DENDROCHRONOLOGICAL ANALYSIS OF OAK TREES AT LEIGH WOOD, VALLEY ROAD, BRISTOL, ENGLAND.

Tree-Ring Services Report: BSLW/45/16

By Dr Andy Moir

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SUMMARY

Ring-width measurements from ten out of twelve oak trees sampled at Leigh Woods are successfully cross-matched to form a 211-year mean chronology called BRSTL-LW, which spans from AD 1806 to AD 2016.

Three main cohorts of oak trees at Leigh Woods are identified: four small oaks (around 1.5m in girth) which were planted/germinated at the end of the 19th century; three oaks between 2 and 3m in girth, planted/germinated in the early 19th century; and two slower-grown oaks, likely to have been planted/germinated in the 18th century.

One large 5.5m girth oak that was blown over in 2015 is estimated to have been planted/germinated in the 15th century. This tree shows that healthy radial growth rates (>1.4mm/yr) can be achieved in veteran oak, even after decades of slow (0.75mm/yr) growth. Examining the relationship between the haloing of veteran oak trees and radial growth is highlighted for future research.

Only young, dying or dead oak were sampled in this study. This resulted in many of the tree-ring series showing disturbed growth, which limited the conclusions. Nevertheless, the extraction of sawn sections from dead veteran oak trees and their dendrochronological analysis is shown to be a valuable approach to dating ancient trees in historic landscapes.

KEYWORDS

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

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 main aim of this analysis was to determine the age of a large oak tree in Leigh Wood recently felled by wind. A secondary aim was to examine the potential of other fallen and low-value trees to provide environmental information about the woods.

METHODOLOGY

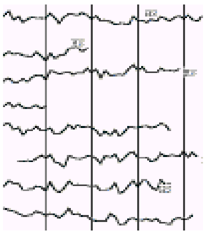
Sampling and Preparation

Live trees were sampled using a 3-thread Haglof increment borer, dead trees by chainsaw. One core was taken from each live tree, and between 1 and 3 sections were cut from dead trees. The samples were generally taken close to 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. Core samples and sections were labelled and left to dry for subsequent analysis (**Photo 1**).

Photo 1: A section taken from trees BSLW01

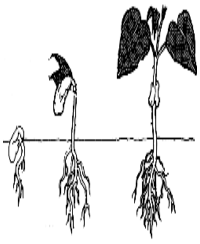
All tree-ring sequences were revealed through sanding, with progressively finer grits, to a 400 abrasive grit finish to produced results suitable for measuring.

Measuring and Cross-matching



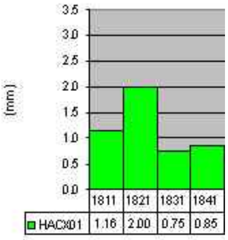
Tree-ring sequences were measured under a ×20 stereo microscope to an accuracy of 0.01 mm using a microcomputer-based travelling stage. Each sample was measured twice, wherever possible from the centremost ring to the outermost. The measured series were then visually plotted to support or reject possible cross-matches and serve as a means of identifying measuring errors. Where series visually matched satisfactorily at the appropriate offset they were averaged and the resulting average for the tree used in subsequent analysis. 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 inappropriate for many 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).

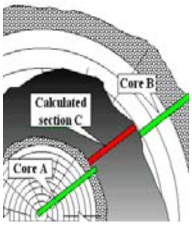
Growth Rates



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 growth of ≤1.00mm/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 ≤0.50mm/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 regions 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 analysis and graphics are achieved via a dendrochronological program suite developed by Ian Tyers of Sheffield University (Tyers 1999).

RESULTS

Leigh Woods was visited on the 5th September 2016. Twelve oak trees that had either previously fallen, or were live specimens in ill health or with little value were agreed with Victoria Stanfield (National Trust) for sampling. The samples were given a site code BSLW and numbered 01–12 (**Table 1 & Photos 2 to 12**). Bark was recovered on seven trees sampled (**Appendix III**). No photograph was taken of sample BSLW03.

Table 1: Summary of tree sampling details

Tree code	Girth (m)	National grid reference	Tag number	Notes on tree & site
BSLW01	5.50	ST 5573 7315	7769	Large fallen tree, woodland pasture
BSLW02	2.95	ST 5587 7338	7252	Located on outer ramparts of hillfort, woodland pasture
BSLW03	3.38	ST 5599 7352		Dead tree nearest path on the minor path from pond
BSLW04	1.76	?		Small fallen tree
BSLW05	3.38	?	7311	Standing dead tree
BSLW06	1.78	ST 5574 7322		Maiden live tree (Janine's tree)
BSLW07	1.50	ST 5582 7361		Lapsed pollard with 2 main trunks in ancient woodland
BSLW08	1.13	ST 5581 7352		Dead lapsed pollard in ancient woodland
BSLW09	2.50	ST 5604 7370	7411	Dying lapsed pollard in ancient woodland
BSLW10	2.04	ST 5605 7390		Falled maiden near cliff edge in ancient woodland
BSLW11	2.33	ST 5565 7395		Maiden trunk in poor health. Near path edge in ancient woodland
BSLW12	1.53	ST 5566 7355		Maiden trunk in poor health. Next to stone wall in ancient woodland

Photo 2: Tree BSLW01

Photo 3: Tree BSLW02

Photo 5: Tree BSLW03

Photo 4: Tree BSLW04

Photo 6: Tree BSLW05

Photo 7: Tree BSLW06

Photo 8: Tree BSLW07

Photo 9: Tree BSLW09

Photo 10: Tree BSLW10

Photo 11: Tree BSLW11

Photo 12: Tree BSLW12

Samples were successfully taken from all twelve trees. However, in samples BSLW04 and BSLW05, the rings were insufficiently clear under the microscope to be measured. Four samples contained sudden and sustained periods of ring-width reduction characteristic of management and were identified by the suffix '-M'. Samples BSLW07-M and BSLW11-M contained extremely narrow rings in the end section that could not be accurately measured and so were ring counted (**Figure 1**).

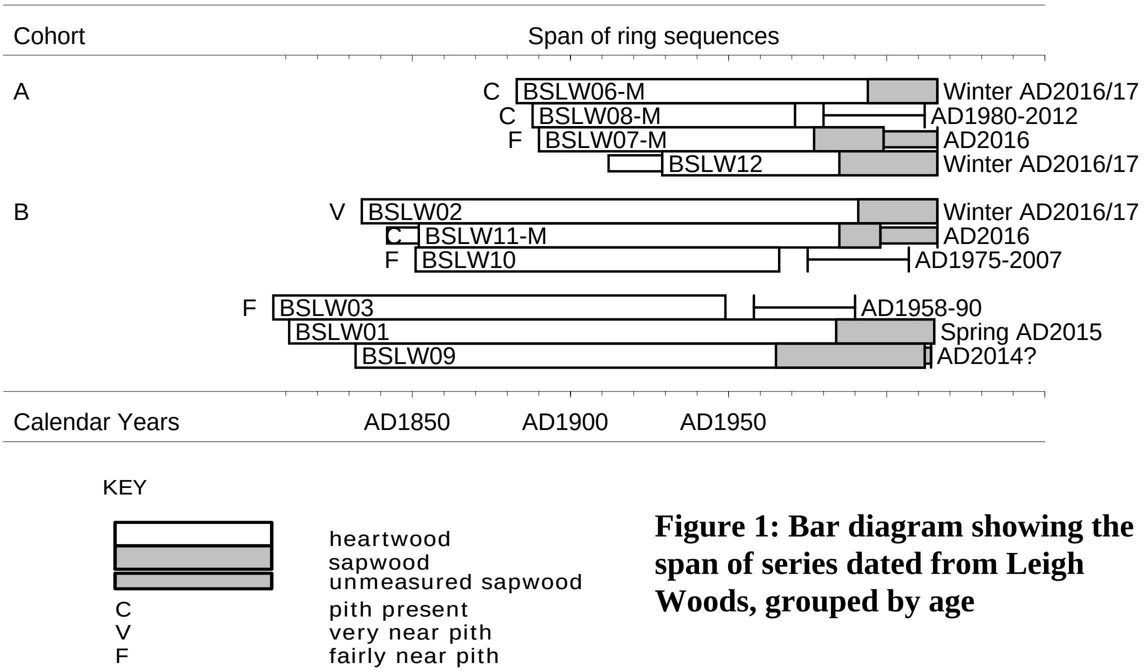


Figure 1: Bar diagram showing the span of series dated from Leigh Woods, grouped by age

All ten measured series were found to cross-match together (see **Table 2**) and were combined to form a 211-year mean chronology called BRSTL-LW.

Table 2: Cross-matching between series from Leigh Woods

Filenames	Start dates	End dates	BSLW02	BSLW03	BSLW06-M	BSLW07-M	BSLW08-M	BSLW09	BSLW10	BSLW11	BSLW12
BSLW01	AD1811	AD2015	-	3.24	-	-	-	-	-	3.81	-
BSLW02	AD1834	AD2016		4.52	-	3.58	4.00	-	4.85	-	4.51
BSLW03	AD1806	AD1949			4.36	6.12	5.34	5.71	7.03	4.92	5.00
BSLW06-M	AD1883	AD2016				5.47	-	5.84	5.05	-	5.41
BSLW07-M	AD1890	AD1999					7.96	5.89	7.63	5.82	6.47
BSLW08-M	AD1888	AD1971						4.87	6.05	4.55	4.47
BSLW09	AD1832	AD2012							8.85	4.19	4.41
BSLW10	AD1851	AD1966								5.08	4.45
BSLW11	AD1852	AD1998									4.71
BSLW12	AD1929	AD2016									

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

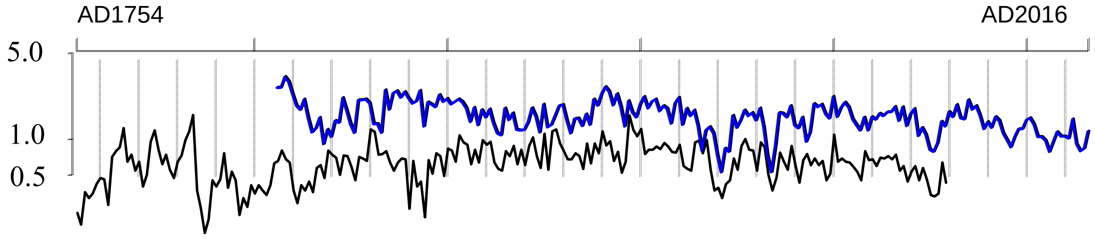
The BRSTL-LW chronology spans from AD 1806 to AD 2016, and the annual resolution of this chronology is confirmed by cross-matching against a wide number of previously established oak reference chronologies from across the south of England (**Figure 2** & **Table 3**).

Table 3: Cross-matching of BRSTL-LW against reference chronologies

BRSTL-LW dated AD 1806 to AD 2016					
File	**Start Date**	**End Date**	**t-value**	**Overlap (yr.)**	**Species & Reference chronology**
SWEST149	AD799	AD2015	11.22	210	South West chronology (Author, unpublished)
BATH	AD1754	AD1979	8.69	174	Bath - Somerset (Pilcher and Baillie 1980)
YATLY-WW	AD1829	AD2003	8.02	198	Wych Wood - Yateley - Hampshire (Author, unpublished)
OXFORD	AD1781	AD1978	7.54	173	Oxford Oak - Oxfordshire (Pilcher and Baillie 1980)
LANGLEY	AD1856	AD2011	7.39	206	Langley Park - Bucks 7 timber mean (Agin 2011)
SAVENAKE	AD1651	AD2006	7.28	201	Savenake Forest - Wiltshire (Author, unpublished)
WINCHSTR	AD1635	AD1972	7.10	167	Winchester - Hampshire (Barefoot 1975)
SLG	AD1764	AD1993	6.86	188	Scarles Grove - Sotterley Estate - Suffolk (Moir 1996)
EYNSF-LL	AD1737	AD2011	6.41	206	Lullingstone County Park - Eynsford - Kent (Moir 2012b)
BSWR01	AD1807	AD2011	6.37	206	Modern Oak at Yeo Mead - Congresbury - Somerset (Moir 2012a)
MDEAN-OR	AD1779	AD2013	6.15	208	Oakraven Field Centre - Mitcheldean - Glou (Moir 2014)
TAFA01	AD1740	AD2015	5.82	210	Oak tree - Forde Abbey - Somerset (Moir 2016)

KEY: ***** = components of the SEYEW11 chronology.

Figure 2: Plot of site chronologies Leigh Wood (blue) and BATH (black) from oak trees located in Bath, Somerset, which cross-match together with a *t*-value of 8.69



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

Tree Age

Pith or near pith was recovered from seven of the ten trees sampled and therefore the age and germination dates for these trees can be accurately identified (**Appendix III)**. Three trees, 6-M, 7-M and 8-M, are identified to have germinated between 1877 and 1882. Three trees are identified to have germinated between 1828 and 1841, and one tree germinated around 1795. No pith information was removed from trees 1, 9 and 12, and therefore age estimations using mean growth rates for the missing sections are used. Cumulative ring widths (**Figure 3**), bar charts of decadal growth rates (**Appendix II)** and a table with further details on the age estimation calculations (**Appendix III)** are shown.

INTERPRETATION

Growth Trends

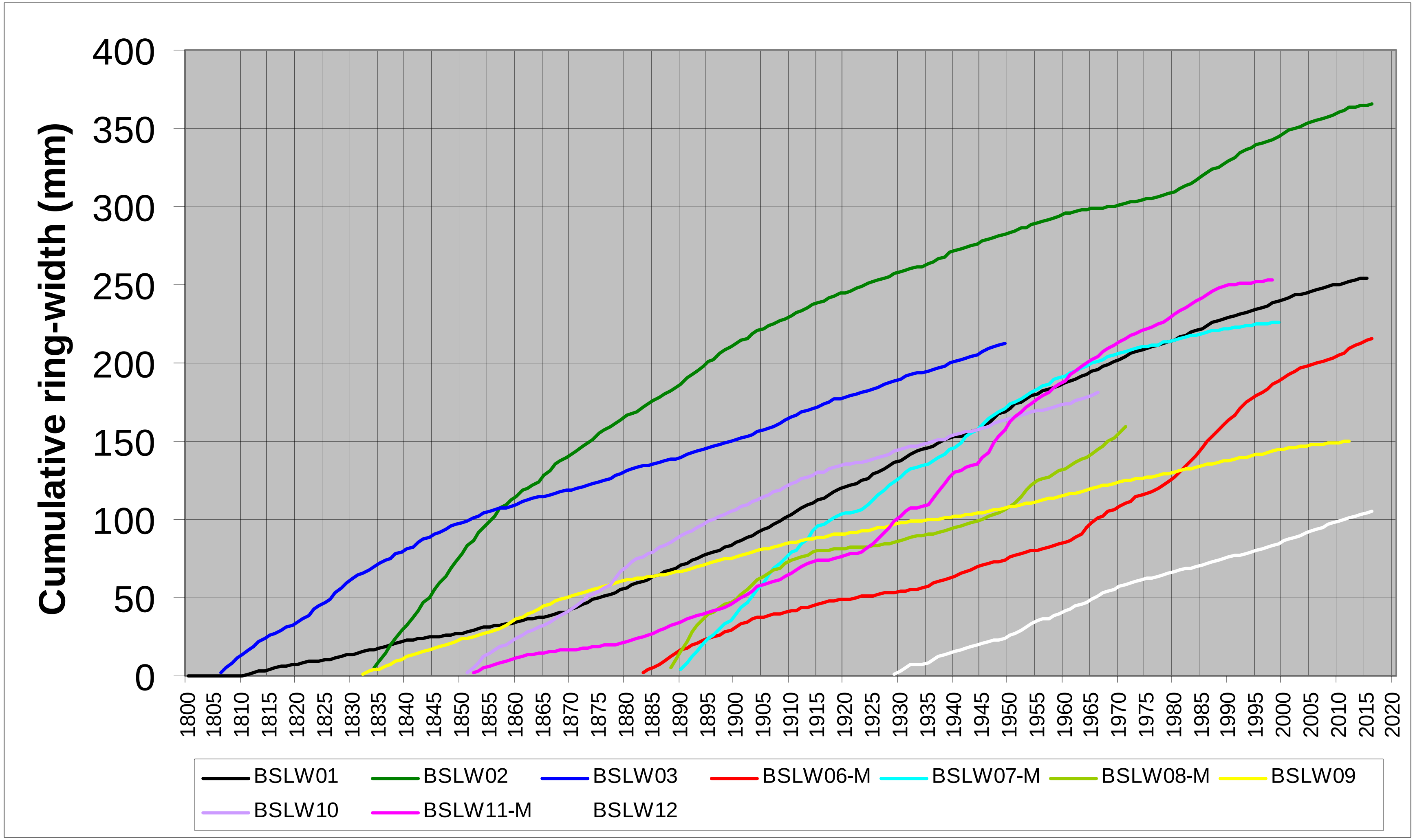
Given that seven of the samples were recovered close to pith, surprisingly, only four trees, 02, 3, 7-M and 10, display a classic transition from formative to mature growth patterns, although even tree 02 shows a distinct reduction in its mature growth phase in the 1960s and 70s. The other trees sampled show distinct disturbances to normal growth patterns. The large number of trees showing disturbances is likely a result of selecting dead or dying trees (as opposed to healthy trees) during the sampling process. Despite this problem, a mean formative growth rate of 2.52mm/yr for the first 80 years of growth is calculated for the site from these trees. In other words, an average 252mm of radial growth would be expected be produced in the first 80 years of an oak tree's growth at this site. This compares closely with an expected formative growth rate of 2.5mm/yr for the first 70 years of growth indentified from inside woodland trees (White 1998). This rate of growth suggests that much of the site has been classed as inside woodland (as opposed to woodland boundary pollard or open woodland as more of the site appears to be classed as today).

Table 4: Summary of growth phases interpreted from the plots of decadal growth rates and cumulative ring width

Tree code	Girth (m)	Interpretated growth phases
BSLW01	5.50	1st 7 decades senescent growth (0.71 mm/yr) but returning to mature growth from 1880s until 2000s (1.49 mm/yr)
BSLW02	2.95	Disturbed in 1960s & 1970s but otherwise formative growth for 1st 8 decades (3.06 mm/yr), followed by mature growth (1.39 mm/yr).
BSLW03	3.38	Formative for 1st 5 decades (2.23 mm/yr), mature for last 10 decades (1.16 mm/yr)
BSLW04	1.76	
BSLW05	3.38	
BSLW06-M	1.78	1st 8 decades of suppressed & disturbed growth, followed by 6 decades of formative growth (2.29 mm/yr)
BSLW07-M	1.50	Formative growth for 1st 8 decades (2.88 mm/yr), followed by 2 decades of mature growth (1.01 mm/yr)
BSLW08-M	1.13	Disturbed in 1910s & 1920s but otherwise 8 decades of formative growth (2.69 mm/yr)
BSLW09	2.50	8 decades of mature growth (1.08mm/yr), followed from 1910s by 10 decades of senescent growth (0.67 mm/yr)
BSLW10	0.65	Formative for 1st 6 decades (2.01 mm/yr), mature for last 6 decades (1.04 mm/yr)
BSLW11-M	2.33	1st 7 decades of suppressed & disturbed growth, followed by 7 decades of formative growth (2.46 mm/yr)
BSLW12	1.53	10 decades of mature growth (1.20 mm/yr).

A mean mature growth rate of 1.36mm/yr is calculated for this site from seven trees 1, 2, 3, 7-M, 9, 10, and 12.

Figure 3: Cumulative ring-width plots of the cross-matched series sampled from Leigh Woods



Age Estimations

Age estimates based on a combination of partial increment cores and the use of mean growth rates for the missing inner portion of the trees are used for trees 1, 9 and 12

- Tree 12 has a radius (minus bark) of 0.220m. As 0.125m of the tree was recovered, a missing section of 0.095m is identified. Assuming a formative rate of growth of 2.52mm/yr, the missing section would contain 38 rings and its age would be *c*. 143 years.

- Tree 9 has a radius (minus bark) of 0.368m. As 0.150m of the tree was recovered, a missing section of 0.218m is identified. Again assuming a formative rate of growth of 2.52mm/yr, the missing section would contain 87 rings, giving it a total age of *c*. 268 years.

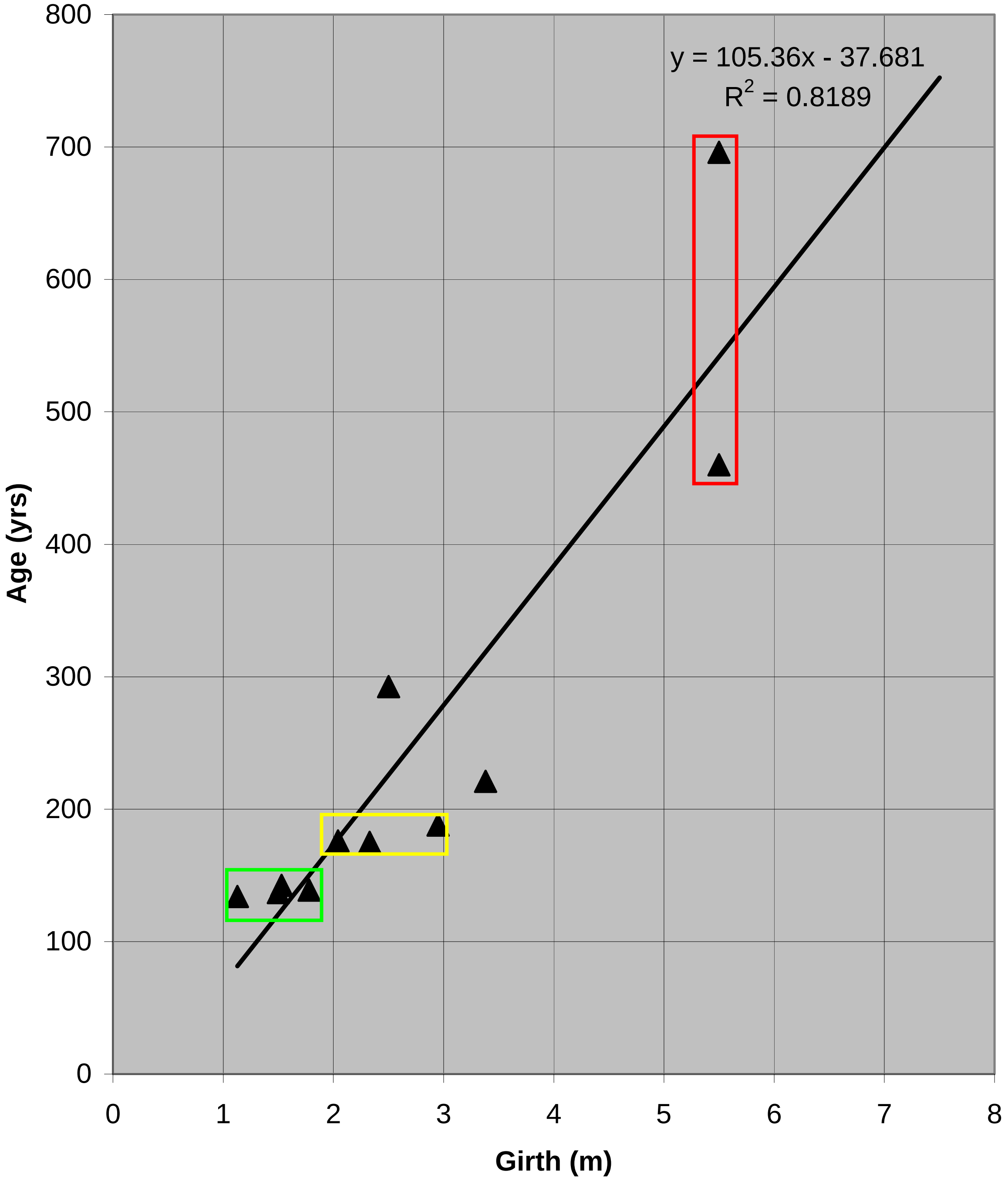
- Tree 1 has a radius (minus bark) of 0.823m. As 0.254m of the tree was recovered, a missing section of 0.569m is identified. Using the mean formative rate of 2.52mm/yr identified for this site for the first 80 years of growth of this tree, a missing section 0.368m in length remains unaccounted for. The tree rings recovered show this tree underwent a very low (senescent-like 0.75mm/yr) rate of growth between 1810 and 1870, but between 1880 and 2010 it recovered a higher (mature-like 1.44mm/yr) rate of growth, therefore it is difficult to know which rate of growth should be applied to the missing section. Applying either 0.75mm/yr or 1.44mm/yr to the 0.569m of missing section indicates the tree to have a total age of *c*. 628 or *c*. 426 years, respectively. Both the probable minimum and maximum ages for this tree are shown in Appendix III, but in this circumstance, it is thought best to take the mean, which suggests the tree to be around 600 years old and that it started growing around the 1400s.

The age calculations are shown in **Appendix III**, and the linear trend is shown below (**Figure 4**). From the dendrochronological analysis of the ten trees sampled here, as an easy-to-remember rule of thumb for estimating the age of other oak trees at Leigh Woods, every 1 metre of girth equals 100 years of age.

Given the small number of trees sampled and individual variations of growth, this analysis still suggests three main cohorts of trees at Leigh Woods:

a) Four small oaks (around 1.5m in girth), planted at the end of the 19th century;
b) Three oaks (between 2 and 3m in girth), planted in the early 19th century;
c) Three slower-grown oaks, two likely to have been planted or germinated in the 18th century and one large 5.5m veteran in the 15th century.

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



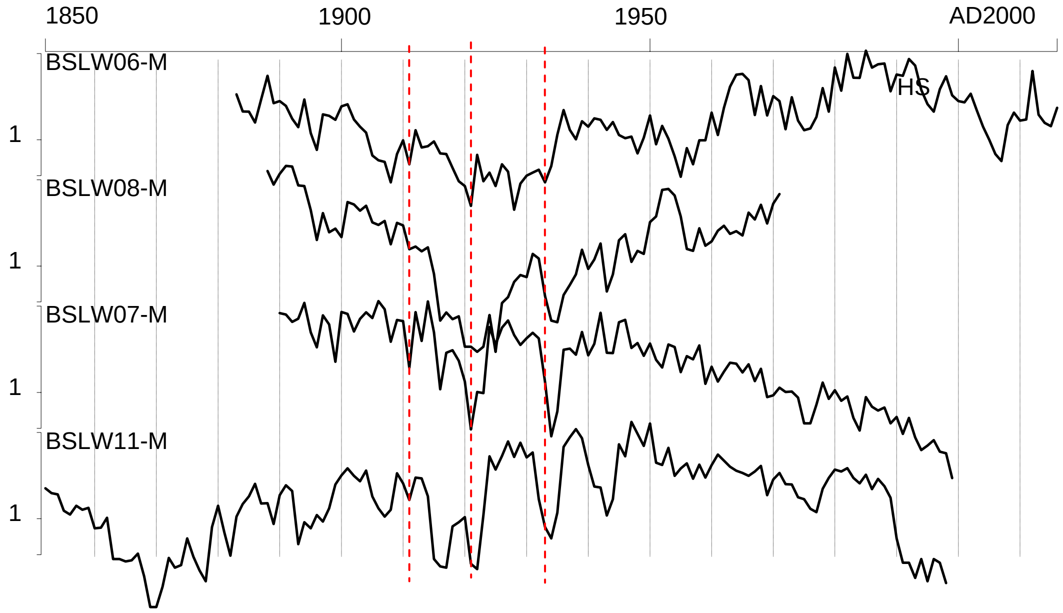
KEY: The linear trend (black line) and regression equation are shown, together with tree cohort A (green), B (yellow) and maximum & minimum calculated age for tree BSLW01 (red). Note: To allow comparisons, all tree age is plotted as if the tree grew until 2016.

Variations in Radial Growth

Tree 1 clearly shows that higher radial growth rates in veteran oak trees is possible. While a number of the trees sampled in this study have had nearby competing trees removed (a procedure typically called haloing), unfortunately these procedures were too recent to quantify the possible increases in radial growth in this study. Examining the relationship between the haloing of veteran oak trees and radial growth is, however, highlighted for future research.

During measurement, four trees, 6-M, 7-M, 8-M and 11-M, were identified to contain ring-width reductions that appeared to be characteristic of management. Climate analysis is beyond this study, but interestingly, a recent aridity index (Marsh 2004), highlights some summer droughts in 1911, 1921, 1933, which appear to coincide with the ring-width reductions measured (**Figure 5**). It may be that a combination of site factors and that these trees were quite young made them more susceptible to summer drought; however, a much larger sample would be required to test this hypothesis.

Figure 5: Ring-width plots showing in red some common periods of growth reduction which coincide with summer drought.



The large number of trees showing disturbances in typical growth in this study is likely a result of the selection of dead or dying trees during the sampling process and clearly limits the conclusions. A larger sample of larger healthy trees would be required to help establish mean growth rates at this site and possible changes in the density of woodland. Nevertheless, this study reinforces other studies (Moir 2012b) in that there can be wide variations in the growth of individual trees, and age estimates using girth alone should only be used in general terms.

CONCLUSIONS

Ring-width measurements from ten out of twelve oak trees sampled at Leigh Woods are successfully cross-matched to form a 211-year mean chronology called BRSTL-LW, which spans from AD 1806 to AD 2016.

Three main cohorts of oak trees at Leigh Woods are identified: four small oaks (around 1.5m in girth) which were planted/germinated at the end of the 19th century; three oaks between 2 and 3m in girth, planted/germinated in the early 19th century; and two slower-grown oaks, likely to have been planted/germinated in the 18th century.

One large 5.5m girth oak that was blown over in 2015 is estimated to have been planted/germinated in the 15th century. This tree shows that healthy radial growth rates (>1.4mm/yr) can be achieved in veteran oak, even after decades of slow (0.75mm/yr) growth. Examining the relationship between the haloing of veteran oak trees and radial growth is highlighted for future research.

Only young, dying or dead oak were sampled in this study. This resulted in many of the tree-ring series showing disturbed growth, which limited the conclusions. Nevertheless, the extraction of sawn sections from dead veteran oak trees and their dendrochronological analysis is shown to be a valuable approach to dating ancient trees in historic landscapes.

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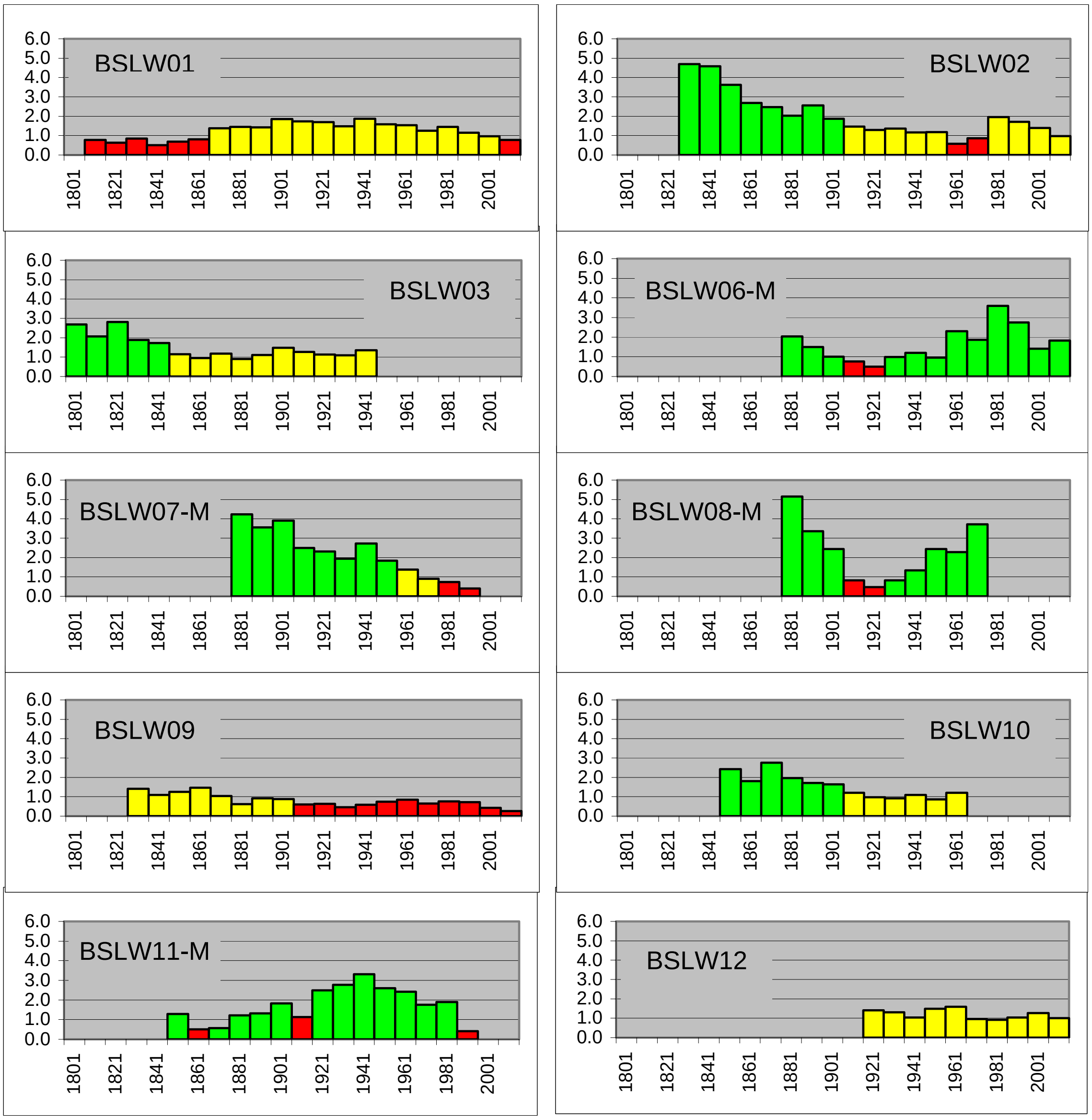
APPENDIX I: Raw ring-width data

TREE-RING DATA REMOVED

APPENDIX II: Mean growth rates of trees



KEY: Formative growth = green, Mature growth = yellow, and senescent or disturbed growth = red

APPENDIX III: Site-specific age estimates for oak at Leigh Woods

Mean tree sequence (or site chronology)	Sequence Date Range	Likely fell	Rings (+unmeasured rings)	Pith	Mean ring width (mm)	Tree girth (mm)	Tree radius (mm)	Bark (mm)	Radius - bark (mm)	Core length (mm)	Formative Growth rate (mm/yr)	Age at transition from Formative to Mature growth	Inside Woodland - Mature Growth rate (mm/yr)	Senescence Growth rate (mm/yr)	Calc. length of unsampled radius to pith (mm)	Calc. 80 years of formative growth (mm)	Calc. missing rings	Age	Germ-ination (AD)	Cohort
BSLW01	AD1811-AD2015		205	15	1.24	5500	875	52	823	254				0.75	569	201	491	*696*	*1319*	
BSLW01													1.44		569	201	255	*460*	*1555*	
BSLW02	AD1834-AD2016		183	5	2.00	2950	470	26	444	366	3.06	90	1.39					188	1828	B
BSLW03	AD1806-AD1949	AD1974	144	10	1.48	3380	538		509	213	2.23	60	1.16					179	1795	
BSLW04						1760														
BSLW05						3380														
BSLW06-M	AD1883-AD2016		134	5	1.61	1780	283	24	259	216	2.29							139	1877	A
BSLW07-M	AD1890-AD1999		110(+17)	10	2.05	1500	239	20	219	260	2.88	90	1.01					137	1879	A
BSLW08-M	AD1888-AD1971	AD1996	84	5	1.89	1130	180		151	159	2.68							114	1882	A
BSLW09	AD1832-AD2012		181	15	0.83	2500	398	30	368	150			0.89		218		87	*268*	*1723*	
BSLW10	AD1851-AD1966	AD1991	116	10	1.56	2041	325		296	181	2.01	70	1.04					151	1840	B
BSLW11-M	AD1852-AD1998		(10+)147(+18)	0	1.72	2330	371	26	345	318	2.46							175	1841	B
BSLW12	AD1929-AD2016		(17+)88	15	1.19	1530	244	24	220	125			1.20		95		38	*143*	*1873*	A
							Mean	**29**			**2.52**	**78**	**1.36**							