DENDROCHRONOLOGICAL ANALYSIS OF OAK TREES AT LULLINGSTONE COUNTY PARK, EYNSFORD, KENT, ENGLAND.

Tree-Ring Services Report: BRLL/01/12

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DENDROCHRONOLOGICAL ANALYSIS OF OAK TREES AT THE LULLINGSTONE COUNTRY PARK, EYNSFORD, KENT, ENGLAND.

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SUMMARY
Thirteen oak trees sampled from Lullingstone Country Park are used to form a 275-year mean chronology called EYNSF-LL, which spans from AD 1737 to AD 2011.

The results suggest three main cohorts of oak trees at the Lullingstone Country Park: two small young oak, likely planted at the beginning of the 20th century; eight large veteran oaks, likely planted around the mid 15th century; and four very large ancient oaks, likely to have been planted or germinated before the 13th century.

Possible examples of management, as well as higher than expected radial growth rates in the two largest trees sampled, are suggested to be linked to variation in crown size, a relationship highlighted for further research.

KEYWORDS
Dendrochronology, Veteran trees, English oak, *Quercus* spp.

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INTRODUCTION

Tree-Ring Research

Dendrochronology has been defined as "the dating of annual growth layers in wood plants and the exploitation of the environmental information which they contain" (Fritts 1971). The science is based on the premise that the annual growth rings of trees vary from year to year, largely according to the climatic conditions. "Tree-ring Dating and Archaeology" and "A Slice Through Time" (Baillie 1982, 1995) provide interesting backgrounds into the science, while a free guideline booklet explaining methods of dendrochronology is offered by English Heritage (1998).

The fundamental basis of dendrochronology is the annual growth ring which forms inside the bark by division of cambial cells. Large, thin-walled wood or xylem cells (earlywood) are produced at the beginning of the growing season, and small, thick-walled wood cells (latewood) towards the end of the growing season. The abrupt change in cell size between the last-formed wood of one year and the first-formed wood of the next year usually delineates the boundary between the annual growth increments or annual rings (Fritts 1966).

A. E. Douglass pioneered tree-ring work on living trees in the early part of this century, developing a 3,220-year-long record of ring widths from the giant sequoia (Douglass 1919, Douglass 1928). Douglass demonstrated that the widths of annual rings in trees can correlate with variations in climate, and that their unique sequences of wide and narrow rings can be recognized and the same patterns cross-matched (cross-dated) in felled trees from adjacent areas. Cross-dating from living trees to dead trees made it possible to determine the actual year in which the dead trees were felled. The vigorous programme of tree-ring research that followed these discoveries led to the new discipline called dendrochronology. By statistically comparing timbers against established UK master chronologies dating back to 5289 BC it is now possible to obtain precise calendar year dates for timbers of various species by dendrochronological analysis.

Live Tree Coring

An increment borer is a specialized tool designed to extract a section of wood tissue from a living tree with minimal injury. The core is typically 4–5 mm in diameter and can extend from the bark to the pith of a living tree. This sampling method has become a standard global procedure for determining tree age and examining patterns of annual ring widths, and is intrinsic to our understanding of tree growth–climate relationships, forest dynamics and natural hazards (Fritts 1976, Frelich 2002, Vaganov *et al.* 2006, Stoffel *et al.* 2010).

Understandably, there has been some concern over the potential impact core holes may cause. However, trees have natural defence mechanisms to help maintain their vitality (Shigo 1984, Loehle 1988). One important method of defence is the compartmentalization of injuries by which a boundary is developed to limit the spread of pathogenic micro-organisms (Shigo 1984). While tree coring typically leads to some discoloration of wood, discoloration, decay and wood-decaying fungi should never be equated with each other (Weber and Mattheck 2006). Wood-decay fungi may occur in the hole left from increment coring, but a tree may successfully compartmentalize or repel it.

The degree of sensitivity to tree coring damage appears to vary depending on species, and in general conifers are thought to be the most resistant (Grissino-Mayer 2003). Early studies in North America found that over 50% of core holes healed within 2–3 years; trees that did not heal well were typically short-lived species or suppressed individuals (Meyer and Hayward 1936, Lorenz 1944, Hepting *et al.* 1949). In the UK, tree-ring research has tended to concentrate on its three longest-lived tree species: Oak (*Quercus* spp.), Scots pine (*Pinus sylvestris*), and Yew (*Taxus baccata*). As conifers, both Scots pine and Yew are expected to be extremely resistant to coring damage (Grissino-Mayer 2003). Oak is also thought to have a high capability of compartmentalization (Dujesiefken and Liese 1991, Grissino-Mayer 2003)

It is highlighted that any risk of harm to a tree by coring is far less than that caused by tree surgery (Kersten and Schwarze 2005), and there is no evidence of tree mortality after increment coring (Meyer and Hayward 1936, Lorenz 1944, Hepting *et al.* 1949, Eckstein and Dujesiefken 1999, van Mantgem and Stephenson 2004, Weber and Mattheck 2006). However, as more research would be needed to conclude categorically that coring causes no significant harm, a number of methods are usually employed to help minimize any possible impact:

- Sampling is kept to a minimum, typically one core per tree, or two cores in the case of dendroclimatic studies.
- Corers are kept clean and sharp, as a blunt borer leads to greater damage (Smith 1988).
- Core holes are angled slightly upwards to help minimize water ingression.
- Core holes are left open to allow them to dry out and heal naturally, which is thought to help discourage infection by decay fungus (Kersten and Schwarze 2005). There is little evidence that plugging core holes reduces the discoloration of wood or prevents potential decay (Meyer and Hayward 1936, Lorenz 1944, Hepting *et al.* 1949) and some research indicates plugging hinders the natural healing process (Dujesiefken *et al.* 1999).

Tree Age Estimates

Britain's ancient trees, and the wildlife they support, are as much part of our heritage as the venerable buildings they often pre-date, and in whose grounds they often now reside (Green *et al.* 1999). Although there is some variation between species, in general, trees are thought to progress through three phases of growth: formative, mature and senescent (White 1998). Formative incremental growth nourished by the increasing foliage tends to increase each year until optimum crown size is reached, usually achieved in 40 to 100 years. During the mature phase (foliage, weather and all other factors being equal), the annual increment produced remains constant in terms of volume. However, as a tree's girth increases, the annual increment is spread over a larger area and hence its width reduces. Dieback of the crown and branches occurs during senescence, the final phase, and causes further reduction in the width of the annual increment.

Exceptionally large trees have been analysed by a variety of methods in the past, and this has resulted in often wide variation in the age estimates. Tree age estimation in the UK has remained largely based on girth measurements of known date. However, age estimates based on external measurement and comparison with other trees of the same species has intrinsic problems in accuracy. Age estimates based on simple linear extrapolation of average girth yield age overestimates because they take no account of the increase in ring width towards the trees' centres. Conversely, age estimates based on an assumption that basal area increment is constant (i.e., trees add a constant amount of basal area each year) have been shown to underestimate the trees' ages (Hartesveldt *et al.* 1975). Some estimates have unfortunately also suffered from poor quantitative descriptions on the method of estimating, particularly in respect to calculation of the probable rate at which rings increase in size toward the centre. John White (1998) makes good provision for the effects of tree growth stages in his tree age estimating. However, his assessment of the age when optimum crown development is achieved (a factor critical to the accuracy of an estimate) can be very subjective without precise increment information. Differences in growth due to specific local ecological conditions may also affect an individual tree's growth, and therefore a sample of a number of trees is recommended to increase the accuracy of estimates.

Until a new technique of non-intrusive tree-ring measuring is developed, dendrochronological analysis using complete or partial increment coring (cores that fall well short of a tree's pith) offers the least destructive means of accurately dating living trees and dispels a great deal of the uncertainty that remains about the age of many of our largest trees. While the girth of our very largest trees (and hence the trees of greatest interest) often makes it impossible to reach their piths with hand-driven increment borers, age estimates based on partial increment sampling still offer the most accurate empiric refinement to the estimation of a tree's age. A good example of the use of this method was by Nathan Stephenson, who successfully combined knowledge on tree size with information gained directly from partial increment cores to estimate the age of giant sequoias (Stephenson and Demetry 1995).

Aim of the Analysis

The aim of this analysis was to determine the ages of the large oak trees located in Lullingstone Country Park.

METHODOLOGY

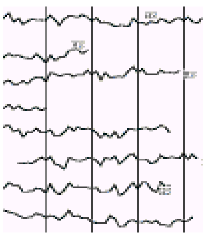
Sampling and Preparation

Timbers were sampled using a 3-thread Halglof increment borer: 600 mm length × 5.15 mm core diameter. One core was taken from each tree, normally at breast height (approximately 1.3m) above the ground. Girth measurements were recorded at the sampling height. Extracted core samples were immediately taped and glued onto wooden laths on site, labelled, and left to dry for subsequent analysis (**Photo 1**).

Photo 1: Two increment cores taken from trees BRLL05 (top) and BRLL07 (bottom)

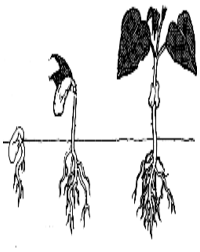
All tree-ring sequences were revealed through sanding, with progressively finer grits, to a 400 abrasive grit finish to produced results suitable for measuring.

Measuring and Cross-matching



Tree-ring sequences were measured under a ×20 stereo microscope to an accuracy of 0.01 mm using a microcomputer-based travelling stage. Each core sample was measured twice, wherever possible from the centremost ring to the outermost. The core samples from each core were measured and sets (e.g., BRLL05A and BRLL05B) visually plotted to support or reject possible cross-matches and serve as a means of identifying measuring errors. Where sequences visually matched satisfactorily at the appropriate offset they were averaged and the resulting average for the tree used in subsequent analysis (e.g., sequence BRLL05). Where samples did not contain bark of known date to act as a datum point for cross-matching, statistical cross-correlation algorithms were employed to search for the positions where tree-ring sequences correlate. The search produces "*t*-values", and the higher this value, the more certain the correlation. Those *t*-values in excess of 3.5 are taken to be significant and indicative of acceptable matching positions (this value happening by chance about once in every 1000 mismatches (Baillie 1982)). Visual comparisons of sequences are again employed to support or reject possible cross-matches between samples and serve as a means of identifying measuring errors.

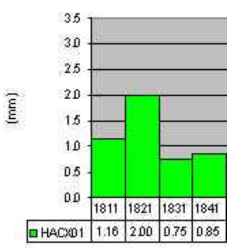
Determination of Germination Date



A method for determining the precise germination dates of trees is based on the wood's anatomical characteristics and dendrochronology. Unfortunately, the procedure requires the destructive sampling of the tree for an extensive analysis of the zone between the roots and the trunk (Telewski 1993) and is clearly inappropriate for this and most other investigations.

The centre-of-tree (pith) date obtained by sampling at a height above the ground may not necessarily represent the absolute age of the tree or the year of germination (Telewski and Lynch 1991). Nevertheless, the discrepancy between the pith date obtained at a sampling height of approximately 1.37m/4.5ft above ground and a precise germination date obtained at ground level is only likely to be significant with suppressed understorey trees, which can grow for 100 years before attaining a height over 1m (Tucker *et al.* 1987). Here 5 years is arbitrarily added to the age to account for the likely discrepancy between a precise pith date obtained at ground level and that obtained from increment cores and sections.

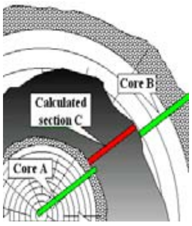
Growth Rates



Formative, mature and senescent phases of growth normally occur during the development of a tree's crown (Mitchell *et al.* 1994). The formative stage is generally characterised by relatively rapid growth and more or less constant ring width. The mature phase which follows is normally characterised by a reduction in the rate of growth, further reducing over time. The transition between the formative and mature phases of growth is gradual, but may be identified to have occurred over a relatively short period in some trees. Ten-year averages of ring width are plotted to help demonstrate overall patterns of tree growth. Using them, it is sometimes possible to identify the probable changes between phases of growth or other changes in rates of growth related to management or the relative state of health of the tree.

For most purposes, the senescent phase of growth equates to the term overmaturity, which is generally said to occur in oak at around 250 years (Evans 1984). Here we use decadal of growth ≤ 1.00 mm/yr to identify the onset of senescent growth. Trees are identified as likely to be in terminal decline where consecutive decades have mean growth of ≤ 0.50 mm/yr, which is a level that most species of tree can barely survive (White 1998).

Site-specific Age Estimates



In terms of general UK tree species growth, higher maximum mean annual increments are achieved in the climatically favoured south-west of England and, to a lesser extent, in Wales and southern and eastern England, although the variation between region is small (Evans 1984). However, a tree's radial growth rate may vary enormously according to site, effects of exposure, rooting depth and soil nutrient status, and where site-specific evidence is absent, mean average radial growth rate curves to predict tree age should only be used in the most general terms.

Nevertheless, site-related average growth rates "yield classes" is in standard use by the Forestry Commission (James 1982), and the use of a younger tree on the same site to represent the missing younger growth of hollow trees has been reasonably established (White 1998, Tabbush and White 1996). The dendrochronological analysis of increment cores can provide precisely known age and rate of growth information for solid trees. This information, when combined with the partial increment core information from larger trees, is used to represent the missing younger core growth of these usually hollow trees. This combination of full and partial increment cores is then used to produce empirical information on the radial growth rates specific to the site and to calculate an age estimate for hollow trees.

Tree-Ring Services - Methods and Criteria

TREE-RING SERVICES

Tree-ring analysis and graphics are achieved via a dendrochronological program suite developed by Ian Tyers of Sheffield University (Tyers 1999).

RESULTS

Lullingstone Country Park was visited on the 4th November 2011. A brief survey identified fourteen oak trees, which were agreed for sampling. The samples were given a site code BRLL and numbered 01–14 (**Table 1 & Photos 2 to 14**. Considerable depth of bark was observed on the largest-girth oak trees. Depth of bark was recorded on trees BRLL03, BRLL06, BRLL08 and BRLL13 (**Appendix III**).

Table 1: Summary of tree sampling details

Tree code	Girth (m)	National grid reference	Tag number	Notes on tree
BRLL01	7.08	TQ 5105 6441	00019	Hollow trunk, large crown but some dieback of branches
BRLL02	6.10	TQ 5119 6450	00018	Hollow trunk, large crown but with some dieback and loss of a major branch
BRLL03	4.86	TQ 5121 6450	00017	Hollow trunk, large crown but with dieback of all but one major branch
BRLL04	9.05	TQ 5132 6453	00022	Hollow trunk, small crown due to dieback of all major branches
BRLL05	6.26	TQ 5134 6460	00025	Hollow burnt trunk, no crown except on one main branch
BRLL06	11.14	TQ 5136 6461	00026	Hollow trunk, small crown due to dieback of most major branches
BRLL07	5.39	TQ 5136 6455	00023	Hollow trunk, large crown but some dieback of branches
BRLL08	2.74	TQ 5143 6454	no tag	Solid trunk, with large full crown
BRLL09	6.42	TQ 5157 6459	00033	Hollow trunk, small crown due to dieback of all major branches
BRLL10	2.12	TQ 5153 6464	no tag	Solid trunked tree but cut back crown
BRLL11	6.09	TQ 5129 6461	00027	Hollow trunk, large crown but with dieback of all but two major branches
BRLL12	7.91	TQ 5126 6459	00028	Hollow trunk, large crown but dieback has left only medium size branches
BRLL13	8.42	TQ 5122 6462	00029	Hollow trunk, large crown but with dieback of all but two major branches
BRLL14	6.00	TQ 5079 6459	00012	Apparent solid trunk with large crown, but all large branches of crown cut back

Photo 2: Tree BRLL01

Photo 3: Trees BRLL02 (right) and BRLL03 (left)

Photo 4: Tree BRLL04

Photo 5: Tree BRLL05

Photo 7: Tree BRLL06

Photo 6: Tree BRLL07

Photo 9: Tree BRLL08

Photo 8: Tree BRLL09

Photo 10: Tree BRLL10

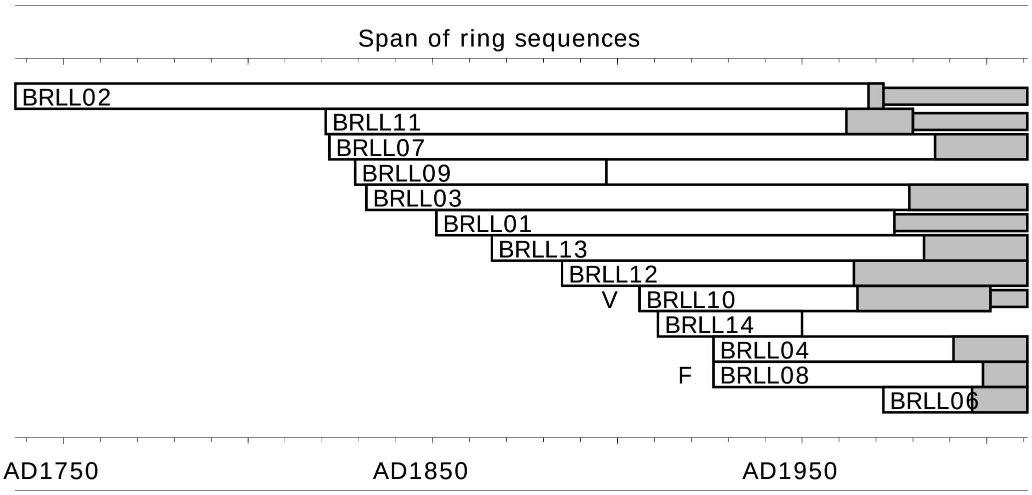
Photo 11: Tree BRLL11

Photo 13: Tree BRLL12

Photo 12: Tree BRLL13

Photo 14: Tree BRLL14

A total of fourteen core samples were recovered. All the samples were recovered with bark, but during preparation and measurement it became clear that a number of the samples contained periods of narrow rings, especially in the end rings. In six samples, periods of narrow rings meant that the end section could only be ring counted (**Figure 1**).



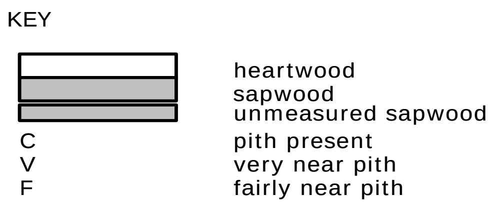


Figure 1: Bar diagram showing the span of series dated from Lullingstone Country Park

Thirteen series were found to cross-match together (see **Table 2**) and were combined to form a 275-year mean chronology called EYNSF-LL. Series BRLL05 did not cross-match with any other samples.

Table 2: Cross-matching between series from Lullingstone Country Park

Filenames	Start date	End date	BRLL02	BRLL03	BRLL04	BRLL06	BRLL07	BRLL08	BRLL09	BRLL10	BRLL11	BRLL12	BRLL13	BRLL14
BRLL01	AD1851	AD1975	4.69	6.36	-	\	7.31	4.17	-	4.56	7.46	-	4.79	3.65
BRLL02	AD1737	AD1972		7.18	4.52	\	4.87	-	4.91	-	6.17	-	4.32	-
BRLL03	AD1832	AD2011			4.00	5.74	7.36	4.29	3.59	4.95	6.77	4.08	6.07	-
BRLL04	AD1926	AD2011				-	-	3.93	\	4.05	3.77	-	-	\
BRLL06	AD1972	AD2011					4.10	-	\	-	\	-	-	\
BRLL07	AD1822	AD2011						5.30	4.68	4.66	7.19	4.13	6.68	-
BRLL08	AD1926	AD2011							\	3.63	4.58	-	6.20	\
BRLL09	AD1829	AD1897								\	4.92	\	-	\
BRLL10	AD1906	AD2001									5.01	-	4.44	-
BRLL11	AD1821	AD1980										3.72	5.08	4.67
BRLL12	AD1885	AD2011											-	-
BRLL13	AD1866	AD2011												-
BRLL14	AD1911	AD1950												

KEY: - = *t*-values less than 3.50. \ = overlap < 30 years.

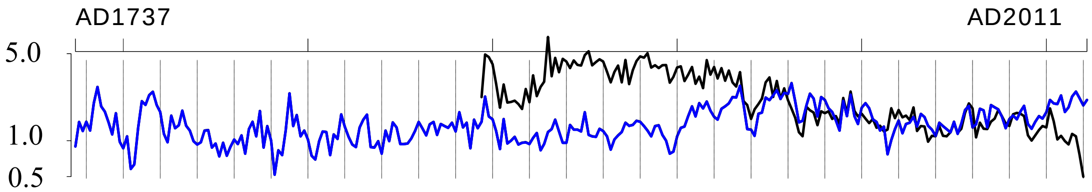
The EYNSF-LL chronology spans from AD 1737 to AD 2011, the annual resolution of this chronology is confirmed by cross-matching against a wide number of previously established oak reference chronologies from across the south of England (**Figure 2** & **Table 3**).

Table 3: Cross-matching of EYNSF-LL against reference chronologies

EYNSF-LL dated AD1737 to AD2011					
File	**Start Date**	**End Date**	**t-value**	**Overlap (yr.)**	**Species & Reference chronology**
HEDGE-S4	AD1847	AD2010	8.57	164	Modern trees - Hedgeley - Bucks (Moir, unpublished)
MSC	AD1820	AD1995	8.56	176	Mendhams Corner – Sotterley Estate - Suffolk (Moir 1996)
EVSLY-BR	AD1815	AD2003	8.31	189	Brick House - Eversley - Hampshire (Moir, unpublished)
SWW	AD1806	AD1992	7.75	187	Southwell Lane - Sotterley Estate - Suffolk (Moir 1996)
SOTTERLY	AD1586	AD1981	7.63	245	Sotterley Park - Suffolk (Briffa *et al.* 1986)
YATLY-WW	AD1829	AD2003	7.48	175	Wych Wood - Yateley – Hampshire (Moir, unpublished)
WINCHSTR	AD1635	AD1972	7.37	236	Winchester - Hampshire (Barefoot 1975)
OAKLEY	AD1847	AD1978	7.07	132	Oakley Wood - Buckinghamshire (Pilcher, unpublished)
HYOAK00	AD1814	AD2000	6.98	187	Oak trees - Coulsdon - G London made (North 2000)
ENGLAND	AD404	AD1981	6.19	245	England Master Chronology (Baillie and Pilcher 1982 unpubl)
HERWOR2	AD1729	AD1969	5.58	233	Hereford and Cumberland Modern (Siebenlist-Kerner 1978)
CHARL-12	AD1822	AD2002	5.56	181	12 trees - Two Copse - Charlwood - Surrey (Moir, unpublished)

KEY: * = components of the SEYEW11 chronology.

Figure 2: Plot of site chronologies EYNSF-LL (blue) and HEDGE-S4 (black) from oak trees located in Hedgeley, Buckinghamshire, which cross-match together with a *t*-value of 8.57



Note: The ring width (mm) is plotted on a (y axis) logarithmic scale using common axis for both samples

Cumulative ring widths (**Figure 3**) and decadal growth rates (**APPENDIX III**) were plotted to help identify phases of growth and variations in growth.

INTERPRETATION

The following age estimates are based on either full recovery of rings or a combination of partial increment cores and the use of mean growth rates. Bar charts of decadal growth rates are plotted in **Appendix II**, and **Appendix III** contains a table with further details of the age estimation calculations.

Mean Growth Rates

Two trees, BRLL08 and BRLL10, were sampled close to the pith and their ages accurately calculated to be 100 and 109 years, respectively. A mean formative growth rate of 3.15 mm/yr for the first 100 years of growth is calculated for the site from these trees. In other words, an average 315 mm of radial growth will be produced in the first 100 years of an oak tree's growth at this site. This compares reasonable closely with an expected formative growth rate of 3.5 mm/yr for the first 100 years of growth in parkland trees (White 1998). Six trees, BRLL01, BRLL02, BRLL03, BRLL11, BRLL12 and BRLL13, were used to calculate a mean mature growth rate of 1.45 mm/yr for this site.

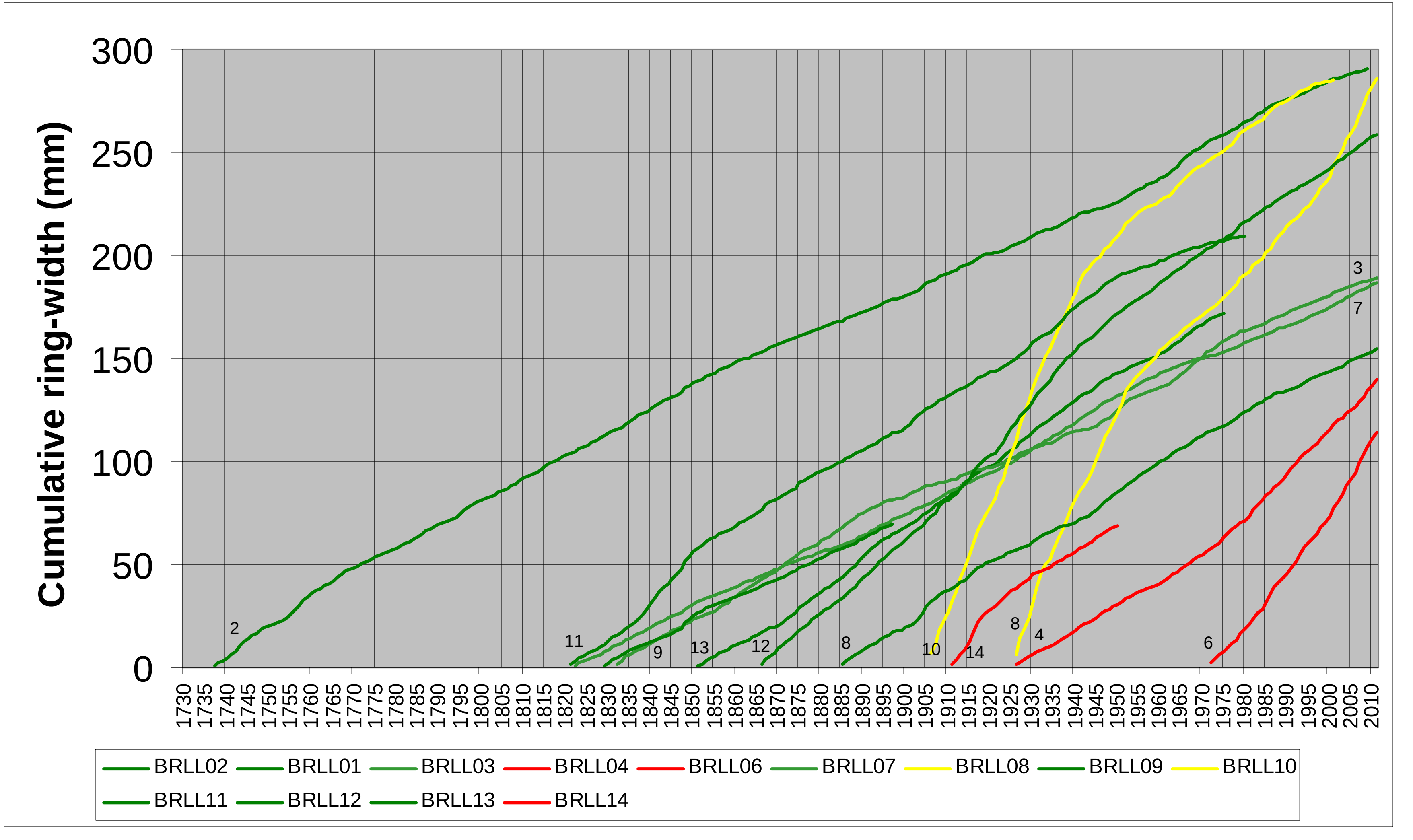
Table 4: Summary of growth phases interpreted from the plots of decadal growth rates and cumulative ring width, the trees are ordered from smallest to largest girth

Tree code	Girth (m)	Interpretated growth phases
BRLL10	2.12	Formative (2.97 mm/yr)
BRLL08	2.74	Formative (3.32 mm/yr)
BRLL03	4.86	Mature for 1st 6 decades (1.28 mm/yr), Senescent for last 12 decades (0.99 mm/yr)
BRLL07	5.39	Senescent for 19 decades (0.98 mm/yr)
BRLL14	6.00	Disturbed growth due to management
BRLL11	6.09	Mature for 1st 13 decades (1.46 mm/yr), Senescent for last 3 decades (0.67 mm/yr)
BRLL02	6.10	Mature for 1st 4 decades (1.40 mm/yr), Senescent for last 3 decades (1.03 mm/yr)
BRLL05	6.26	Disturbed growth due to management and fire
BRLL09	6.42	Senescent for 7 decades (1.01 mm/yr)
BRLL01	7.08	Mature for 1st 7 decades (1.38 mm/yr).
BRLL12	7.91	Mature for 1st 4 decades (1.43 mm/yr), Senescent for last 9 decades (1.13 mm/yr)
BRLL13	8.42	Mature for 15 decades (1.77 mm/yr).
BRLL04	9.05	Disturbed, possible due to growing new crown
BRLL06	11.14	Disturbed, possible due to growing new crown

KEY: Yellow = trees categorized with formative growth; Green = trees with mature/senescent growth; Red = trees showing atypical growth.

The four trees, BRLL04, BRLL05, BRLL06, and BRLL14, which show abnormal growth trends were not used in the calculation of mean growth rates for this site.

Figure 3: Cumulative ring width plots of the cross-matched series sampled from Lullingstone Country Park (BRLL05 is not shown)

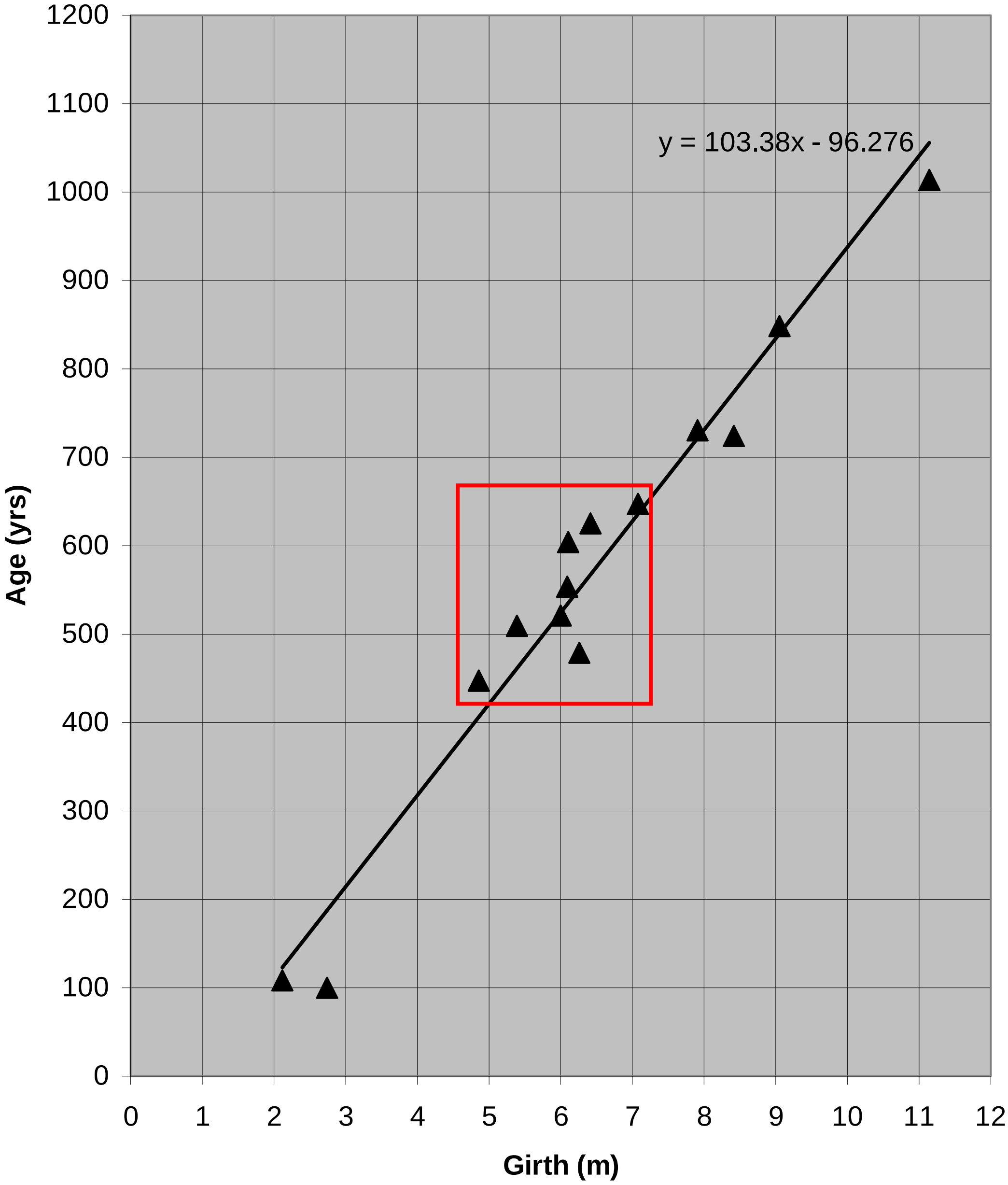


KEY: Yellow = trees categorized as showing formative growth; Green = trees with mature/senescent growth (light green highlights two of the smaller trees); Red = trees considered to show atypical/disturbed growth.

Age Estimation

The tree-ring series recovered from oak at this site provide a record of annual growth back 274 years to AD 1737. However, due to the hollow nature of the larger oak their age was estimated using a combination of partial increment cores and mean growth rates. The four bark measurements were used to estimate depth of bark at 0.05% of a tree's radius. The age calculations are shown in **Appendix III**, and the results and linear trend are shown below (**Figure 4**). Here it is proposed that every 1 metre of girth equals 100 years of age – 100 years, as a useful and easy-to-remember rule of thumb for estimating the age of other large oak trees at Lullingstone Country Park.

Figure 4: The linear trend of the relationship between oak tree girth and age at Lullingstone Country Park established through tree-ring analysis



KEY: The linear trend (black line) and regression equation of the trend is also shown, together with a cohort of trees with a standard deviation in age of around 70 years (red square).

Given the individual variations of growth between trees, the analysis suggests three main cohorts of trees at the Lullingstone Country Park:

a) Two small young oaks, likely planted at the beginning of the 20th century;
b) Eight large veteran oaks, likely planted around the mid 15th century;
c) Four very large ancient oaks, likely to have been planted or germinated before the 13th century.

Variations in Radial Growth

A total of four trees are identified to have atypical patterns of growth. Tree BRLL14 shows extremely narrow rings >0.2 mm/yr between 1952 and 1980. However, a mean ring width of 1.74 mm/yr between 1981 and 2011 indicates that this tree has now achieved a mature rate of radial growth. It is assumed that the variations of radial growth in this tree are associated with the observation of past crown cut-back. Tree BRLL05 could not be cross-matched, probably due to two narrow bands of rings *c*. 1988–90 and *c*. 2001–4. These periods of narrow growth are also assumed to be associated with an observation of crown reduction and fire. A mean ring width of 3.01 mm/yr for the last 8 years indicates that this tree has now achieved a radial growth rate equivalent of formative growth, and this may also be associated with the observation of new crown development. Both these examples of possible management identify that (as might be expected) the radial growth of oak may be linked to crown size. Although not showing atypical growth, the slight reductions in the growth rates of BRLL11 and BRLL13 from the 1940s, may be a result of the reduction in light caused by the growth of the surrounding plantation.

Higher than expected radial growth rates in the two largest and oldest trees at the site, BRLL04 and BRLL06, is also suggested to be related to crown. Both trees currently show formative to mature rates of growth, with a mean ring width of over 2.0 mm/yr over the last 30 years. A hypothesis is that the high radial growth in these old trees is a result of the development of new crowns to replace the loss of their main branches. These results identify that even very old oak trees are capable of returning to a mature or even formative rate of growth. Further research on the relationship between radial growth rate and crown is recommended. The possible variations in the growth of individual trees highlights that even where site-specific growth rates are known, age estimates should only be used in general terms.

CONCLUSIONS

Thirteen oak trees sampled from Lullingstone Country Park are used to form a 275-year mean chronology called EYNSF-LL, which spans from AD 1737 to AD 2011.

The results suggest three main cohorts of oak trees at the Lullingstone Country Park: two small young oak, likely planted at the beginning of the 20th century; eight large veteran oaks, likely planted around the mid 15th century; and four very large ancient oaks, likely to have been planted or germinated before the 13th century.

Possible examples of management, as well as higher than expected radial growth rates in the two largest trees sampled, are suggested to be linked to variation in crown size, a relationship highlighted for further research.

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