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Dendrochronological assessment of British veteran sweet chestnut (*Castanea sativa*) trees: successful cross-matching, and cross-dating with British and French oak (*Quercus*) chronologies

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Dendrochronological assessment of British veteran sweet chestnut (*Castanea sativa*) trees: successful cross-matching, and cross-dating with British and French oak (*Quercus*) chronologies

Across Britain and continental Europe there are many ancient *Castanea sativa* trees of great significance for natural and cultural heritage, yet scant assessment has been made of them for dendrochronological information. This paper describes the dendrochronological analysis of 28 *Castanea sativa* trees (veteran historic trees, forest trees and coppice stems) sampled from 15 sites in southern Britain: 56 growth-ring sequences were collected for analysis, by boring living trees and by cutting transverse sections from dead fallen trees and previously cut stumps. Twenty-three single-tree sequences from 14 sites were cross-matched ($t \geq 3.5$) and then cross-dated with 17 oak *Quercus* reference chronologies from England and northern France: a *Castanea sativa* master chronology spanning AD 1660–2014 has been created. The results demonstrate the viability of dendrochronological analysis of *Castanea sativa* wood; and confirm that *Castanea sativa* can be cross-dated with oak *Quercus* reference chronologies, inter-regionally and inter-nationally. The findings provide the potential means for dating *Castanea sativa* timbers sampled from palaeoenvironmental and historical contexts. The extraction of sawn sections from long-dead (up to 60 years in this study) trees and stumps is proven to be a reliable method for dating veteran trees in cultural landscapes and ancient woodlands; and for revealing the growth history of historic/iconic trees. The germination dates calculated for the *Castanea sativa* trees in this study span the period AD 1640–1943. The inaccuracy of estimating veteran *Castanea sativa* tree ages from girth measurements is highlighted.

Keywords: sweet chestnut *Castanea sativa*; oak *Quercus robur/Q. petraea*; dendrochronology; veteran trees; cultural landscapes.

Declarations of interest: none.

1. Introduction

Castanea sativa is a tree species widely dispersed across western Eurasia (Conedera et al., 2016), but localised depending on favourable soil and climatic environments and natural and human-mediated colonisation. The history of *Castanea sativa* in Europe since the last glacial maximum (LGM) has been assessed, using pollen and palaeoenvironmental evidence (Huntley and Birks, 1983; Krebs et al., 2004); historical records (Conedera et al., 2004; Squatriti, 2013); and DNA analysis (Mattioni et al., 2013; Mattioni et al., 2017). These studies have distinguished some refugia locations, with indigenous *Castanea sativa* populations, from human-mediated, non-indigenous populations.

Castanea sativa has a long and diverse cultural history in Europe, so trees can take many forms: ancient pollards, high forest standards, multi-stemmed coppice stools, orchard trees and linear hedgerow trees, *inter alia*. The tree is highly valued for its commercial production of wood and nuts; and for its cultural values, for ecology, history and aesthetics. López-Sáez et al. (2017) and Roces-Díaz et al. (2018) have usefully summarized this background.
This research aims to investigate the application of dendrochronological analysis to the history of *Castanea sativa,* especially veteran trees, in Britain.

European dendrochronological context

Previous studies of *Castanea sativa* in continental Europe have concluded that the species is of variable suitability for use in dendrochronological studies: Romagnoli et al. (2004) were optimistic; Schweingruber (2012) was pessimistic. Various studies, *inter alia* by Donati et al. (1988), Fossati (1990), Pérez Antelo (1993), Fonti et al. (2006), Mirchev et al. (2009), Čufar et al. (2013), Domínguez-Delmás et al. (2013), Cuenca et al. (2014) and Čufar et al. (2014), have applied dendrochronological methods to *Castanea sativa* trees and historic timbers. The continental European research indicates that is feasible to establish growth-ring chronologies for *Castanea sativa*, subject to constraints caused by the wood structure: the tendency for radial and circular splits and the typically rapid growth rate that does not provide sufficient rings for dendrochronological analysis even in relatively large timbers.
Grissino-Mayer (1993) defined *Castanea sativa* (CASA)[1] as of 'minor importance' for dendrochronological studies, rating it with a 'CDI' (Cross-dating Index) Value of 1. Speer (2010) endorsed this rating.

British dendrochronological context

Britain has an important population of ancient *Castanea sativa* (sweet chestnut) trees (including coppice stools), dispersed across a wide range of significant cultural landscapes – historic parks and gardens, ancient woodlands, wood pastures and ancient boundaries. The Ancient Tree Inventory for the UK (Woodland Trust, 2018) lists over eleven hundred *Castanea sativa* trees of more than six metres girth, with the largest girthed trees of <13 metres. Sweet chestnut is conventionally described as non-indigenous in Britain (Godwin, 1975; Huntley and Birks, 1983; Preston et al., 2002; Rackham, 2006; Stace and Crawley, 2015): recent research (Jarman et al., unpublished results) has been unable to verify the evidence that had been used to justify its classification as a Roman archaeophyte. However – and whenever – *Castanea sativa* came to Britain, there is a conservation imperative to know more about the rare ancient tree stock, the origins and the history of *Castanea sativa*, not least because of the present threat from introduced chestnut blight *Cryphonectria parasitica* and other pathogens (Forestry Commission, 2018).

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[1] 'CASA' is the formal species code for *Castanea sativa* used by the International Tree Ring Data Bank (ITRDB).

In Britain, only thirty finds of alleged *Castanea sativa* wood/charcoal have been recorded in prehistoric and historic contexts up to AD 650 (Jarman et al., unpublished results): of these, only two finds appear to have been dendrologically assessed (Nayling, 1991; Museum of London Archaeology, 2011) and neither had sufficient growth rings for dendrochronological analysis. Hillam (1998) states >50 rings are necessary, whilst other researchers (Domínguez-Delmás et al., 2013; Fowler and Bridge, 2017) recommend >70. Searches for reported finds of *Castanea sativa* wood in Britain post-dating AD 650 have revealed only two: Hillam (1985) reported finds from the late 16th–early 17th century AD; and Groves (1993) discussed finds from the late 18th–early 19th century AD. None of the specimens they reported had sufficient rings (>50) for dendrochronological studies.

There are no records for any British *Castanea sativa* (CASA) data in the International Tree Ring Data Base (ITRDB, 2018): the only CASA datasets there are from studies in Switzerland by Braker, Conedera and Fonti.

The only study of *Castanea sativa* dendrochronology in Britain before the present research seems to be that of Bridge et al. (1996), who cross-matched a group of oak, hickory, chestnut and beech specimens sampled at Kew (Cutler et al. 1993); only a single specimen of *Castanea sativa*, with 98 growth rings, was recorded.

Research objectives

The primary objective of this research was to test a method for dating veteran trees and historic timbers of *Castanea sativa* in Britain. This research would include an assessment of the suitability of *Castanea sativa* for cross-matching and cross-dating, by reference to oak *Quercus*[2] chronologies and dendroclimatological assessment. The secondary objective was to determine precise germination dates and management histories for some of the historic and iconic veteran *Castanea sativa* trees in Britain, in association with separate research into the origins of *Castanea sativa* in Britain and Ireland.

2. Methods

A preliminary study was undertaken in 2014–16 (Jarman et al., 2017): one dead and seven living *Castanea sativa* trees were sampled from five sites in the west of England (Gloucestershire and Herefordshire). That preliminary study proved successful, so an extended collection of timber sections was undertaken during 2016–17 in selected historic sites across southern Britain (south-west, west, central and south-east England and south-east Wales.

Living *Castanea sativa* trees were sampled using increment borers. Dead wood was sampled by cutting transverse radial or whole round disc sections from deadwood components of fallen trunks and major limbs and previously cut stumps. Standing deadwood components of living trees were not sampled.

Analysis of growth-rings was undertaken, to produce precise ring counts for tree sections and to create measured growth-ring sequences for *Castanea sativa*. These were compared with

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[2] In this paper '*Quercus*' means *Quercus robur* and/or *Quercus petraea*; when another species of *Quercus* is being referred to, it will be specified. 'QUPE' and 'QURO' are the formal species codes for *Quercus petraea* and *Quercus robur*, respectively, used by the International Tree Ring Data Bank (ITRDB).

dendrochronological reference sequences for oak *Quercus*, to test for similarity of growthring sequences between *Castanea sativa* and *Quercus*.

Site selection

A range of potential study sites across southern Britain was examined, to find ancient and mature *Castanea sativa* trees and coppice-grown stems suitable for sampling. Fifteen sites were selected and permission to bore or cut sections from living trees and fallen deadwood was received from the site owners.

Sampling and sample preparation

Living trees were cored using 5.15 mm diameter (660 mm length) or 12 mm diameter (900 mm length) Haglöf increment borers. Core samples were taken at 1.3–1.5 metres up from the soil level whenever practicable. Tree girth was measured at the point of sampling. Extracted cores were glued to wooden laths on-site and stored so as to reduce shrinkage before analysis. Boreholes were left open after removal of the borer and not sealed (Grissino-Mayer, 2003). Fallen dead trees and deadwood components were sampled using chain saws with a cutting bar of <1.2 metres (4 feet) length. Sections for cutting were selected from trunk segments as close as possible to 1.3–1.5 m above the soil level, when upright. Where basal trunk sections were not available (owing to poor timber quality or missing tree components), large upper trunk and main bough sections were sampled. More than one sample was collected from each tree, where possible from different aspects of the tree to test the reliability of synchronous growth and potential for cross-matching, generating a mean growth-ring sequence for the tree. At one site a previously sawn (~AD 1970) dead stump was re-cut to provide a clean (undecayed) sampling face for sectioning. Sections were sawn out of large dead roundwood segments as transverse rectangular blocks (using plunge cuts with the chainsaw) or as quarter-round wedges; or were cut from smaller roundwood as complete circular discs. Sections were selected to incorporate pith-to-bark growth-ring sequences whenever possible and to avoid knots, decay, cavities and shake. Exploratory cutting was used to test the integrity of the selected wood and to avoid asymmetric growth or wood defects. The position (height above soil level and trunk aspect) of each section as it would have been on the original upstanding tree was calculated, considering the possible rotation of the falling tree; and the tree girth at the point of sampling was recorded.

The large timber pieces were removed to the laboratory and one or more sample sections marked out to include bark, sapwood:heartwood boundary and pith, avoiding defects and asymmetric growth wherever possible. A 50x25 mm wooden batten was glued and screwed to the desired radial section and a 60x60x60 mm triangular wedge cut out of the section, using a 210 mm diameter circular saw with a fine-toothed blade. Most of the large-dimensioned sections were sampled by cutting out two or more radial sub-sections, to represent different growing points or orientations on the original upstanding tree, and combined into a mean growth-ring sequence for the tree.

The upper faces of the wedge and core sections were power-planed and/or sanded to produce a flat surface perpendicular to the grain suitable for microscope stage analysis. All growth-ring sections were sanded with progressively finer gritpapers up to 400 grit, to enable precise ring observation and microscopic measurement of ring widths.

Measuring and cross-matching

Standard dendrochronological techniques were used for sample preparation, measurement, cross-matching and dating (Hillam, 1998). Growth-ring sequences were measured using a

×20 stereomicroscope with a microcomputer-based travelling stage, to an accuracy of 0.01 mm. Each sample was measured twice, from the centremost (closest to pith) ring to the outermost (closest to bark) ring. Growth-ring analysis was undertaken using Dendro for Windows programme (Tyers, 1999).

The growth-ring measurements from each sample were visually plotted to identify cross-matches and eliminate errors. Where sequences visually cross-matched satisfactorily at the appropriate offset, they were averaged for use in the subsequent analysis. Statistical cross-correlation algorithms were used to search for growth-ring sequence correlations (Baillie and Pilcher, 1973) to produce *t* values[3]*:* where $t \geq 3.5$ and >50 growth-rings are measured, the correlation is deemed statistically significant (Baillie, 1982). Fowler and Bridge (2017) reviewed the statistical viability of Baillie's '$t = 3.5$ rule of thumb' method and concluded that a *t* value of 3.5 would provide 99.9% confidence of acceptable matching positions if >70 growth-rings were present in the measured sequence. For sequences between 50 and 70 growth-rings, $t \geq 3.5$ would provide a confidence level of ~99.84%. Ideally, to achieve 99.9% confidence of a matching position, a sequence ≥70 rings with $t \geq 3.7$ is required.

Growth rate and mean sensitivity

Tree growth-ring sequences typically contain life-cycle trends, reflecting the general reduction in growth-ring widths as trees progressively age, termed 'formative', 'mature' and 'senescent' phases of growth (White, 1998). For visual comparison of tree growth rates, cumulative plots were produced to indicate growth trends. Trees are presumed to be in decline where consecutive decades have mean growth of ≤0.50 mm/yr (White, 1998): a decadal growth rate of ≤2.00 mm/yr was used to identify the onset of senescent growth for *Castanea sativa*.

Mean sensitivity is a measure of the mean relative change between adjacent ring-widths (Fritts, 1976). Sensitivity analysis was undertaken to test the responsiveness of *Castanea sativa* to climatic and environmental growth signals and to assess *Castanea sativa* for its suitability for cross-matching and cross-dating purposes.

Determination of Germination Date

The centre-of-tree (pith) date obtained by sampling at a height above the ground may not represent the absolute age of the tree (Telewski and Lynch, 1991). In the present study, five years were added to the measured age to account for the period between germination and tree growth where sampling heights were <1.3 m. above the soil level; and ten years were added to the measured age where sampling heights were ≥1.3 m.

Where sampled sections came close to the pith but did not include the innermost rings, the number of missing rings to the pith was estimated using a transparent acetate sheet marked with concentric rings of uniform width to match the inner-most ring widths of the sample (Villalba and Veblen, 1997).

Where sections did not include interior portions of the tree, owing to loss of heartwood, then the number of missing rings (*N*) was calculated using the equation $N = (r - m) / w$ [where *r* is the pith-bark section radius, calculated from girth or diameter measurement ($r = girth/2\pi$); *m* is the width of the measured section of the radius, being the sum of all measured ring widths; *w* is the mean of all measured ring widths in that section]. This method of calculating missing

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[3] All references to *t* values in this paper refer to the Baillie and Pilcher *t* values.

rings works satisfactorily when the tree growth is symmetrical (the pith is relatively central in the stem) and when growth-ring widths in the measured section are representative of the entire radius.

Sapwood growth-rings were measured where present; and bark width was recorded. Where sapwood was absent, six years were added as a standard sapwood component to a sequence age (being the mean sapwood band recorded for the *Castanea sativa* trees in this study). Fonti et al. (2006), working in the southern Swiss Alps, found ~5 sapwood rings to be the norm for *Castanea sativa.*

3. Results

Fifty-six sections (9 bored, 47 sawn) were collected from 28 *Castanea sativa* trees in 15 geographically separate sites located across southern Britain. The sites represent living trees in ancient woodland and historic garden settings, from which cores were bored; and dead fallen trees or previously cut stumps in historic parkland, ancient woodland and historic boundary settings, from which sections were sawn.

Table 1 provides a summary list of sites: detailed site information is provided in S1.
Map 1 displays the site locations, labelled with their site numbers as provided in Table 1. A .kml file (S2) is provided, with GPS-referenced site locations.
[t] Table 1 [t]
[Supplementary file S1]
[t] Map 1 [t]
[File S2 .kml here]

The fifty-six collected sections were visually assessed and microscopically examined prior to preparing growth-ring sequences: 54 sections (96%) were readable and had ≥50 rings, so were retained for analysis. The fifty-four readable sections were assessed: the growth-ring measurements are provided in S3. The raw data will be archived in the ITRDB. The measured sequences included multiple samples from single trees, where several radial samples were cut from a sawn whole round transverse section, to compare growth-rings from different aspects of the same tree: these multiple samples were collated into single-tree mean sequences. Overall, 28 single-tree sequences were produced (S4).
[Supplementary file S3]
[Supplementary file S4]

Cross-matching of Castanea sativa trees

The twenty-eight single-tree sequences were tested for cross-matching between trees: 23 sequences were found to cross-match, with $t \geq 3.5$ (Table 2), representing 14 of the 15 sampled sites. All except 3 of these sequences contained ≥70 rings and all cross-matched at $t \geq 3.7$, meeting Fowler and Bridge (2017) 99.9% confidence levels. Five single-tree sequences remain to be cross-matched (those marked ‘unmatched’ in S3), but they were used to provide an estimated age for the sampled tree, quantified with measured growth-ring counts and information on the known last year of growth and the presence of bark and/or sapwood and/or pith.
[t] Table 2 [t]

Cross-matching structured by climatic zones in Britain

The sites for the 23 cross-matched *Castanea sativa* trees range from south-west England and south-east Wales through southern, central and south-east England. Table 2 shows the 23 cross-matched sequences ordered by their west to east location and also by Seed Zones (Forestry Commission, 2017), which might be considered as climatic ‘sub-regions’: four Seed Zones cover the 14 sites for the cross-matched trees.

Cross-dating of Castanea sativa trees with oak Quercus chronologies

The 23 cross-matched *Castanea sativa* single-tree sequences were individually compared with a library of oak *Quercus* reference chronologies: single-tree cross-dating *t* values were calculated, summarised in Table 2. Detailed cross-dating *t* values are given in S5: 21 ex 23 of the cross-matched sequences were cross-dated individually with oak *Quercus* chronologies with $t \geq 3.5$.
[Supplementary File S5]

For overall cross-dating purposes, the 23 single-tree *Castanea sativa* sequences were collated into a single master CASA chronology, labelled ‘CASA23’ (S6): this was cross-dated with 17 oak *Quercus* reference chronologies, selected from across England and northern France (Table 3), generating *t* values of 5.50–9.01. The timespan of the 23 cross-dated *Castanea sativa* sequences (AD 1660–2014) is presented in Fig. 1. The precise date range for each single-tree sequence, derived from cross-dating with the oak *Quercus* reference chronologies, is presented in Table 2.
[Supplementary File S6]
[t] Table 3 [t]
[Fig. 1 here]

Tree growth

Seventeen sections (29%) were recovered with full sapwood ring sequences: the mean number of sapwood rings was 5.53 (range 2–8 rings). Six years was set as the standard sapwood measure for the calculated ages of the sampled trees (where sapwood was missing or not measurable). The mean ring width from 54 measured sequences (including heartwood and sapwood) was 2.84 mm (range 0.71–6.50 mm). The mean ring width for the 23 cross-matched single-tree sequences was 3.13 mm. (range 1.65–5.64 mm), as shown in Table 2. The *Castanea sativa* trees in this study did not show distinct life-cycle growth phases; and symmetrical growth was the norm, with only two significantly asymmetrical sections recorded (SONE02, WSCP02). Cumulative growth-ring widths were plotted for the 23 cross-matchedsequences (Fig. 2).
[Fig. 2. here]
Analysis of the relationship of age to girth is presented in Fig. 3: the R_2 value for the linear trend coefficient of determination was determined as 0.53833.
[Fig. 3. here]

Mean sensitivity

The mean sensitivity values for the 23 cross-matched single-tree sequences are presented in Table 2: the overall mean sensitivity is 0.20 (range 0.14–0.29).

4. Discussion

Castanea sativa growth characteristics

Many of the sampled sections did not display the shake (star or concentric) or radial and circumferential splits often experienced with mature *Castanea sativa* wood (Everard and Christie, 1995; Spina and Romagnoli, 2010; Schweingruber, 2012): even sections with >150 rings had consistently uninterrupted growth-ring sequences.
Most of the sections did not display life-cycle growth phases and only a single, relatively

constant, growth rate was identified. This is useful information for analysis of *Castanea sativa* timbers, should they be found in archaeological/historic contexts, where typically small wood pieces with relatively few growth-rings do not provide much material for comparison with oak *Quercus* and for dendrochronological dating. These regular growth rates might arise because the sampled trees were predominantly from parkland/avenue environments, so not subject to the typical forest or coppice dynamics of canopy closure and competition from neighbours.

In addition to the regularity of growth, some sections were found to be uncommonly slow-grown, with growth-ring sequences consistently displaying mean ring-widths <3 mm: 13 ex 54 measured sections (24%) had mean ring-widths <2 mm (S3). Such slow growth could be considered uncharacteristic of *Castanea sativa* and be mistaken for the wood of oak *Quercus*, which is often slow grown. *Quercus* can also display the uniseriate medullary rays normally diagnostic of *Castanea* (not the multiseriate rays normally diagnostic of *Quercus*), as described by Schweingruber (1990), Hather (2000) and Jarman et al. (unpublished results). In contrast, Romagnoli et al. (2004) reported mean ring-width values for *Castanea sativa* of >8 mm and described broad ring-widths as a common characteristic of *Castanea*, citing other researchers (Cambini 1962; Génova and Gracia 1984; Donati et al., 1988).

The present study found that sapwood consistently formed narrow bands, typically of 5–7 rings (mean = 5.53), as also demonstrated by studies such as Fonti et al. (2006). Some of the sections examined were missing the sapwood element, but preserved a strong heartwood:sapwood boundary as the surviving outer face, so that determination of missing rings could confidently be presumed as six.

Many of the sections had well preserved heartwood, even to the pith. Pith was found in sections from dead trees known to have blown down in the AD 1987 storm in southern Britain (BESF02, WSHP01) and also in several trees known to have fallen before that date (BESU01, HRCC01, KEPE01, KEPE02, WALC02, WALC04), thereby containing dead wood that had survived undecayed on the ground for over 30 years. The presence of pith in these sections, cross-dated back even to AD 1660, indicates that living standing trees >250 years old may still possess pith even in their basal trunk sections. This might indicate that some living standing trees of this vintage still retain intact heartwood to the pith and are not, as might typically be presumed, rotted hollow.

The bough sections analyzed in this study were also of considerable antiquity, even >200 years old: they contributed as much useful information about the age of the tree – as a *terminus ante quem* – as if they had been extracted from basal trunk components. In some cases, the upper bough sections retained pith and were cross-dated older than the recovered sections from the lower trunk where inner rings were missing.

Many of the >500 veteran *Castanea sativa* trees observed in the course of this study (and the separate research project referred to in the Introduction) displayed stubs of previously sawn off major boughs in low parts of trees: growth-ring counts of some of these stubs *in situ* estimated >250 rings and many retained pith–bark sections. These dead stubs may be a productive source of new sawn sections for dendrochronological analysis to add to the present study, without requiring labour-intensive cutting of major dead tree sections and with minimal impact on the standing living tree.

The age:girth ratio

The age:girth ratio established from the 23 cross-matched samples is illustrated in Fig. 3. The linear relationship drawn appears valid up to *circa* 200 years of age: thereafter the relationship is poorly linear and incorporates considerable variation, such that trees of 300–350 years age can have girths ranging between 3.5–9 metres. The slow rates of growth found in this study, even for 'middle-aged' trees, are unexpected for *Castanea sativa*: the implication is that veteran trees could be under-estimated in age, if dates are based on girth measurements alone.

Cross-matching

We have established a broadly replicated 355-year continuous chronology (AD 1660–2014) from 23 (ex 28 sampled = 82%) cross-matched *Castanea sativa* trees, labelled 'CASA23'. The 23 trees, drawn from 14 different sites, demonstrate effective cross-matching of *Castanea sativa* within and between sites in the same locality and also between regions across southern Britain (Table 2): the strong *t* values (following Fowler and Bridge, 2017) indicate the potential for constructing regional *Castanea sativa* chronologies. This provides a more optimistic outcome than the study by Romagnoli et al. (2004) of *Castanea sativa* in central Italy, which found poor cross-matching ('intra-specific synchronization') within 89 trees from 5 geospatially dispersed sites. Pezzo et al. (2014) constructed a *Castanea sativa* master chronology 456 years long (spanning AD 1557–2012), with 52 cross-matched sequences from 200 samples of wood from living trees and historic building timbers in Liguria, Italy.

Table 2 structures the 23 cross-matched sequences according to Seed Zones (Forestry Commission, 2018), interpreted here as climatic sub-regions, ranging from west to east across southern Britain. The cross-matching of 14 sites across 4 Seed Zones demonstrates the replicable sensitivity of *Castanea sativa* to macro-climatic signals at a broad regional scale – in this case, southern Britain – without too much interference from local (micro-climatic) signals. This appears to be supported by the growth-ring width data from the measured sections in Fig. 2 and Fig. 3, where there is no apparent differentiation of growth rates by geographical location, whether in western (wetter, cooler) or eastern (drier, warmer) sites.

The master chronology CASA23 (combining the 23 cross-matched *Castanea sativa* singletree sequences) has been cross-dated with 17 oak *Quercus* reference chronologies, drawn from across England and northern France (Table 3). The *t* values obtained (5.50–9.01) indicate significant matches for *Quercus* (Fowler and Bridge, 2017). This successful cross-dating indicates that oak *Quercus robur/Q. petraea* chronologies might be used as references for dating *Castanea sativa* sequences: both species evidently respond similarly to climatic signals across ecological/climatic regions and create directly comparable growth-ring sequences.

The cross-dating results indicate the potential for international cross-dating of *Castanea sativa* trees against oak *Quercus* chronologies, perhaps beyond the northern France sequences used here. Comparison with other continental European studies, which have successfully cross-dated *Castanea sativa* sequences with oak *Quercus* chronologies, is informative. For example, Pérez Antelo (1993) reported cross-dating of six oak (*Quercus robur, Q. petraea, Q pyrenaica*) sequences and one *Castanea sativa* sequence in Galicia, Spain and their synchronization with several British and Irish *Quercus* sequences; Romagnoli et al. (2004) reported cross-dating ('inter-specific synchronization') between *Castanea sativa* and oak (*Quercus cerris, Q. pubescens, Q. spp.)* for several sites in central Italy; and Mirchev et al. (2009) successfully cross-dated sixty *Castanea sativa* tree-ring sequences against oak

(*Quercus frainetto*) chronologies in SW Bulgaria. Čufar et al. (2013), working on timbers from the historic Ban's House at Artiče, Slovenia, and Čufar et al. (2014), working on timbers from Castle Pišece, Slovenia, cross-dated *Castanea sativa* against oak (*Quercus petraea, Q. robur, Q. cerris*) chronologies from the 17th–18th centuries AD.

Domínguez-Delmás et al. (2013) cross-matched two *Castanea sativa* planks from the 'Arade 1' shipwreck in Portugal to produce a mean curve (t = 4.74), which was cross-dated with six oak *Quercus* timbers from the same ship: a shipbuilding date of AD 1579–1583 was derived from the oak *Quercus* chronologies. The *Castanea* mean curve showed excellent matches (t >5.5) with local oak *Quercus* chronologies from the Pays de la Loire in W France and was taken to indicate this region as the probable source of the *Castanea* timbers.

Mean sensitivity and the Cross-Dating Index (CDI)

Grissino-Mayer (1993) presented the Cross-Dating Index (CDI) and defined the CDI Values: *Castanea sativa* was described as 'complacent', with a CDI of Value 1. A CDI of 1 means 'Species is known to cross-date between cores from the same tree as well as between trees from the same site (between-tree cross dating), representing a species useful for interpreting local site conditions'. A CDI of Value 2 means 'Species is known to cross-date between sites in a region (between-site cross dating), and represents a species of major importance in dendrochronology owing to a strong macroclimatic signal that will yield information on a regional scale'. Grissino-Mayer (2001) stated that 'low values for mean sensitivity would range between 0.10–0.19, intermediate values between 0.20–0.29, while sensitive measurement series would be represented by values above 0.30'; this was stated in the context of 'high values are desirable for both standard deviation and mean sensitivity'.

Speer (2010) explained how the sensitivity measure can be used to define a species as 'complacent' or 'sensitive': a mean sensitivity of 0.1 is too complacent to allow dating, whereas a mean sensitivity >0.4 is too sensitive to date, owing to frequent micro or absent rings next to very wide rings. A mean sensitivity of c. 0.2 is preferred for climate reconstruction applications. In the present study, mean sensitivity for *Castanea sativa* has been calculated as 0.20 (Table 2): following Speer (2010), we suggest that a description of *Castanea sativa* as 'sensitive' might be appropriate, with a CDI (Cross-dating Index) of Value 2. The successful cross-matching of *Castanea sativa* across 23 trees and 14 sites and cross-dating of the CASA23 master chronology with 17 oak *Quercus* reference chronologies, across a broad geographical range in southern Britain and northern France, are offered in evidence.

The method of extracting growth-ring sequences by sawn sections from dead trees

The use of sawn sections from dead components of fallen trees has provided viable growth-ring sequences and indicates the predictability of this method compared with cores bored from living trees.

There is great potential for further assessment of the dendrochronological potential of *Castanea sativa*, through examination of the deadwood 'archive' that survives in many historic/cultural sites across Britain, Ireland and continental Europe. This study has shown that dead tree components and stumps that have been dead on the ground even for 50 years can provide viable sawn sections, including pith to sapwood sequences. The selective exposure of the internal tree structure, by low intervention trial cutting, enables the collection of optimal components for analysis; and it reduces the risks inherent in deep boring and of sampling non-measurable sections owing to heartwood rot, edge erosion of sapwood, contortion and shake. The dead stubs of major boughs of standing living trees, often observed in British veteran trees, might provide a convenient accessible resource for harvesting growth-ring sequences of >200 years, with minimal impact on the standing tree and its environs.

Application of the findings to historic timbers

There are no confirmed reports of *Castanea sativa* timbers (apart from small roundwood) found in building structures in Britain, although the literature over several centuries carries various allegations (and refutations) of historic buildings containing *Castanea sativa* timbers, most apparently owing to confusion with *Quercus* (*inter alia* Ducarel, 1771; Loudon, 1838; Rackham, 2003). Several studies in continental Europe, where the use of *Castanea sativa* timbers in construction has been locally practised for many centuries, have successfully sampled *Castanea sativa* wood (beams and boards) from historic buildings: these samples have been cross-matched with samples from living *Castanea sativa* trees (Pezzo et al., 2014) and also cross-dated with other species' chronologies (Čufar et al., 2013; Čufar et al., 2014). A potential study in England of historic building timbers of *Castanea sativa* might be conducted at Penshurst Place in Kent. Here, it is held that the roof of the Baron's Hall, known to have been constructed in ~AD 1341, contains the original roof timbers including sweet chestnut *Castanea sativa* (Kent County Council, 2018). There is no record of any specific timber assessment for this building: the present study has confirmed that *Castanea sativa* trees were growing in Penshurst Place park in AD 1650; and other historical records evince their presence even before that, suggesting that an assessment of the roof timbers in the Hall could be rewarding.

The main constraint with assessing wood specimens in archaeological and palaeoenvironmental contexts is the typically small size of the fragments, with fewer than 50 growth rings, which prohibits standard dendrochronological measures. Fowler and Bridge (2017) discussed the potential to work with t values <3.5 and with low sample depths. Complimentary techniques such as 'wiggle matching' can broaden the range of acceptable samples (Gamberti et al., 2004).

Finally, it is worth emphasising that *Castanea sativa* does not often appear in building/dendrochronological reports – some surveyors might not sample non-oak *Quercus* timbers and may not therefore report their presence in the archive. This study has confirmed that non-oak timbers can provide invaluable information for archaeological, historical and ecological research.

Relevance to conservation of Castanea sativa in Britain and continental Europe

In general terms, this dendrochronological study has provided a cluster of *Castanea sativa* tree germination dates from the 17th century AD, possibly evincing the vogue of that period for planting trees symbolic of continental Europe. The planting of *Castanea sativa* was keenly promoted in Britain by John Evelyn, who first presented his *Sylva* in 1662 (Evelyn, 1664) and published its Fourth Edition in 1706 (Evelyn, 1706).

The dendrochronological analysis presented here provides for the first time accurate ages for key veteran British *Castanea sativa* trees; it also confirms the potential for using oak *Quercus* reference chronologies to accurately date *Castanea sativa* wood found in palaeoenvironmental and archaeological excavations and historic structures, should it be discovered and be measurable. Such information could enable the earliest presence of *Castanea sativa* in Britain since the last ice age (LGM) to be more clearly defined (Jarman et al. forthcoming).

The conservation of *Castanea sativa* can be motivated by better information on the antiquity and cultural history of veteran trees and their contextual landscapes. Some of the ancient *Castanea sativa* trees and stools across western Eurasia can be proven to be many hundreds of years old, indicating a long continuity of certain cultural landscapes that inspires respect.

5. Conclusions

A master chronology for sweet chestnut *Castanea sativa*, spanning AD 1660–2014, has been successfully developed from 23 veteran trees in 14 sites of historic landscapes and ancient woodland across southern Britain. This chronology has been cross-dated with 17 oak *Quercus* reference chronologies from southern Britain and northern France: it should be possible to date *Castanea sativa* wood recovered from archaeological and historical contexts in southern Britain by comparison with oak *Quercus* reference chronologies.

The method of sampling trees for dendrochronological information by cutting sawn sections from veteran tree deadwood components has proved successful, even from timber sections >250 years old that have been dead for 50 years and lying on the ground. The discovery of well-preserved *Castanea sativa* heartwood also including pith and sapwood decades after tree death is remarkable.

The dense growth-rings found in this study indicate that even small *Castanea sativa* wood sections can display a sufficient number of rings for dendrochronological analysis. Confusion with typically slow grown oak *Quercus* wood may be problematic, especially given the habit of *Quercus* sections displaying uniseriate medullary rays normally diagnostic of *Castanea*.

The study has quantified the age and historical status of certain trees and their cultural landscapes in southern Britain and verified some previous assessments of their ages and origins. The age:girth ratio for *Castanea sativa* has been shown to be quite unpredictable, such that trees measured as 300–350 years old had girth measurements ranging from 3.5–9 metres: this has implications for the age estimates presently allocated to many veteran *Castanea sativa* trees.

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