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Fairfield House, Stogursey, near Bridgewater, Somerset
Tree-ring Analysis of Oak Trees from the Estate Woodlands

Alison Arnold and Robert Howard

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SUMMARY

Dendrochronological analysis was undertaken on cross-sectional slices from seven recently felled trees along with core samples from 13 living trees from three locations on the Fairfield House estate. This analysis produced a single site chronology comprising 19 samples with an overall length of 227 rings. These rings were dated as spanning the years AD 1786–2012.

CONTRIBUTORS

Alison Arnold and Robert Howard

ACKNOWLEDGEMENTS

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ARCHIVE LOCATION

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DATE OF INVESTIGATION

2013

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CONTENTS

INTRODUCTION

Fairfield House is a Grade II* listed manor house located just to the west of the village of Stogursey in Somerset (Figs 1a–b). The manor house has origins in the medieval period but it underwent substantial remodelling in later centuries. It is set in an extensive, well-wooded, estate containing several areas of woodland comprising a variety of trees including a large number of potentially long-lived oak trees (Figs 2a–b). Whilst there are what are almost certainly late-nineteenth century or early-twentieth century plantings, there are a substantial number of trees that are potentially older, some thought possibly to have started growing in the late-eighteenth century.

Fairfield House, and a barn on the estate, known as Wood Barn, have been the subject of a programme of tree-ring dating (Arnold and Howard 2013; Arnold and Howard 2014) which resulted in the production of a series of site chronologies running from the late-fourteenth century to the latter part of the eighteenth century. A number of fallen trees in two of the estate woodlands suggested that these were of significant age and that they could potentially add to the understanding of the history of the estate woodlands, thought to have been used in the house at various times.

SAMPLING

Following discussions with relevant parties, tree-ring analysis was commissioned to examine the potentially long-lived oak trees of the surrounding Fairfield estate woodlands. In addition to enhancing the understanding of the extant woodland within the estate, it was hoped that it might be possible to produce a site chronology anchored in the present day (2012 being the last full growing season at the time of sampling) which overlapped with the site chronologies from the building timbers on this estate (last ring date AD 1778), thus providing valuable reference data for the region for more recent centuries. It was anticipated that such local reference data may allow undated timbers from the latter phases in Fairfield House and Wood Barn to be successfully dated, and prove valuable for other buildings of late date in the region that have previously proven undated or may be included in future programmes of dendrochronology.

Although oak trees are to be found widely distributed about the estate, discussions led to the decision that this programme of analysis would concentrate on collections of trees growing in groups in three distinct areas: Martin's Wood, the Great Plantation, and those growing along the field boundary close to Wood Barn (Fig 3). All three areas contain a mixture of trees. However oak, beech, sycamore, and sweet chestnut predominate, all growing in moderately dense proximity, with some hazel under-storey and occasional clumps of bracken, though the field boundary trees are of a more open aspect.

From these trees a total of 20 samples were obtained in April 2013, 13 samples being taken with a Haglof borer as cores from living oak trees, while a further seven samples were obtained by taking cross-sectional slices with a chainsaw from relatively recently fallen trees. Each sample was given the code FFD-M (for Fairfield 'modern' trees) and numbered 01–20 (Table 1).

The position of both the cored and sliced trees was known (the fallen examples not having been moved any distance) and was plotted approximately on plans of the respective woodlands (Figs 4a–c). The sampled trees were also photographed (Figs 5a–t). It may be determined from the maps that the majority of trees within each woodland are never more than a few hundred metres apart, with the greatest separation between trees in Martin's Wood and the Great Plantation being about half a kilometre. The trees at Wood Barn are about one kilometre south of both Martin's Wood and the Great Plantation.

ANALYSIS AND RESULTS

Each of the 20 samples obtained from the three areas on the Fairfield estate were prepared by sanding and polishing. It was seen at this time that one sample, FFD-M20, had some distortion and knotting to its growth, precluding accurate measurement of the annual rings. This sample was therefore rejected from this programme of analysis.

The annual growth ring widths of the 19 suitable samples were measured (the data of these measurements being given at the end of this report) with the data then being compared with each other by the Litton/Zainodin grouping procedure (see Appendix). This comparative process produced a single group comprising all 19 measured samples, the samples cross-matching with each other as shown in Figure 6. The 19 cross-matching samples were combined at their indicated offset positions to form site chronology FFDMSQ01, this having an overall length of 227 rings.

Site chronology FFDMSQ01 was then compared to an extensive corpus of reference material for oak matching with a high number of these when the date of its first ring is AD 1786 and the date of its last full growth ring is AD 2012 (Table 2).

INTERPRETATION AND CONCLUSION

Analysis by dendrochronology of samples from both living and recently felled trees on the Fairfield estate has produced a single site chronology comprising 19 samples. This site chronology is 227 rings long and spans the period AD 1786–2012, thus providing very valuable data spanning the late-eighteenth to early-twenty-first centuries. Unfortunately, though, this modern tree chronology does not overlap with the site chronologies from Fairfield House or Wood Barn, ending at AD 1778 and AD 1771 respectively, nor has it proven useful in dating any previously undated samples from either building.

The analysis demonstrates that the oldest trees in both Martin's Wood and the Great Plantation are of similar ages and, allowing for uncored additional rings towards the centres of the trees and the location of the samples along the trunks, are generally well in excess of 150 years old, with a few, FFD-M12, M15, M16, probably being in excess of 200 years of age. As may be seen from Table 1, where the approximate growth start date is estimated, these trees may therefore be associated with plantings in the early- and mid-nineteenth century. The undated Wood Barn field boundary tree, FFD-M20, appears to be of similar age to those in Martin's Wood and the Great Plantation, while the other tree here, FFD-M19, appears to have begun growing in the late-eighteenth century, perhaps shortly after the adjacent Wood Barn itself was constructed (AD 1771).

The analysis also provides useful information on the level of similarity between ring series derived from trees growing a known distance apart. It may be seen from the *t*-value/off-set matrix (Fig 7) that the samples from the trees in Martin's Wood (FFD-M01–FFD-M11) generally match strongly with each other, with a number of *t*-values in excess of 10.0, although *t*-values actually range from 3.7 to 11.5 and have a mean value of 7.5. The trees from the Great Plantation (FFD-M12–FFD-M18) are a similar distance apart as those in Martin's Wood but the level of cross-matching is a generally slightly lower with *t*-values ranging from 3.2 to 9.5 with a mean value of 6.0. Such information provides comparative material for assemblages used in the construction of historic buildings and can thus provide an insight into nature of woodland source, or sources, utilised within historic buildings.

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TABLES

Table 1: Details of tree-ring samples from the Fairfield House Estate, Stogursey, Somerset

Sample number	Sample location	Circumference at breast height (m)	Total rings	Sapwood rings	Growth start date (approximate)	First measured ring date AD	Last heartwood ring date AD	Last measured ring date AD
	Martin's Wood							
FFD-M01	Tree (fallen) *	1.50	150	14	1819	1819	1954	1968
FFD-M02	Tree (fallen) *	1.60	140	30C	1830	1830	1939	1969
FFD-M03	Tree (fallen) *	1.50	116	11	1835	1835	1939	1950
FFD-M04	Tree (fallen) *(centre rotted)*	2.00	157	37C	1830	1845	1964	2001
FFD-M05	Tree (fallen) *	1.80	125	h/s	1842	1842	1966	1966
FFD-M06	Tree (live)	2.80	166	26C	1840	1847	1986	2012
FFD-M07	Tree (live)	2.60	165	31C	1845	1848	1981	2012
FFD-M08	Tree (live)	2.50	177	29C	1820	1836	1983	2012
FFD-M09	Tree (live)	3.60	169	23C	1840	1844	1989	2012
FFD-M10	Tree (live)	2.90	158	29C	1850	1855	1983	2012
FFD-M11	Tree (live)	2.30	157	31C	1850	1856	1981	2012
	Great Plantation							
FFD-M12	Tree (live)	2.85	197	35C	1810	1816	1977	2012
FFD-M13	Tree (live)	3.60	138	24C	1850	1875	1988	2012
FFD-M14	Tree (live)	3.00	161	28C	1850	1852	1984	2012
FFD-M15	Tree (live) *(inner 65-70 rings distorted)*	2.80	141	27C	1800	1872	1985	2012
FFD-M16	Tree (live)	3.50	194	35C	1800	1819	1977	2012
FFD-M17	Tree (fallen) *	1.75	168	16	1839	1839	1990	2006
FFD-M18	Tree (fallen) *	1.90	146	25C	1844	1844	1964	1989
	Trees at Wood Barn							
FFD-M19	Tree (live)	2.10	220	28c	1780	1786	1984	2005
FFD-M20	Tree (live)	1.90	NM	29C	------	------	------	------

NM = not measured; C = complete sapwood is retained on the sample; c = complete sapwood is found on the tree, but some rings were lost during coring; *centre of tree on sample

Table 2: Results of the cross-matching of sample FFDMSQ01 and relevant reference chronologies when the first-ring date is AD 1786 and the last-ring date is AD 2012

Reference chronology	Span of chronology	*t*-value	Reference
Gloucestershire woodlands	AD 1724 – 1998	12.1	(Howard 1999 unpubl)
Sydenham Estate, Lewdown, Devon	AD 1741 – 2013	10.9	(Arnold *et al* forthcoming)
Clovelly, Devon	AD 1750 – 1981	9.3	(Briffa 1986)
Winchester, Hampshire	AD 1635 – 1972	9.2	(Barefoot 1975)
Ashe House, Iddesleigh, Devon	AD 1775 – 2002	8.8	(I Tyers *pers comm*)
Radley woods, Radley, Oxfordshire	AD 1812 – 1979	8.4	(Briffa *pers comm*)
Bath, Avon	AD 1754 – 1979	8,2	(Pilcher and Baillie 1980)
Exeter Cathedral, Exeter, Devon	AD 1780 – 1921	7.7	(Arnold *et al* 2003)

FIGURES

Figure 1a: Map to show the general location of Stogursey. © Crown Copyright and database right 2015. All rights reserved. Ordnance Survey Licence number 100024900

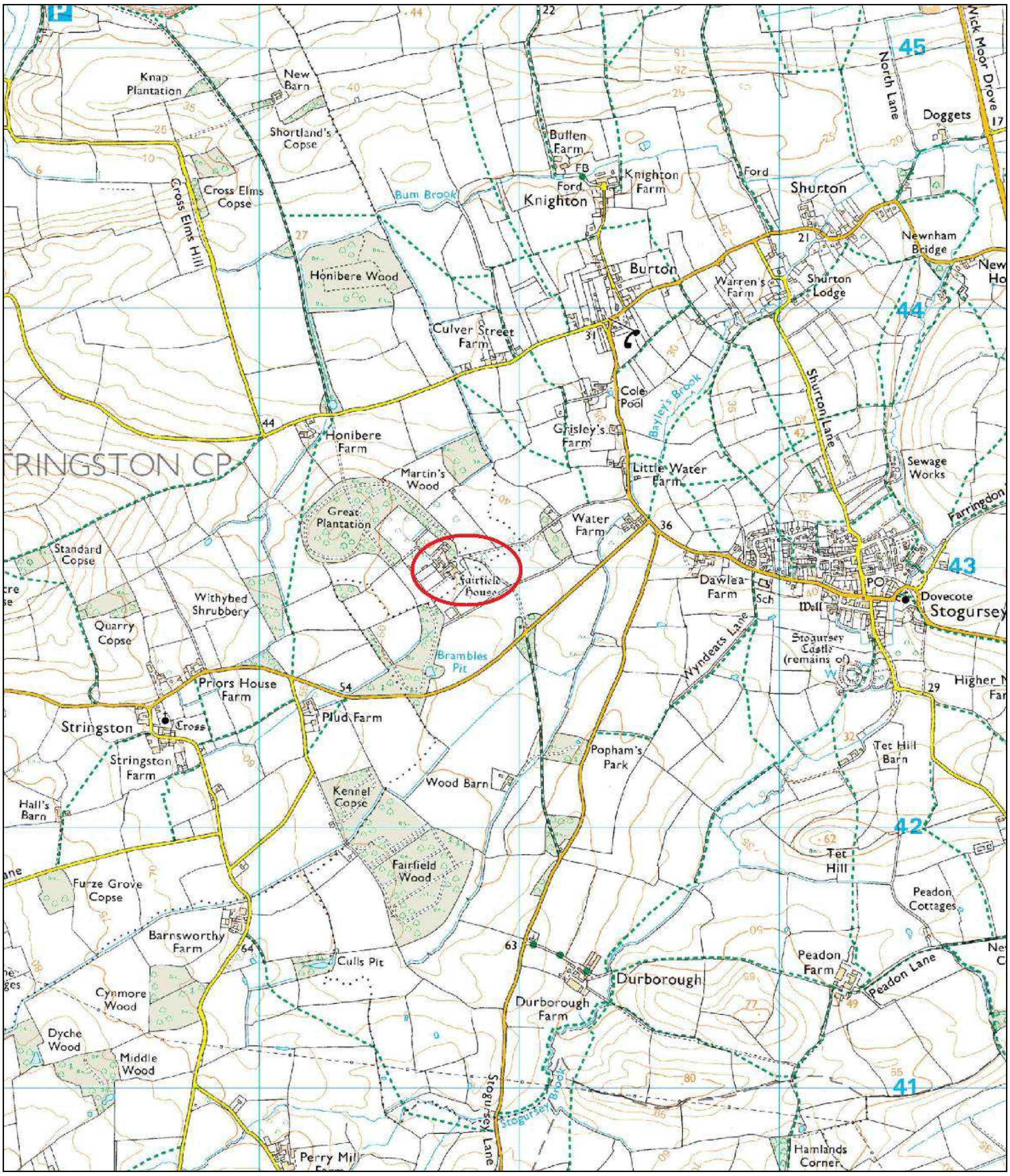


Figure 1b: Map to show the location of Fairfield House. © Crown Copyright and database right 2015. All rights reserved. Ordnance Survey Licence number 100024900

Figure 2a–b: Illustrative examples of oak trees on the Fairfield estate (photographs Robert Howard)

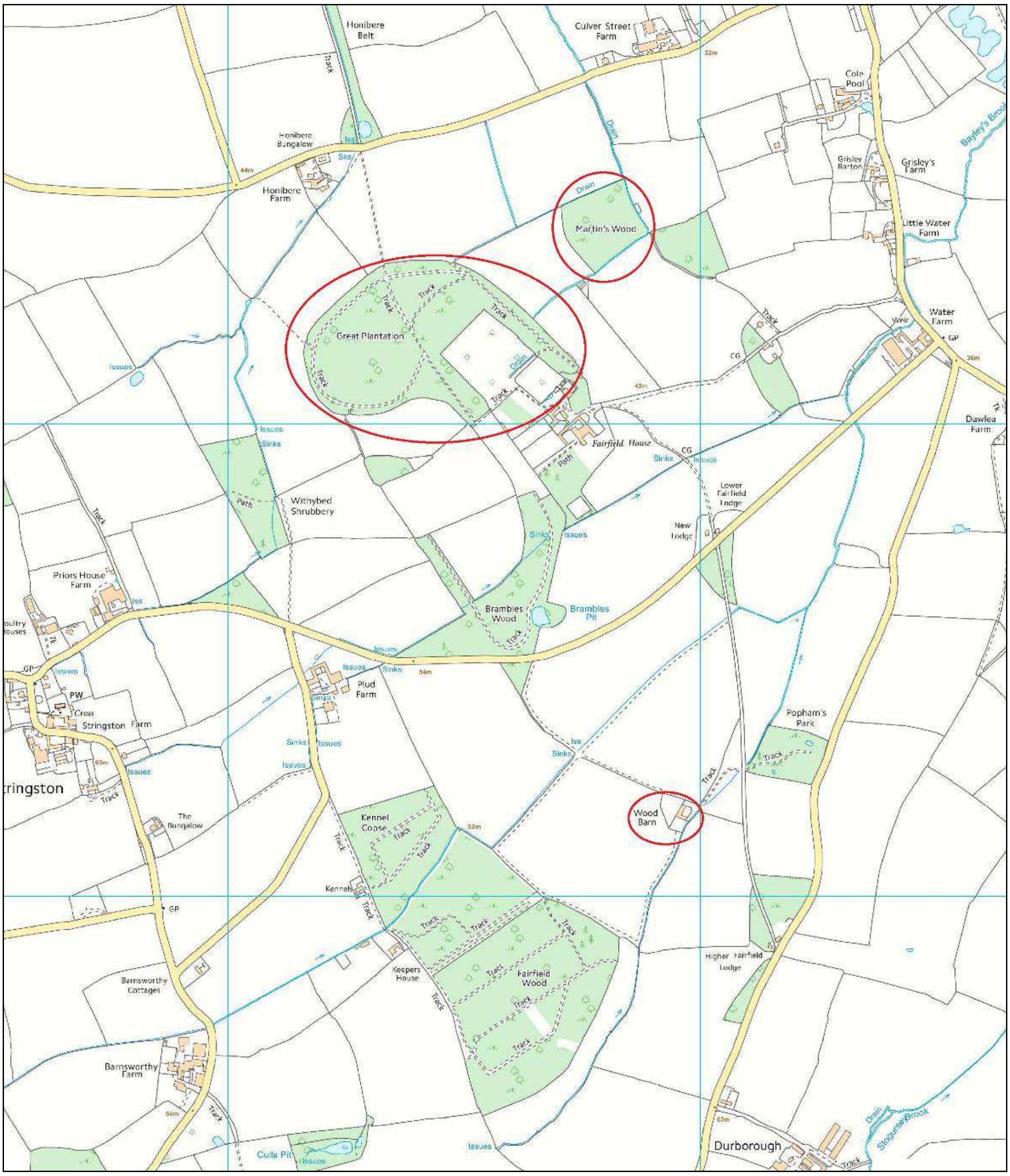


Figure 3: Map to show the location of the three sample areas. © Crown Copyright and database right 2015. All rights reserved. Ordnance Survey Licence number 100024900

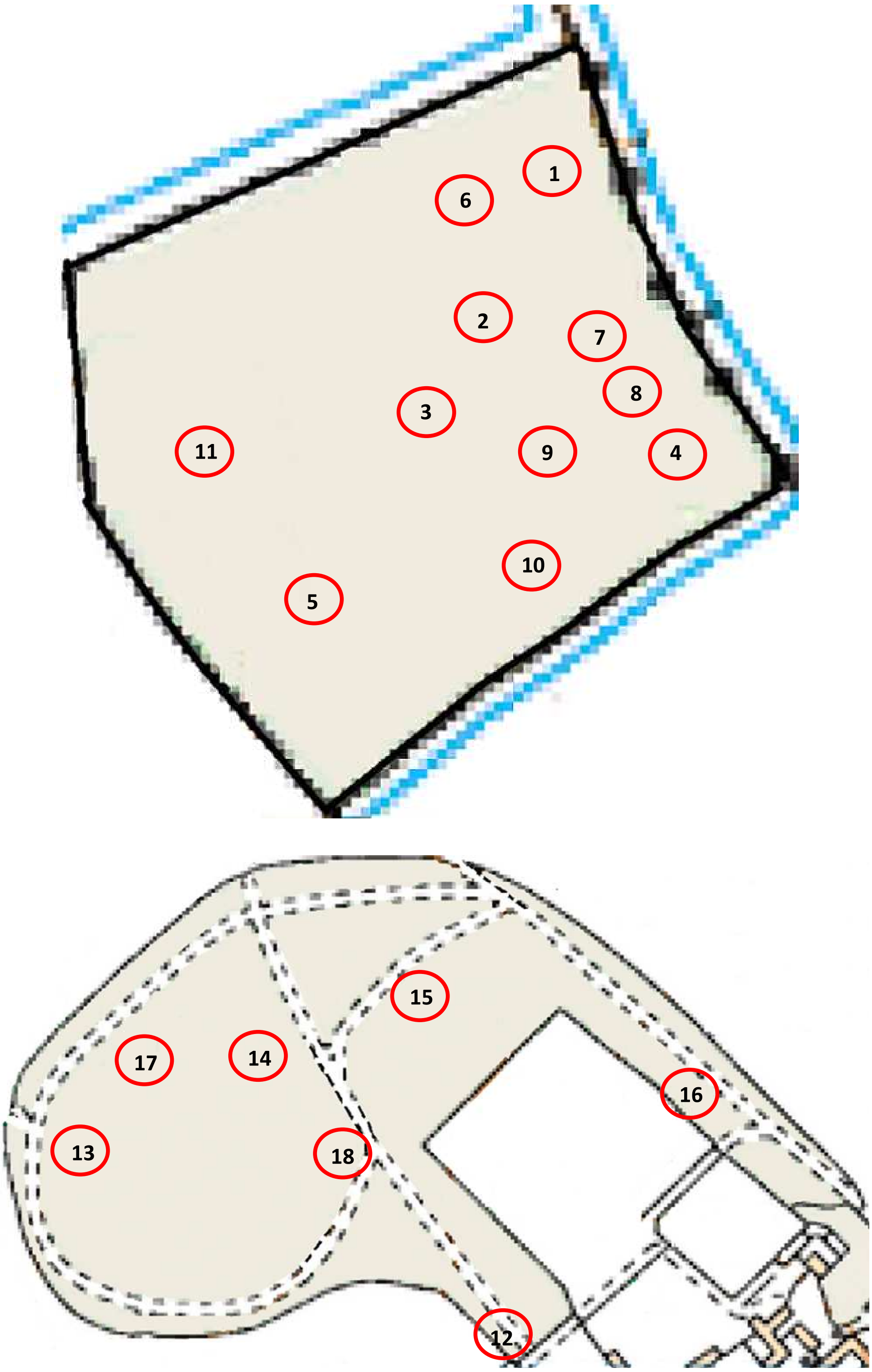


Figure 4a–b: Map to help locate sampled trees in Martin's Wood (top) and the Great Plantation (bottom). © Crown Copyright and database right 2015. All rights reserved. Ordnance Survey Licence number 100024900

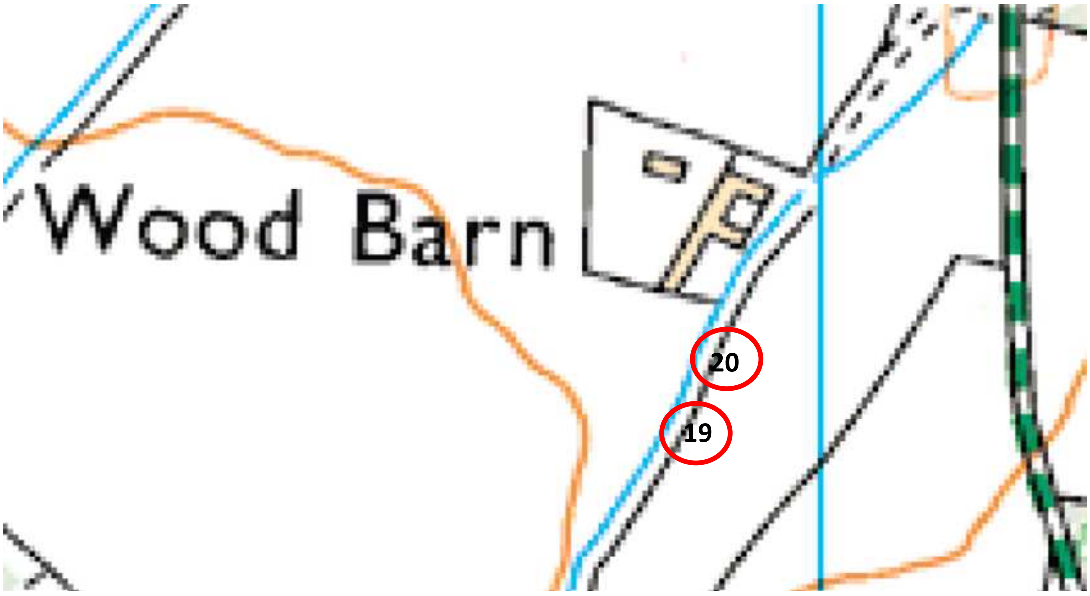


Figure 4c: Map to help locate sampled trees near Wood Barn. © Crown Copyright and database right 2015. All rights reserved. Ordnance Survey Licence number 100024900

FFD-M01 (Martin's Wood) FFD-M02

FFD-M03 (Martin's Wood) FFD-M04

FFD-M05 (Martin's Wood)

Figure 5a–e: Photographs to help identify the sampled trees (photographs Robert Howard)

FFD-M06 (Martin's Wood) FFD-M07

FFD-M08 (Martin's Wood) FFD-M09

Figure 5f–i: Photographs to help identify the sampled trees (photographs Robert Howard)

FFD-M10 (Martin's Wood) FFD-M11

FFD-M12 (Great Plantation) FFD-M13

Figure 5j–m: Photographs to help identify the core-sampled living trees (photographs Robert Howard)

FFD-M14 (Great Plantation) FFD-M15

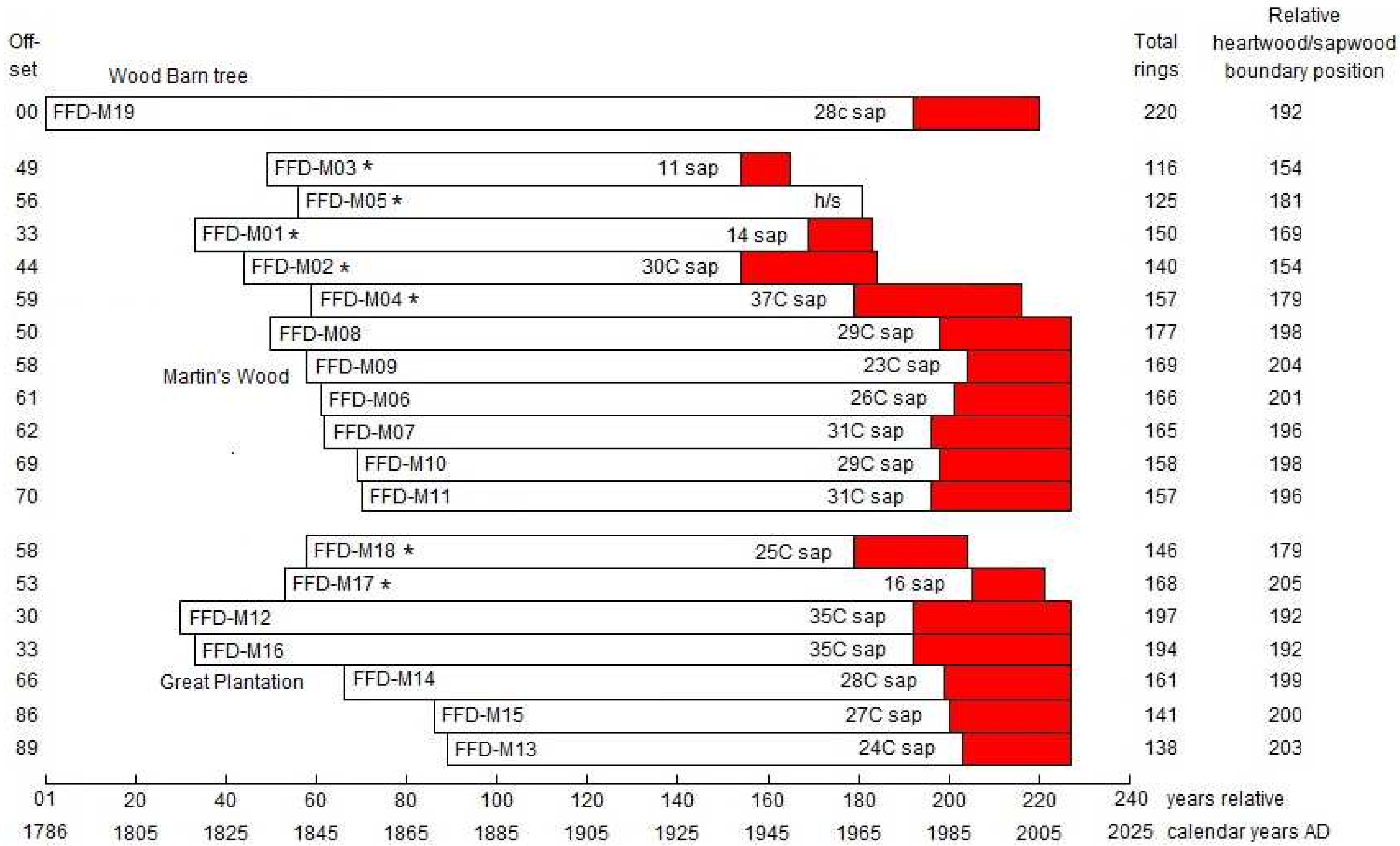
FFD-M16 (Great Plantation)

Figure 5n–p: Photographs to help identify the core-sampled living trees (photographs Robert Howard)


FFD-M17 (Great Plantation) FFD-M18


FFD-M19 (Trees at Wood Barn) FFD-M20

Figure 5q–t: Photographs to help identify the core-sampled living trees (photographs Robert Howard)



White bars = heartwood rings; shaded bars = sapwood rings; C = complete sapwood is retained on the sample; c= there is complete sapwood on timber, but part has been lost in sampling; h/s = heartwood/sapwood boundary; * = fallen tree

Figure 6: Bar diagram of the samples in site chronology FFDMSQ01

Martin's Wood

Great Plantation

Tree at Wood Barn

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
FFD-M01	1	***	-11	-16	-26	-23	-28	-29	-17	-25	-36	-37	3	-56	-33	-53	0	-20	-25	33
FFD-M02	2	10.1	***	-5	-15	-12	-17	-18	-6	-14	-25	-26	14	-45	-22	-38	11	-9	-14	44
FFD-M03	3	7.5	8.9	***	-10	-7	-12	-13	-1	-9	-20	-21	19	-40	-17	-37	16	-4	-9	49
FFD-M04	4	6.8	5.9	5.7	***	3	-2	-3	9	1	-10	-11	29	-30	-7	-27	26	6	1	59
FFD-M05	5	6.9	6.1	5.7	5.5	***	-5	-6	6	-2	-13	-14	26	-33	-10	42	23	3	-2	56
FFD-M06	6	10.9	10.6	8.9	7.4	8.7	***	-1	11	3	-8	-9	31	-28	-5	-112	28	8	3	61
FFD-M07	7	9.7	9.0	8.5	7.5	7.5	11.3	***	12	4	-7	-8	32	-27	-4	-65	29	9	4	62
FFD-M08	8	6.4	5.6	6.7	8.2	7.5	8.1	10.0	***	-8	-19	-20	20	-39	-16	-36	17	-3	-8	50
FFD-M09	9	4.9	4.7	3.7	6.8	5.9	5.4	6.1	6.8	***	-11	-12	28	-31	-8	-28	25	5	23	58
FFD-M10	10	5.3	5.4	7.5	7.8	7.0	6.2	7.3	11.5	6.0	***	-1	39	-20	3	-17	36	16	11	69
FFD-M11	11	6.8	7.2	10.1	6.9	7.4	8.1	9.2	9.2	4.7	11.4	***	40	-19	4	-66	37	17	12	70
FFD-M12	12	5.7	5.7	7.0	6.8	6.7	6.4	7.5	9.3	6.5	10.0	9.1	***	-59	-36	-79	-3	-23	-28	30
FFD-M13	13	5.9	6.3	5.4	4.7	5.0	5.3	4.5	6.3	3.2	6.5	6.0	5.9	***	23	3	56	36	31	89
FFD-M14	14	5.5	5.4	6.8	4.9	5.1	5.6	5.8	7.7	4.0	9.9	9.1	6.0	7.3	***	-20	33	13	8	66
FFD-M15	15	3.5	3.2	3.2	3.9	3.6	2.7	3.6	3.7	4.9	5.8	3.5	4.1	4.8	5.4	***	103	33	28	-30
FFD-M16	16	8.4	9.1	6.5	7.1	7.3	9.8	11.5	9.7	6.7	8.2	7.8	7.1	6.1	6.1	3.2	***	-20	-25	33
FFD-M17	17	7.1	6.3	7.9	3.8	5.7	6.2	7.3	7.5	3.6	6.7	8.4	5.9	5.5	7.9	3.4	7.5	***	-5	53
FFD-M18	18	6.5	5.7	6.0	4.2	4.4	4.2	6.2	6.2	2.7	6.6	7.6	6.9	7.9	9.5	5.3	5.0	5.4	***	58
FFD-M19	19	6.8	5.8	7.2	5.6	5.7	6.8	6.1	7.0	7.2	4.8	7.1	7.4	5.0	4.5	3.4	8.5	5.0	4.9	***

Figure 7: t-value/off-set matrix of the cross-matching between the 19 dated samples

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

FFD-M01A 150
100 150 117 82 128 200 94 193 303 439 503 498 348 296 232 295 143 253 92 112
184 92 133 150 174 82 152 134 131 224 146 125 130 150 348 159 200 145 238 134
192 93 123 125 82 185 264 200 263 164 206 185 200 221 226 162 322 109 126 209
260 154 164 147 126 118 85 174 126 259 134 178 233 143 121 140 168 100 96 68
68 133 118 98 189 121 100 64 74 50 77 134 65 114 83 138 143 163 189 168
116 124 81 129 43 110 92 82 206 122 99 72 132 132 65 51 92 216 155 109
241 212 168 128 124 176 159 146 212 163 145 306 145 103 121 111 162 132 76 179
156 203 133 133 117 106 108 176 132 137
FFD-M01B 150
136 153 119 85 129 185 94 187 301 418 418 525 371 310 214 300 153 262 93 89
192 94 135 151 171 84 153 132 132 220 150 132 116 162 351 157 193 150 243 121
179 95 142 112 81 188 269 189 263 160 196 192 196 225 214 171 306 117 132 200
257 156 174 142 121 114 90 169 123 260 122 197 227 153 118 137 150 102 93 72
78 121 119 90 205 112 91 71 74 44 77 134 59 121 94 130 138 150 198 178
124 125 81 133 41 108 91 84 190 121 90 76 122 127 73 43 100 215 166 112
239 213 165 125 128 177 155 159 212 154 143 306 141 104 109 104 148 134 81 165
158 213 121 107 112 105 106 176 131 138
FFD-M02A 140
154 83 68 83 140 106 198 220 133 146 72 88 86 120 65 89 42 65 61 60
54 75 108 266 279 306 247 298 277 354 349 343 260 171 259 457 264 326 166 245
193 268 192 192 142 375 221 237 332 376 208 157 134 134 123 96 226 181 303 137
264 315 287 197 173 143 104 123 98 68 170 204 123 109 115 90 139 134 90 93
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46 128 81 66 33 33 96 84 43 79 107 72 58 43 56 75 115 127 54 81
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289 275 179 156 174 323
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239 157 153 179 217 126 171 154 151 264 142 139 245 223 153 250 119 106 98 125
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FFD-M07B 165
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FFD-M08A 177
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FFD-M10A 158
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196 175 214 191 178 287 367 151 162 222 177 149 154 149 177 107 109 220 270 210
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FFD-M10B 158
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FFD-M11A 157
261 338 347 410 464 503 489 390 387 457 296 457 322 459 387 383 446 407 275 482
278 401 495 431 300 198 225 179 186 185 217 171 182 141 103 214 264 170 179 198
176 243 171 178 202 202 151 133 146 122 153 154 123 190 146 108 146 178 173 137
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FFD-M11B 157
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157 120 98 112 139 123 142 225 183 117 143 122 113 105 79 68 71 72 46 68

71 110 170 148 112 84 93 114 110 121 143 120 83 71 64 79 82 71 65 62
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FFD-M12B 197
394 147 126 156 87 208 141 100 97 67 87 141 128 198 239 283 285 289 364 203
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FFD-M13A 138
444 466 618 683 541 707 566 407 459 567 478 676 419 570 457 689 776 734 500 439
315 240 326 271 271 346 431 300 345 396 308 273 281 258 282 328 223 289 263 325
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129 87 109 118 242 160 237 196 193 206 141 119 167 165 157 128 126 177
FFD-M14A 161
371 595 364 330 300 340 332 371 465 561 414 250 220 364 382 421 318 615 494 527
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FFD-M16B 194
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135 106 59 52 32 44 27 19 59 118 62 100 189 295 420 564 532 566 485 322
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FFD-M18B 146
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FFD-M19A 220
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FFD-M19B 220
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APPENDIX: TREE-RING DATING

The Principles of Tree-Ring Dating

Tree-ring dating, or dendrochronology as it is known, is discussed in some detail in the Nottingham Tree-ring Dating Laboratory's Monograph, *An East Midlands Master Tree-Ring Chronology and its uses for dating Vernacular Buildings* (Laxton and Litton 1988) and *Dendrochronology: Guidelines on Producing and Interpreting Dendrochronological Dates* (English Heritage 1988). Here we will give the bare outlines. Each year an oak tree grows an extra ring on the outside of its trunk and all its branches just inside its bark. The width of this annual ring depends largely on the weather during the growing season, about April to October, and possibly also on the weather during the previous year. Good growing seasons give rise to relatively wide rings, poor ones to very narrow rings and average ones to relatively average ring widths. Since the climate is so variable from year to year, almost random-like, the widths of these rings will also appear random-like in sequence, reflecting the seasons. This is illustrated in Figure A1 where, for example, the widest rings appear at irregular intervals. This is the key to dating by tree rings, or rather, by their widths. Records of the average ring widths for oaks, one for each year for the last 1000 years or more, are available for different areas. These are called master chronologies. Because of the random-like nature of these sequences of widths, there is usually only one position at which a sequence of ring widths from a sample of oak timber with at least 70 rings will match a master. This will date the timber and, in particular, the last ring.

If the bark is still on the sample, as in Figure A1, then the date of the last ring will be the date of felling of the oak from which it was cut. There is much evidence that in medieval times oaks cut down for building purposes were used almost immediately, usually within the year or so (Rackham 1976). Hence if bark is present on several main timbers in a building, none of which appear reused or are later insertions, and if they all have the same date for their last ring, then we can be quite confident that this is the date of construction or soon after. If there is no bark on the sample, then we have to make an estimate of the felling date; how this is done is explained below.

The Practice of Tree-Ring Dating at the Nottingham Tree-Ring Dating Laboratory

1. **Inspecting the Building and Sampling the Timbers.** Together with a building historian the timbers in a building are inspected to try to ensure that those sampled are not reused or later insertions. Sampling is almost always done by coring into the timber, which has the great advantage that we can sample *in situ* timbers and those judged best to give the date of construction, or phase of construction if there is more than one in the building. The timbers to be sampled are also inspected to see how many rings they have. We normally look for timbers with at least 70 rings, and preferably more. With fewer rings than this, 50 for example, sequences of widths become difficult to match to a unique

position within a master sequence of ring widths and so are difficult to date (Litton and Zainodin 1991). The cross-section of the rafter shown in Figure A2 has about 120 rings; about 20 of which are sapwood rings – the lighter rings on the outside. Similarly the core has just over 100 rings with a few sapwood rings.

To ensure that we are getting the date of the building as a whole, or the whole of a phase of construction if there is more than one, about 8–10 samples per phase are usually taken. Sometimes we take many more, especially if the construction is complicated. One reason for taking so many samples is that, in general, some will fail to give a date. There may be many reasons why a particular sequence of ring widths from a sample of timber fails to give a date even though others from the same building do. For example, a particular tree may have grown in an odd ecological niche, so odd indeed that the widths of its rings were determined by factors other than the local climate! In such circumstances it will be impossible to date a timber from this tree using the master sequence whose widths, we can assume, were predominantly determined by the local climate at the time.

Sampling is done by coring into the timber with a hollow corer attached to an electric drill and usually from its outer rings inwards towards where the centre of the tree, the pith, is judged to be. An illustration of a core is shown in Figure A2; it is about 150mm long and 10mm diameter. Great care has to be taken to ensure that as few as possible of the outer rings are lost in coring. This can be difficult as these outer rings are often very soft (see below on sapwood). Each sample is given a code which identifies uniquely which timber it comes from, which building it is from and where the building is located. For example, CRO-A06 is the sixth core taken from the first building (A) sampled by the Laboratory in Cropwell Bishop. Where it came from in that building will be shown in the sampling records and drawings. No structural damage is done to any timbers by coring, nor does it weaken them.

During the initial inspection of the building and its timbers the dendrochronologist may come to the conclusion that, as far as can be judged, none of the timbers have sufficient rings in them for dating purposes and may advise against sampling to save further unwarranted expense.

All sampling by the Laboratory is undertaken according to current Health and Safety Standards. The Laboratory's dendrochronologists are insured.

Figure A1: A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can be determined by counting back from the outside ring, which grew in 1976

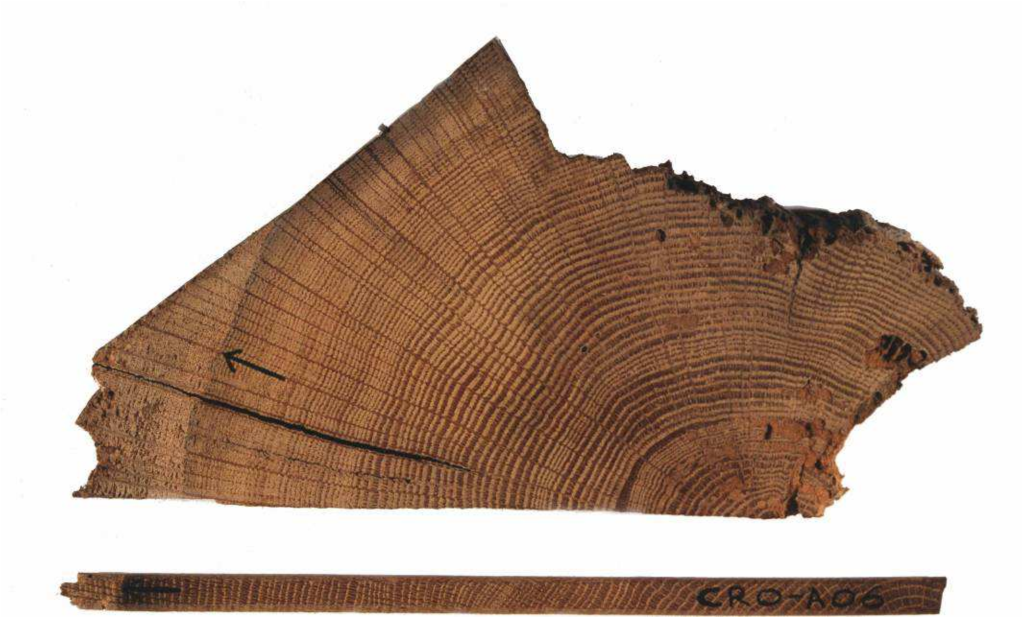


Figure A2: Cross-section of a rafter, showing sapwood rings in the left-hand corner, the arrow points to the heartwood/sapwood boundary (H/S); and a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil

Figure A3: Measuring ring widths under a microscope. The microscope is fixed while the sample is on a moving platform. The total sequence of widths is measured twice to ensure that an error has not been made. This type of apparatus is needed to process a large number of samples on a regular basis

Figure A4: Three cores from timbers in a building. They come from trees growing at the same time. Notice that, although the sequences of widths look similar, they are not identical. This is typical

2. Measuring Ring Widths. Each core is sanded down with a belt sander using medium-grit paper and then finished by hand with flourgrade-grit paper. The rings are then clearly visible and differentiated from each other with a result very much like that shown in Figure A2. The core is then mounted on a movable table below a microscope and the ring-widths measured individually from the innermost ring to the outermost. The widths are automatically recorded in a computer file as they are measured (see Fig A3).

3. Cross-Matching and Dating the Samples. Because of the factors besides the local climate which may determine the annual widths of a tree's rings, no two sequences of ring widths from different oaks growing at the same time are exactly alike (Fig A4). Indeed, the sequences may not be exactly alike even when the trees are growing near to each other. Consequently, in the Laboratory we do not attempt to match two sequences of ring widths by eye, or graphically, or by any other subjective method. Instead, it is done objectively (ie statistically) on a computer by a process called cross-matching. The output from the computer tells us the extent of correlation between two sample sequences of widths or, if we are dating, between a sample sequence of widths and the master, at each relative position of one to the other (offsets). The extent of the correlation at an offset is determined by the *t*-value (defined in almost any introductory book on statistics). That offset with the maximum *t*-value among the *t*-values at all the offsets will be the best candidate for dating one sequence relative to the other. If one of these is a master chronology, then this will date the other. Experiments carried out in the past with sequences from oaks of known date suggest that a *t*-value of at least 4.5, and preferably at least 5.0, is usually adequate for the dating to be accepted with reasonable confidence (Laxton and Litton 1988; Laxton *et al* 1988; Howard *et al* 1984–1995).

This is illustrated in Figure A5 with timbers from one of the roofs of Lincoln Cathedral. Here four sequences of ring widths, LIN-C04, 05, 08, and 45, have been cross-matched with each other. The ring widths themselves have been omitted in the bar diagram, as is usual, but the offsets at which they best cross-match each other are shown; eg the sequence of ring widths of C08 matches the sequence of ring widths of C45 best when it is at a position starting 20 rings after the first ring of C45, and similarly for the others. The actual *t*-values between the four at these offsets of best correlations are in the matrix. Thus at the offset of +20 rings, the *t*-value between C45 and C08 is 5.6 and is the maximum found between these two among all the positions of one sequence relative to the other.

It is standard practice in our Laboratory first to cross-match as many as possible of the ring-width sequences of the samples in a building and then to form an average from them. This average is called a site sequence of the building being dated and is illustrated in Figure A5. The fifth bar at the bottom is a site sequence for a roof at Lincoln Cathedral and is constructed from the matching sequences of the four timbers. The site sequence width for each year is the average of the widths in each of the sample sequences which has a width for that year. Thus in Figure A5 if the widths shown are 0.8mm for C45, 0.2mm for C08, 0.7mm for C05, and 0.3mm for C04, then the corresponding width of the site sequence is the average of these, 0.55mm. The actual sequence of widths of this site sequence is stored on the computer. The reason for creating site sequences is that it is usually easier to date an average sequence of ring widths with a master sequence than it is to date the individual component sample sequences separately.

The straightforward method of cross-matching several sample sequences with each other one at a time is called the 'maximal *t*-value' method. The actual method of cross-matching a group of sequences of ring-widths used in the Laboratory involves grouping and averaging the ring-width sequences and is called the 'Litton-Zainodin Grouping Procedure'. It is a modification of the straightforward method and was successfully developed and tested in the Laboratory and has been published (Litton and Zainodin 1991; Laxton *et al* 1988).

4. **Estimating the Felling Date.** As mentioned above, if the bark is present on a sample, then the date of its last ring is the date of the felling of its tree (or the last full year before felling, if it was felled in the first three months of the following calendar year, before any new growth had started, but this is not too important a consideration in most cases). The actual bark may not be present on a timber in a building, though the dendrochronologist who is sampling can often see from its surface that only the bark is missing. In these cases the date of the last ring is still the date of felling.

Quite often some, though not all, of the original outer rings are missing on a timber. The outer rings on an oak, called sapwood rings, are usually lighter than the inner rings, the heartwood, and so are relatively easy to identify. For example, sapwood can be seen in the corner of the rafter and at the outer end of the core in Figure A2, both indicated by arrows. More importantly for dendrochronology, the sapwood is relatively soft and so liable to insect attack and wear and tear. The builder, therefore, may remove some of the sapwood for precisely these reasons. Nevertheless, if at least some of the sapwood rings are left on a sample, we will know that not too many rings have been lost since felling so that the date of the last ring on the sample is only a few years before the date of the original last ring on the tree, and so to the date of felling.

Various estimates have been made and used for the average number of sapwood rings in mature oak trees (English Heritage 1998). A fairly conservative range is between 15 and 50 and that this holds for 95% of mature oaks. This means, of course, that in a small number of cases there could be fewer than 15 and more than 50 sapwood rings. For example, the core CRO-A06 has only 9 sapwood rings and some have obviously been lost over time – either they were removed originally by the carpenter and/or they rotted away in the building and/or they were lost in the coring. It is not known exactly how many sapwood rings are missing, but using the above range the Laboratory would estimate between a minimum of 6 (=15–9) and a maximum of 41 (=50–9). If the last ring of CRO-A06 has been dated to 1500, say, then the estimated felling-date range for the tree from which it came originally would be between 1506 and 1541. The Laboratory uses this estimate for sapwood in areas of England where it has no prior information. It also uses it when dealing with samples with very many rings, about 120 to the last heartwood ring. But in other areas of England where the Laboratory has accumulated a number of samples with complete sapwood, that is, no sapwood lost since felling, other estimates in place of the conservative range of 15 to 50 are used. In the East Midlands (Laxton *et al* 2001) and the east to the south down to Kent (Pearson 1995) where it has sampled extensively in the past, the Laboratory uses the shorter estimate of 15 to 35 sapwood rings in 95% of mature oaks growing in these parts. Since the sample CRO-A06 comes from a house in Cropwell Bishop in the East Midlands, a better estimate of sapwood rings lost since felling is between a minimum of 6 (=15–9) and 26 (=35–9) and the felling would be estimated to have taken place between 1506 and 1526, a shorter period than before. Oak boards quite often come from the Baltic region and in these cases the 95% confidence limits for sapwood are 9 to 36 (Howard *et al* 1992, 56).

Even more precise estimates of the felling date and range can often be obtained using knowledge of a particular case and information gathered at the time of sampling. For example, at the time of sampling the dendrochronologist may have noted that the timber from which the core of Figure A2 was taken still had complete sapwood but that some of the soft sapwood rings were lost in coring. By measuring into the timber the depth of sapwood lost, say 20mm, a reasonable estimate can be made of the number of sapwood rings lost, say 12 to 15 rings in this case. By adding on 12 to 15 years to the date of the last ring on the sample a good tight estimate for the range of the felling date can be obtained, which is often better than the 15 to 35 years later we would have estimated without this observation. In the example, the felling is now estimated to have taken place between AD 1512 and 1515, which is much more precise than without this extra information.

Even if all the sapwood rings are missing on a sample, but none of the heartwood rings are, then an estimate of the felling-date range is possible by adding on the full complement of, say, 15 to 35 years to the date of the last heartwood ring (called the heartwood/ sapwood boundary or transition ring and denoted H/S). Fortunately it is often easy for a trained dendrochronologist to identify this boundary on a timber. If a timber does not have its heartwood/sapwood boundary, then only a *post quem* date for felling is possible.

5. **Estimating the Date of Construction.** There is a considerable body of evidence collected by dendrochronologists over the years that oak timbers used in buildings were not seasoned in medieval or early modern times (English Heritage 1998; Miles 1997, 50–5). Hence, provided that all the samples in a building have estimated felling-date ranges broadly in agreement with each other, so that they appear to have been felled as a group, then this should give an accurate estimate of the period when the structure was built, or soon after (Laxton *et al* 2001, Fig 8; 34–5, where 'associated groups of fellings' are discussed in detail). However, if there is any evidence of storage before use, or if there is evidence the oak came from abroad (eg Baltic boards), then some allowance has to be made for this.

6. Master Chronological Sequences. Ultimately, to date a sequence of ring widths, or a site sequence, we need a master sequence of dated ring widths with which to cross-match it, a Master Chronology. To construct such a sequence we have to start with a sequence of widths whose dates are known and this means beginning with a sequence from an oak tree whose date of felling is known. In Figure A6 such a sequence is SHE-T, which came from a tree in Sherwood Forest which was blown down in a recent gale. After this other sequences which cross-match with it are added and gradually the sequence is 'pushed back in time' as far as the age of samples will allow. This process is illustrated in Figure A6. We have a master chronological sequence of widths for Nottinghamshire and East Midlands oak for each year from AD 882 to 1981. It is described in great detail in Laxton and Litton (1988), but the components it contains are shown here in the form of a bar diagram. As can be seen, it is well replicated in that for each year in this period there are several sample sequences having widths for that year. The master is the average of these. This master can now be used to date oak from this area and from the surrounding areas where the climate is very similar to that in the East Midlands. The Laboratory has also constructed a master for Kent (Laxton and Litton 1989). The method the Laboratory uses to construct a master sequence, such as the East Midlands and Kent, is completely objective and uses the Litton-Zainodin grouping procedure (Laxton *et al* 1988). Other laboratories and individuals have constructed masters for other areas and have made them available. As well as these masters, local (dated) site chronologies can be used to date other buildings from nearby. The Laboratory has hundreds of these site sequences from many parts of England and Wales covering many short periods.

7. Ring-Width Indices. Tree-ring dating can be done by cross-matching the ring widths themselves, as described above. However, it is advantageous to modify the widths first. Because different trees grow at different rates and because a young oak grows in a different way from an older oak, irrespective of the climate, the widths are first standardized before any matching between them is attempted. These standard widths are known as ring-width indices and were first used in dendrochronology by Baillie and Pilcher (1973). The exact form they take is explained in this paper and in the appendix of Laxton and Litton (1988) and is illustrated in the graphs in Figure A7. Here ring-widths are plotted vertically, one for each year of growth. In the upper sequence of (a), the generally large early growth after 1810 is very apparent as is the smaller later growth from about 1900 onwards when the tree is maturing. A similar phenomenon can be observed in the lower sequence of (a) starting in 1835. In both the widths are also changing rapidly from year to year. The peaks are the wide rings and the troughs are the narrow rings corresponding to good and poor growing seasons, respectively. The two corresponding sequence of Baillie-Pilcher indices are plotted in (b) where the differences in the immature and mature growths have been removed and only the rapidly changing peaks and troughs remain, that are associated with the common climatic signal. This makes cross-matching easier.

t-value/offset Matrix

	C45	C08	C05	C04
C45		+20	+37	+47
C08	5.6		+17	+27
C05	5.2	10.4		+10
C04	5.9	3.7	5.1	

Bar Diagram

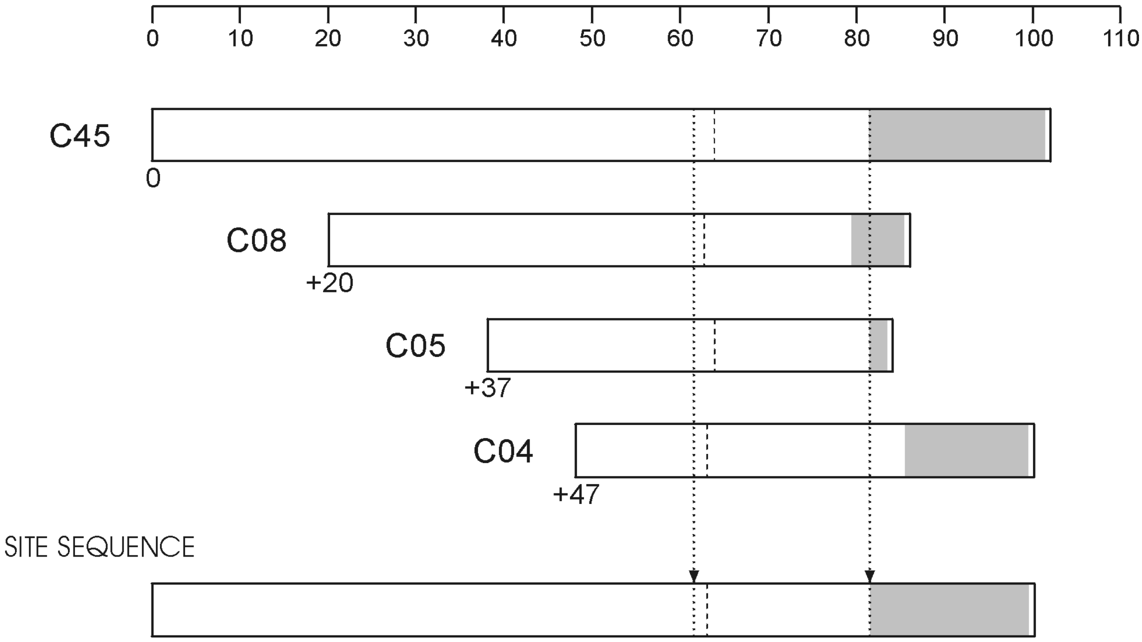


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

The bar diagram represents these sequences without the rings themselves. The length of the bar is proportional to the number of rings in the sequence. Here the four sequences are set at relative positions (offsets) to each other at which they have maximum correlation as measured by the *t*-values. The *t*-value/offset matrix contains the maximum *t*-values below the diagonal and the offsets above it. Thus, the maximum *t*-value between C08 and C45 occurs at the offset of +20 rings and the *t*-value is then 5.6. The site sequence is composed of the average of the corresponding widths, as illustrated with one width.

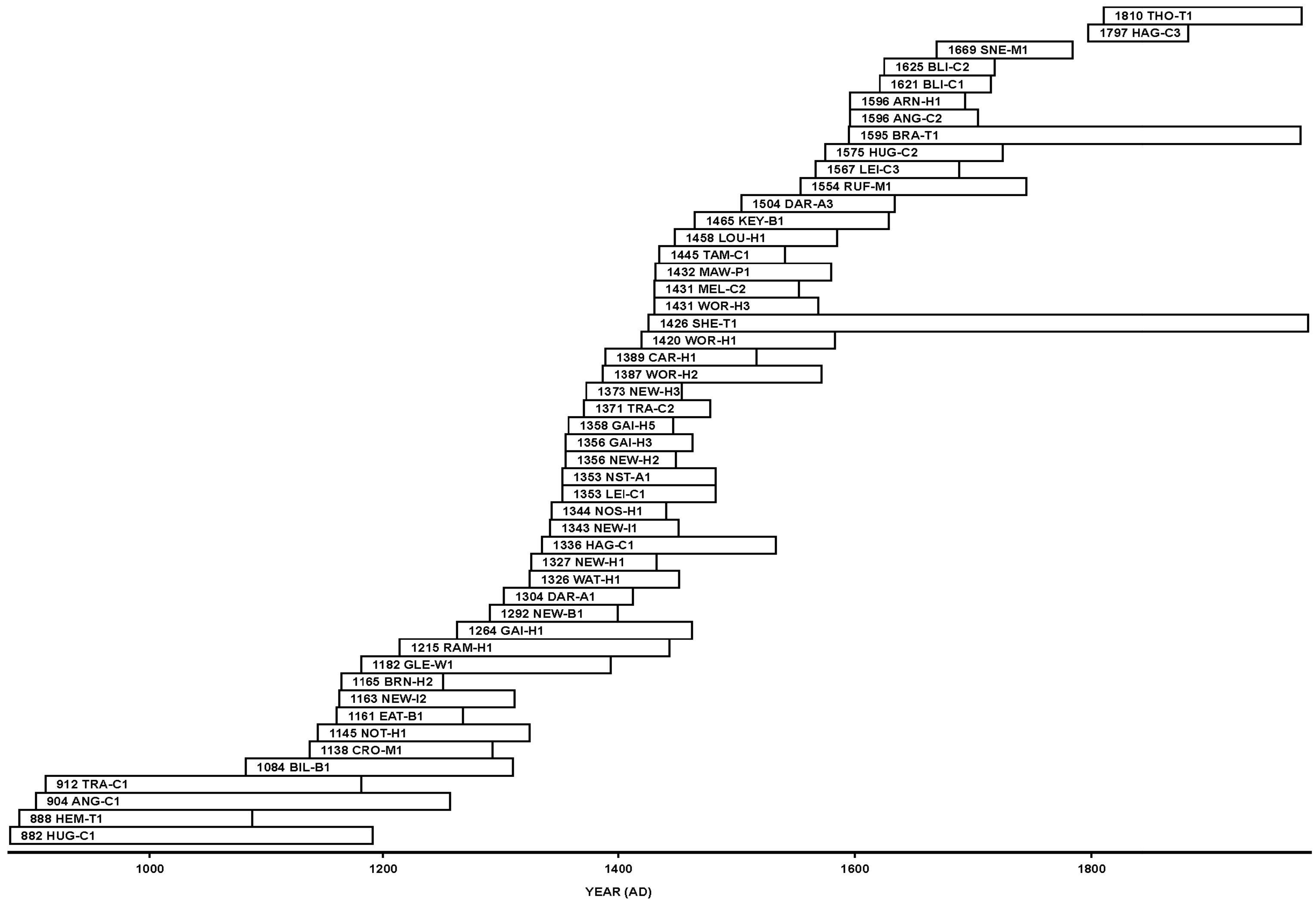
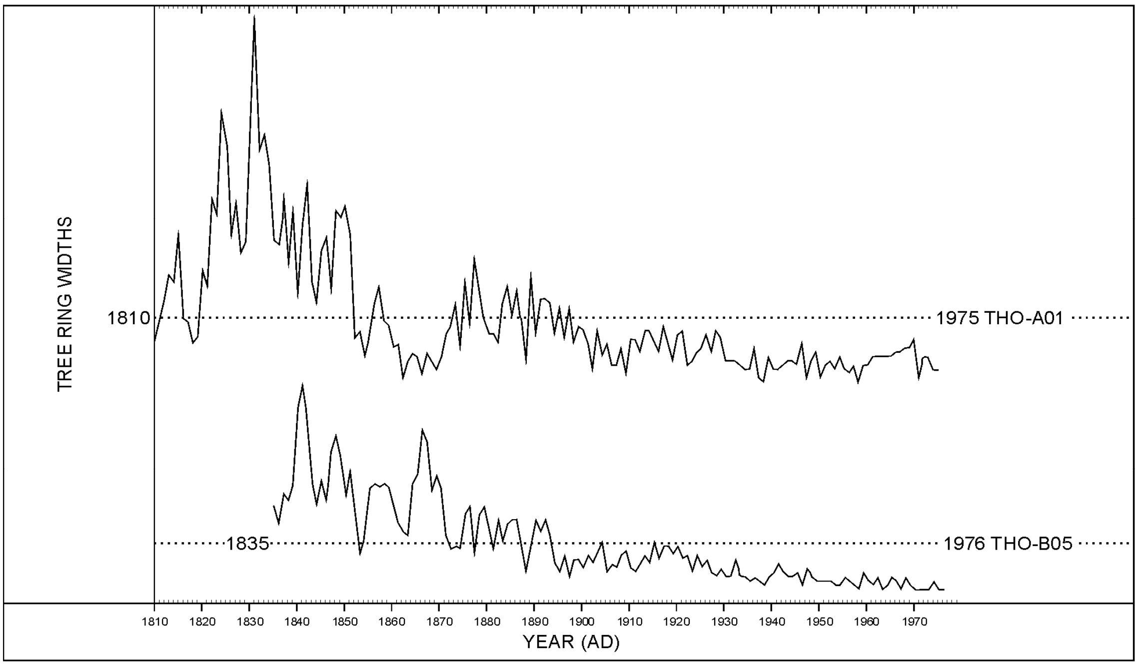


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

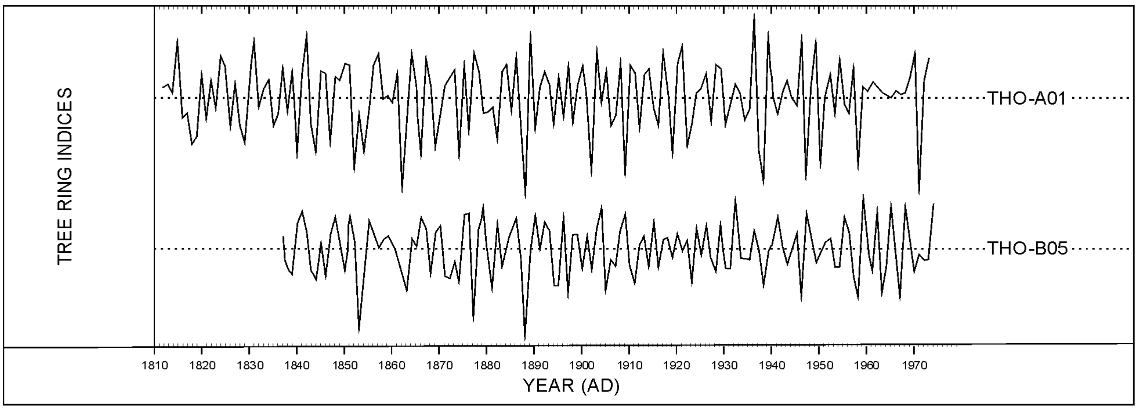


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree are wider than the later ones of the older tree in both sequences.

Figure A7 (b): The Baillie-Pilcher indices of the above widths

The growth trends have been removed completely.

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