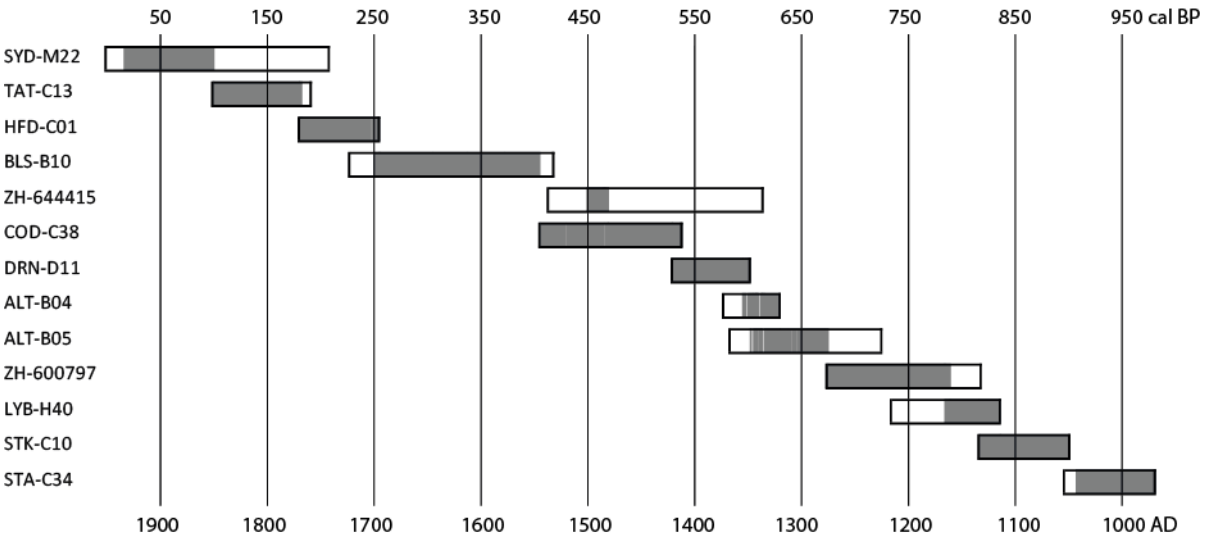

Figure S1.1: radiocarbon measurements obtained on single growth-rings from the 13 timbers analysed (grey), and the growth-rings included in each timber (outline).

All the samples had been prepared previously for measurement and tree-ring analysis by polishing with a belt sander using progressively finer belts down to a fineness of 400 grit, and the annual growth rings had been marked out. Dissection of the eleven samples from England was undertaken

by Alison Arnold and Robert Howard at the Nottingham Tree-Ring Dating Laboratory. Prior to sub-sampling the cores were checked against the tree-ring width data to ensure that the sample contained the required rings. Once this was determined the selected annual growth rings were split from the rest of the sample using a chisel or scalpel blade. Each sample consisted of a complete annual growth ring, including both earlywood and latewood. The sub-sample was then weighed and placed in a labelled bag.

Dissection of the two samples from Switzerland was undertaken by Lukas Wacker, on radial sections cut by Niels Bleicher from the slices taken for dendrochronology. Their rings had been made visible by clearing their surfaces using razor blades. The selected annual growth rings were split tangentially from the rest of the sample using a scalpel blade. Each sample consisted of a complete annual growth ring, including both earlywood and latewood. The sub-sample was then weighed and directly placed in glass test tubes for cellulose extraction.

STA-C34

This sample consisted of a core taken for dendrochronology from the median transverse ridge rib, south post 4–5 of the presbytery roof of the Abbey Church of St Alban, St Albans, Hertfordshire, UK (51.75°N, 0.34°W). This oak timber contained 85 heartwood rings, spanning AD 969 – AD 1053 and ended at the heartwood/sapwood transition.

The tree-ring analysis of the presbytery roof and ceiling at St Alban's cathedral has been fully reported by Howard *et al.*[1] Core samples from 38 oak timbers were obtained from the roof, all but one of which had sufficient (> 50) rings to proceed with analysis. A further 27 samples were obtained by sawing from the ends of overlapping boards in the ceiling, all of which had sufficient rings for analysis. These samples were prepared by sanding and polishing and their growth-ring widths were measured to a precision of 0.01 mm. A further five ring-width series from decorative bosses were measured *in situ* by graticule. The data of the measured samples were compared with each other using the Litton/Zainodin grouping procedure (Laxton *et al.*[2]; Litton and Zainodin[3]). At a minimum *t*-value of 4.4, five groups formed. STA-C34 crossmatched with STA-C32 (*t*=18.1), and their ring-width series were combined at their indicated offset positions to form STACSQ03, a site chronology with an overall length of 85 rings. This site chronology is dated as spanning AD 969–1053 (Table S1.1).

*Table S1.1: Results of the cross-matching of site sequence STACSQ03 and relevant independent site reference chronologies when the first-ring date is AD 969 and the last-ring date is AD 1053 (*t*-values after Baillie and Pilcher[4]).*

Reference chronology	*t*-value	Span of chronology (AD)	Reference
Guildhall, London	9.2	498–1212	Tyers[5]
Bull Wharf, London	8.3	620–1181	Tyers and Boswijk[6]
Seal House, London	7.8	862–1194	Tyers[7]
Vintry, London	7.4	743–1241	Hibberd[8]
White Tower, Tower of London, London	7.4	816–1092	Miles[9]
Billingsgate (BIG82), London	7.3	611–1243	Tyers and Hillam[10]
The Brooks, Winchester	7.2	443–1128	Hillam[11]
Fleet Valley, London	7.2	745–1316	Tyers and Hibberd[12]
Fennings Wharf, London	7.1	802–1435	Tyers[13]
Old Bailey, London	7.0	908–1065	Tyers[14]

The raw ring-width data of all the measured samples from the presbytery roof and ceiling at the Abbey Church of St Alban's can be found in Howard et al and at https://www.ncdc.noaa.gov/paleo-search/study/28328.

STK-C10

This sample consisted of a core taken for dendrochronology from the north stub tie in frame 9 of the chancel roof of the Church of St Mary, Stockport, Greater Manchester, UK (53.41°N, 2.15°W). This oak timber contained 85 heartwood rings, spanning AD 1049 – AD 1133.

The tree-ring analysis of the chancel roof at the Church of St Mary, Stockport has been fully reported by Arnold and Howard[15].Core samples from 12 oak timbers were obtained from the roof, all of which had sufficient (> 50) rings to proceed with analysis. These samples were prepared by sanding and polishing and their growth-ring widths were measured to a precision of 0.01 mm. The data of the measured samples were compared with each other using the Litton/Zainodin grouping procedure (Laxton *et al.*[2]; Litton and Zainodin[3]). At a minimum *t*-value of 4.5, two groups formed. STK-C10 was included in the first group of three samples, which matched each other at a least value of *t*=7.9. The ring-width series of these samples were combined at the indicated offset positions to form STKCSQ01, a site sequence of 115 rings. This site chronology is dated as spanning AD 1019–1133 (Table S1.2).

*Table S1.2: Results of the cross-matching of site sequence STKCSQ01 and relevant independent site reference chronologies when the first-ring date is AD 969 and the last-ring date is AD 1053 (*t*-values after Baillie and Pilcher (1973)[4]).*

Reference chronology	*t*-value	Span of chronology (AD)	Reference
Blackfriars Priory, Gloucester, Gloucestershire	8.5	1024–1237	Howard *et al.* [16]
The Hall, Oakham Castle, Rutland	8.5	923–1153	Arnold and Howard[17]
Peterborough Cathedral (nave roof), Cambridgeshire	8.0	887–1225	Tyers[18]
Dundas Wharf, Bristol	7.7	770–1202	Nicholson and Hillam[19]
Lancaster Castle, Lancaster, Lancashire	7.0	950–1404	Arnold *et al.*[20]
Staircase House, Stockport, Greater Manchester	6.8	1069–1248	Howard *et al.*[21]
Eastgate, Beverley, East Yorkshire	6.5	858–1310	Groves[22]
St Hugh's Choir, Lincoln Cathedral, Lincolnshire	6.4	882–1184	Laxton *et al.*[23]
Chapter House/Deanery, Brecon Cathedral, Brecon, Wales	6.4	996–1227	Howard *et al.* [24]
Yarpole Bell Tower, Yarpole, Herefordshire	6.4	1004–1195	Tyers[25]

The raw ring-width data of all the measured samples from the chancel roof at the Church of St Mary, Stockport can be found in Arnold and Howard[15] and at https://www.ncdc.noaa.gov/paleo-search/study/28329.

LYB-H40

This sample consisted of a core taken for dendrochronology from ceiling joist 2 in room 4 of The Bede House, Lyddington, Rutland, UK (52.56°N, 0.71°W). This oak timber contained 102 heartwood rings, ending at the heartwood/sapwood transition and has been dated as spanning AD 1114 – AD 1215.

The tree-ring analysis of The Bede House has been fully reported by Arnold *et al.*[26]. Core samples from 92 oak timbers were obtained from this building, 79 of which had sufficient (> 50) rings to proceed with analysis. These samples were prepared by sanding and polishing and their growth-ring widths were measured to a precision of 0.01 mm. The data of the measured samples were compared with each other, and with a further 21 ring series that were measured *in situ* from plank doors and floor boards, using the Litton/Zainodin grouping procedure (Laxton *et al.*[2]; Litton and Zainodin[3]). This analysis resulted in the formation of five groups, containing 81 of the measured ring series. LYB-H40 was included in the first of these groups, which produced a site sequence of 137-rings when the ring-width series of these samples were combined at the indicated offset positions. This site chronology, LYBHSQ01, is dated as spanning AD 1085–1221[26].

Samples LYB-H39–LYB-H42 group together at a minimum *t*-value of 7.6, but the fifth sample in LYBHSQ01, LYB-H133, is only included at a *t*-value of 2.7. For this reason, evidence for the dating of LYB-H40 as a single ring series is provided in Table S1.3.

*Table S1.3: Results of the cross-matching of LYB-H40 and relevant independent site reference chronologies when the first-ring date is AD 1114 and the last-ring date is AD 1215 (*t*-values after Baillie and Pilcher (1973)[4]).*

Reference chronology	*t*-value	Span of chronology (AD)	Reference
Nevill Holt, Leicestershire	8.7	1118–1174	Arnold *et al.*[27]
Barley Barn, Cressing Temple, Essex	8.3	1120–1196	Tyers[28]
Polesworth Abbey Gatehouse, West Midlands	8.0	1446–1582	Arnold and Howard[29]
Billingsgate (BIG82), London	7.7	611–1243	Tyers and Hillam[10]
Abbas Hall, Great Cornard, Suffolk	7.6	1150–1289	Bridge[30]
Dover Castle, Kent	7.3	1101–1241	Howard *et al.*[31]
Grange Barn, Coggeshall, Essex	7.2	1105–1228	Tyers[32]
Manor House, Medbourne, Leicestershire	6.8	1068–1287	Howard *et al.*[33]
Kenilworth Castle Gatehouse	6.6	1092–1332	Arnold *et al.*[34]
Southview Cottage, Norwell, Nottinghamshire	6.3	1114-1215	Hurford *et al.*[35]

The raw ring-width data of all the measured samples from Lyddington Bede Hall can be found in Arnold *et al.*[26] and at https://www.ncdc.noaa.gov/paleo-search/study/28325.

ZH-600797

The sample is from a rectory in Lengnau in the Cantone of Aargau. It was a slice taken from the roof beam of a chamber in the first floor of the north-eastern corner of the house. It is oak and originally showed 144 rings, measured to a precision of 0.01mm (Table S1.4). Today, it has 139 rings as a piece with 5 rings has broken off on the inside at some time during the decade long storage. The remaining sample spans the time from AD 1136 to AD 1275 (Table S1.5).

Table S1.4: Ring-width data for ZH-600797 (Heidelberg format)

HEADER:
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DateEnd=1275
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Species=QUSP
Length=144
Location=AG/LENGNAU-PFARRHAUS
ExcavNr=1
CreationDate= 20160210
Dated=dated
DATA:Tree

378 322 423 517 383 356 471 363 420 507
361 368 273 324 174 201 156 180 113 127
105 104 129 142 162 133 108 161 188 181
181 118 99 110 110 95 149 240 190 206
114 147 152 165 175 173 216 175 154 120
206 132 138 115 197 217 163 147 247 201
161 155 199 282 286 197 185 163 170 293
212 199 151 158 170 167 240 250 252 248
217 209 169 183 167 175 193 217 181 223
214 243 255 209 335 232 205 222 166 139
141 114 170 193 189 205 228 171 226 162
214 141 326 212 229 228 186 181 234 184
181 262 219 273 232 207 212 205 201 210
174 188 212 180 274 167 154 232 152 219
212 212 173 180

*Table S1.5: Results of the cross-matching of ZH-600797 with independent regional reference chronologies when the first-ring date is AD 1132 and the last-ring date is AD 1275 (*t*-values after Baillie and Pilcher (1973)[4]).*Reference chronology

Reference chronology	*t*-value	Span of chronology (AD)	Reference
Western German Oak Standard	6.3	724–1975	Hollstein[36]
Oak standard Cantone Schaffhausen "4120"	5.8	755-1730	Unpublished
Oak Standard City of Zurich "4657"	6.2	1135–1996	Unpublished

ALT-B04 and ALT-B05

These samples consist of cores taken for dendrochronology from timbers from the nave roof of the Church of St Mary, Alton Barnes, Wiltshire, UK (51.36°N, 1.85°W). ALT-B04 was a core from an oak timber which forms the west brace on the south side of truss 1 in this roof, and included 53 heartwood rings ending in the heartwood/sapwood transition that have been dated as spanning AD 1320 – AD 1372. ALT-B05 was a core from an oak timber which formed the north blade of truss 2 in this roof, and included 142 heartwood rings ending in the heartwood/sapwood transition that have been dated as spanning AD 1225 – AD 1366.

The tree-ring analysis of the nave roof at the Church of St Mary, Alton Barnes has been fully reported by Arnold et al[37]. Core samples from 16 oak timbers were obtained from the roof, all but one of which had sufficient (> 50) rings to proceed with analysis. These samples were prepared by sanding and polishing and their growth-ring widths were measured to a precision of 0.01 mm. The data of the measured samples were compared with each other using the Litton/Zainodin grouping procedure (Laxton *et al.*[2]; Litton and Zainodin[3]). At a minimum *t*-value of 4.4, a single group of 14 timbers formed. The ring-width series of these samples were combined at the indicated offset positions to form ALTBSQ01, a site sequence of 170 rings. This site chronology is dated as spanning AD 1203–1372 (Table S1.6).

*Table S1.6: Results of the cross-matching of site sequence ALTBSQ01 and relevant independent site reference chronologies when the first-ring date is AD 1203 and the last-ring date is AD 1372 (*t*-values after Baillie and Pilcher (1973)[4]).*

Reference chronology	*t*-value	Span of chronology (AD)	Reference
Bremhill Court, Bremhill, Wiltshire	8.4	1111–1323	Hurford *et al.* [38]

Reading Waterfront, Berkshire	8.0	1160–1407	Groves *et al.*[39]
Ulverscroft Priory, Ulverscroft, Leicestershire	7.9	1219–1463	Arnold *et al.* [40]
Exeter Cathedral, Exeter, Devon	7.5	1137–1332	Mills[41]
Exeter Cathedral (western nave), Exeter, Devon	7.4	1132–1337	Arnold *et al.*[42]
The Granary, Barton Farm, Bradford-on-Avon, Wiltshire	7.4	1167–1360	Arnold *et al.*[43]
Polesworth Abbey (gatehouse), Warwickshire	7.3	1095–1342	Arnold and Howard[29]
Wadhayes, Awliscombe, Devon	7.2	1179–1331	Tyers *et al.*[44]
Dauntsey House, Dauntsey, Wiltshire	7.1	1122–1355	Tyers *et al.*[45]
The Deanery, Exeter, Devon	7.1	1233–1406	Howard *et al.*[46]

The raw ring-width data of all the measured samples from the Church of St Mary, Alton Barnes can be found in Arnold *et al.*[37] and at https://www.ncdc.noaa.gov/paleo-search/study/28310.

DRN-D11

This sample consisted of a core taken for dendrochronology from the south principal rafter of truss 4 in the main range of Dronfield Hall Barn, Dronfield, Derbyshire, UK (53.30°N, 1.47°W). This oak timber contained 73 heartwood rings, ending in the heartwood/sapwood transition, dated as spanning AD 1348 – AD 1420.

The tree-ring analysis of Dronfield Hall Barn has been fully reported by Arnold and Howard[47]. Core samples from 19 oak timbers were obtained from the structure, seventeen of which had sufficient (> 50) rings to proceed with analysis. These samples were prepared by sanding and polishing and their growth-ring widths were measured to a precision of 0.01 mm. The data of the measured samples were compared with each other using the Litton/Zainodin grouping procedure (Laxton *et al.*[2]; Litton and Zainodin[3]). At a minimum *t*-value of 3.9, a single group formed consisting of 13 timbers. The ring-width series of these samples were combined at the indicated offset positions to form DRNDSQ01, a site sequence of 89 rings. This site chronology is dated as spanning AD 1341–1429 (Table S1.7).

*Table S1.7: Results of the cross-matching of site sequence DRNDSQ01 and relevant independent site reference chronologies when the first-ring date is AD 1341 and the last-ring date is AD 1429 (*t*-values after Baillie and Pilcher (1973)[4]).*

Reference chronology	*t*-value	Span of chronology (AD)	Reference
7-12 Church Street, Dronfield, Derbyshire	10.5	1313–1526	Arnold and Howard[47]
Manor House, West Bromwich, West Midlands	10.2	1318–1590	Arnold and Howard[48]
Sinai Park, Burton on Trent, Staffordshire	10.2	1227–1750	Tyers[49]
Lea Road Foundry site, Church Street, Dronfield, Derbyshire	10.2	1344–1526	Tyers[50]
Primrose Hill, Kings Norton, Birmingham	10.0	1354–1593	Arnold and Howard[51]
All Hallows Church, Kirkburton, West Yorkshire	8.5	1306–1633	Arnold and Howard[52]
Halesowen Abbey, Dudley, West Midlands	8.4	1310–1535	Arnold and Howard[53]
Ightfield Hall Barn, Shropshire	8.4	1341–1566	Groves[54]
Foresters Lodge, Upper Millichope, Shropshire	8.2	1352–1450	Miles *et al.*[55]
Anne Hathaway's Cottage, Stratford upon Avon, Warwickshire	8.0	1319–1462	Alcock *et al.*[56]

The raw ring-width data of all the measured samples from Dronfield Hall Barn can be found in Arnold and Howard[47] and at https://www.ncdc.noaa.gov/paleo-search/study/28317.

COD-C38

This sample consisted of a core taken for dendrochronology from a timber reused as the east purlin of truss 1 in the northern extension of the barn at Codnor Castle, Castle Lane, Codnor, Derbyshire, UK (53.04°N, 1.36°W). This oak timber contained 133 heartwood rings, ending in the heartwood/sapwood transition, dated as spanning AD 1412 – AD 1544.

The tree-ring analysis of Codnor Castle has been fully reported by Arnold and Howard[57]. Core samples from 54 oak timbers were obtained from the floors and roofs of the farmhouse and barn, 44 of which had sufficient (> 50) rings to proceed with analysis. These samples were prepared by sanding and polishing and their growth-ring widths were measured to a precision of 0.01 mm. The data of the measured samples were compared with each other using the Litton/Zainodin grouping procedure (Laxton *et al.*[2]; Litton and Zainodin[3]). At a minimum *t*-value of 4.5, four groups formed consisting of 36 samples. COD-C38 was included in the second group, which included 25 samples. The ring-width series of these samples were combined at the indicated offset positions to form CODCSQ02, a site sequence of 179 rings. This site chronology is dated as spanning AD 1381–1559 (Table S1.8).

*Table S1.8: Results of the cross-matching of site sequence CODCSQ02 and relevant independent site reference chronologies when the first-ring date is AD 1381 and the last-ring date is AD 1559 (*t*-values after Baillie and Pilcher[4]).*

Reference chronology	*t*-value	Span of chronology (AD)	Reference
Wakelyn Old Hall, Hilton, Derbyshire	11.5	1415–1573	Arnold *et al.*[58]
Ightfield Hall Barn, Shropshire	10.9	1341–1566	Groves[54]
Howley Hall Farm, Morley, West Yorkshire	10.8	1415–1635	Arnold and Howard[59]
Black Ladies, near Brewood, Staffordshire	9.5	1372–1671	Tyers[60]
Kingsbury Hall, Kingsbury, Warwickshire	9.4	1391–1564	Arnold *et al.*[61]
Sinai Park, Burton on Trent, Staffordshire	9.4	1227–1750	Tyers[49]
Woodseats Hall, Barlow, Derbyshire	9.3	1417–1535	Howard *et al.*[62]
Headlands Hall, Liversedge, West Yorkshire	9.3	1388–1487	Tyers[63]
Brookgate Farm, Plealy, Shropshire	9.3	1362–1611	Miles *et al.*[64]
Orsall Hall, Salford, Greater Manchester	9.3	1366–1534	Arnold *et al.*[65]

The raw ring-width data of all the measured samples from Codnor Castle farmhouse and barn can be found in Arnold and Howard[57] and at https://www.ncdc.noaa.gov/paleo-search/study/28315.

ZH-644415

The sample was recovered from a historical timber-framed building in Maur (Cantone Zürich). The building was systematically sampled all over the different rooms. Several building phases were identified. The house was taken down in 1994. During the destruction an oaken sill was accessible and a disk was taken with a bandsaw. The sample yielded a series of 201 rings, measured to a precision of 0.01mm (Table S1.9). It can be securely dated as spanning the time from AD 1336 to AD 1536 in comparison with two regional oak standard chronologies (Table S1.10). The same cutting date was also recorded in several spruce samples from the same building.

Table S1.9: Ring-width data for ZH-644415 (Heidelberg format)

HEADER:
Keycode=644415.0
DateEnd=1536
QualityCode=reliable

Species=Quercus spec.
Length=201
SapWoodRings=24
Pith=p
WaldKante=Autumn/Winter
Location=ZH/MAUR-MUEHLESTR.2
PersId=Felix Walder
ExcavNr=26_A
Coordinates=47°20'24.464 N 8°40'07.5 E
CreationDate= 20160210
Dated=dated
DATA:Tree
415 155 165 132 155 139 131 132 143 123
114 112 132 101 208 144 191 140 159 119
147 155 135 185 262 148 149 165 165 206
155 191 175 179 194 211 165 183 189 173
221 203 199 167 218 214 185 272 239 189
238 173 224 221 165 139 155 155 161 132
137 136 217 143 170 206 238 218 185 208
136 175 159 170 238 241 170 189 168 188
182 151 182 191 93 168 125 126 179 182
153 153 151 132 183 121 110 126 97 95
141 119 142 98 99 110 114 98 103 114
110 132 98 170 153 110 112 89 97 100
105 118 84 86 104 81 70 86 79 79
91 96 88 106 89 86 121 99 157 180
187 120 159 191 203 184 194 140 142 165
166 154 150 161 129 122 117 100 121 94
122 105 87 120 112 112 126 112 98 135
128 151 184 145 142 157 126 126 105 120
109 80 69 90 92 102 117 76 107 88
87 109 84 96 103 94 78 94 70 75
85

*Table S1.10: Results of the cross-matching of ZH-644415 with independent regional reference chronologies when the first-ring date is AD 1336 and the last-ring date is AD 1536 (*t*-values after Baillie and Pilcher (1973)[4]).*

Reference chronology	*t*-value	Span of chronology (AD)	Reference
Oak Standard Cantone Schaffhausen "4120"	5.9	755-1730	Unpublished
Oak Standard Cantone Aargau "4663"	5.5	1123-1973	Unpublished
Oak Standard City of Zürich "4657"	6.7	1135–1996	Unpublished

BLS-B10

This sample consisted of a core taken for dendrochronology from the east principal rafter in truss 3 of the east roof of the Keep, or 'Little Castle', at Bolsover Castle, Bolsover, Derbyshire, UK (53.23°N, 1.29°W). This oak timber contained 191 heartwood rings, ending in the heartwood/sapwood transition, dated as spanning AD 1532 – AD 1722.

The tree-ring analysis of the Keep at Bolsover Castle has been fully reported by Arnold *et al.*[66]. Core samples from 16 oak timbers were obtained from the east and west roofs of the Keep, all of which had sufficient (> 50) rings to proceed with analysis. These samples were prepared by sanding and

polishing and their growth-ring widths were measured to a precision of 0.01 mm. The data of the measured samples were compared with each other using the Litton/Zainodin grouping procedure (Laxton *et al.*[2]; Litton and Zainodin[3]). At an unusually high minimum *t*-value of 6.2, all 16 samples cross-matched. The ring-width series of these timbers were combined at the indicated offset positions to form BLSBSQ01, a site sequence of 218 rings. This site chronology is dated as spanning AD 1532–1749 (Table S1.11).

*Table S1.11: Results of the cross-matching of site sequence BLSBSQ01 and relevant independent site reference chronologies when the first-ring date is AD 1532 and the last-ring date is AD 1749 (*t*-values after Baillie and Pilcher (1973)[4]).*

Reference chronology	*t*-value	Span of chronology (AD)	Reference
Bolsover Castle (Riding House), Derbyshire	20.1	1494–1744	Arnold *et al.*[67]
Bingham, Nottinghamshire	10.9	1445–1752	Arnold and Howard[68]
Brewhouse Yard, Castle Boulevard, Nottinghamshire	10.5	1544–1701	Howard *et al.*[24]
Ledston Hall, Ledston, West Yorkshire	9.8	1424–1668	Arnold *et al.*[69]
Melbourne Hall muniment room, Melbourne, Derbyshire	9.7	1601–1708	Arnold and Howard[70]
Combermere Abbey, Whitchurch, Cheshire	9.7	1595–1727	Howard *et al.*[71]
Church of St Giles (bellframe), Elkesley, Nottinghamshire	9.5	1628–1722	Arnold *et al.* [72]
Church of the Holy Cross (bellframe), Epperstone, Nottinghamshire	9.2	1477–1647	Arnold *et al.*[73]
Middleton Hall, Middleton, Warwickshire	8.6	1593–1718	Arnold *et al.*[61]
Old Clarendon Building, Oxford, Oxfordshire	8.5	1539–1711	Worthington and Miles[74]

The raw ring-width data of all the measured samples from the Keep at Bolsover Castle can be found in Arnold *et al.* [66] and at https://www.ncdc.noaa.gov/paleo-search/study/28313.

HFD-C01

This sample consisted of a core taken for dendrochronology from rafter 7 from the east side of the north pitch of the dovecote at Breakspear House, Breakspear Road North, Harefield, Hillingdon, Greater London, UK (51.60°N, 0.47°W). This oak timber contained 75 rings, including 21 sapwood rings and ended with bark edge. It is dated as spanning AD 1695 – AD 1769.

The tree-ring dating of the roof of the dovecote at Breakspear House has been fully reported by Arnold and Howard[75]. Core samples from 11 oak timbers were obtained from this roof, of which ten had sufficient (> 50) rings to proceed with analysis. These samples were prepared by sanding and polishing and their growth-ring widths were measured to a precision of 0.01 mm. The data of the measured samples were compared with each other using the Litton/Zainodin grouping procedure (Laxton *et al.*[2]; Litton and Zainodin[3]), allowing a single group of nine cross-matching ring-width series to be formed at a particularly high minimum value of *t*=8.0. These series were combined at their indicated offset positions to form HFDCSQ01, a site chronology with an overall length of 75 rings. This site chronology is dated as spanning AD 1695–1769 (Table S1.12).

Table S1.12: Results of the cross-matching of site sequence HFDCSQ01 and relevant reference chronologies when the first-ring date is AD 1695 and the last-ring date is AD 1769 (t-values after Baillie and Pilcher (1973)[4]).

Reference chronology	***t*-value**	**Span of chronology (AD)**	**Reference**
Tilbury Fort, Thurrock, Essex	7.9	AD 1678–1777	Groves[76]

45 Main Street, Caldicote, Rutland	7.7	AD 1657–1789	Arnold and Howard[77]
The Firs, Lyddington, Rutland	6.9	AD 1675–1772	Arnold and Howard[78]
Winchester modern, Hampshire	6.5	AD 1635–1972	Barefoot[79]
Ely Cathedral, Ely, Cambridgeshire	6.2	AD 1678–1828	Esling *et al.*[80]
HMS Victory, Greenwich, London	6.2	AD 1640–1800	Barefoot[79]
Clothall Bury Farmhouse, Wallingford, Hertfordshire	6.1	AD 1636–1753	Arnold *et al.*[81]
Reading Abbey waterfront, Berkshire	6.1	AD 1708–1766	Groves *et al.*[39]
Skeleton Barn, Oakhouse Farm, Hampstead Norreys, Berkshire	6.0	AD 1722–1811	Miles[82]
White Tower, Tower of London, London	5.9	AD 1629–1782	Miles[9]

The raw ring-width data of all the measured samples from Breakspear House is provided by Arnold and Howard[75] and at https://www.ncdc.noaa.gov/paleo-search/study/28320.

TAT-C13

This sample consisted of a core taken for dendrochronology from the eastern main north-south base beam of the Link Moat Footbridge (Bridge 2) at Tattershall Castle, Lincolnshire, UK (53.10°N, 0.19°W). This oak timber contained 92 heartwood rings, dated as spanning AD 1759 – AD 1850.

The tree-ring dating of the timbers from Tattershall Castle has been fully reported by Arnold *et al.*[83]. Core samples from 39 oak timbers were obtained from three bridges over the moat and three *ex situ* timbers on display in the castle, all of which had sufficient (> 50) rings to proceed with analysis. These samples were prepared by sanding and polishing and their growth-ring widths were measured to a precision of 0.01 mm. The data of the measured samples were compared with each other using the Litton/Zainodin grouping procedure (Laxton *et al.*[2]; Litton and Zainodin[3]), allowing five cross-matching groups comprising 31 samples to be formed at a minimum value of t=3.8. TAT-C13 was included in the first group of 23 samples. The ring series from these timbers were combined at their indicated offset positions to form TATCSQ01, a site chronology with an overall length of 223 rings. This site chronology is dated as spanning AD 1759–1981 (Table S1.13).

*Table S1.13: Results of the cross-matching of site sequence TATCSQ01 and relevant reference chronologies when the first-ring date is AD 1759 and the last-ring date is AD 1981 (*t*-values after Baillie and Pilcher (1973)[4]).*

Reference chronology	*t*-value	Span of chronology (AD)	Reference
Modern Trees, Oxfordshire	12.2	1781–1978	Pilcher and Baillie[84]
Modern Trees, Gloucestershire	11.0	1724–1998	Howard *et al.*[85]
Stoneleigh Abbey, Stoneleigh, Warwickshire	10.7	1701–1998	Howard *et al.*[86]
Bradgate Park, Bradgate, Leicestershire	10.7	1595–1975	Laxton and Litton[87]
Sydenham House, Lewdown, Okehampton, Devon	10.6	1741–2013	Arnold *et al.*[88]
Sotterley Park, nr Beccles, Suffolk	10.4	1586–1981	Briffa *et al.*[89]
Savernake Forest, Wiltshire	10.2	1651–1982	Briffa *et al.* [89]
Winchester, Hampshire	10.1	1635–1972	Barefoot[79]
Hayley wood, Cambridgeshire	9.8	1777–1981	Bridge[90]
Forest of Dean, Gloucestershire	8.4	1672–1981	Briffa *et al.*[89]

The raw ring-width data of all the measured samples from Tattershall Castle is provided by Arnold *et al.* [83] and at https://www.ncdc.noaa.gov/paleo-search/study/28331.

SYD-M22

This sample consisted of a core taken for dendrochronology from a felled/fallen tree at Sydenham House, Devon, UK (50.63°N, 4.22°W). This oak timber contained 263 rings, including 29 sapwood rings and complete bark edge, and has been dated as spanning AD 1742 – AD 2004.

The tree-ring dating of the timbers from Sydenham House and woodlands has been fully reported by Arnold *et al.*[88]. A total of 123 samples were obtained from timbers in the house, with two further ring series from decorative corbels and 35 ring series from dismantled panelling being obtained by *in situ* measurement. Slices were obtained by chain-sawing from seven fallen/felled trees in the area to the west of the house, and 20 living trees in Sydenham wood were sampled by coring using a 4mm Haglof corer. SYD-M22 was from one of the seven fallen/felled trees. Analysis of the historic timbers from the house and the modern trees was undertaken separately.

Each of the 27 samples obtained from modern trees on the estate was prepared by sanding and polishing. It was seen at this time that the ring sequence of sample SYD-M18 was distorted and decayed. Thus, as the growth rings could not be measured reliably, it was excluded from further analysis. In addition, sample SYD-M19 had a short section of growth towards the middle of the core in which the rings could not be reliably distinguished, also due to distortion and decay. In this instance, the rings on either side of this unmeasurable section were suitable for measurement. The annual growth ring widths of the 26 samples considered suitable for analysis were therefore, measured to a precision of 0.01 mm. These data were then compared with each other by the Litton/Zainodin grouping procedure (Laxton *et al.*[2]; Litton and Zainodin[3]), allowing a single group comprising all 26 measured samples to be formed at a minimum *t*-value of 4.5. The ring series from these trees were combined at their indicated offset positions to form site chronology SYDMSQ01, this having an overall length of 273 rings. This site chronology is dated as spanning AD 1741–2013 (Table S1.14).

Table S1.14: Results of the cross-matching of site sequence SYDMSQ01 and relevant reference chronologies when the first-ring date is AD 1741 and the last-ring date is AD 2013 (t-values after Baillie and Pilcher (1973)[4]).

Reference chronology	*t*-value	Span of chronology (AD)	Reference
Modern Trees, Gloucestershire	11.9	1724–1998	Howard *et al.*[85]
Fairfield House, Stogursey, Somerset	10.9	1786–2013	Arnold and Howard[91]
Tattershall Castle Moat Bridges, Lincolnshire	10.6	1759–1981	Arnold *et al.*[83]
Clovelly, Devon	10.5	1750–1981	Loader and Switsur[92]
Exeter Cathedral, Exeter, Devon	9.9	1780–1921	Arnold *et al.*[42]
Abbeyford wood, Devon	9.8	1845–1985	Loader and Switsur[93]
Enniscarthy, County Wexford, Ireland	9.6	1811–1978	Pilcher and Baillie[84]
Winchester, Hampshire	9.5	1635–1972	Barefoot[79]
Bradgate Park, Bradgate, Leicestershire	9.3	1595–1975	Laxton and Litton[87]
Modern Trees, Oxfordshire	9.0	1781–1978	Pilcher and Baillie[84]

The raw ring-width data of all the measured samples from Sydenham House and woodlands are provided by Arnold *et al.*[88] and at https://www.ncdc.noaa.gov/paleo-search/study/28330.

1515 AD reference ZH 672736

The wood sample was retrieved from the threshold of an enterprise building at Lenzburg, Schlossgasse 23 in the Cantone of Aargau. The building was demolished in 1980. The timber shows 221 rings. The center was not measured as it is distorted. The sample had neither bark nor bast and it is uncertain whether the last ring is the waney edge, but it has 14 sapwood rings.

The surface was cleared using razor blades and the rings measured with a precision of 0.01 mm. The crossdating was done using a number of regional standard chronologies as references.

*Table S1.15: Results of the cross-matching of ZH-672736 with independent regional reference chronologies when the first-ring date is AD 1463 and the last-ring date is AD 1683 (*t*-values after Baillie and Pilcher (1973)[4]).*

Reference chronology	*t*-value	Span of chronology (AD)	Reference
Oak Standard Cantone Schaffhausen "4120"	5.8	755-1730	Unpublished
Oak Standard Cantone Aargau "4663"	8.9	1123-1973	Unpublished
Oak Standard City of Zürich "4657"	8.1	1135–1996	Unpublished

Table S1.16: Ring-width data for ZH-644415 (Heidelberg format)

HEADER:
Location=AG/LENZBURG-SCHLOSSGASSE 23
Species=Quercus L.
Length=221
HasSapwood=yes
HasPith=no
Waldkante=Uncertain
KeyCode=672736
DateMeasured=20180419
MeasuredTreeRingsNr=221
Dated=AbsoluteDated
DateEnd=1683
QualityCode=Reliable
SapwoodRingsNr=14
MissingRingsBefore=15
PersID=Felix Walder
CommentMeasurement=Threshold Economy building
DATA:Single

579 545 268 427 573 352 507 410 390 463
449 386 482 268 173 244 394 335 285 402
523 556 394 290 390 328 265 247 299 260
204 214 249 273 212 290 290 228 262 285
208 198 257 293 273 312 249 208 212 328
225 180 230 190 147 123 117 160 130 128
123 168 168 182 182 230 170 178 200 138
170 147 165 150 160 124 156 132 158 110
111 150 165 134 114 132 137 109 100 102
114 105 96 97 117 99 115 120 117 177
147 126 141 137 117 124 115 126 100 90
102 117 112 66 62 68 55 56 82 74
70 71 70 81 89 68 88 79 84 58
55 76 61 56 77 77 83 91 84 68
64 79 72 75 81 78 79 67 85 68
75 75 57 61 98 115 82 112 76 89
72 86 86 78 103 79 91 65 66 62
69 72 78 77 95 87 57 82 67 66
62 47 60 54 55 57 48 44 65 82
93 89 90 86 84 69 64 60 66 59
55 55 55 72 53 96 61 65 57 55
49 64 69 46 86 67 69 62 75 69
64

The reference chronologies used for the dating of the ZH samples mentioned above were checked against each other and against the western German Oak standard Chronology as an independent reference. The early medieval part of the Western German chronology has been debated recently[94], but the medieval and early modern part is undisputed. The multi-century chronologies prove to be a consistent regional network (Table S1.17).

Table S1.17: Results of the cross-matching of the regional chronologies of the Cantones of Aargau and Schaffhausen as well as the City of Zurich and the Western German Standard (t-values after Baillie and Pilcher (1973)[4]).

	Aargau	Schaffhausen	Zurich	W-Germany
Aargau	-	24.3	24.5	15.3
Schaffhausen		-	27	17.3
Zurich			-	15.8
W-Germany				-

S2 Quality control

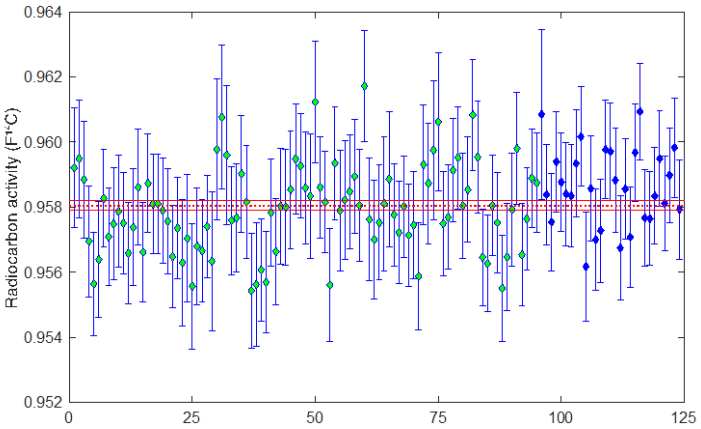

Figure S2: *The results of all 124 1515AD-reference samples (green from the Pine and blue from the Oak reference) repetitively prepared and measured between June 2017 and September 2018 measured together with the annual samples are given with 1-σ uncertainties. The mean value with 1-σ uncertainty is given in red.*

S3 Reconstruction of solar modulation parameter

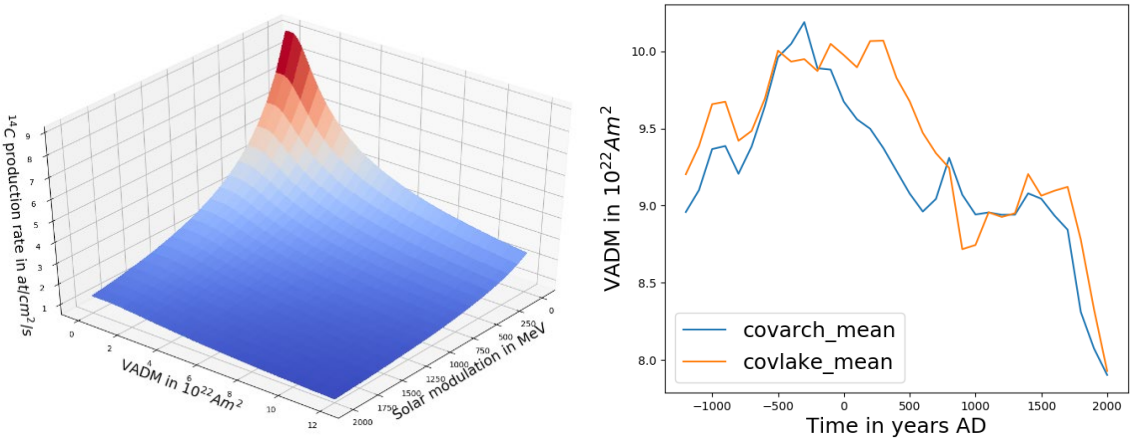

Figure S3 *Left: ^{14}C production rate dependence on earth's virtual axis dipole moment and solar modulation parameter[95]. Right: Two geomagnetic field records of the last 2000 years expressed as the intensity of virtual axial dipole field (VADM) [96]*

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