**Multi-Parameter Crossdating for Sub-fossil and Historical Samples**

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**Abstract**

Crossdating of sub-fossil or historical samples almost exclusively involves the use of a single tree-ring (TR) parameters such as ring-width (RW), Blue Intensity (BI) or stable isotopes. This paper details a new method that combines the information from multiple TR parameters – in this case specifically using RW, earlywood BI and latewood BI. The approach builds on standard approaches where sliding correlations are used to identify the position of maximal correlation to denote the correct temporal date. For the multi-parameter dating approach, the time-series of these sliding correlations are averaged to maximise the common correct highest correlation temporal position while minimising spurious correlations that individual parameter may express. The correlation time-series for the individual parameters as well as their average (the COMBO variant) are further transformed to t-values with the degrees of freedom being adjusted lower by considering the autocorrelation structure of the Reference and Undated chronologies while the inter-correlation of the parameter chronologies is further used to adjust the COMBO degrees of freedom. The COMBO method shows great promise for combining information from individual parameter chronologies (single or multiple timbers) that may express a relatively weak signal and also for the dating of shorter sequenced samples.

1. **Introduction**

The underlying foundation of dendrochronology is crossdating (Douglass 1941) – a dating technique that pattern matches narrow and wide rings (or other ring anatomical structures) between tree-ring samples of the same species from roughly the same region to assign correct calendar dates to annual rings. Crossdating relies on the fact that the growth of trees is consistently controlled by similar environmental forcing (i.e. climate) within a region. Qualitative visual approaches to crossdating using skeleton plots (Douglass 1941, Stokes and Smiley 1968) or pointer years (Schweingruber et al. 1990) are effective, especially with living trees, but are arguably cumbersome approaches for large groups of samples especially if working with historical or sub-fossil samples and trying to push living data-sets back in time. Quantitative methods, essentially relying on cross-correlation analysis, allow for the intercomparison of large numbers of samples. There is a long history of correlation-based computational methods for tree-ring dating to assign the rings of samples to an exact calendar date (Baillie and Pilcher 1973, Holmes 1983, Wigley et al. 1987; Bunn 2010; Loader et al. 2019; Reynolds et al. 2021). For all these approaches, the method essentially compares an undated tree-ring series (single tree series or a composite average of multiple) by “sliding” it against a dated master reference chronology to find the position of maximum positive correlation. This peak correlation represents the potential correct temporal position of the undated tree-ring series. A perhaps more Eurocentric addition to cross-correlation based crossdating is that the correlation values are transformed onto the T-distribution using equation [1] to provide an estimate of the significance of the identified date (Baillie and Pilcher 1973). A 't-value' of 3.5 is generally accepted as a minimum threshold to denote a correct date.

[1]

Over the past 50 years, however, the original t-value approach of Baillie and Pilcher (1973) has been refined, including considering the impact of different detrending methods, accounting for multiplicity, and adjustment of the degrees of freedom due to series autocorrelation. These advances have led to more robust estimates of both the t-value and, perhaps more importantly, defining a specific 'p-value' for the identified date (Munro 1984; Wigley et al. 1987; Fowler et al. 2017; Flower and Bridge 2017; Loader et al. 2019). However, all of these methodological approaches and refinements follow the same basic methodology – comparison of an undated series with a dated reference series using only a ***single tree-ring parameter***.

There is now a large range of variables that can be routinely measured from the rings of trees, including width, stable isotopes, multiple wood anatomical properties, and density (McCarroll et al., 2002; McCarroll and Loader, 2004; Drew et al., 2012; von Arx et al., 2016; Björklund et al., 2020). Many of these parameters express different but spatially coherent signals and the combined information from multiple parameters will likely improve the ability of attaining a correct date for a specific sample or a group of samples. Although many of these ring variables require specialist expensive equipment and training, Blue Intensity (BI, Björklund et al., 2024) is a substantially cheaper and quicker method for deriving relative wood density information. BI is essentially a method for the masses, and although it may suffer from sample discolouration issues (e.g. heartwood/sapwood changes and fungal staining) which can impact low frequency trends, a potentially serious problem for dendroclimatic studies, such colour trend biases will have little influence on sub-fossil or historical sample dating as they can be removed via detrending and the dating is performed on the high frequency signal.

Wilson et al. (2017) introduced the utility of using latewood Blue Intensity (LWBI, Björklund et al. 2024) to enhance the ability of attaining a correct date for historical structures constructed using Scots pine timbers in Scotland. This work developed from the substantial subfossil sample dating work undertaken in the Scottish Highlands (Wilson et al. 2012; Rydval et al. 2017) where it quickly became clear that the confidence for dating samples increased substantially with the use of LWBI. Several other studies have also shown the utility of LWBI for archaeological dating (Mills et al., 2017; Myglan et al., 2018; Akhmetzyanov et al. 2020).

The success of LWBI for dating simply reflects the “cleaner” climate signal, and strong spatial coherence expressed by LWBI measured from higher elevation pine trees in Scotland – generally July-August temperatures – while RW expresses an amalgam of multiple environmental signals as well as a generally weaker temperature response (Wilson et al. 2012; Rydval et al. 2014; Mifsud et al. *subm*). Rydval et al. (2018) further showed that LWBI, measured from spruce trees in the Carpathians, expressed minimal or no deleterious effects of site-specific disturbance that can often be strongly expressed in RW data. The same observations can be shown for Scotland as well, and such site-specific signals can lead to poor or inconclusive dating results for samples covering such disturbance periods using RW data alone (Mills and Crone, 2012). It is therefore no surprise that LWBI can provide a robust parameter for dating both sub-fossil and historical material.

A rarely used tree-ring parameter in dendrochronology is minimum earlywood density (MND), likely because maximum latewood density (MXD) has been such an important variable for dendroclimatic reconstruction of summer temperatures over the last 30 years (Briffa et al. 1992; Schneider et al. 2015; Wilson et al. 2016). Across the Northern Hemisphere, MND appears to show a consistent positive response to late winter/early spring temperatures (Björklund et al. 2017) which, although weaker than the late summer response expressed in MXD, is notably consistent between sites. Within North-West Europe, Earlywood Blue Intensity (EWBI, Björklund et al. 2024), the BI equivalent of MND, has been shown to express a late winter/early spring temperature response. Using Scots pine trees in southern Sweden, the EWBI temperature response is expressed in March-April (Seftigen et al. 2020) while the signal is earlier in Scotland for February-March (Mifsud et al. subm). What is of note, however, is that where the July-August temperature response fades as one moves away from upper treeline (loss in temperature limitation towards lower elevations), the temperature response expressed by EWBI, although weaker, is essentially consistent from high to low elevations (Mifsud et al. subm). This consistency in elevational response may allow the dating of low elevation pine historical samples using high elevation reference chronologies. This phenomenon needs further exploration, but for the analyses presented here, EWBI provides a further new variable that can be employed for historical dating.

The explosion in the use of BI in dendrochronology in recent years (Kaczka and Wilson 2021) and the ability to generate several tree-ring variables (e.g. RW, EWBI, LWBI) cheaply and quickly, provides a huge opportunity for dating sub-fossil and historical samples as they provide mutually independent information. Although, several examples of multi-parameter dating have been published (Wilson et al, 2017, Mills et al. 2017, Römer et al. 2023), they all utilised traditional methods performing the dating individually for each parameter and comparing the results. This is computationally inefficient and, when working with large numbers of samples, rather time consuming. This paper introduces the concept and theory of a new approach to multi-parameter dating by utilising the combined information from several tree-ring parameters – in this case RW, EWBI and LWBI - to enhance the ability to robustly date sub-fossil and historical samples.

1. **Data**

To introduce multi-parameter crossdating, data from two living test sites are compared with an independent regional reference chronology. All datasets are located in the Cairngorm region of the Scottish Highlands (Figure 1). The reference chronology (NCairn – Northern Cairngorms) used for dating experiments is constructed from a mix of living trees and dated sub-fossil material from three lakes - Loch Gamnha (LGN), Loch an Eileen (LEI) and Greenloch (GRN)) - ranging in elevation from 260-480 m.a.s.l. NCairn was used to reconstruct summer temperatures back to 1200 AD (Rydval et al. 2017) as well as the regional dating reference chronology in Wilson et al (2017). A modified version of NCairn is used herein, using only living trees from around the three lakes where sub-fossil samples were extracted. Further, the sub-fossil samples for this region have been redated using the multi-parameter dating methods detailed herein and so at this time, the pre 1700 period replication of the current version is lower to that used in Rydval et al. (2017) and Wilson et al. (2017) as the reference chronology is still being “re-built”. The period covered by NCairn is 1093-2017 with 541 RW series and 457 EWBI/LWBI series. The higher number of RW series represents that BI has not been measured from all living samples.

The two living test sites are 19th century plantation pine woodlands (Loch Coldair (LCL) and Loch Garten (LGL)) that are located outside of the NCairn reference chronology region (Figure 1). LCL is at a similar elevation (310 m.a.s.l.) to the NCairn reference chronology but is located about 30 km to the south-west. LGL is located ca. 5 km to the north of the NCairn reference region but is situated at a slightly lower elevation (240 m.a.s.l.). From each of these two test woodlands, data from 6 random trees were extracted and the outer portions truncated to reduce the mean sample length to about 80-90 years. These subset-chronologies with low replication and short sample lengths represent a typical assemblage of many historical sample collections dated in Scotland (Wilson et al. 2017; Mills et al. 2017). The truncated end dates for these two test sites are 1950 (MSL = 85 years) and 1965 (MSL = 84 years) respectively for LCL and LGL (See Table S1 – supplementary 1).

1. **Method – multi-parameter dating - multiXdateR**

The R-script code (beta version) for the multi-parameter dating method – multiXdateR - is available at XXX and the theory is introduced here while the code user manual description is detailed in Supplementary 2. For NCairn and the two test sites (LCL and LGL), RW, EWBI and LWBI were generated using standard methodologies using CooRecorder/CDendro (Rydval et al. 2014; Maxwell and Larsson 2021; Heeter et al. 2022). For the purposes of introducing the multi-parameter dating method, all TR series were detrended using a flexible 31-year cubic smooth spline (via division) with a frequency cut-off of 50% (Cook and Peters 1981). Pre-whitened, so-called “residual”, chronology variants were used to minimise the impact of autocorrelation on the degrees of freedom in the t-value calculation (equation 1), while the Spearman’s correlation was used for inter-chronology comparison as it is less sensitive to outliers or potential heteroscedastic variance changes than the Pearson’s correlation. However, it should be noted that the code allows for different spline windows for detrending as well use either Spearman’s or Pearson’s correlation (see Supplementary 2). Wigley et al. (1987) discussed the impact of using different digital filter lengths and concluded that no one specific filter window could be definitively assigned for optimising crossdating and stated that filter lengths between 10-50 years provided an optimal range. This observation likely reflects the variable mean length of the samples which imposes a systematic bias on the resolvable amount of low frequency one can capture from a chronology when using single series data adaptive detrending methods (Cook et al. 1995). As crossdating is generally performed on the high frequency signal extant in tree-ring series, a flexible spline with associated pre-whitening appears to be an optimal approach for data processing. The detrending code embedded in ‘multiXdateR’ utilised the dplR package (Bunn, 2008).

Finally, there is also an option to transform the pre-whitened tree-ring chronologies to 1st differences. This has implications for the autocorrelation structure of the chronologies (i.e. the autocorrelation will be strongly inverse – around -0.5) and will impact estimates of the t and p-values for any derived dates (see later discussion).

* 1. **Cross-correlation analysis**

Sliding correlations are calculated between the undated detrended tree-ring series and the reference chronology for each parameter (RW, EWBI and LWBI) and the 1st and 2nd highest positive correlation values highlighted in the graphical output. Another user defined option in ‘multiXdateR’ is to set the minimum overlap allowed between the undated series and the reference chronology which, for this example, is set to a rather low overlap of 30 years to highlight potential spurious correlations. This aspect of the code allows for the theoretical identification of a correct date beyond the start/end dates of a reference chronology.

Using the full 6-sample replicated chronologies for both test sites, the cross-correlation analysis against NCairn for each parameter show maximal correlations at 1950 (LCL – Figure 2; RW r = 0.53; EWBI r = 0.52; LWBI r = 0.74) and 1965 (LGL – Figure 3; RW r = 0.65; EWBI r = 0.54; LWBI r = 0.68 – see Table S2). If the strongest correlation represents the “true date”, the 2nd highest correlation values should essentially be random through time as they represent random spurious correlations. It is this consistency of the year of maximum correlation between the parameters which is the foundation of the multi-parameter approach to crossdating. However, these current results essentially follow the current standard computation approach to correlation-based crossdating as the results are presented individually for each parameter.

For the two test sites, the coincident common dates for maximal correlations (Figures 2 and 3) provide strong evidence that the same date has essentially been independently derived using three different parameters. Theoretically, therefore, if the individual parameter cross-correlation time-series are averaged together, the resultant combined mean correlation time-series will maximise the common peak of highest correlation (i.e. the correct date) and minimise the spurious random correlations. The resultant averaged correlation time-series, hereafter referred to as the ‘Combo’ approach, is shown in the lower plots of Figures 2 and 3. The overall variance of the correlation time-series is now much reduced compared to the individual parameter correlation time-series while the maximum correlation value is relatively accentuated. Even the rather noisy erratic correlations at each end of the sliding correlation time-series for each parameter, where the overlap goes down to 30 years, is substantially reduced in the Combo version. Clearly the maximum correlation values for these two Combo examples (Figure 2 and 3) are well outside the 4 standard deviation range of the correlation value distribution denoting high significance. The final step, therefore, is to transform these correlation values to t-values with appropriate robust p-value estimates.

* 1. **T-value calculations and p-value estimates**

The magnitude of a t-value (derived using equation 1) rests on two parameters – the correlation coefficient (*r*) and the degrees of freedom (*n-2*). The success of oxygen isotope dating of oak samples in central England (Loader et al. 2019) rests mainly on the fact that there is a strong common regional signal expressed in the oxygen isotopes with correlations between individual oxygen isotope series and the regional reference chronology often exceeding 0.6 and 0.7. In such a situation, this means that samples can be dated with substantially fewer rings than would normally be required as appropriate (ca. 80-100 years) for dendro-historical dating (English Heritage, 1998 – Figure 4).

The signal strength of LWBI data is often weaker compared to its maximum density counterpart (Rydval et al. 2014, Wilson et al. 2014; Kaczka et al. 2018). Therefore, a single LWBI series may not always correlate well with a regional reference series. However, Wilson et al. (2017) showed that the expressed population signal strength (Wigley et al. 1984) quickly improves as sample replication increases and a replicated site chronology with only 4-5 timber series could return strong correlations and robust high t-values to identify a correct date. Higher sample replication is therefore important for attaining a robust date when using BI data. However, when dating sub-fossil samples, one is constrained to dating a single timber. If the overall correlation with the reference chronology for a single timber is rather low, it is likely therefore that a robust date cannot be identified using traditional single-parameter cross-correlation dating methodologies (Baillie and Pilcher 1973, Holmes 1983, Wigley et al. 1987; Loader et al. 2019).

However, correlation is not the only parameter driving the t-value calculation (equation 1). The number of rings (*n*) in a sample is crucial. If the correlation is low, high t-values can still be attained if *n* is high (Figure 4). However, as stated earlier, in Scotland, the length of the historical samples can often be rather low (i.e. around 80 years). The primary novelty of the multi-parameter approach for crossdating is that each TR parameter likely offers some degree of independent information although this will vary between species and parameters used. In Scotland, the fact that RW, EWBI and LWBI express a mostly unique climatic response (Mifsud et al. *subm*) allows for an increase in the effective degrees of freedom, so in essence, increasing *n* which will increase the t-value using equation 1.

To illustrate the benefits of multi-parameter dating over traditional single-parameter approaches, imagine a situation where an undated sample has 100 rings. Using cross-correlation analysis, the maximum correlation for each parameter is identified at the same date, but with a rather low correlation value of 0.3. For such low correlations, one would need to have > 160 rings to have a t-value > 4.0 (Figure 4). For the individual parameters, a correlation of 0.3 would equate to a t-value of 3.1 and would not normally be deemed significant despite the 1-tailed p-value of the correlation being 0.001. However, if the parameter chronologies have zero autocorrelation and the three parameters (RW, EWBI and LWBI) are independent (i.e. not inter-correlated), then the effective degrees of freedom is (3 x 100) - 6 = 294. Using the Combo mean r value of 0.3, this would now return a t-value of 5.4 (1-tailed p < 0.0001). The potential strength of multi-parameter dating therefore, is that it increases the effective degrees of freedom, increasing the chance of attaining a robust date even if the signal is relatively weak or even if the number of rings in the sample is low. However, to do this robustly, one must also consider the autocorrelation of the chronologies being used as well as the inter-correlation of the parameters used. If the parameter chronologies (undated series or reference) are strongly inter-correlated, this means that they portray similar information and therefore do not provide unique information.

Chronology autocorrelation will impact the effective degrees of freedom for correlation analysis and will therefore impact the estimates of the resultant p-value (Wigley et al. 1987, Loader et al. 2019). Although it is well known that RW data often express higher autocorrelation values than ring density parameters (Franke et al. 2013, Lücke et al. 2019, Reid and Wilson 2020), the persistence properties of other tree-ring parameters (e.g. EWBI) are not so well explored (Zheng and Wilson 2024). Ultimately, the different persistence properties of tree-ring parameters can be minimised by processing the data in a consistent way to minimise the impacts of autocorrelation. As detailed earlier, the default detrending method used in ‘multiXdateR’ is to use a flexible spline and pre-whiten the data through autoregressive modelling to create the so-called ‘residual’ chronology. This essentially reduces the autocorrelation of the final chronology close to zero and is an applicable approach for processing any tree-ring parameter. However, autocorrelation could become a problem if the chronologies were then 1st differenced (an option in ‘multiXdateR’) which results in chronologies with strong inverse autocorrelation close to -0.5. Equation 2 (Dawdy and Matalas 1964), utilising the 1st order autocorrelation values of sample *x* and sample *y*, is often used to calculate the effective degrees of freedom (*N’*) for bivariate analyses. For example, for a correlation based on an overlap of 100 (*N*) years, using 1st differenced chronologies that both have an autocorrelation of -0.5 (note that any negative autocorrelation value is inverted for use in equation 2), the resulting adjusted *N’* value would be 60.

[2]

Therefore, continuing this example where the 1st differenced transform was used, then the resulting Combo degrees of freedom would be (3 x 60) - 6 = 174; already a substantial reduction from 294. If the RW, EWBI and LWBI chronologies (undated and reference) are uncorrelated with each other, then the resultant p-value of the Combo correlation (mean r = 0.3) between the undated series and reference chronology, would still be highly significant (1-tailed p = 0.00003).

However, if the different parameter chronologies are correlated with each other, then they are not providing unique information. To calculate a final adjustment of *N’* for attaining a robust p-value for the Combo approach, the univariate degrees of freedom adjustment (equation 3) of Dawdy and Matalas (1964) uses the mean-interseries correlation (*rbar*) of the undated and reference chronologies – *rbar* is calculated separately for both the undated series and the reference chronology and these two values averaged and used in Equation 3. Therefore, if the mean-interseries correlation of RW, EWBI and LWBI is 0.5, then the final *ComboN’* value is reduced to 58, resulting in a Combo t-value of 2.4 which would fail criteria for acceptance for a robust date, despite the fact that p = 0.01. This is a specifically severe example and between parameter correlations may not be as high as 0.5. The strength of the multi-parameter crossdating approach comes from using tree-ring parameters that are not strongly correlated with each other as they provide unique mutual information.

[3]

Finally, following guidelines detailed in Wigley et al. (1987) and Loader et al. (2019) the resultant p-values for the individual parameters and Combo approach are further adjusted using the “Bonferroni correction”. This minimises the risk of type 1 error (Helama 2023) by adjusting the p-value upwards (to a maximum of 1) as a function of the number of sequential correlations. This can have a rather conservative impact on the p-value (especially for the Combo approach when the number of sliding correlations is tripled in the 3-parameter example), especially if one is comparing undated series to a long reference chronology (925 years in the case of NCairn) which could result in a type 2 error of missing a correct date. ‘multiXdateR’ has the option to restrict the reference period of comparison (see Supplementary 2) if there is other *a priori* information that can constrain potential dates to a certain period.

As was detailed above, if chronology autocorrelation is high and there is a strong common signal between different parameters, the resultant degrees of freedom for correlations can be substantially reduced. However, using the pre-whitened chronology effectively reduces autocorrelation to zero and, at least within Scotland, the inter-correlation between RW, EWBI and LWBI ranges from about 0.2 to 0.3. In this context, the Combo approach potentially offers a much more robust date than any individual parameter alone. Of course, ideally, one would want to identify a robust date individually using each parameter as well as the Combo approach.

Finally, one might question why the 1st differenced transform is an option in ‘multiXdateR’ as it so severely reduces the effective degrees of freedom due to the strong negative autocorrelation. In our early attempts to use RW and LWBI to date sub-fossil samples (Wilson et al. 2012, 2017; Rydval et al. 2017), it was often the case that 1st differencing resulted in stronger correlations with the reference chronologies, especially for LWBI. There is therefore a balance between the gain of an increased r value for equation 1 and the limitation of the decrease in the degrees of freedom due to the negative autocorrelation (equation 2). The next sections will present results using the test site data using both approaches for comparison.

* 1. **Dating of the test sites using multiXdateR**
     1. **Individual series**

Data from the individual samples for each of the test sites were compared against NCairn using ‘multiXdateR. The data were detrended using a 31-year spline and pre-whitened (PW) as well as then 1st-differenced to compare the results for both approaches (FD - Table 1 (LCL) and Table 2 (LGL). This single timber approach is analogous to the dating of individual sub-fossil samples and is a particularly stringent methodological test using LCL as this 19th century plantation is located 30 km from the NCairn region (Figure 1).

Initially, following Wilson et al. (2017), a date is deemed significant using minimum acceptance threshold of a t-value > 4 and a p-value < 0.05. Note that Wigley et al. (1987) and Loader et al. (2019) suggested that the Bonferroni corrected probability values should be presented also as 1/p (≥100 ideal, equating to p ≤ 0.01), as well as detailing the ‘isolation factor (IF) – a value of 10 denoting that the lowest p value should be an order of magnitude lower than the next p-value. The output for ‘multiXdateR’ provides all this information. For this paper, four levels of “Dating” status are defined; *Assured* – consistent date from ≥ 2 parameters plus Combo; *Secure* – 1 parameter plus Combo; *Tentative* - Combo date only but also including an inconsistent date; *No date* – no Combo date regardless of what the parameters may show.

For the LCL site, none of the series were dated using all individual parameter and the Combo approach. For PW (FD), 2 (3) series were dated successful using RW, with 2 (2), 4 (4) and 6 (5) for EWBI, LWBI and Combo respectively. In fact, for EWBI, samples LCL18 and 23 were incorrectly dated using the FD approach (Table 1) while the dating using PW was non-significant (ns). The poor dating success using RW is not surprising. Before the utilisation of LWBI for dating (Wilson et al. 2017), historical dating within Scotland using RW alone was notoriously difficult (Mills and Crone, 2012), likely mainly related to site specific signals related to woodland management and disturbance that is expressed strongly in the RW data (Rydval et al. 2016). The poor single timber EWBI result may reflect the poor signal strength expressed in the EWBI data for this site (Table S1a). The stronger results for LWBI agree with the basic theory of Wilson et al. (2017) where this parameter expresses a consistent strong regional climate signal. What is important to note, however, is that despite some of the individual parameters failing to pass the minimum threshold for dating, all of the series (except LCL09) show generally strong dating results using the Combo approach.

Similar individual timber results are identified for the LGL site (Table 2). For the PW (FD) approaches, 3 (2), 3 (3), 3 (4) and 6 (6) series were dated using RW, EWBI, LWBI and Combo respectively. A spurious incorrect date is identified for LGL4 although the RW and Combo dates are correct. As with the LCL results (Table 1), the Combo results consistently identify the correct date for each sample.

* + 1. **Using subset site master reference chronologies**

Imagine now that these samples were taken from a historical structure and portray a potential single phase of construction. Focussing on those samples that were assigned either ‘assured’ or ‘secure’ dates, a sub-master series for the site can be compiled using these series. For site LCL a site-specific reference master was built using samples 2, 7, 8 and 18, while for LGL site samples 2, 3, 6 and 12 were used. The tentatively dated samples using NCairn (Tables 1 and 2) are now compared against their respective site-specific reference master series. For LCL, series 9 still dates tentatively using PW, but is an assured date using FD with only EWBI failing to date (Table 3). The dating of LCL23 is now “assured”. For LGL, the results are much improved and all dates using PW or FD are now assured for both LGL 4 and 14 (Table 4). Creating sub-set phase master reference chronologies is a standard approach for dendro-historical dating and appears to work well using the multi-parameter approach.

* + 1. **Full replicated site chronologies**

Dating single timbers is always more challenging than working with replicated groups of samples (Wilson et al. 2017). Based on the previous sections, for both sites, the test site data can be clustered into three groups of “strongly” dated (LCL 2, 7, 8 and 18; LGL 2, 3, 6 and 12), “weakly” dated (LCL 9, and 23; LGL 4 and 14) as well as the full replicated 6-series chronologies. Comparing these test site group chronologies against the NCairn reference highlights strongly how even modest replication can improve dating success substantially. Dating of the “strong” group for both sites returns t-values greater around 10 or greater (p < 0.0001 – Table 5). Even for the “weak” dated groups, t-values using the Combo approach are ca. 5 or greater with strong confidence. The full replicated 6-series chronology dating results for LCL and LGL (Table 5, Figures 5 and 6 (PW); Figures S1 and S2 (FD) and Table S2) express very strong dating results with NCairn showing marginally weaker results for RW and EWBI compared to LWBI and Combo, but t-values are still > 5, with p < 0.0001 and an IF > 1000.

1. **Conclusions and Final Comments**

Dating of sub-fossil and historical samples using RW and LWBI had been a staple approach for crossdating undated tree-ring samples at the St Andrews Tree-Ring Laboratory (Rydval et al. 2017; Wilson et al. 2017). The realisation that unique early season temperature information was extant in EWBI data (Björklund et al. 2017; Seftigen et al. 2020) presented the lab with a quandary as EWBI data had never been specifically saved. Early experiments of EWBI from living sites in Scotland not only showed a significant February-March temperature response, but that it was consistent over space, and essentially did not change with elevation (Mifsud et al. *subm*). EWBI has now been generated from all living pine chronologies across Scotland as well as historical and sub-fossil samples (Rydval et al. 2017; Wilson et al. 2017, Mills et al. 2017).

The rebuilding of the sub-fossil composite chronologies for NCairn and other regions in Scotland, quickly showed that our previous reliance on CDendro (Rydval et al. 2014) and COFECHA (Holmes 1983) for dating was inefficient as crossdating had to be repeated separately for each parameter (RW, EWBI and LWBI). The multi-parameter method detailed herein provides a single step analysis to combine the crossdating information for each parameter when dating single timber series or even groups of samples (see Supplementary 2). The primary strength of the method is that the near-unique information that each parameter provides – at least for Scots pine in Scotland – maximises the identification of the common year of maximal correlation while reducing the impact of spurious corelations. The method effectively increases the degrees of freedom, so even if the mean Combo correlation value between the series to be dated and the reference chronologies is rather modest, the resultant t-values can still be high (> 4.0) with associated low p-values.

‘multiXdateR’ has provided a revolution for crossdating of sub-fossil and historical samples within Scotland. Reprocessing all the sub-fossil samples has not only identified a few samples that had originally been spuriously dated (a very low number of samples) but has also identified many samples that previously had not been dated as the added information from EWBI, and the pooled information from the three parameters, has proved crucial in identifying a robust date. Even sub-fossil samples with ca. 40 rings have been shown to date robustly. Similarly, we have redated all the Scottish historical buildings constructed with pine. Mifsud et al. (*subm*) present results for buildings already dated using RW and LWBI (Wilson et al. 2017; Mills et al. 2017) to showcase the ‘multiXdateR’ code and the multi-parameter approach for historical dating. More importantly, we have now dated buildings that previously could not be dated which will be the focus of future publications.

In this paper, the multi-parameter approach has focused on three parameters (RW, EWBI and LWBI) as this has been shown to be an optimal approach for dating of pine within Scotland. The current code (see Supplementary 2) has been written for one, two and three parameters, but there is theoretically no restriction to how many parameters could be included. One could also consider, for example, early/late-wood width, varying quantitative wood anatomical (QWA) variables and even isotopes. Ideally, the method works best when using parameters that are not strongly correlated with each other, although the Dawdy and Matalas (1964) adjustment methods described above will cater for strongly correlated variables with an associated substantial reduction in the combined degrees of freedom. What is perhaps the main factor in deciding what variables should be used in multi-parameter dating is the availability of relevant reference chronologies. When measuring scanned images of samples using CooRecorder (Rydval et al. 2014; Maxwell and Larsson 2021; Heeter et al. 2022), generating RW, EWBI and LWBI (even early/late-wood width) is straight forward for multiple sites if one wanted to create a network of relevant reference chronologies. However, this would be a challenge for the more expensive and time-consuming tree-ring parameters such as QWA and isotopes.

Ultimately, the quick and cost-effective methods for generating RW, EWBI and LWBI data suggest that, for conifers at least, these would represent the key variables to use in multi-parameter dating. It is important to stress that the parameter chronologies do not necessarily need to express a strong climate signal so long as they correlate well (r > 0.4) between trees and between sites. The stronger the intercorrelation the better. What is now needed is a concerted community effort to develop a spatial network of relevant parameter reference chronologies, derived using consistent methods (Kaczka and Wilson 2021). Such networks are not only for important historical dating, but will facilitate the provenancing of material, which likely can be further improved by using multi-parameters.

**Acknowledgements**

Thank you to Duncan V. Mifsud, Emily Reid, and Kayleigh Letherbarrow for testing the ‘multiXdateR’ code as it was being developed. I appreciated discussions with Neil Loader, Danny McCarrol and Andrea Wilson on the nuances of deriving robust p-values. Funding…

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