Journal of Archaeological Science 78 (2017) 99–111

Contents lists available at ScienceDirect

Journal of Archaeological Science

journal homepage: http://www.elsevier.com/locate/jas

Facilitating tree-ring dating of historic conifer timbers using Blue Intensity

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A R T I C L E I N F O

Article history:
Received 26 August 2016
Received in revised form
28 November 2016
Accepted 30 November 2016

Keywords:
Tree-ring dating
Dendroarchaeology
Blue Intensity
Conifers

A B S T R A C T

Dendroarchaeology almost exclusively uses ring-width (RW) data for dating historical structures and artefacts. Such data can be used to date tree-ring sequences when regional climate dominates RW variability. However, the signal in RW data can be obscured due to site specific ecological influences (natural and anthropogenic) that impact crossdating success. In this paper, using data from Scotland, we introduce a novel tree-ring parameter (Blue Intensity – BI) and explore its utility for facilitating dendrohistorical dating of conifer samples. BI is similar to latewood density as they both reflect the combined hemicellulose, cellulose and lignin content in the latewood cell walls of conifer species and the amount of these compounds is strongly controlled, at least for trees growing in temperature limited locations, by late summer temperatures. BI not only expresses a strong climate signal, but is also less impacted by site specific ecological influences. It can be concurrently produced with RW data from images of finely sanded conifer samples but at a significantly reduced cost compared to traditional latewood density. Our study shows that the probability of successfully crossdating historical samples is greatly increased using BI compared to RW. Furthermore, due to the large spatial extent of the summer temperature signal expressed by such data, a sparse multi-species conifer network of long BI chronologies across Europe could be used to date and loosely provenance imported material.

1. Introduction

Dendrochronology is multidisciplinary in nature and has many applications in the environmental sciences including ecology, geomorphology and climatology (Schweingruber, 1996; Hughes et al., 2010; Speer, 2010; Stoffel et al., 2010). The common fundamental keystone to all dendrochronological sub-disciplines is the ability to ensure exact calendar dating of the tree-ring (TR) series. Crossdating is the ability to pattern-match or synchronise TR sequences between samples of the same species across a climatically homogenous region to allow the identification of the exact year in which a particular TR was formed (Stokes and Smiley, 1968; Fritts, 1976). One of the earliest uses of dendrochronological methods was the dating of historical structures and artefacts (so-called dendroarchaeology) and a large body of published work now exists

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http://dx.doi.org/10.1016/j.jas.2016.11.011

detailing the development of this sub-discipline (Baillie and Pilcher, 1973; Baillie, 1982; Pilcher et al., 1984; Kuniholm, 2001).

Until now, dendroarchaeology has almost exclusively utilised ring-width (RW) as the main tree growth variable for crossdating. RW is inexpensive to produce, not only directly from samples (via microscope graticules or measuring stages), but can also be measured from sample casts (Crone, 2008), photographs (Mills, 1988; Levanič, 2007) and scanned images (Rydval et al., 2014). The success of dendroarchaeology from many regions across both the Old (Baillie, 1995; Kuniholm and Striker, 1987; Manning and Bruce, 2009) and New (Douglass, 1929; Nash, 1999) Worlds highlights the importance of this variable for historical dating.

Crossdating is possible because trees of the same species within the same region respond in a similar way to climate. This means that during years of favourable growth conditions, all trees, on average, will develop a relatively wide ring, whereas thinner rings will develop when environmental conditions are less favourable. RW patterns, therefore, can be synchronised between trees in the same area and the strength of the common signal between trees and across wide regions often reflects the strength of the climatic influence on growth.

The sensitivity of tree-growth to climate is a function of the tree's geographical location which influences what aspect of climate most limits tree productivity. As a general rule, in high latitude/altitude situations, growth is limited by summer temperatures, whereas at low latitude/altitude sites, tree-growth is more commonly limited by moisture availability. Many transect and regional network studies have shown this change in general tree response to climate with elevation and/or latitude (Fritts et al., 1965; LaMarche, 1974; Lingg, 1986; Kienast et al., 1987; Wilson and Hopfmueller, 2001; Babst et al., 2012; St. George, 2014). In regions of complex topography, however, the varying response of tree-growth to climate for a single species can complicate between-site crossdating and dendroarchaeological dating. For example, Wilson et al. (2004) showed for the Bavarian Forest in Germany, that when using RW, low elevation moisture limited Norway spruce trees (<700 m.a.s.l.) could not be crossdated with high elevation temperature sensitive trees above 1100 m.a.s.l despite these two regions being only about 50 km apart.

An additional limiting factor influencing the utility of RW for dendroarchaeology is that RW variability is an aggregated product of multiple environmental factors (e.g. climate, site ecology, natural and anthropogenic disturbance, etc.) influencing tree-growth throughout the year (Cook, 1985). From a dating perspective, it is desirable for the common regional scale climatic influence upon growth to dominate the variability in RW series and the impact of local factors (natural and anthropogenic) to be minimal. Optimising the climatic influence expressed in TR series and minimising the "noise" of all other factors therefore facilitates crossdating. This is strategically performed through careful site selection in dendroclimatological studies (Fritts, 1976), but for dendroarchaeology, the exact provenance of historic timbers may never be ideal to optimise the climatic influence expressed by RW data and so the climate related signal is often weaker with resultant detrimental implications for dating.

RW is not the only variable that can be measured from tree rings however. Density based parameters (Polge, 1970; specifically maximum latewood density) have been successfully used over the last 30 years as an effective proxy of past summer temperatures (Briffa et al., 1992, 2001; Wilson and Luckman, 2003; Esper et al., 2012; Schneider et al., 2015). Stable isotopes, in recent years, have also been shown to provide additional information expressing a whole new swath of climatic information that can be extracted from TR samples (McCarroll and Loader, 2004; Treydte et al., 2007; Young et al., 2015). However, measuring ring density or stable isotopes requires specialised equipment (which few TR laboratories possess) and are much more expensive to produce compared to RW.

A novel TR variable that has been championed for dendroclimatology in recent years is Blue Intensity (BI - McCarroll et al., 2002; Björklund et al., 2014; Rydval et al., 2014; Wilson et al., 2014). BI is similar to maximum latewood density (MXD) as they both essentially measure the combined hemicellulose, cellulose and lignin content (related to cell wall thickness) in the latewood of conifer trees. The intensity of the light reflectance in the blue part of the spectrum is a good proxy of the amount of these compounds (especially lignin) and cell wall thickness as they readily absorb blue light. Therefore, dense, darker latewood will result in less reflected blue light. BI and MXD are therefore related (inversely correlated) and have been shown to express a much stronger relationship with summer temperatures than RW as they express a "purer" climate signal and are less influenced by other site specific non-climatic factors (Björklund et al., 2014; Rydval et al., 2014; Wilson et al., 2014). BI data can be generated at the same time as RW data at no additional cost by measuring directly from images (scans or photographs) of finely sanded conifer wood samples and can theoretically be generated by any dendrochronological laboratory with minimal investment (see Campbell et al. (2011); Rydval et al. (2014) and Österreicher et al. (2015) for different approaches for BI measurement). As BI generally expresses a stronger summer temperature signal than RW, at least at inter-annual time-scales (Rydval et al., 2014, 2016b; Wilson et al., 2012; 2014) and is less susceptible to site specific ecological "noise", we hypothesise that the use of BI will substantially improve our ability to successfully date historical structures where conifer wood is the main construction material.

In this paper, we present the first exploration of using BI data to aid dendro-historical dating using a Scottish case study. In Scotland, the dendrochronological dating of imported archaeological oak using RW has been reasonably successful, aided by a network of reference chronologies across northern Europe (Crone and Mills, 2012). However, dating native timber is less straightforward, in part due to chronological and geographical gaps in native reference chronologies (Mills and Crone, 2012). Using just RW data, historical dating of native pine in Scotland has been an especially formidable challenge (Crone and Mills, 2002, 2011) and until recently only a few structures, built with local pine, had been dated (Mills and Crone, 2012). While in part this is related to the need for the development of a network of native pine reference chronologies (Mills, 2008) it also appeared to be related to intrinsic characteristics of pine used in Scottish buildings, including the predominant use of young (<80-year) timbers, which make dating more difficult (Crone and Mills, 2011; Mills and Crone, 2012). BI has changed this situation substantially, and its use has significantly increased the chance of attaining a robust date for historical structures – whether the conifer construction material was sourced in Scotland or from other regions in Europe.

This paper first details the current status of the Scottish pine TR network and the defined regional reference chronologies used for historical dating. The dating potential of BI versus RW is then examined using four independently sampled living sites and six historical structures. A sub-sampling exercise, using the full Scottish pine data-set, is then performed to model how many timbers would theoretically need to be measured and dated from a historical phase/structure to "guarantee" a successful crossdate using either RW and BI. The paper ends by examining the wider implications of using BI data for crossdating and provenancing across Europe in light of the significant amount of trade and transportation of conifer construction material over the last 500 years throughout the whole region.

2. Data and methods

The current network of Scots pine chronologies, developed as part of the Scottish Pine Project (https://www.st-andrews.ac.uk/~rjsw/ScottishPine/), includes 44 sites of which BI data have been measured from 20 (Rydval et al., 2016b, Fig. 1). For historical dating purposes, the individual site data have been pooled to create five regional reference series to maximise replication and common signal and minimise site specific noise. The North-West (NW – AD 1621–2013), South-West (SW – AD 1508–2011) and Southern Cairngorm (SC– AD 1477–2012) regional reference series are derived entirely from living trees while West-Central (CNT – AD 1260–2013) and the Northern Cairngorms (NC – AD 1089–2013) have been extended using preserved sub-fossil material collected from near-shore shallow lake sediments (Wilson et al., 2012; Rydval et al. in review-a). The data from all five regions were also combined to create the Scottish Mega Master (SMM).

Sample replication for each regional reference series decreases back in time (Supplementary Fig. 1) with associated weakening in the expressed population signal (EPS) strength statistic (Wigley

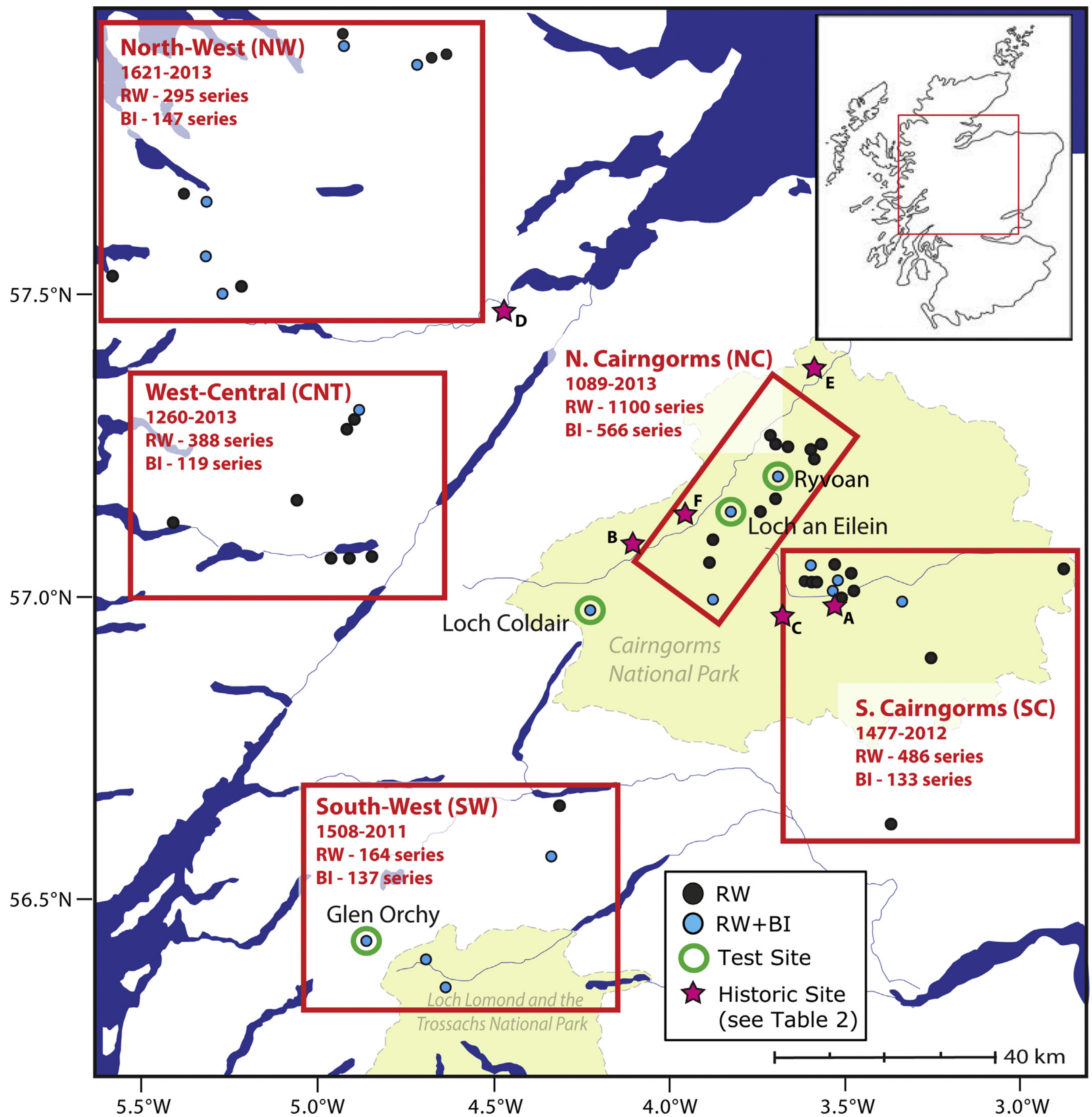

Fig. 1. Location map showing the individual locations of all 44 pine sites in Scotland, the regions represented by the five pine region reference series (including individual TR series replication for each parameter), the four living "analogue" test sites and the six historical structures.

Table 1
Analogue historical sites using independent living data from the Scottish Pine network. MSL = mean sample length. RBAR = mean inter-series correlation of 1st differenced detrended data; N (EPS 0.85) = number of trees needed to attain an EPS of 0.85.

Site name	Site code	Period	No. of trees	MSL	RW RBAR	N (EPS 0.85)	BI RBAR	N (EPS 0.85)
Ryvoan Pass	RYV	1787–1900	9	88.3	0.30	13.0	0.46	6.6
Loch an Eilein	LAE	1850–1950	6	80.5	0.26	15.8	0.44	7.1
Glen Orchy	GOS	1800–1900	10	77.7	0.34	10.9	0.27	15.5
Loch Coldair	LCL	1863–1960	10	85.7	0.34	11.1	0.42	7.9
				Mean	**0.31**	**12.7**	**0.40**	**9.3**

et al., 1984). EPS is an empirical metric commonly used in dendroclimatology to assess how well a sample chronology of finite replication represents the theoretical infinitely replicated population chronology. It is derived using the following equation:

$$EPS = \frac{n\,\bar{r}}{n\,\bar{r} + (1-\bar{r})} \quad (1)$$

where n is the number of TR series and $\bar{r}$ (often referred to as RBAR) is the mean inter-series correlation of all possible detrended bivariate pairs of TR series in a chronology. RBAR is a measure of the common signal between the TR series and the EPS values can be interpreted as the squared correlation between the sample chronology and the theoretical population chronology. Values > 0.85 are often cited as adequate for dendroclimatological purposes (Wigley et al., 1984). All analyses in this paper are focussed on the post 1700 period where EPS is >0.85 for most regional reference series (Supplementary Fig. 1). The above equation can be rearranged to predict how many TR series would be needed to attain an EPS of a certain value (i.e. 0.85) for a given empirically estimated chronology RBAR value:

$$n = \frac{(\bar{r}-1)EPS}{\bar{r}\,(EPS-1)} \quad (2)$$

Comparison of the dating potential of BI versus RW was performed using data from; (1) four living sites (Fig. 1 and Table 1) that were used as historical “analogues”, where sample provenance is known, and (2) data from six historical sites (Fig. 1 and Table 2), where the original growth location of the timbers is unknown but presumed to be local to the sampled structure. Although the data for the living sites come up to present, the recent end of the RW and BI time-series was truncated to create site chronologies with a mean sample length (MSL) of ca. 80 years to create “analogue” chronologies that represent the mean sample length often observed from samples taken from historical structures in Scotland (Table 2). It should be noted that the six test historical sites represent data measured from samples that have been successfully dated using both RW and BI. Many samples from each of these structures have not been successfully dated mainly due to short sequences, fragmented samples or substantial worm related decay (Table 2).

The RW and BI data for the regional reference series and test sites were detrended via 1st differencing and the individual transformed series averaged to create regional and site chronologies. 1st differencing removes all low frequency variability in the TR series (reducing 1st order autocorrelation) and allows crossdating to be performed using only the inter-annual signal. The chronologies for each TR variable were correlated with each regional reference chronology and the associated T-value (Baillie and Pilcher, 1973) calculated to assess the significance of the crossdate. The T-value, commonly used in European dendroarchaeology, essentially transforms the correlation between two time-series to a probabilistic value following the Student T-distribution using the following equation:

$$T = \frac{r\sqrt{n-2}}{\sqrt{1-r^2}} \quad (3)$$

where n is the number of years in the period of overlap and r is the Pearson's correlation value between the two time-series. A T-value >3.5 is often used as a minimum threshold to identify a significant crossdate but herein we use a value of 4.0 as a more conservative acceptance threshold.

To model the theoretical number of TR series needed to acquire a “robust” crossdate, a bootstrapped sub-sampling exercise, for both RW and BI, was performed using the full SMM data-set. Random sample chronologies (from 1 TR series up to 20 TR series) were extracted from the full SMM data-set (performed using the 1721–1800 and 1821–1900 periods) and the correlation between each random sub-sample mean chronology and the mean of the remaining series calculated. For each replication step, this random sub-sampling was performed 1000 times allowing an estimate of the range in correlation values for each incremental increase in n.

Finally, to examine the potential utility of using BI to facilitate crossdating of historical material from various conifer species with unknown provenance from regions around Europe, RW, BI (Scotland, Sweden, the Alps) and MXD (Sweden, the Alps and the Pyrenees) chronologies were used to examine the spatial climatic fingerprint of each of these TR variables. The BI data were inverted to exhibit the same positive correlation relationship with temperature displayed by the MXD data.

3. Results and discussion

3.1. Chronology metrics

Table 1 details meta information for the four living “analogue” test sites while their locations are shown in Fig. 1. Ryvoan (RYV) and Loch an Eilein (LAE) are located in the core pine woods of the northern Cairngorms, the latter area being chosen as there is a strong history of human felling related disturbance (Rydval et al., 2016a) which might affect the ability to crossdate tree samples taken from these woods. Glen Orchy (GOS) is located on the south-western edge of the Scottish pine network while Loch Coldair (LCL), an abandoned 19th century plantation, is situated in what we refer to as “the network hole” where no semi-natural pine woodlands exist today. The RBAR values for RW vary from 0.26 (LAE) to 0.34 (GOS and LCL) with a mean of 0.31, while values are generally higher for BI ranging from 0.27 (GOS) to 0.46 (RYV) with a mean of 0.40 (Table 1). Using Equation (2), on average about 13 trees are needed to attain an EPS of 0.85 for RW, while only 9 trees are needed using BI. Examining the same metrics for the six historical sites (Table 2) identifies a similar range for RW (0.25–0.49; mean = 0.36) and BI (0.27–0.46; mean = 0.36). Statistically, there is no difference between the overall RBAR values for RW and BI between the living and historic sites (Tables 1 and 2) and 11 trees would be needed to attain an EPS > 0.85 in both cases.

Table 2
Historical site meta-information. MSL = mean sample length. RBAR = mean inter-series correlation of 1st differenced detrended data; N (EPS 0.85) = number of trees needed to attain an EPS of 0.85.

Site name	Fig. 1 code	Date	MSL	No. of dated series	No. of trees	No. of undated series and comment	RW RBAR	N (EPS 0.85)	BI RBAR	N (EPS 0.85)
Inverey Byre	A	1668–1791	85.0	10	10	1. Short sequence	0.40	8.5	0.41	8.1
MacRobert House	B	1724–1848	93.0	7	7	13. Fragmented, broken and short series	0.25	17.0	0.32	12.2
Red House	C	1707–1808	89.3	2	2	14. Fragmented, broken and short series	0.29	13.7	0.32	11.9
Belladrum	D	1742–1861	97.8	4	2	zero	0.40	8.5	0.46	6.7
Granton-on-Spey	E	1775–1852	62.7	32	12	3. Short series	0.34	10.8	0.38	9.1
Badden Cottage	F	1691–1801	70.5	11	5	2. Fragmented, broken and short series	0.49	5.8	0.27	15.0
						Mean	**0.36**	**10.7**	**0.36**	**10.5**

Low RBAR values can reflect either (1) non-climatic influences on tree-growth which could explain the lower values for LAE or (2) mixed assemblages of timbers reflecting different source areas for the historical timbers. Although BI reflects a stronger climate signal than RW (Wilson et al., 2012; Rydval et al., 2016b), the quality of the reflectance data can be impacted by discoloration (e.g. due to algal staining and decay), sample integrity (i.e. worm holes) and/or the presence of reaction wood, resulting in lower RBAR values. Overall, however, the signal strength metrics of the six historical sites are generally similar to those seen for the living analogue sites, although this is perhaps not surprising as these data represent samples which have been successfully dated. The signal strength analysis for both groups (Tables 1 and 2) indicate that the actual replication in the dated historical samples is often lower than needed to attain an EPS of 0.85. This is not a problem *per se*, but does hint that crossdating against the regional reference chronologies would improve if site/phase chronology replication was higher (see later discussion).

3.2. Crossdating results

The T-values for each of the four living "analogue" sites against the five regional reference chronologies and the SMM (Fig. 2) show that BI is clearly superior to RW for crossdating the living pine chronologies. In all cases, and compared with all regional reference series, T-values using BI are substantially higher than 4.0 and many values are >10. For RW, the crossdating results are much weaker and more variable. RYV, LAE and GOS still, however, yield significant dating results with the regional reference series from where the trees were actually located. LCL shows marginally stronger results with the Northern Cairngorms – the geographically closest regional reference data-set. Both GOS and LCL show reasonably strong T-values using RW against all regional records. This observation might reflect the higher replication (and stronger signal strength, Table 1) of these two sites compared to RYV and LAE. Weakest crossdating results are noted for the LAE site using RW affirming the weak signal strength results (Table 1) as well as the "muddying" effect of the signal related to known felling related disturbance (Rydval et al., 2016a). Surprisingly, however, the BI based crossdating results for LAE are the strongest of all four living sites with a T-value of 13.2. These observations for LAE clearly show the "purer" climatically dominated common signal expressed in BI compared to RW which can be strongly affected by non-climatic factors.

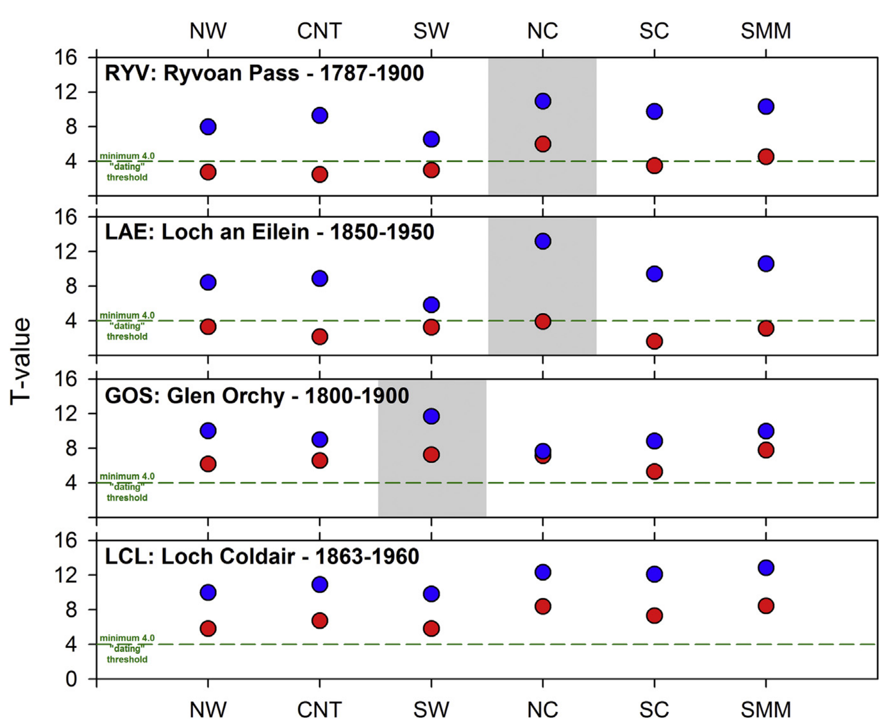

Fig. 2. T value crossdating results against regional and SMM reference chronologies. RW in white and BI in black. Grey shading denotes the region within which each site is located. Loch Coldair is located in the so called "network hole" so no shading is shown but geographically it is more closely located to NC

It is important to highlight that the T-value results for both RW and BI against the SMM are only marginally weaker than for the "optimal" regional reference record. This is an encouraging observation as it suggests that initial dating of a historical site could be performed using the full SMM data-set. Once dated, provenancing the historical material could then be performed using the regional reference data-sets or even individual sites.

As with the living "analogue" sites (Fig. 2), BI based T-values for the six historical sites are generally stronger compared to RW, but overall the results are weaker (Fig. 3). This observation is partly related to the relatively low number of dated TR series included in some of the historical site chronologies (e.g. only two timbers for Red House and Belladrum, Table 2). However, the fact that a significant crossdate can be identified using such a low number of timbers is encouraging (but see later discussion). The low T-values when using RW (Fig. 3) clearly show why it has been so difficult to date historical structures in Scotland using this TR variable alone. The utilisation of BI has greatly improved our chances of dating historical pine samples.

Compared to living "analogue" sites (Fig. 2), the provenancing results for the historical samples are more ambiguous (Fig. 3). Often, the highest T-values using RW and BI identify different timber source regions. For example, for Inverey Byre, RW suggest SC, while BI suggests CNT. We are fairly confident that the Inverey Byre timbers would have been locally sourced and therefore should crossdate more strongly with the SC region (highlighted in Fig. 3). Similar ambiguities with respect to potential timber provenance are noted for all the historical sites except Badden Cottage which appears to be most closely related to the NC region. These ambiguous provenancing results do not influence the overall conclusion that BI is a superior TR variable for dating historical conifer material but they do indicate that site/phase chronology replication is an important factor that must be taken into account when crossdating.

3.3. Crossdating and site replication

Fig. 4 presents the mean correlation (±2 standard deviations) between the increasingly replicated sub-sampled site chronologies (1 through to 20 trees) and the mean of the rest of the data in the SMM data-set. As would be expected (see Wigley et al., 1984) the mean correlation is lower for chronologies derived from only a single tree and becomes higher as replication increases. On average, the mean correlation for a site chronology of only a single tree is 0.35 and 0.48 for RW and BI respectively. For 10 trees, these values increase to 0.76 and 0.86. So again, the correlation results are higher for BI than RW as was noted from the crossdating T-value results (Figs. 2 and 3).

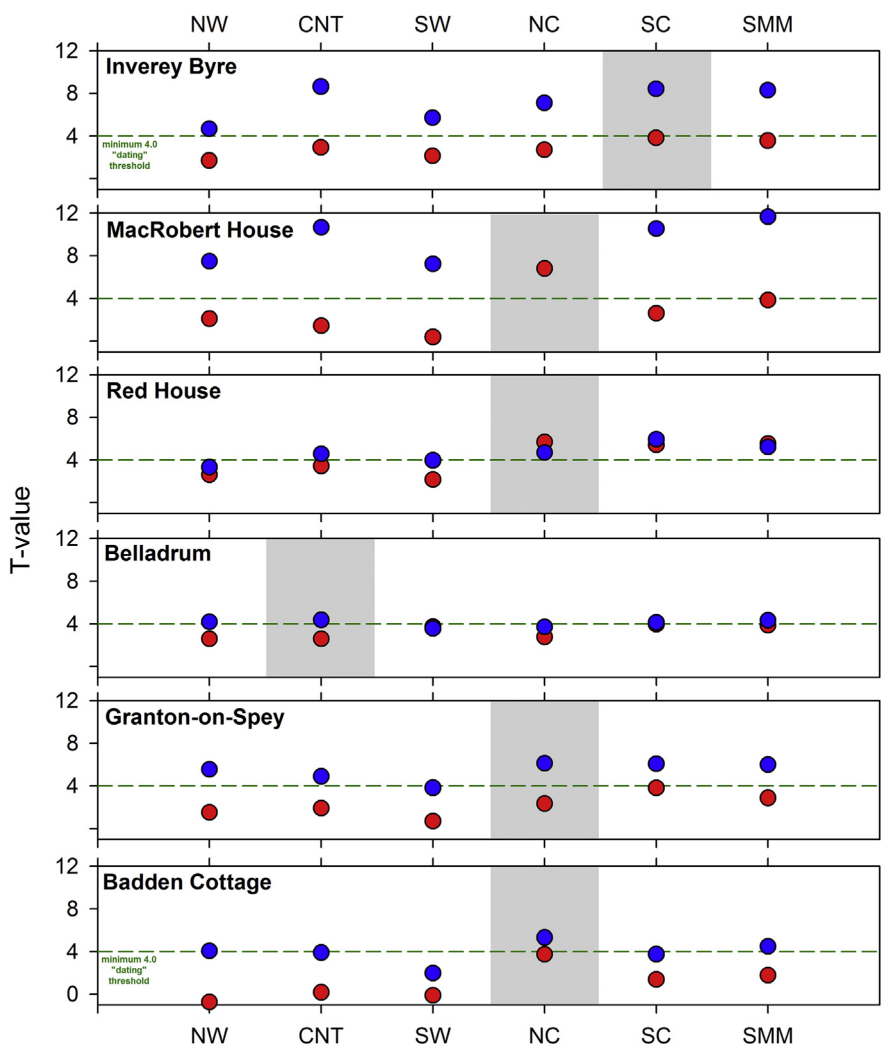

Fig. 3. As Fig. 2 but for the historical sites. Grey shading denotes the closest regional reference series to the historic sites.

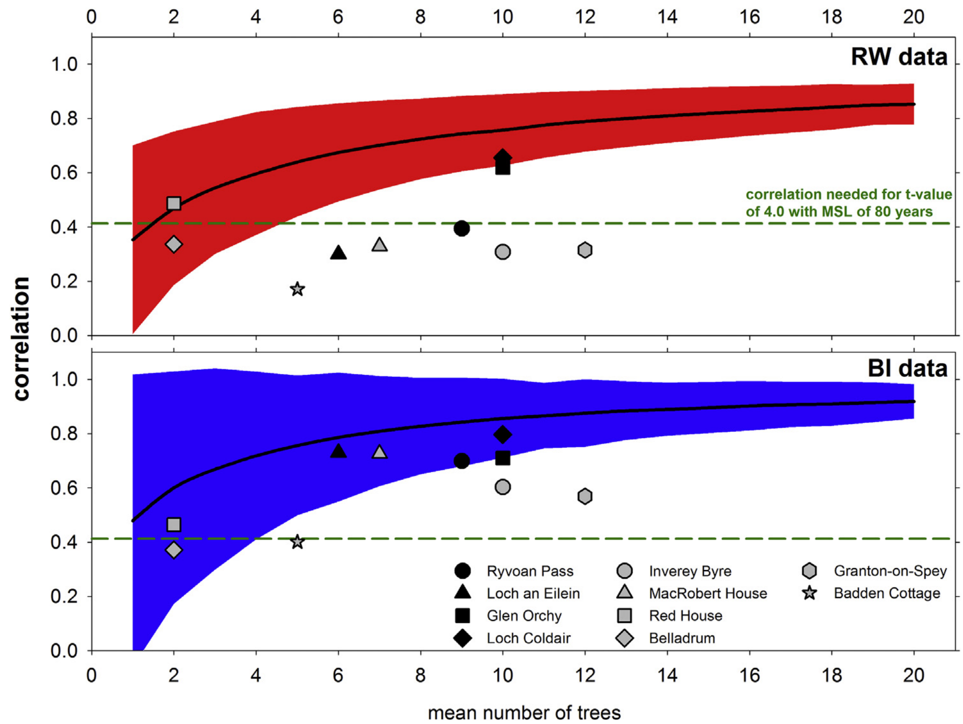

Fig. 4. Modelled change in correlation as sample replication (N) increases. The black line mean correlation and 2-sigma envelopes (upper = RW; lower = BI) denotes bootstrap sampling (1000 times) of the SMM of sample replication with 1–20 trees using two 80-year periods (1720–1800 and 1820–1900). The full period correlation values used to generate T-values in Figs. 2 and 3 are also plotted against the number of timbers for the four test and six historical sites.

These mean correlation values, however, only tell half the story. As with any sub-sampling exercise, the range in values is crucial to understand the noise and variability in the data. It is not surprising that for sites replicated with only one tree, the 2-sigma standard deviation range of correlation values is rather large – essentially from 0 to 1 for BI. As replication increases, this 2-sigma range decreases. Crucially, this large range in potential correlation values, when replication is low, highlights the potential danger of both type I and II dating errors and caution is advised when dating using only single series. This is also relevant when attempting to date single sub-fossil samples (Wilson et al., 2012). Of course, identifying the same calendar date using both RW and BI provides added confidence that the identified date is more likely to be correct. The horizontal dotted lines in Fig. 4 denote the correlation needed (r = 0.41) to attain a T-value of 4.0 when the period of overlap is 80 years. As the 2-sigma error range decreases with increasing replication, we can use this variability range to predict that a "correct" date can be identified 95% of the time when site/phase chronology replication is ca. 5 and ca. 4 trees when using RW and BI respectively.

In many respects, the subsampling exercise of the SMM data-set (Fig. 4) is an idealised exercise as the results likely will only be relevant for historical sites built using timbers that grew originally in the areas represented by the SMM data. However, the exercise does provide a guide to identify an ideal minimum number of samples needed to date a historical phase chronology within the Scottish Highlands. To test the applicability of this modelling exercise, the correlation values for the living "analogue" and historical sites used to generate the T-values in Figs. 2 and 3 are also plotted on Fig. 4. Although the results are better for BI than RW, the actual correlation values for many of the sites are outside the 2-sigma variability range of the sub-sampling results. Using BI, the four living analogue site correlations do sit within the modelling range, but for RW, LAE and RYV are weaker than expected. Although the LAE results could be explained by disturbance influences on this site's growth (Rydval et al., 2016a), this explanation is likely not relevant for RYV. The results are less robust for the historical sites. Only Red House and Belladrum sit within the modelled range using RW. The other four sites are much weaker and a T-value of 4.0 could not be attained against the SMM. Results are marginally better using BI for Inverey Byre, Granton-on-Spey and Badden Cottage but are still weaker than expected.

To explore these poorer than expected results, we examine the coherence between the historical site chronologies and the SMM reference chronology in more detail (Fig. 5). Specifically, sliding 31-year window correlations are shown between the historical and SMM chronologies for both TR variables. As expected, the BI based correlations are higher than RW. However, for all six sites, the coherence between the site and regional chronologies is not time-stable and in general terms, when replication is low, between series correlation is also low. This is hardly surprising (see Fig. 4), but it does appear that when calculating the correlation (and associated T-value) using the full period of overlap, the values can be detrimentally impacted due to poorly replicated periods. To partly overcome this, the mean of the sliding correlations could be used rather than the correlation calculated over the full overlap period. This reduces the overall influence of the low replicated periods. The difference between the correlation values for the full period and the mean of the sliding correlations (Fig. 5 - top right corner of each panel) can be substantial. For example, the full period RW (BI) based correlation for Inverey Byre is 0.31 (0.60), but increases, using the sliding correlations, to 0.55 (0.75). In fact, the mean of the sliding correlations is almost always higher than the full period correlation except for Belladrum where there is a slight decrease for RW.

As well as deriving a mean correlation using 31-year sliding windows, mean tree replication (derived from the replication histograms in Fig. 5) can also be calculated via the sliding window

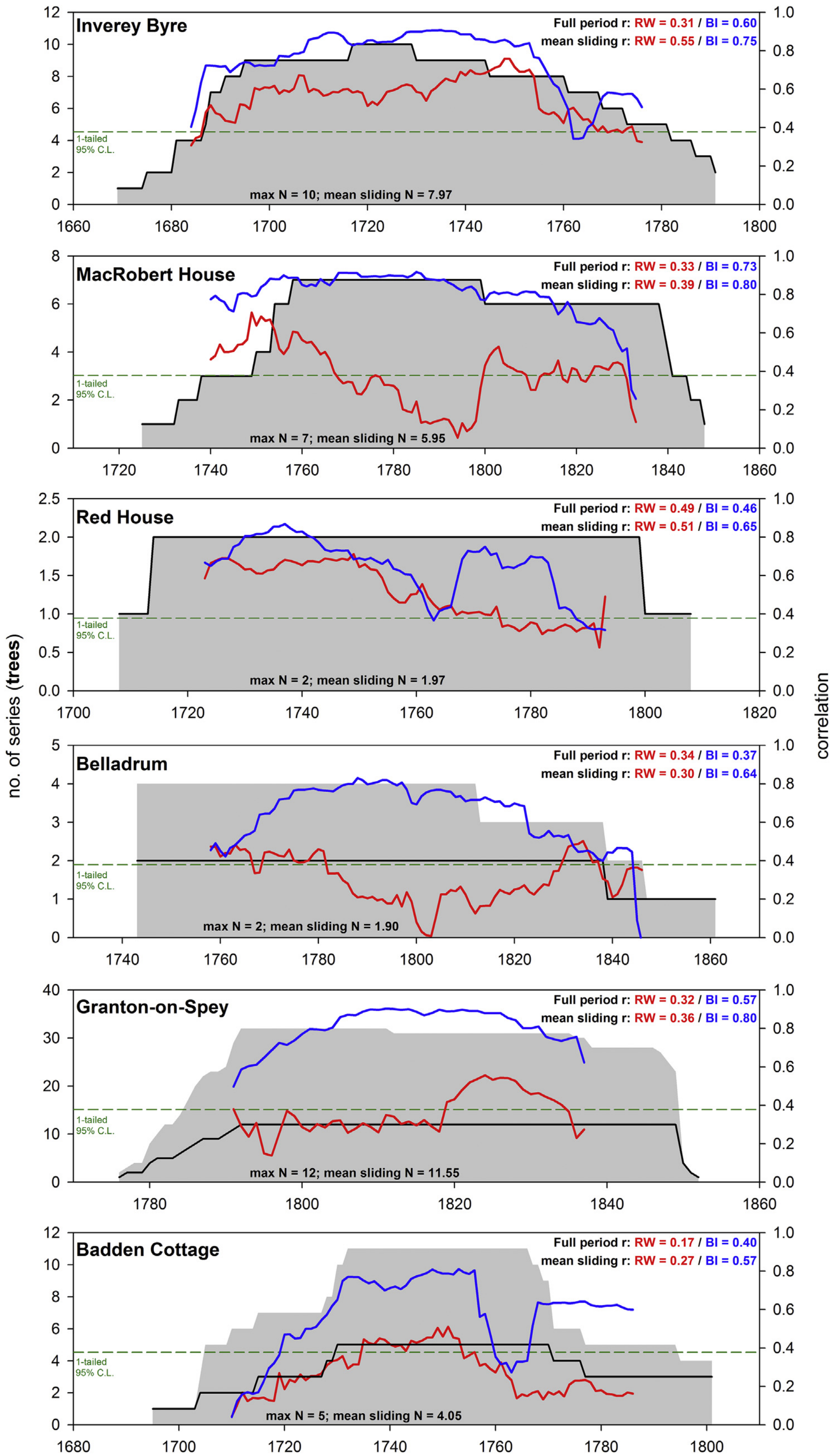

Fig. 5. Sliding 31-year correlation values between each historical site chronology and the SMM master chronologies for both RW (triangles) and BI (black line). Grey histograms denote TR series replication for each historical site, while the black line shows individual tree replication. "Full period r" = the correlation value generated between the historical chronology and SMM used to produce the T-values in Fig. 3. "Mean sliding r" = the mean correlation from the sliding 31-year correlations.

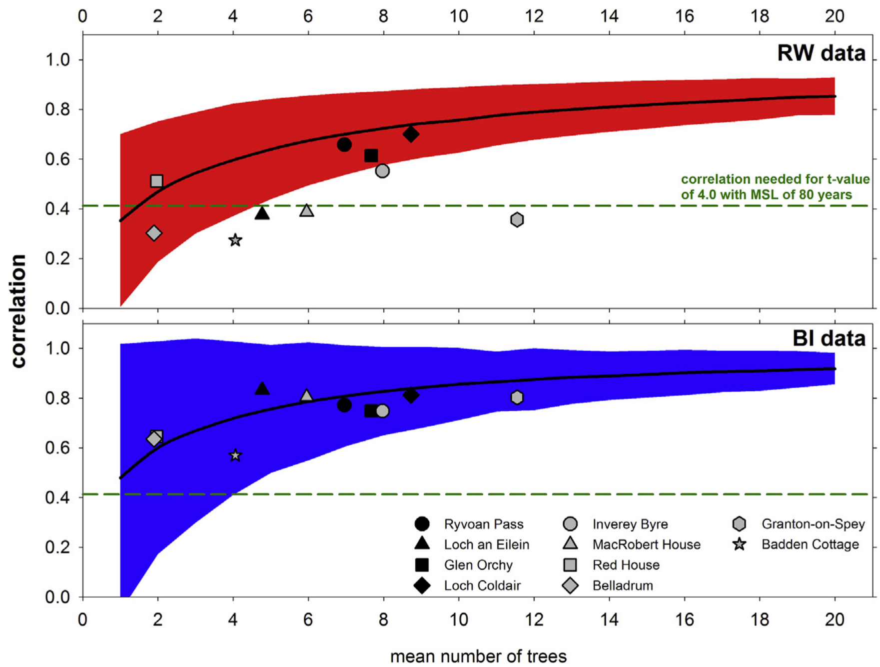

Fig. 6. As Fig. 4 but using mean of sliding correlation and mean n through time.

approach. In the case of Inverey Byre, for example, although the historical site includes 10 timbers, the mean replication of the sliding 31-year windows is 7.97. Using these new estimates for *r* and *n*, the site based correlation results shown in Fig. 4 are updated and presented along with the same modelling results in Fig. 6. Focussing on BI, the living "analogue" and historic site results now sit well within the modelled 2-sigma range. The results for RW, although improved, still however identify some sites (LAE, Badden Cottage, MacRobert House, Inverey Byre and Granton-on-Spey) outside the 2-sigma variability range. As discussed earlier, the LAE RW results can be explained by human disturbance (see also Rydval et al., 2016a). Explaining the poor RW based results for the other historical sites is more of a challenge as we do not know the original growth location of the timbers. The sliding correlations (Fig. 5) clearly show more time stable coherence between the site chronologies and the SMM for BI data. The RW data for almost all the sites express periods with significant weak coherence which may well be related to some form of disturbance (Rydval et al., 2016a) obscuring the climatic influence on tree growth. This is a difficult hypothesis to test without specifically focussing on living sites only (i.e. LAE), but one clear conclusion from this work is that BI appears to be less sensitive to such issues and shows great potential as an important new TR variable for crossdating conifer material (see also discussion in Rydval et al. in review-b).

3.4. The wider geographical potential of BI based dating

The discussion so far has focussed specifically on the ability of using BI to improve the likelihood of identifying a correct crossdate of historic conifer wood samples in Scotland. We believe, however, that BI has the potential to improve the dating of imported conifer material where the original provenance is unknown. Scotland has a long history of timber importation for construction (Crone and Mills, 2012). This adds a substantial challenge for dendrohistorical dating as a network of relevant reference chronologies from across Europe is needed for the locations where the timbers originated. It is also likely that construction timbers may reflect different species. For conifer species, however, we hypothesise that the use of BI may minimise the need for the development of specific local/species reference chronologies because, at least for locations where temperature is the dominant control on tree growth, BI (and MXD) almost always reflects late growing season temperatures. Therefore, BI or MXD chronologies from different conifer species may correlate significantly with each other as their variability represents the same general response to late summer temperatures. Also, as temperature is spatially more homogenous than precipitation, crossdating using temperature sensitive BI or MXD chronologies could theoretically be possible over quite large regions. The number of long (>500 years) BI/MXD records is continually increasing as a result of dendroclimatic studies (Wilson et al., 2016), and although the Northern Hemispheric TR network is still sparse in places, these data should help facilitate the dating and provenancing of historical material, especially within Europe.

To explore this hypothesis, we compare the spatial climate response of the SMM record (RW and BI) with TR records from Jämtland (central Sweden (RW and MXD from Scots pine) – Zhang et al., 2015), Rogen (central Sweden (RW and BI from Scots pine) - Fuentes et al., in review), Miseri (Austria (RW and BI from Cembran pine) – Nicolussi et al., 2015), Lötschental (Switzerland (RW and MXD from European larch) – Büntgen et al., 2005, 2006) and the Pyrenees (RW and MXD from Mountain pine – Büntgen et al. in review). The spatial correlation for each of these site/regional chronologies for BI/MXD and RW against mean July–August (May–September for PYR) gridded mean temperatures across Europe (Harris et al., 2014) allow an assessment of the potential spatial extent over which these data could be used for the dating of historical material (Fig. 7). The stronger climate signal expressed by BI/MXD compared to RW is evident with an expected weakening of the temperature signal at lower latitudes (Babst et al., 2012). Importantly, the spatial domain expressed by the strong BI/MXD correlations is much greater than RW suggesting that these BI and MXD data-sets could be used as historical reference chronologies over relatively large regions (ca. 300–500 km around each reference chronology) – meaning that the current relatively sparse network of long BI/MXD chronologies may suffice to facilitate crossdating over most parts of Europe.

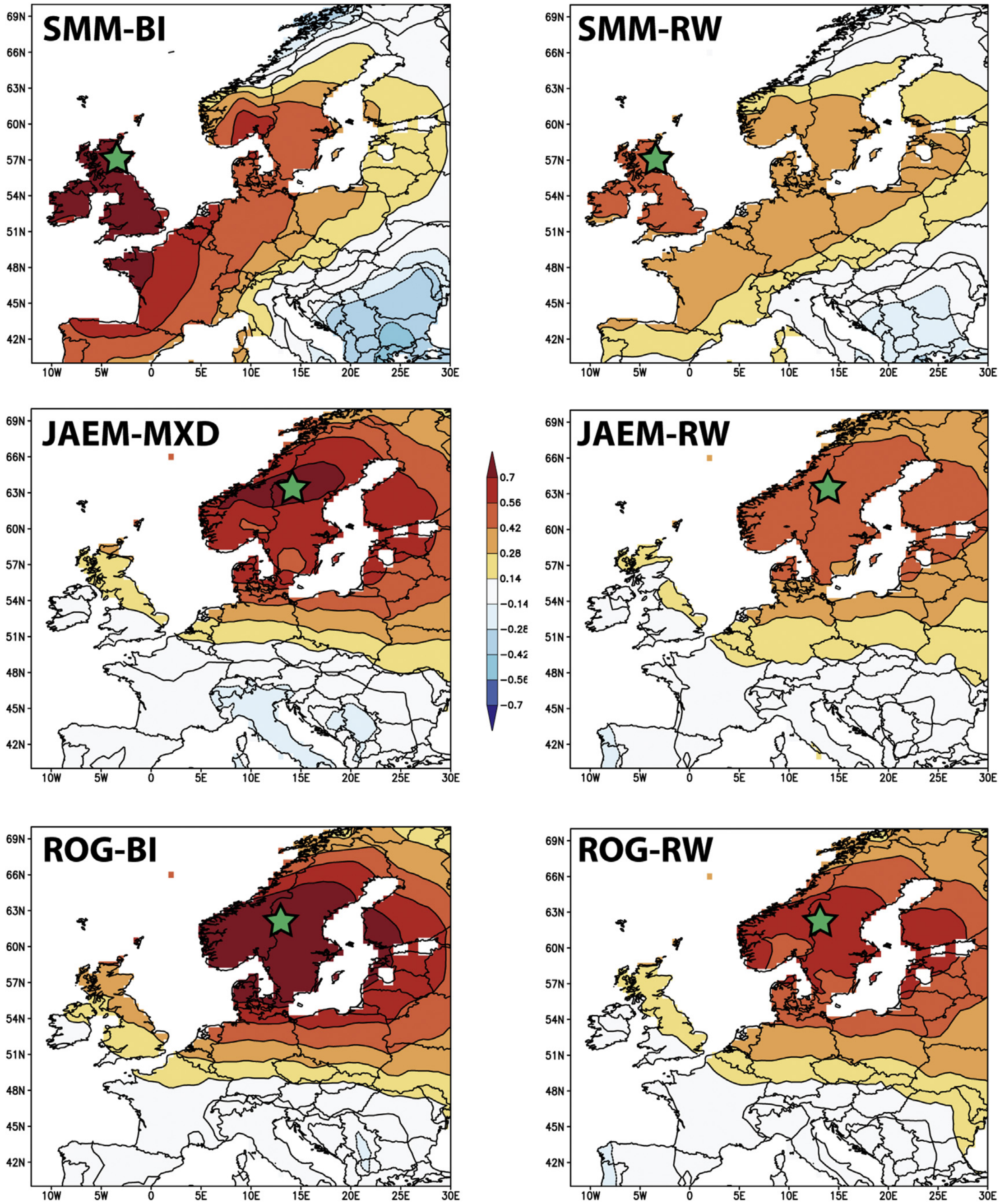

Fig. 7. Spatial correlation (1902–2004) between site/regional BI/MXD and RW chronologies from Scotland (SMM – this paper), central Sweden (Jämtland – JAEM (Zhang et al., 2015); Rogen – ROG (Fuentes et al., in review)), Austria (Miseri – MIS (Nicolussi et al., 2015)), Switzerland (Lötschental – LOTS (Büntgen et al., 2005, 2006)) and the Pyrenees (PYR – Büntgen et al. in review) and CRU TS3.23 (Harris et al., 2014) 0.5-degree gridded mean July–August temperatures (May–September for PYR). The BI data have been inverted to provide the same positive correlation with temperature as expressed by the MXD and RW data. All data were 1st differenced prior to analysis.

4. Conclusion

Using a Scottish case study, this paper has shown that the utilisation of BI can substantially increase the probability of attaining a successful crossdate of conifer samples taken from historical structures. Site specific factors influencing growth can potentially weaken the climatic signal expressed in RW while BI appears more resilient to such effects and retains a "purer" common climate related signal even from sites affected by disturbance. RW data should however not be ignored. From our experience of dating subfossil material using both RW and BI (Wilson et al., 2012; Rydval et al. in review-a), more confidence in a crossdate can be attained for a sample when the same calendar date is independently indicated by both TR variables. The quality of BI data can be detrimentally affected by discolouration, rot, wormholes and reaction wood which weaken the signal and so the RW based validated crossdate can often be important if T-values using BI are low.

A general guide for crossdating in Scotland is that so long as pine timbers are sourced locally (or within the region represented by the SMM), dating should be guaranteed, when using BI, so long as a site/phase master is replicated with at least 4 trees (with a mean sample length of 80 years) although varying replication through

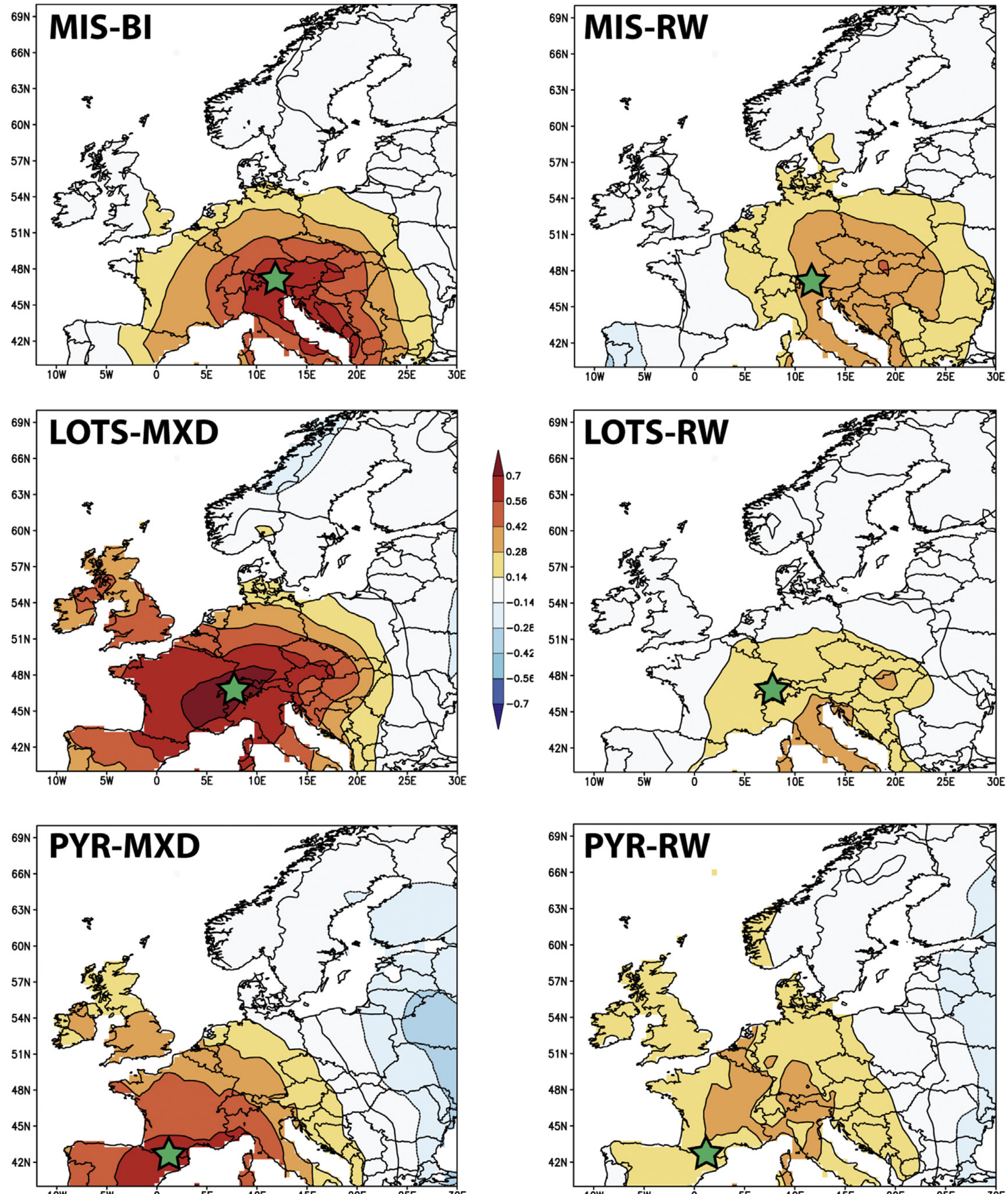

Fig. 7. (*continued*).

time may have a significant impact on dating success and caution is advised when including poorly replicated sections of chronologies. Samples of greater length, as well as measuring 2 or more radii from the same sample, will of course increase the probability of crossdating success. Crossdating is undoubtedly possible with RW data, but as such data express a weaker regional scale climate signal and can be influenced by site specific effects, the probability of acquiring a correct date will be reduced without also concurrently using BI.

Finally, it is important to emphasise that the Scottish pine network was sampled for dendroclimatic purposes (Wilson et al., 2012; Rydval et al., 2016b; in review-a) using trees from sites located at higher elevations (300–600 m a.s.l.) where temperature is the predominant limiting factor controlling growth. It is basic dendroecological theory that the response of trees to climate will vary with elevation (Fritts et al., 1965; LaMarche, 1974; Kienast et al., 1987; Wilson and Hopfmueller, 2001) so low and high elevation chronologies of the same species may not necessarily correlate (Wilson et al., 2004). This is not a problem in itself, but reference chronologies must be developed for regions (and species) relevant to the source regions of construction timbers. The large spatial finger-print of the temperature signal expressed by BI (and MXD) data across Europe (Fig. 7) suggests that a sparse network of temperature sensitive BI/MXD chronologies could suffice for dating and possibly provenancing historical material from across this large continental region. However, no analysis of the climate signal expressed in BI/MXD data from lower elevation conifer sites has been performed. Therefore, for historic structures built with conifer timbers from lower elevations, substantial effort is needed to create lower elevation BI/MXD reference chronologies not only to test their spatial coherence but also to assess their dating (and climatic) potential.

Acknowledgments

The Scottish pine network expansion has been an ongoing task since 2006 and funding must be acknowledged to the following projects: EU project 'Millennium' (017008-2), Leverhulme Trust project 'RELiC: Reconstructing 8000 years of Environmental and Landscape change in the Cairngorms (F/00 268/BG)', the Native Oak and Pine project or 'NOAP' (Historic Scotland) and the NERC project 'SCOT2K: Reconstructing 2000 years of Scottish climate from tree rings (NE/K003097/1)'. Further PhD funding for Milos Rydval is acknowledged from The Carnegie Trust.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jas.2016.11.011.

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