Paper:
Gagen, M. The tree ring growth histories of UK native oaks as a tool for investigating Chronic Oak Decline: an example from the Forest of Dean. *Dendrochronologia*

Submitted to Dendrochronologia -accepted manuscript. Revision accepted 01/03/19

The tree ring growth histories of UK native oaks as a tool for investigating Chronic Oak Decline: an example from the Forest of Dean.

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Abstract

Declines are a distinctive category of tree disease, complex to define and quantify and challenging to mitigate due to their multiple causes and heterogeneous tree response patterns. In many parts of Europe oak decline syndromes are severely impacting tree health and having a measurable economic impact on forestry. In the UK the impact of periodic oak declines is expanding against a backdrop of multiple environmental pressures, to levels capable of threatening the UK's native oak woodland. Here we explore the growth histories of oak trees at a site symptomatic of Chronic Oak Decline (COD), in the South of England; Speculation Cannop in the Forest of Dean, Gloucestershire. The dendrochronological picture at the site reveals that trees with current external COD symptoms have shown suppressed growth, in relation to the regional average, from early on in their lives. Moreover, there is an amplified reduction in minimum ring width in Symptomatic trees as compared to a healthy subsample of Control trees, likely to be heavily dominated by reduced latewood width in affected trees, as decline sets in. Broadly, the site reveals the initial appearance of decline, roughly 40 years after planting, in 1860. There is considerable variability in the later decline history pattern in Symptomatic trees but there are clusters of decline episodes in the 1920s, 1960s, 1980s and 1990s at this site. The Control trees are not always unaffected but rather show growth releases after each historical decline phase. The trees that currently show external decline symptoms do not have a history of these growth releases. We conclude that investigating the tree ring growth histories at sites impacted by COD could provide an important management tool, and ring width histories of trees at affected sites

should be used in the identification of the decline predisposing factors, that a management strategy requires.

Introduction and background

Declines are a distinctive category of tree disease, first conceptualised by Sinclaire (1965), and developed by Manion (1981) and Manion and Lachance (1992). They are among the most complex tree pathologies to define and quantify and are challenging to mitigate due to their multiple causes and heterogeneous tree response patterns (see Denman et al. 2017 and references therein). Decline syndromes involve multiple biotic and abiotic factors (Brown et al 2017; Manion 1981; Manion and Lachance 1992; Delatour 1983; Gibbs and Greig 1997; Thomas 2002, 2008). These factors may interact in different ways to produce symptoms that develop over many years and may themselves vary within and between sites. Trees at affected sites may show periods of remission and the pace of decline symptom development may vary over time.

In many parts of Europe oak decline syndromes are severely impacting tree health and vitality and having a measurable economic impact on forestry (Hartman and Blank 1993; Helama et al 2009; Lévy et al 1992; Sonesson and Drobyshev 2010; Thomas et al 2002; Fekete e al 2017). Whilst pathogens are clearly involved, abiotic factors, including changing precipitation and temperature regimes, will play a part in determining both the geographical spread of decline syndromes and the prognosis of vulnerable individuals. In the UK the impact of damaging, periodic oak declines, probably going back 100 years, is now expanding against a backdrop of multiple environmental pressures, to levels potentially capable of threatening the UK's ecologically and environmentally indispensable native oak species (Denman et al. 2014; 2017).

Britain's native oak species *Quercus robur* and *Q. petraea* suffer from two syndromes identified as chronic and acute decline (Denman 2014, Brown et al 2016). Chronic Oak Decline (COD) and Acute Oak Decline (AOD) can occur in a mosaic pattern across landscapes (Samec et al 2017) but have distinctions in their associated casual agents, and in the speed of onset and nature of external symptoms (Denman and Webber 2009, Denman et al. 2014). Chronic Oak Decline develops over decades and seems to be associated with poor root health. A progressive deterioration in tree crown condition, a loss of fine twigs and branch dieback are all associated symptoms. COD is thought to be marked by long term growth reductions that take place over many years before the appearance of external symptoms (Denman and Webber, 2009). By contrast, AOD is characterised by suites of factors which affect the above ground parts of the tree, leading to a rapid decline in external condition. AOD is marked by visible wounds between bark plates and necrosis of the inner bark, the beetle *Agrilus biguttatus* is involved but its specific role in AOD has not yet been fully revealed (Reed et al 2017). The relationship between the two decline syndromes is convoluted with AOD described as a specific condition within the wider oak decline complex (Brown et al 2016; Denman 2014). There are agents that seem distinct to one syndrome and those that seem to be related to both; canopy deterioration is marked in both syndromes (Denman and Webber, 2009; Hendry, 2005) although onsets faster in AOD. Root pathogenic fungi - *Armillaria* spp., *Collybia fusipes*, *Phytophthora* sp. - seem to be involved in both syndromes (Denman *et al*., 2016; Marçais & Bréda, 2006). Refinement of definitions and a reliable, early metric that can be used to identify trees with a predisposition are still required, as well as resolution of the relationship between the two disease forms (Denman et al. 2017).

Little is known about trunk growth reductions prior to the onset of external decline symptoms, in either syndrome, or in the baseline ring width growth histories of trees with and without visible external decline symptoms. Some trees are known to periodically recover leaving little externally visible evidence of decline episodes (Manion 1981; Manion and Lachance 1992). However, records of earlier periods of decline might be contained in tree ring growth records. The annual growth rings, which oak trees reliably lay down in their trunk wood, are commonly used as a dating tool for archaeological timbers (e.g. Haneca et al 2009) and for the record of past climate variability they hold (e.g. Pilcher et al 1984). Tree ring analysis has also begun to emerge as a method to explore the growth history of trees in decline-affected woodland (e.g. Helema et al 2009; 2014; 2016). However, it’s exploration in terms of assessing vulnerability and predisposition has been limited.

Dendrochronological assessments of annual growth ring widths might usefully supplement crown condition assessments giving insights into temporal effects, because changes in growth rates within trunk wood may precede the appearance of visible crown symptoms by several years (e.g. Bigler & Bugmann, 2003; Bigler et al., 2004, Drobyshev et al., 2007). We are not the first to note a mismatch between crown canopy symptoms and the broader decline condition with Keča et al (2017) noting that, particularly in mature oak, it is common to find a lack of correlation between the degree of root decay and crown symptoms. The history of growth, as contained in the tree ring record might thus elucidate useful information on growth history differences in trees that are externally symptomatic and asymptomatic at affected sites as part of a building picture of this multi biotic and abiotic parameter condition.

There is a pressing need to understand more about the nature of the causes and interactive effects of factors involved in declines over time. Best practice recommendations need to be developed, and trialled, to manage oak into good health and resilience, particularly against a background of changing climate and increasing levels of environmental pollutants. In identifying, and monitoring trees suffering from decline syndromes, emphasis is often placed on the description of crown conditions or other visible external symptoms, and on their development over time. Tree ring growth records offer a valuable additional source of information by which to assess the broader health of trees at affected sites.

Summer crown condition assessment is generally carried out via percentage defoliation, loss of fine branching and twigs, and discolouration of foliage (Innes, 1990). Winter crown condition assessments commonly follow the Hessian system (Hessian Forest Research Institute Hahn, Műnden, Germany), or the ARCHI epicormic shoot evaluation system (Drénou et al. 2016), whereby assessment methods allocate individual trees to groups according to visible health status. Such methods are used to allow a rapid evaluation of timber potential in areas experiencing decline (Drénou et al. 2016). However, crown assessment is not without its challenges, it can be subjective and only marks one component of a syndrome which is known to impact the whole tree and to exhibit variability through time. As a sole method of assessing and monitoring decline status, crown assessment would seem at odds with an emerging systems approach, which rather aims to take a holistic view of forest health in an attempt to more fully understand COD and AOD and the pathway trees might follow to mortality (Brown et al 2017). Whilst external assessment does give useful information on symptom expression within and between different stands at the time of assessment, elucidating the syndrome’s history at a particular site requires a picture of the long-term growth histories of individual trees, and groups of differentially symptomatic ones. Tree ring growth records are an ideal candidate for building this long-term overview.

Annual ring forming trees store historical records of growth and performance in their trunk wood. Thus, the ring width may well mark the initiation of the decline process, which then expresses in crown condition later. There is an emerging literature exploring the use of tree ring analyses in the study of decline syndromes as the value of long term growth information becomes recognised (see Young, 1965; Tainter et al., 1984, 1990; Cook & Zedaker, 1992; Hartmann & Blank, 1992; Pedersen, 1998; Bigler et al., 2006). Dendrochronological investigations in declining trees may also hold clues to the syndrome’s history at a particular site as trees also lock information about carbohydrate allocation and water use efficiency in their trunk wood stable isotope chemistry (McCarroll and Loader 2004), reflecting how defoliation and loss of fine roots have impacted photosynthate allocation within the tree (McCarroll et al 2017). Because the ring width of the spring and summer portion of the ring can be measured separately (the Early and Latewood), tree ring width time series can also be used to explore how the tree partitions resources differently as defoliation sets in. An overarching goal of exploring growth ring histories is to identify long term differences in growth patterns between symptomatic and asymptomatic individuals. Predisposition might be revealed by differences in the ring growth patterns between those trees which later became symptomatic, and those which stayed healthy. Predisposition is considered a critical evidence gap in the quest to understand the mechanisms of oak declines (Brown et al., 2016; Brady et al., 2017) and one which tree ring analysis might contribute to.

Here we explore the dendrochronological history of a southern English oak woodland severely impacted by COD, with the aim of 1) building the long-term growth overview in symptomatic and healthy 'control' trees and 2) identifying long term differences in growth between the two groups as 3) useful background relevant to identifying the predisposing factors that a management strategy requires (Barsoum et al., 2015; Delatour, 1983). Site tree ring records are used to investigate the past growth histories of trees exhibiting COD and those without currently visible external symptoms. We test the hypothesis that there will be differences in the growth histories of trees with external COD symptoms and that those growth histories give the background context to external symptom severity. With evidence that individual trees might have vulnerability to developing decline syndrome from seedling, we also explore how long before the onset of external symptoms healthy and affected trees reveal differences in ring widths.

Methodology

We explore the tree-ring growth histories in 39 mature *Quercus robur* (pedunculate oak) trees at a site affected by COD, Speculation Cannop in the Forest of Dean, Gloucestershire, England). The sampled trees were distributed over an area of approximately 4 ha (Figure 1) at a site with a considerable history of management. The trees at Speculation Cannop have been known to exhibit external COD symptoms for much of the last decade. We took increment core samples from 39 trees for tree-ring width analysis, of which 15 were declined, showing visible symptoms of crown thinning and canopy die-back at the time of coring, and 24 were considered to be healthy control trees on the basis of a lack of external canopy symptoms (Table 1). A lack of fine branch die back and a healthy crown is indicative of decline free control trees, this was identified by choosing individuals for the control pool which had a Hessian score (see above and Table 1) of only 1 or 2 via summer crown condition assessment.

Speculation Cannop (SC) is in an area of extensive rural industry with a history of coal and iron ore mining, quarrying, charcoal and timber production, and chemical manufacturing. The SC oaks were planted in the period around 1812, a known period of oak woodland planting in England, earning the descriptor ‘Napoleonic Oaks’ (Hart, 1971). The SC site itself has undergone extensive forestry management which is only partly recorded, with anecdotal evidence for thinning operations shortly after World War II, and again in the 1970s. More recently heavy thinning operations were carried out in 2010/11 to bring the woodland density to that of other parts of the forest dominated by Napoleonic oaks, and to compensate for previous under thinning (Forestry Commission, Pers. Comm.).

The SC wood is seasonally waterlogged and slow to drain and is therefore considered locally as a ‘wet wood’, fitting with the presence of *Q. robur*. The site is split into a wetter southern compartment and a somewhat better drained northern compartment (Figure 1). Within the southern compartment drainage ditches are visible whilst in the northern compartment numerous shallow pits are observed, thought to relate to charcoal burning and/or mining explorations, which were widespread throughout the forest from the thirteenth century until after World War II (Hart, 1971). The predominant soil types within this part of the Forest of Dean are seasonally waterlogged fine loams overlying clay soils. They are derived from Carboniferous shales. Historically soil fertility in the Forest of Dean oak plantings was comprised due to removal of beech and heavy thinning, within some plantations oaks failed to establish where planted on steep slopes with thin soils (Hart, 1966).

Core samples were taken using a standard increment borer several times between 2009 and 2016; a 5mm increment borer was used to reach very near to pith in most cases (max core length was 50cm). Two cores were taken, parallel to any minor slopes to minimise the chances of coring through tension wood which can obscure rings (Stokes and Smiley 1996). Core samples were air dried and mounted prior to tree-ring width measurement using standard dendrochronological techniques (Stokes and Smiley, 1996). Crown symptoms were also assessed at the time of coring (Table 1). Five decline categories were used to grade canopy symptoms based on photographs from the Forestry Commission Field book 12: Assessment of Tree Condition (Innes, 1990).

Standard methods (Fritts 1976) were used to measure tree-ring widths and to cross date each core sample against other trees at the site, and against a regional master chronology (Wilson et al 2013). Measurement was carried out using a Lintab™ 5 digital positioning table and TSAP-Win software (RINNTECH, Heidelberg, Germany). Measurement was challenged by the extremely narrow rings; pinched rings and uneven boundaries were common in all samples (Baillie and Pilcher 1973; Fritts, 1976). Despite this, T-values, which indicate the statistical strength of cross-dating (Fritts, 1976), were acceptably high with the use of careful surface preparation and iterative measuring. The SC chronologies were further cross dated against two master chronologies comprised of oak trees from across the southern UK (e.g. Briffa et al 1996; Wilson et al 2013) and T values obtained, along with visual comparisons, to check for missed or falsely measured rings. A full discussion of standard dendrochronological methods can be found in standard texts (e.g. Stokes and Smiley 1996; Fritts 1976; Speer 2010).

Throughout this study the samples taken from trees with no visible external symptoms at the time of coring are referred to as 'control' trees and those with visible external symptoms at the time of coring are referred to as 'symptomatic'. The mean SC control chronology includes samples from 24 control trees and covers the period AD 1822 to 2016. The mean SC symptomatic chronology includes samples from 15 trees and covers the period AD 1811 to 2016. Minimum sample depths are shown in Figure 2. Sample depth was kept as high as possible in order to maximise the robustness of the common signal (Fritts, 1976). Whilst more a requirement for dendroclimatological studies, where deriving a climate reconstruction from ring width measurements is the primary goal, the narrow uncertainty on the mean chronologies (see Figure 2) is a useful measure of confidence in the cross-dating of samples which have visually challenging ring growth. The common signal between the symptomatic trees is higher than for the control trees. The average between tree correlation is r = 0.75 (n=15) for the symptomatic tree, as compared to r = 0.45 (n=24) for the control trees. In order to establish signal to noise ratio, as a basic descriptive statistic, we wished to calculate the Expressed Population Signal (Wigley et al 1984) on that portion of the ring width time series free from age related trends, which could influence the common signal strength. The time series EPS was calculated for the period of common overlap, post juvenile phase (1880 to 2009). The EPS in this time period is 0.89 for the Symptomatic trees and 0.94 for the Control trees.

In order to investigate the changes through time in the SC ring width data, in comparison to those in trees from non-declining sites, we carried out comparisons with a regional master chronology by Wilson et al (2013). Ring width master chronologies represent the stand-level tree ring width signal for a particular species, in a particular area (Speer 2010). They are used to explore the tree ring width growth dynamics at a particular site and are made up of time series from many 100s of trees, giving the baseline growth for an 'average' UK oak tree from the relevant geographical region. Comparisons with regional master chronologies allow exploration of deviations in the SC ring width data as compared to average regional growth, for trees of a specific age. Where we carry out such comparisons, ring width series are aligned by cambial age (number of years from the pith), rather than by calendar age, as the average ring width needs to be viewed as a function of tree age. Such comparisons thus require an estimate of pith age for each tree. Pith age estimation is a standard practice and is used here, adjusted for recent insights after Altman et al (2015). Pith age estimates were derived from the measured diameter of each tree and the number of rings in the total core length. The average ring count in the core, assuming a stable radial growth rate, was then used to extrapolate the 'missing' number of rings between the end of the core and the pith of the tree. Thus, a cambial age for the first ring of each tree ring series is derived. Here the vast majority of the trees were cored very close to pith, so the pith offsets are small, the average being 12 years. The method is not without errors but gives a reasonably accurate estimate of tree age from cores which do not pass through the pith. Furthermore, the pith estimations calculated here give dates which correspond to the anecdotal planting year for Speculation Cannop. The ring width-based pith age estimate method gave pith dates for the SC trees of AD 1830 +/- 6 years, in line with known estimates of the planting dates for these English Napoleonic oaks (Hart, 1971).

Detrended ring width series are used in dendrochronological studies where deriving a climate reconstruction is the overall goal, because standardisation removes age-related biological growth effects and disturbance events, which would otherwise add noise to the common signal of interest. Standardisation is achieved by the fitting of simple functions describing the growth trend (Fritts, 1976). Standardisation is, for the main part, not carried out here to preserve disturbance events, such as decline onset, recovery and the initiation of another phase of decline. Such declines and releases could be removed by most forms of standardisation. We wished to assess the impact on mean growth of all potential growth influencing factors (age trends, climate, internal and forest processes and stochastic variations) (Cook 1987) and hence work with raw ring width values in most analyses. Where detrending is carried out, in order to carry out simple comparisons with climate data to investigate the impact of anomalous years, a simple linear detrending is used. This is a simple process of fitting a linear trendline through the ring width data and differencing the raw ring widths from this, to remove the long term linear trend (Fritts, 1976). This is the most conservative method of detrending ring width data and preserves all but the long-term age relate decline in ring widths. In climate data comparisons we refer to a robust regional climate data set, the Central England Temperature time series (Parker et al 1992).

Results and discussion

Trees add approximately the same amount of wood each year around an expanding circumference and, as such, time series of raw ring widths often display a negative exponential growth trend in conifer trees, with more complex growth trends often apparent in oaks (Fritts 1976). This is clearly visible in the SC chronologies (Figure 2). Both the mean Control and Symptomatic chronologies (Figure 2), and all the individual series (Figure 3) display comparable initially wide (juvenile) rings, followed by a rapid decline in width through the first decades of the tree's life. Ring width then decreases exponentially until the juvenile growth phase is complete, with the mean ring width curves appearing reasonably level by the time the trees are roughly 70 years old (around 1900, Figures 2). Superimposed on this negative exponential age trend are various multiyear phases of lower and higher growth, visible throughout the series length (Figures 2). Growth releases are revealed as ring width peaks, and declines appear as troughs of narrow growth. It is clear that growth declines and peaks manifest differently in the Symptomatic and Control trees, throughout the series length, with the Control trees producing a group of slightly higher raw ring widths from early in their life. The broadly higher ring widths in the Control trees (Figure 3) are visible, in comparison to the Symptomatic trees. The differences in average ring width in the two groups (Symptomatic and Control trees) are significant (Kruskal-Wallis *H*-Test). There is a significant difference between the Control and Symptomatic group ring widths upon t-testing when the harmonic means are compared both across years and between trees (not shown).

The mean, maximum and minimum ring width value averages are given in Table 2. The Control trees, which are defined by having crown conditions with less than 30% crown loss (Table 1), have roughly 10% more mean trunk growth on the basis of their total ring width measurements. The Symptomatic trees, (with more than 30% visible crown loss, Table 2) reveal more than 10% less mean trunk growth in comparison to the site average. However, the differential trunk growth between the Control and Symptomatic trees is more than 20%. In terms of maximum ring widths, the trend is less pronounced but similar, with the Symptomatic maximum ring width about 7% less than that of the Control trees. With regards to the minimum ring widths, the reduced growth within the Symptomatic trees can be seen to be amplified, being >20% less than within the Control trees.

Figure 4 shows the Speculation Cannop Control and Symptomatic mean raw ring width chronologies compared to a regional master chronology for the Forest of Dean (after Wilson et al 2013). A visible decline emerges in the AD 1970s and a step jump in the AD 1990s in the Symptomatic trees, as compared to the regional mean Forest of Dean ring width series, and local Control trees (Figure 4). Between about 1900 and 1950 the growth of the Control and Symptomatic trees is again rather similar with a second period of strong divergence in mean annual growth emerging in the 1950s and strengthening from around 1965. The inter-annual correlations between the two SC series and the regional master series are all strong and significant (at 95%). All three series here are normalised to the period 1900-1970, after the negative exponential juvenile growth phase but before the intense phase of decline symptoms (Figure 4). This conservative approach allows comparison of the broad trends in growth, and an exploration of suppressions and releases, without the drawbacks of standardisation. The ring width variability within the local master chronology, made up only of healthy trees (Forest of Dean series, Figure 4), is well correlated with the growth in the SC trees, such that we can assume the local master chronology gives a reasonably accurate mean growth curve for SC. In this way we can use the local master as a reference chronology for expected growth for healthy oak trees in this region.

From the start of the time series to approximately 1860 the two growth curves are similar. Beginning in 1860, however, there is a visible decline in the ring widths of the Symptomatic trees, which becomes pronounced by 1867 (Figure 4). Throughout this period the Control trees increase their average ring widths. This period is coincidental with markedly cool summers in the Central England Temperature series (Parker et al 1992). AD 1860 is the 4th coolest summer period in the 358 years of the CET record. The July-August average temperature in 1860 having been 13.47°C as compared to the average of 15.31°C. This very cool summer was then accompanied by moderately cool summers for the following 5 years (Figure 5). Figure 5 shows the average ring width series from the Symptomatic and Control trees after simple linear detrending. The anomalously cool summer in 1860 is indicated. The simple correlation between the two ring width series and the central England temperature series is poor, however, the association between anomalously cool summer and a low ring width a few years later is apparent, as is the greater impact on the Symptomatic trees than the Control trees. This may relate to a relationship between summer temperature and external biotic factors and pathogens.

The normalised tree ring width time series also reveal a difference in the rate of the age-related growth decline in the two groups of trees (Figure 6). The ring width decline in the Control trees amounts to a 4µm/yr reduction in growth rate, versus a 14µm/yr reduction per year in the Symptomatic trees, over a comparable period (Figure 6).

In order to characterise the growth decline in the Symptomatic trees we compared growth to the average growth rate decline, with age, in the Forest of Dean master chronology (Wilson et al 2013). All three series (SC Contol, SC Symptomatic and Forest of Dean Master) were normalised to a common early period, as previously discussed, and aligned by cambial age, rather than calendar date. Cambial age alignment allows the investigation of growth changes over time normalised by tree age and allows us to compare the Control and Symptomatic mean growth curves to the growth-age profile of the regional master (Figure 7). It allows us to define how 'well' the trees are doing at SC in comparison to a comparable UK oak growing elsewhere. The Control and Symptomatic mean ring width series can be seen to join the average regional growth curve in the initial decades after the planting phase at Speculation Cannop and remain within the confidence limits for that regional growth curve until the trees are roughly 40 years old (Figure 7); around AD 1870. The growth rate within both the Control and Symptomatic trees remains below the regional curve until a growth release in the control trees when they are roughly 125-130 years old (around AD 1955-1960). However, the Control tree's growth is notably higher than the Symptomatic tree's by the time the trees are 40 years old. We note there is no profound change in sample depth throughout the series length that might impact these trends. The Control trees remain in a slightly enhanced growth state as compared to the regional curve for trees of the same age. The Symptomatic trees do not experience the slight growth release of the AD 1960s visible in the master chronology, and also show a visible decline in growth rate in comparison to the regional average when the symptomatic trees reach approximately 160 years old, in the AD 1990s (Figure 7).

As summarised in Table 3 there are differences in the broad pattern of growth histories of trees with and without visible COD symptoms at the time of coring. Essentially the Control trees seem to have done better in terms of annual trunk growth, since early on in their lives, certainly from about 40 years in age. They seem to have experienced a pattern of growth releases at key points and, critically, have not suffered a 1990s growth decline phase, as the Symptomatic trees have (Table 4). Table 4 explores the degree to which the external symptoms correlate to the history of growth declines in the individual trees. In Table 4 a qualitative summary of the relationship between the individual tree and the Control tree mean is given to indicate how well or how poorly a particular tree has grown as compared to the site mean. The severity of the external symptoms is also noted in relation to historical growth suppressions and releases. A pattern emerges whereby trees which are either dead by 2016 or exhibiting very strong decline, also show declining ring width histories. In a broad study on tree mortality Cailleret et al (2017) found ring width declines up to 25 years before the onset of external symptoms of decline. We use Table 4 to ask the question, would ring width history data have allowed us to identify decline before the emergence of external canopy symptoms? In about half the cases we feel that it would have. We also note, however, that the healthy trees also exhibit changes in the 1980s and 1990s in terms of their ring widths but without current evidence for the severe external symptoms and mortality exhibited by the declining trees (Table 4). It is possible that, in the 1980s-1990s the crowns did reflect this stress and that by 2009-2016 the crowns have recovered condition.

There is considerable variability in both the onset of a growth decline in these trees and the last time a particular tree experienced a decline. However, there are clusters of trees in decline in the 1960s, 1980s and 1990s. It is of note (see Table 4) that the healthy trees often experienced a growth release in these periods (e.g. ‘control’ Trees 29, 26 and 40) suggesting that an event involved in the decline onset phases in the 1960s, 1980s and 1990s had the effect of causing a growth release in some trees and initiating the onset of decline in others. Such stand wide disturbance events are, at this site, likely to be management related. The final phase of thinning at the site occurred in 2010 with 4 trees noted as having advanced or severe decline symptoms at that time having subsequently died.

The exploration of tree ring histories is also of use in examining the differences between those Symptomatic trees with the most severe, or moderate, external decline symptoms (Figure 8). Whilst it might be expected that those trees with the most severe decline state currently might show a past pattern of decline phases, there is in fact little difference in their growth ring history until the emergence of the 1960 decline phase of declines. From that onset, their trunk ring growth has been systematically lower than that of the trees with more moderate current decline symptoms. They would appear to be trending strongly towards mortality (Figure 8).

Conclusions

We measured the ring width data on 39 oak trees at a site in the south of England. 15 trees had externally visible decline symptoms in their crowns and were determined to be COD ‘Symptomatic’. 24 trees had no currently visible external crown symptoms of decline and were determined to be healthy ‘Control’ trees. We measured annual ring widths in all trees, cross dated them against regional master ring width chronologies and explored the growth histories in the Control and Symptomatic individuals. Our aim was to build the long-term overview of the trunk growth of symptomatic and asymptomatic control trees at a site severely impacted by COD over recent decades.

There are quantifiable differences in the growth histories of trees with, and trees without, external COD symptoms and within the two groupings as well. There are ‘healthy’ trees that have experienced declines in the past, however, generally Control trees have stronger growth, with the first divergence in growth rates between the Symptomatic and Control trees beginning in the 1860s (Figure 1) when the trees are juvenile.

A simple comparison of the average ring widths in the two groups reveals the trees with current decline symptoms have exhibited lower than average ring widths from early in their life. They also have particularly low minimum ring widths. With regards to the minimum ring widths, the reduced growth within the Symptomatic trees can be seen to be amplified, being >20% less than within the Control samples. This makes sense with the understanding we have of the loss of fine roots and branches in COD, however, the long-term evidence for reduced ring growth strongly suggests these trees would have experienced continuous phases of decline in their past. We see a complex mosaic of decline phases via the ring width histories, with many suppressions and releases from early in the tree’s life. Drenou et al (2015), in an analysis of the external architecture of shoots on recovering, declining and healthy pedunculate oak in France find that individuals they consider to be in ‘irreversible decline’ have multi-year ‘backlogs’ in ring width, after an external stress such as a drought year. More generally a long-term difference in trunk wood growth is commonly found in comparisons between healthy and declining trees (e.g. Helama et al 2014; Haavik et al 2015; Colangelo et al 2017; Cailleret et al 2017).

We hypothesis that these lower overall ring width values, and amplified reductions in minimum ring width, are likely to be heavily dominated by reduced latewood width. An oak tree with limited resources may not produce any latewood at all and solely produce enough earlywood vessels to initiate growth and trunk water movement in the spring. A significant % of ring growth in oaks occurs using stored photosynthate before bud burst, such that crown defoliation, a symptom of COD, has a significant impact on ring width (Drobyshev 2007). Marçais and Desprez-Loustau (2014) note that the reductions in photosynthetic activity associated with decline deplete carbohydrate reserves, but with a considerable delayed damage onset, in subsequent years. The severity of external symptoms broadly correlates with the degree of historical growth suppression but with considerable variability.

In about half the Symptomatic trees, the growth histories could potentially have revealed a tendency towards decline periods before the onset of the most recent phase of externally visible decline (Table 4) and management practices at the site adjusted accordingly.

There is considerable variability in the onset of decline symptoms but there are clusters of decline at 1920s, 1960s, 1980s and 1990s. After these phases the Control trees show releases whilst the Symptomatic trees are further supressed in terms of their trunk growth. The pattern of trunk growth we see, showing life-long evidence of reduced growth in some trees, suggests a combination of abiotic and biotic factors (including potentially genetic) have combined to predispose particular trees to decline at this site. Further analyses, having explored here the differences in total ring width between trees with and without current external COD symptoms, will involve a full exploration of the climate-growth and climate-isotope relationships in these trees, exploring precipitation and additional insect outbreak relationships, oaks being know to alter the osmotic potential of their sap sugar/starch ratio in response to dry spells, potentially making them more attractive to insect defoliators.

There is a clear need for further exploration of how growth histories might indicate likely prognosis for a tree. Of the 5 trees shown in Figure 6 as being in the ‘severe’ decline category, four died in between their first measurements in 2009 and reassessment in 2015. By 2009 their growth, in comparison to trees with less severe external symptoms, was severely supressed. If this information could be worked in to management plans trees at severe decline risk could be identified from the combination of their growth ring history and external symptoms and be protected from invasive management practices to encourage recovery. Additionally, with evidence that some of the organisms involved in decline syndromes, both chronic and acute, may be advantaged by a warming and drying climate in the future (e.g. Reed et al 2016). Haavik et al (2015) find that the combination of soil pathogens and drought years can synergistically enhance tree stress ultimately combining to cause decline and death in oaks and lower rainfall and higher temperatures have specifically been found to be associated with Acute Oak Decline in the UK (Brown et al 2018).There is a clear need to have a benchmark for the decline risk level of both specific sites and indeed individual trees taking into account a suite of biotic and abiotic factors. Tree growth ring history could add a useful perspective to such a multi parameter approach to decline management.

We provide the first dendrochronological investigation of a UK site impacted by Chronic Oak Decline with the aim of informing site management practices in the future. We illustrate that growth ring histories can be used to identify clusters of decline phases in a site's history and, as others have indicated, reveal the potential for future management practices being informed by the historical tree ring perspective (Barsoum et al, 2015). We also show that tree ring width growth histories can indicate the potential for decline phases in specific trees and that, at this typical managed oak woodland, those trees experiencing the worst declines in recent years have shown suppressed growth from a very young age. COD has the potential to severely impact native oak woodland in the UK, clearly ring width history can give a good indication of predisposing risk and the ring width histories of trees at affected sites should be used as a tool in the identification of tree and site specific predisposition that a management strategy requires. We conclude this pioneering study with a recommendation that dendrochronological assessments are considered at sites where decline poses a significant risk to the health of oak trees and the results used to inform the management practices at the site to ensure minimal additional stress impacts on trees that show a pattern of reduced ring growth and a lack of evidence for strong recovery from decline phases.

Acknowledgements.

We would like to thank Woodland Heritage and the Forestry Commission for Funding support, and the Forestry Commission foresters in the Forest of Dean for their co-operative help and support. Dave Wainhouse is thanked for support with the initial investigation at SC.

References.

Altman, J., et al. (2016). "Age estimation of large trees: New method based on partial increment core tested on an example of veteran oaks." Forest Ecology and Management **380**: 82-89.

Barsoum, N., Eaton, E. L., Levanič, T., Pargade, J., Bonnart, X., & Morison, J. I. L. (2015). Climatic drivers of oak growth over the past one hundred years in mixed and monoculture stands in southern England and northern France. *European journal of forest research*, *134*(1), 33-51.

Bigler, C., et al. (2006). "Drought as an inciting mortality factor in Scots pine stands of the Valais, Switzerland." Ecosystems **9**(3): 330-343.

Bigler, C., et al. (2004). "Growth patterns as indicators of impending tree death in silver fir." Forest Ecology and Management **199**(2): 183-190.

Bigler, C. and H. Bugmann (2003). "Growth-dependent tree mortality models based on tree rings." Canadian Journal of Forest Research **33**(2): 210-221.

Brown, N., et al. (2016). "Spatial and temporal patterns in symptom expression within eight woodlands affected by Acute Oak Decline." Forest Ecology and Management **360**: 97-109.Brown, N., et al. (2017). "Acute Oak Decline and Agrilus biguttatus: The Co-Occurrence of Stem Bleeding and D-Shaped Emergence Holes in Great Britain." Forests **8**(3).

Brown, N., Vanguelova, E., Parnell, S., Broadmeadow, S., & Denman, S. (2018). Predisposition of forests to biotic disturbance: Predicting the distribution of Acute Oak Decline using environmental factors. *Forest Ecology and Management*, *407*, 145-154.

Brady, C., et al. (2017). "Taxonomy and identification of bacteria associated with acute oak decline." World Journal of Microbiology and Biotechnology **33**(7): 143.Briffa, K R, Wigley, T M L, Jones, P D, Pilcher, J R, and Hughes, M K, 1986. The reconstruction of past circulation patterns over Europe using tree-ring data, final report to the Commission of European Communities, contract no CL.111.UK(H)

Cailleret, M., Jansen, S., Robert, E. M., Desoto, L., Aakala, T., Antos, J. A., ... & Čada, V. (2017). A synthesis of radial growth patterns preceding tree mortality. *Global change biology*, *23*(4), 1675-1690.

Cook, E. R., et al. (1987). "Forest decline: modeling the effect of climate in tree rings." Tree Physiology **3**(1): 27-40.Cook 1987

Cook, E. R. and S. M. Zedaker (1992). The dendroecology of red spruce decline. Ecology and decline of red spruce in the eastern United States, Springer**:** 192-231.Cook & Zedaker, 1992

Colangelo, M., Camarero, J. J., Battipaglia, G., Borghetti, M., De Micco, V., Gentilesca, T., & Ripullone, F. (2017). A multi-proxy assessment of dieback causes in a Mediterranean oak species. *Tree physiology*, *37*(5), 617-631.

Delatour, C. (1983). "Les dépérissements de chênes en Europe." Biologie et Forêt **XXXV**(4): 265-282.

Denman, S., et al. (2017). "Identification of Armillaria species on declined oak in Britain: implications for oak health." Forestry: An International Journal of Forest Research **90**(1): 148-161.

Denman, S., et al. (2017). "Microbiome and infectivity studies reveal complex polyspecies tree disease in Acute Oak Decline." The ISME journal **12**(2): 386.

Denman, S., et al. (2014). "A Description of the Symptoms of Acute Oak Decline in Britain and a Comparative Review on Causes of Similar Disorders on Oak in Europe." Forestry, 2014, Vol. 87(4), Pp.535-551 **87**(4): 535-551.

Denman, S. & Webber., J. (2009). "Oak declines new definitions and new episodes in Britain." Quarterly Journal of Forestry **104**(4): 285-290.

Drénou, C., et al. (2015). "The diagnostic method ARCHI applied on declining pedunculate oaks." Arboricultural Journal **37**(3): 166-179.

Drobyshev, I., et al. (2007). "Relationship Between Crown Condition and Tree Diameter Growth in Southern Swedish Oaks." Environmental monitoring and assessment **128**(1-3): 61-73.

Fekete et al. 2017. Long-term effects of climate change on carbon storage and tree species composition in a dry deciduous forest).

Fritts, H. C. (1976). Tree Rings and Climate. Caldwell, New Jersey, Blackburn Press.

Gibbs, J. and B. Greig (1997). "Biotic and abiotic factors affecting the dying back of pedunculate oak Quercus robur L." Forestry **70**(4): 399-406.

Haavik, L. J., Billings, S. A., Guldin, J. M., & Stephen, F. M. (2015). Emergent insects, pathogens and drought shape changing patterns in oak decline in North America and Europe. *Forest Ecology and Management*, *354*, 190-205.

Haneca, K., et al. (2009). "Oaks, tree-rings and wooden cultural heritage: a review of the main characteristics and applications of oak dendrochronology in Europe." Journal of Archaeological Science **36**(1): 1-11.

Hart, C. E. (1971). The industrial history of Dean: with an introduction to its industrial archaeology, David & Charles Publishers.

Hartmann, G. and R. Blank (1993). Etiology of Oak Decline in Northern Germany. History, Symptoms, Biotic and Climatic Predisposition, Pathology. Recent advances in studies on oak decline. Bari, Italy**:** 277-284.

Helama, S., Läänelaid, A., Raisio, J., Mäkelä, H. M., Hilasvuori, E., Jungner, H., & Sonninen, E. (2014). Oak decline analyzed using intraannual radial growth indices, δ 13 C series and climate data from a rural hemiboreal landscape in southwesternmost Finland. *Environmental monitoring and assessment*, *186*(8), 4697-4708.

Helama, S., et al. (2016). "Oak Decline as Illustrated Through Plant–Climate Interactions Near the Northern Edge of Species Range." The Botanical Review **82**(1): 1-23.

Innes, J. L. (1990). "Assessment of tree condition." Forestry Commission Field Book **12**.

Keča, N., Koufakis, I., Dietershagen, J., Nowakowska, J. A., & Oszako, T. (2016). European oak decline phenomenon in relation to climatic changes. *Folia Forestalia Polonica*, *58*(3), 170-177.

Lévy, G., et al. (1992). "A comparison of the ecology of pedunculate and sessile oaks: radial growth in the centre and northwest of France." Forest Ecology and Management **55**(1-4): 51-63.

Manion, P. D. (1981). Tree disease concepts. Englewood Cliffs, New Jersey, Prentice-Hall, Inc.

Marçais, B., & Desprez-Loustau, M. L. (2014). European oak powdery mildew: impact on trees, effects of environmental factors, and potential effects of climate change. *Annals of Forest Science*, *71*(6), 633-642.

Marcais, B. and N. Breda (2006). "Role of an Opportunistic Pathogen in the Decline of Stressed Oak Trees." The Journal of Ecology **94**(6): 1214-1223.

Manion, P. D. and D. Lachance (1992). Forest decline concepts, APS Press.

McCarroll, D. and N. J. Loader (2004). "Stable isotopes in tree rings." Quaternary Science Reviews **23**(7): 771-801.

McCarroll, D., et al. (2017). "A simple stable carbon isotope method for investigating changes in the use of recent versus old carbon in oak." Tree Physiology **37**(8): 1021-1027.

Parker, D. E., et al. (1992). "A new daily central England temperature series, 1772–1991." International Journal of Climatology **12**(4): 317-342.

Pedersen, B. S. (1998). "The role of stress in the mortality of midwestern oaks as indicated by growth prior to death." Ecology **79**(1): 79-93.

Pilcher, J. R., et al. (1984). "A 7,272-year tree-ring chronology for western Europe." Nature **312**(5990): 150.

Reed, K., et al. (2017). "The lifecycle of Agrilus biguttatus: the role of temperature in its development and distribution, and implications for Acute Oak Decline." Agricultural and Forest Entomology **20**(3): 334-346.

Samec, P., et al. (2017). "Discrimination between acute and chronic decline of Central European forests using map algebra of the growth condition and forest biomass fuzzy sets: A case study." Science of The Total Environment **599-600**: 899-909.

Sinclair, W. A. (1965). "Comparisons of recent declines of white ash, oaks, and sugar maple in northeastern woodlands." Cornell Plant **20**: 62-67.

Sonesson, K. and I. Drobyshev (2010). "Recent advances on oak decline in southern Sweden." Ecological Bulletins **53**: 197-207.

Speer, J. H. (2010). Fundamentals of tree-ring research, University of Arizona Press.

Stokes, M. A. & Smiley, T.L. (1996). An introduction to tree-ring dating, University of Arizona Press.

Tainter, F. H., et al. (1984). "The effect of climate on growth, decline, and death of northern red oaks in the western North Carolina Nantahala Mountains." Castanea: 127-137.

Tainter, F. H., et al. (1990). "Decline of radial growth in red oaks is associated with short-term changes in climate." European Journal of Forest Pathology **20**(2): 95-105.

Thomas, F. M., et al. (2002). "Abiotic and biotic factors and their interactions as causes of oak decline in Central Europe." Forest Pathology **32**(4-5): 277-307.

Thomas, F. M. (2008). "Recent advances in cause-effect research on oak decline in Europe." CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources **3**(037): 1-12.

Wigley, T.M., Briffa, K.R. and Jones, P.D., 1984. On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology. *Journal of climate and Applied Meteorology*, *23*(2), pp.201-213.

Wilson, R., et al. (2013). "A millennial long March–July precipitation reconstruction for southern-central England." Climate Dynamics **40**(3-4): 997-1017.

Young, C. W. T. (1965). "Death of Pedunculate Oak and Variations in Annual Radial Increments Related to Climate." Forestry Commission Bulletin: Forest Record No.55: 1-16.

List of Figures and Tables.

Table 1– change in canopy assessment between 2009 and 2016. Crown symptom categorisations and growth history status where crown categories 1:Healthy = <10% crown loss, 2:Early Decline = 11-30% loss, 3:Moderate Decline = 31-55% loss, 4:Advanced Decline = 56-80% loss, 5: Severe Decline >80% loss.

ID		Inner ring	Outer ring	Number of Cores	Crown symptoms (2009/2010)	Crown condition category 2016	Mean ring width. (min,max, mm/100)
SC2M	Symptomatic	1834	2015	3	4	5	137 (31, 352)
SC6M		1825	2014	3	5	Dead	144 (17, 426)
SC7M		1840	1973	2	5	Dead	181 (74, 399)
SC8M		1829	1982	2	5	Dead	117 (32, 400)
SC21M		1833	2015	3	2	5	102 (28, 392)
SC24M		1841	2009	2	2	Felled	176 (35, 553)
SC25M		1825	2007	3	5	Dead	125 (28, 483)
SC30M		1831	2016	3	2	3	154 (35, 457)
SC37M		1834	2015	2	-	3	184 (57, 425)
SC39M		1811	2015	2	-	3	115 (31, 526)
SC44M		1826	2015	2	-	3	161 (32, 475)
SC45D		1853	2016	1	-	2	140 (23, 457)
SC46D		1831	2016	1	-	1/2	132 (38, 472)
SC47D		1853	2016	1	-	2	184 (55, 533)
SC60M		1848	2016	2	-	4	152 (48, 471)
SC11M	Control	1849	2016	3	1	1	173 (54, 370)
SC12M		1853	2016	3	1	3	166 (43, 451)
SC14M		1833	2016	3	1	1	188 (58, 456)
SC17M		1822	2016	3	2	3	122 (28, 472)
SC18M		1852	2015	3	2	3	164 (55, 475)
SC20M		1823	2015	3	2	2	181 (46, 513)
SC26M		1825	2015	3	1	2	144 (33, 423)
SC28M		1829	2016	3	1	1	159(55,324)
SC29M		1828	2016	3	1	1	206 (19, 491)
SC31M		1840	2016	2	1	1	157 (37, 443)
SC35M		1861	2015	1	-	1	212 (54, 536)

SC36M		1915	2015	1	-	1	207 (70, 493)
SC38M		1838	2015	1	-	1	217 (85, 435)
SC40M		1843	2015	1	-	1	189 (40, 440)
SC41M		1853	2015	1	-	1	214 (71, 441)
SC42M		1831	2015	1	-	1	148 (18, 348)
SC43M		1843	2015	1	-	1	190 (59, 475)
SC45M		1884	2015	1	-	1	202 (60, 581)
SC46M		1850	2015	1	-	1	181 (36, 400)
SC47M		1860	2015	1	-	1	240 (60, 682)
SC48M		1868	2015	1	-	1	176 (47, 443)
SC49M		1843	2015	1	-	1	189 (45, 373)
SC50M		1829	2015	1	-	1	194 (69, 441)
SC51M		1867	2015	1	-	1	266 (69, 590)

Table 2 average chronology statistics. Ring Widths are given in microns.

	Mean	Max	Min
All trees	189	526	64
Control tree ring widths	194	369	73
Symptomatic tree ring widths	164	526	50

1829-2016 (n≥5)	**Mean**	**Max**	**Min**
All trees	175	355	64
Control tree ring widths	191	363	73
Symptomatic tree ring widths	148	348	50

Table 3, a qualitative summary of events in the Symptomatic and Control trees and at the site.

Decade	**Symptomatic trees**	**Date**	**Control Trees**	**Date**	**Site History**	**Date**
1950s	Growth decline emerges	1950	Growth release emerges (now aged about 130 years old) in comparison to the regional growth curve.	1955-1960	Abandonment of the Speculation colliery due to flooding (Parr, 1973)	1956
					Caterpillar defoliation in Forest of Dean (Fletcher, 1974)	1954-1956
1960s	Do not experience a growth release visible in the regional growth curve and SC control trees	Emerging 1960-1965				
1980s					Severe oak dieback weakened, drought stressed trees were attacked by *Agrilus biguttatus* (Gibbs, 1999)	1989-1994
1990s	Visible decline in growth rate in comparison to regional growth curve	1990s				
2000s					Thinning	~2010 ww2 and 1970s

Table 4. Crown symptom categorisations and growth history status where crown categories 1:Healthy = <10% crown loss, 2:Early Decline = 11-30% loss, 3:Moderate Decline = 31-55% loss, 4:Advanced Decline = 56-80% loss, 5: Severe Decline >80% loss.

	Class when cored	**Crown when cored**	**Core sampled in**	**External condition 2009**	**External condition 2016**	**Ring widths indicate**	**Would RW have revealed decline before external symptoms?**
SC2M	S	4	Jul-10	Advanced decline	Severe decline	Average growth prior to severe decline starting mid 1990s	Y
SC6M	S	5	Jun-10	Severe decline	Dead	Average growth prior to a severe decline from 1960	Y
SC7M	S	5	Jun-10	Severe decline	Dead	Core ends in the 1960s with no indication of suppressed growth prior.	NA
SC8M	S	5	Feb-09	Severe decline	Dead	Suppressed growth from pith, increasingly supressed from 1920s.	Y
SC21M	S	3	Feb-09	Early decline	Severe decline	Increasingly suppressed growth from the 1920s onwards.	Y
SC24M	S	2	Jul-10	Early decline	Felled after 2010	Broadly healthy growth, moderate decline evident from late 1980s	Possibly
SC25M	S	5	Jul-10	Advanced decline	Dead	Severe decline beginning approx. 1980.	No
SC30M	S	3	Jul-10	Moderate decline	Moderate decline	Moderate decline beginning late 1960s	Possibly
SC37M	S	3	Mar-16	n/a	Moderate decline	Limited decline visible in ring widths.	No
SC39M	S	3	Feb-16	n/a	Moderate decline	Comparatively supressed growth from pith. Decline from 2001 with evidence of a recovery in 2010.	Y
SC44M	S	3	Mar-16	n/a	Moderate decline	Suppressed from 1930, declining from 2006.	Y
SC45D	S	2	Jul-17	n/a	Early decline	Reduced ring width from 1862, below average growth. Only recovers by 1940. 1991-94 poor years but since similar growth to control group.	N
SC46D	S	1/2	Jul-17	n/a	Healthy/Early decline	Below average growth from 1913 and for the period 1888-1905. 1913-1970 below average growth. From 1975 reduced growth, recovery in 2010.	N
SC47D	S	2	Jul-17	n/a	Early decline	1877 & 1884 – growth releases then a period of above average growth until 1931. After another growth release in 1988, decline then recovery to 2008 then rapid decline to present.	N
SC60M	S	4	Nov-16	n/a	Advanced decline	1859 & 1862 – growth releases. Growth similar to control group until divergence from 1958. Recovery in 2012 then sharp decline to present.	Y
SC11M	C	1	Jun-10	Healthy	Healthy	Healthy growth and a strong growth release in the late 1970s.Evidence of return to normal growth from 1990s	
SC12M	C	1	Jun-10	Healthy	Moderate decline	Normal growth, various growth releases and mild suppressions. No recent evidence of decline in ring widths.	
SC14M	C	1	Jun-10	Healthy	Healthy	Normal growth, growth release from 1990s.	
SC17M	C	2	Feb-09	Early decline	Moderate decline	Growth suppressed from early in time series. Slight decline from 2001	
SC18M	C	2	Feb-09	Early decline	Moderate decline	Normal growth prior to suppression appearing 1970s. Slight recovery from 2006.	
SC20M	C	2	Feb-09	Early decline	Early decline	Normal growth. Slight decline from 2007.	
SC26M	C	1	Jul-10	Healthy	Early decline	Normal growth. Growth release in the 1970s. Slight decline from early 1990s.	
SC28M	C	1	Jul-10	Healthy	Healthy	Normal growth, slight decline from mid-1990s.	
SC29M	C	1	Jul-10	Healthy	Healthy	Highly variable with profound growth release from 1960s.	
SC31M	C	1	Jul-10	Healthy	Healthy	Normal growth. Evidence of slight suppression from 1990s.	
SC35M	C	1	Mar-16	n/a	Healthy	Normal, rather variable growth, slight decline from 2000s.	

SC36M	C	1	Mar-16	n/a	Healthy	Variable growth prior to strong suppression setting in in the 1980s.	
SC38M	C	1	Mar-16	n/a	Healthy	Normal growth, mild suppression from 1990s.	
SC40M	C	1	Mar-16	n/a	Healthy	Normal growth, various suppressions and releases. Lastly from 1980s.	
SC41M	C	1	Mar-16	n/a	Healthy	Strongly variable growth. No evidence of decline in ring widths.	
SC42M	C	1	Mar-16	n/a	Healthy	Normal growth. Gap in chronology rings too narrow to measure 1980s to 2002.	
SC43M	C	1	Mar-16	n/a	Healthy	Strong, variable growth. Evidence of suppression from 1980s.	
SC45M	C	1	Mar-16	n/a	Healthy	Growth release 1890 then above average growth until 1907. Growth releases 1913 & 1943. Growth decline early 1990's but recovered with average growth to present.	
SC46M	C	1	Mar-16	n/a	Healthy	Above average growth until 1903. Growth release in 1922 then average growth until early 1970's. RW's more indicative of symptomatic tree.	
SC47M	C	1	Mar-16	n/a	Healthy	Above average growth until late 1940's. Growth release 1982 then sharp decline late 1990's Growth recovery to present.	
SC48M	C	1	Mar-16	n/a	Healthy	Average or above average growth for a control tree until mid-1970's. After the severe drought of 1976, ring widths drop to that of average symptomatic trees and from this point on never recover to the average control levels tracking closely that of average symptomatic trees until a recovery from 2009 almost reaching average control levels in 2014.	
SC49M	C	1	Mar-16	n/a	Healthy	Starts with below average growth for both symptomatic and control trees but after first ten years shows strong recovery. After 100 years responds well to favourable conditions with above average growth for a control tree. Particularly strong growth release in 2012.	
SC50M	C	1	Mar-16	n/a	Healthy	Growth depressions 1836 and 1857 but strong recoveries within 5 years in 1841 and 1862. Strong growth releases to peaks in 1913 and 1978 but drops to growth levels indicative of symptomatic trees in 1994. Very strong recovery to higher than average growth for a control tree in 2012.	
SC51M	C	1	Mar-16	n/a	Healthy	Average growth for a control tree until growth release 1910-1916. A sharp growth decline until 1920 then gradual recovery to average control growth and above by 1931. Growth decline as with control and symptomatic trees 1933-35 possibly due to caterpillar defoliation. Another decline 1940 as with other control & symptomatic, a January ice storm damaging many trees (Morris & Perring, 1974). Huge growth release to peak in 1944, decline in mid-1950's, again possibly due to caterpillar defoliation. With growth well above average for a control, peaks in 1973, 1991 and 2001	

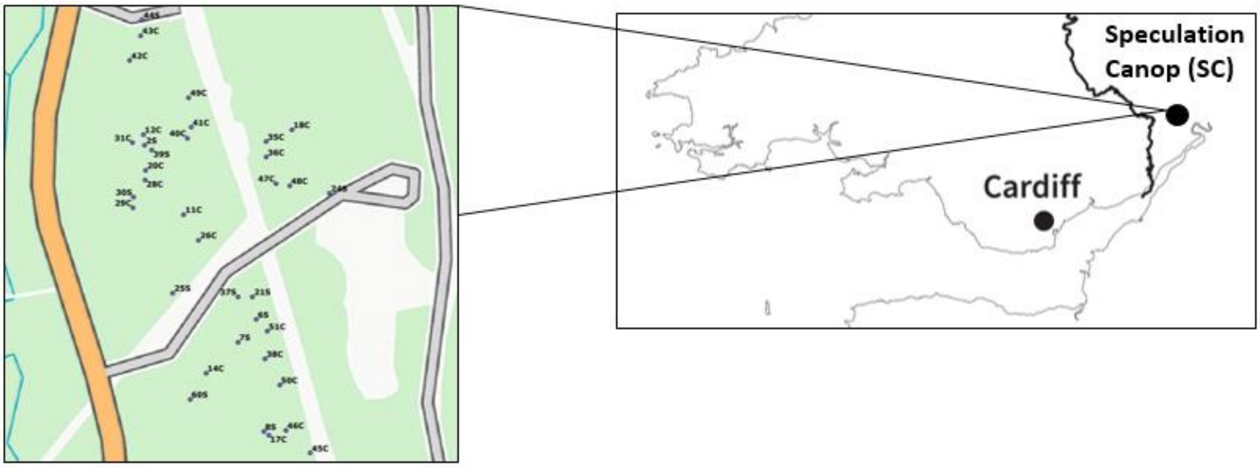


Figure 1: Location Map for the Speculation Cannop site. The Northern and Southern sections of the site are shown.

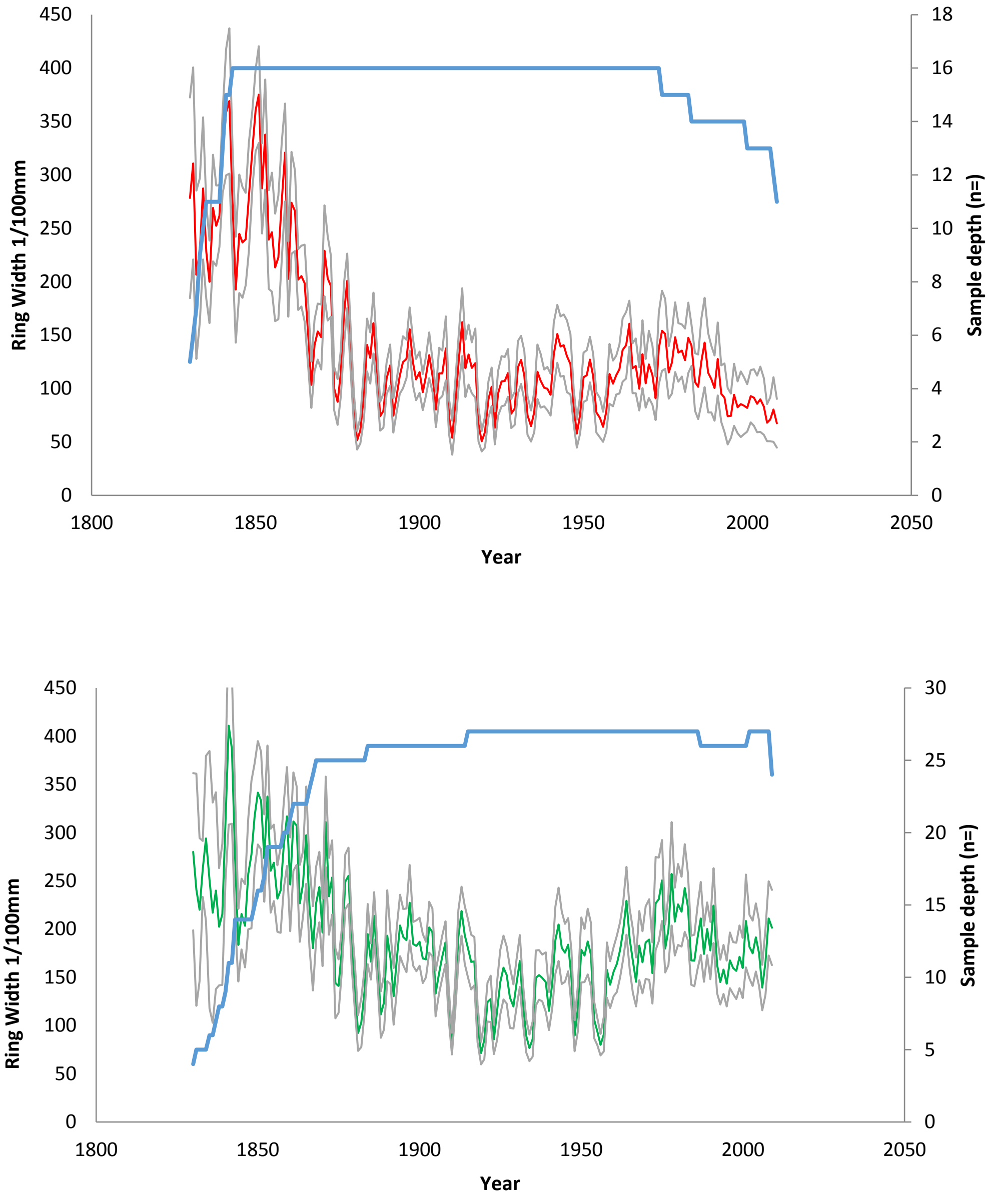


Figure 2. Speculation Cannop raw ring width measurements from trees with visible external COD symptoms. Top: symptomatic trees, n=15, red., and Bottom: control trees, green, n=24. Trees were sampled between 2009 and 2015. Confidence limits (95%) are shown in grey and changes in sample depth throughout the time series are indicated (blue)

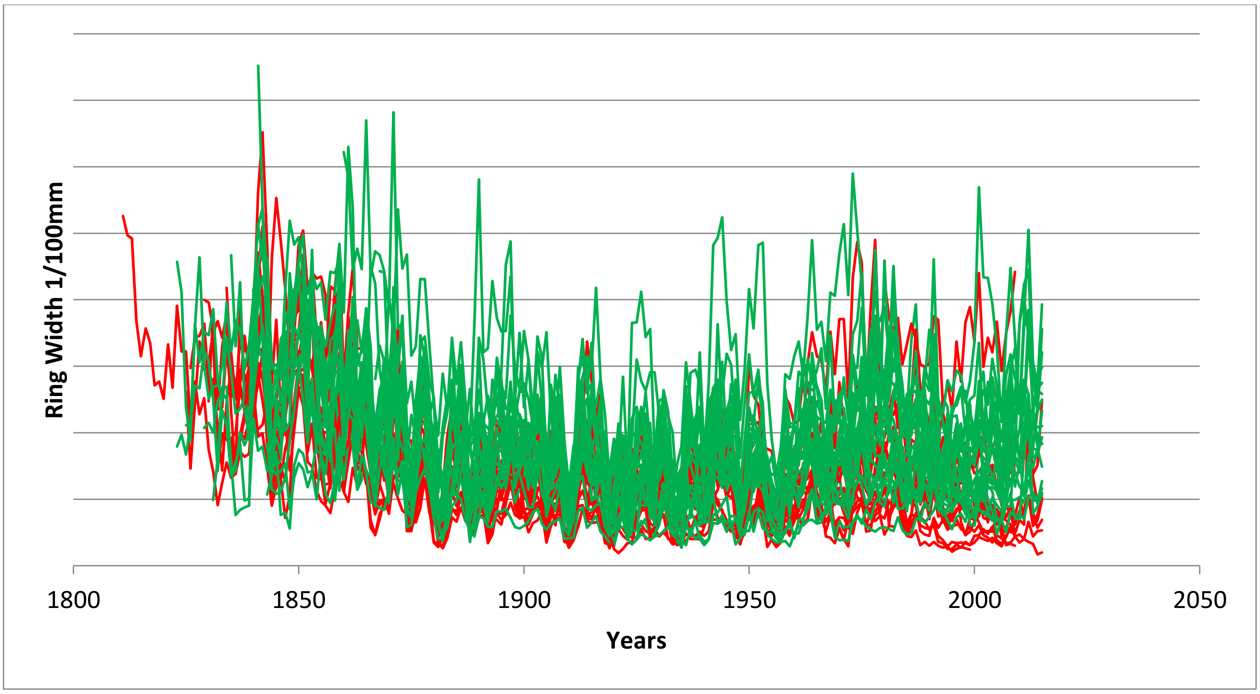
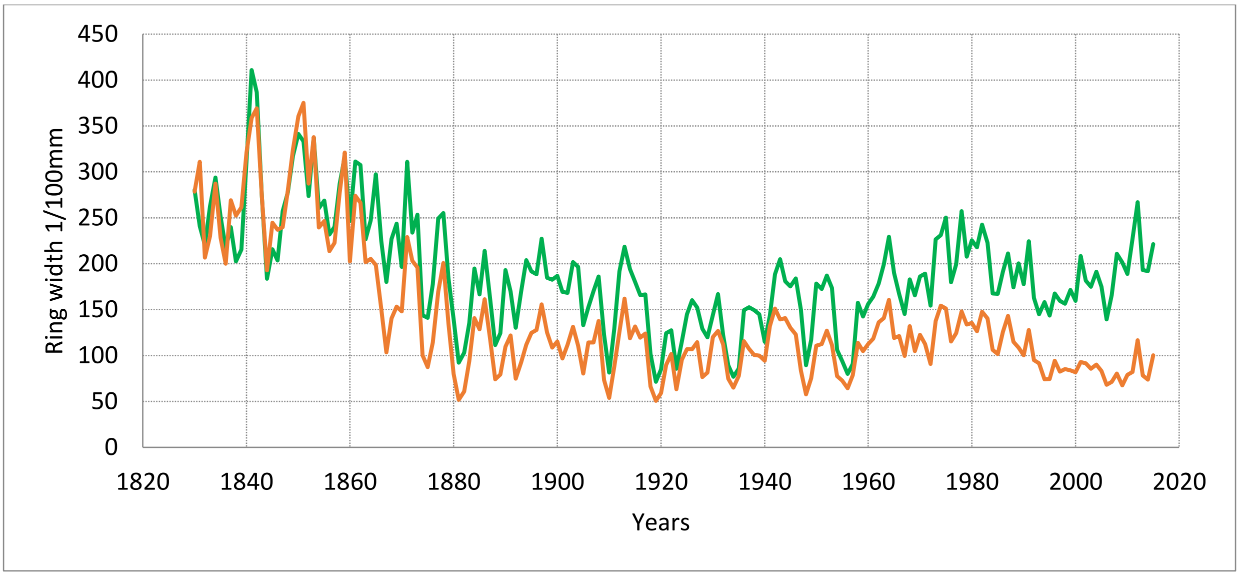
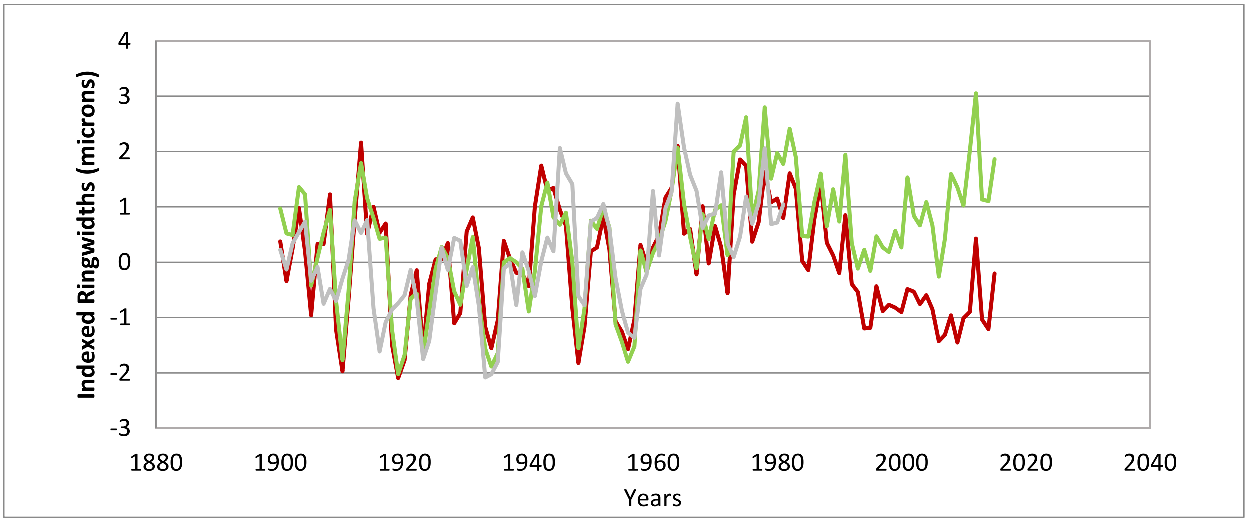


Figure 3 - The average ring width chronologies for the Control and Symptomatic trees. Control trees are indicated in green, Symptomatic trees in red. Ring width 1/100mm.



(a)



(b)

Figure 4 (a) Speculation Cannop raw ring width measurements from trees with visible external COD symptoms (symptomatic trees, n=15, red line) and those without (control trees, green line, n=24). Trees were sampled between 2009 and 2016. (b) Speculation Cannop average ring width series, control (green) and symptomatic (red) trees. Also shown is a regional master chronology (in Grey, Wilson et al 2013). Series are indexed raw ring widths (mm/100). Series are normalised to the period 1900-1970. The inter-annual correlations are strong and significant (symptomatic to control r = 0.84, symptomatic to Forest of Dean master chronology r = 0.54, control to Dean master chronology r = 0.72), all significant at $p<0.05$.

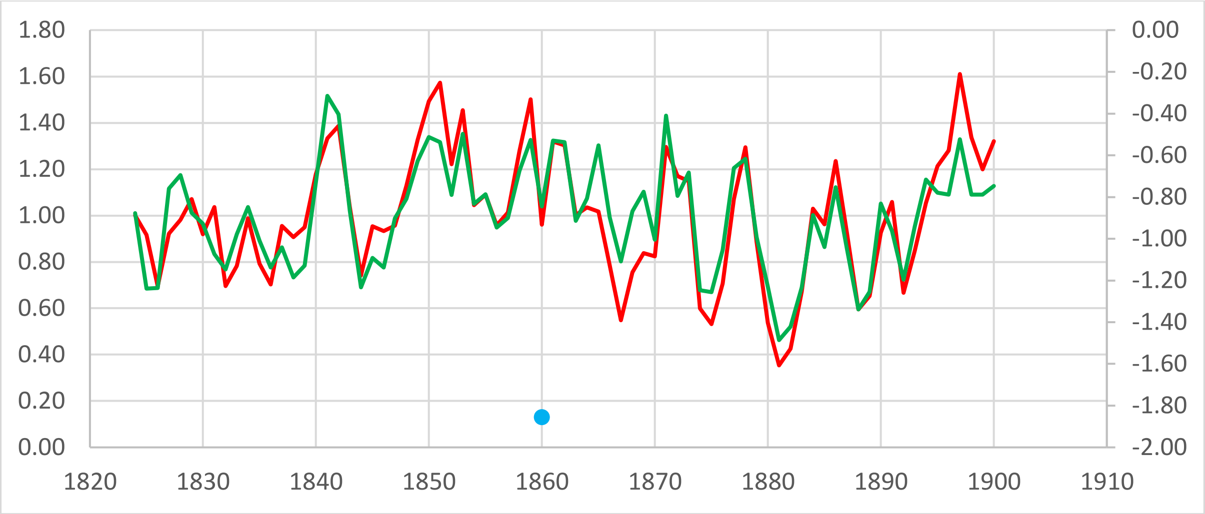


Figure 5. Indexed average ring width values for Control (green) and Symptomatic (red) trees at SC, the start of a phase of cool summers in 1860 is indicated, in comparison to the long-term average summer temperature (Central England Temperature, Parker et al 1992).

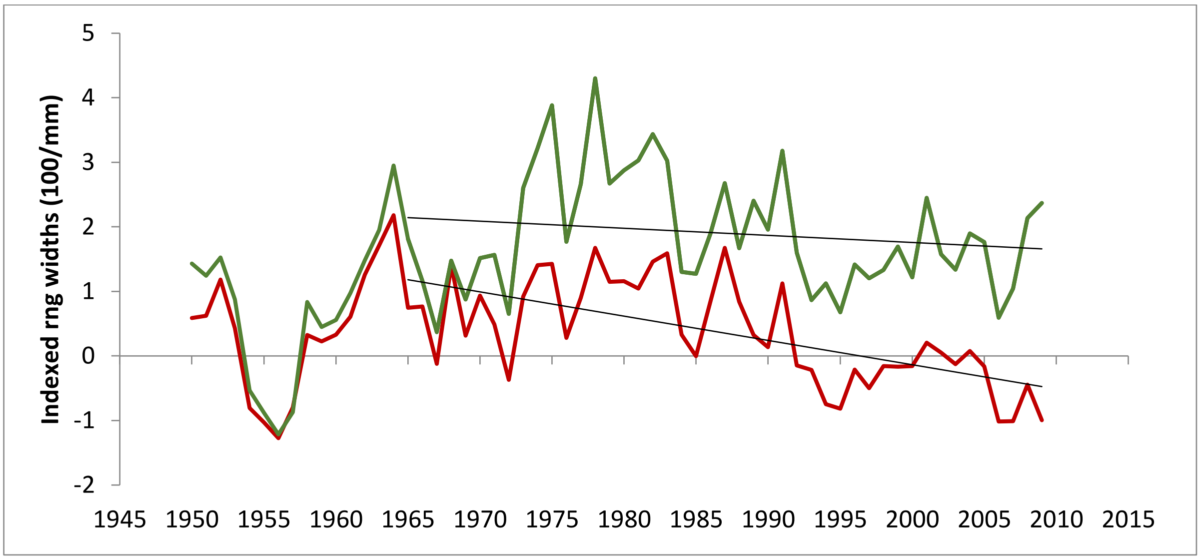


Figure 6. Normalised (AD 1900-1970) Control (green) and Symptomatic (red) raw ring width series averages. The linear trendline is plotted through the series after a divergence point around 1960.

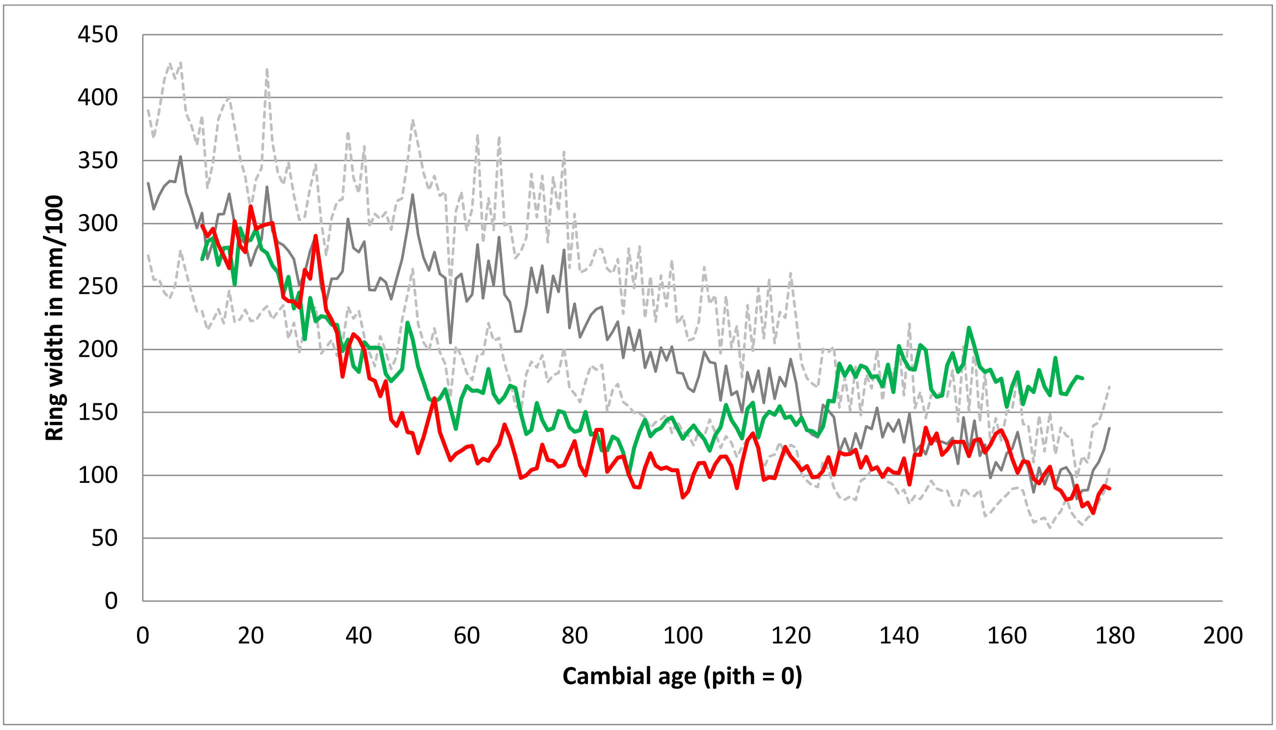


Figure 7. The control (green) and symptomatic (red) average ring width time series for Speculation Cannop and an average regional Forest of Dean ring width series from Wilson et al (2013) (grey with 95% confidence limits in grey dashed). Aligned by pith-estimated cambial age.

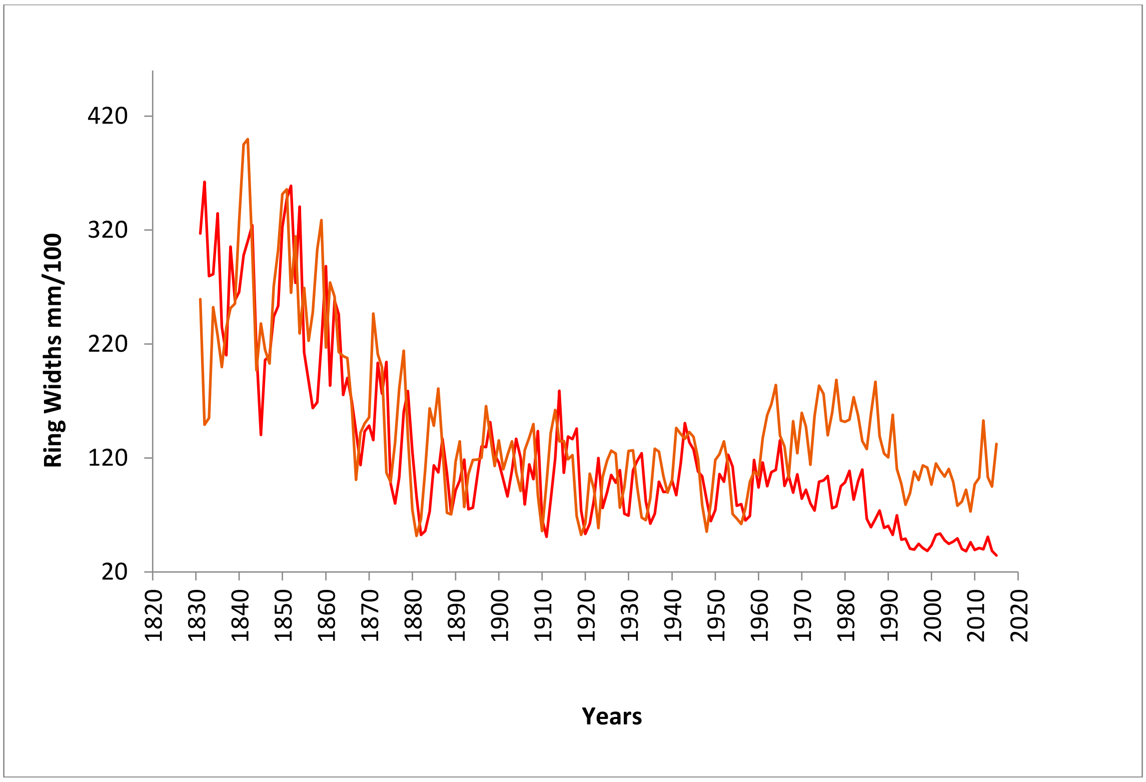


Figure 8. The average ring widths (mm/100) in trees with severe (red line) or moderate external decline symptoms (brown line) as evidenced in Table5.