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ORIGINAL ARTICLE

An evaluation of english oak earlywood vessel area as a climate proxy in the UK

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ABSTRACT

This research evaluates the usefulness of oak earlywood vessel area as a climate proxy in the western United Kingdom (UK). The results demonstrate that at this site earlywood vessel area contains a different environmental signal (March relative humidity) to a ring-width chronology developed from the same trees. The vessel area signal passes commonly used verification statistics and was found to be representative of the climate of a similar geographic area to other tree-ring proxies, albeit with a lower explained variance. Taking the average of all the vessels identified for each year weakened the reconstructed climate signal and it was found for this study that the average of the 10 largest vessels provided the strongest and most stable match. The results demonstrate earlywood vessel area of oak in the UK has potential as a climate proxy, but that further work to strengthen and characterise the climatic target variable controlling vessel area is required.

1. Introduction

Climate proxies provide an approach to examine past changes in climate, and under favourable circumstances, these can be used to extend records back beyond the period of direct instrumental observations. This provides a longer-term context within which to view recent anthropogenic impacts upon the climate system. Climate proxies are contained in a variety of archives (e.g. ice cores, lake sediments and peat cores). However, tree-rings are advantageous in studying the climate of the Common Era as centennial- to millennial- timescales can be studied with perfect annual resolution. The annual resolution is important in the study of the recent past, as it permits the study of extreme events and the application of statistical calibration, verification and measures of confidence to be established (McCarroll and Loader, 2004).

A growing range of physical and chemical properties of tree-rings have been used as annual climate proxies, including: tree-ring width (Wilson et al., 2013), maximum latewood density (Grudd, 2008), blue intensity (Fuentes et al., 2018) and stable isotope measurements (Loader et al., 2020). One approach to extracting intra-annual information is through the study of wood anatomy. Wood cell features (e.g. diameter and lumen area) have been shown to differ between locations and along climatic gradients (Fonti and García-González, 2004). However, constraints (e.g. cost and time) have impeded the production of accurate measurements and well-replicated chronologies (Eckstein, 2004). Since the latter half of the twentieth century, and with the improvement of fully- and semi-automatic image analysis (e.g. CATS, Land et al., 2017; ImageJ, Schneider et al., (2012); ROXAS, von Arx and Carrer, 2014), there have been a number of investigations relating cell characteristics to environmental signals, especially the water-conducting tissues of conifers (e.g. Belokopytova et al., 2019; Fonti and Babushkina, 2016).

Traditionally, earlywood features have been avoided due to difficulties in identifying a direct environmental relationship (Fonti and García-González, 2004) which in some tree species has been linked to the variable use of stored photosynthates in earlywood formation (Hill et al., 1995; Kimak and Leuenberger, 2015; McCarroll et al., 2017; Switsur et al., 1995). Nevertheless, earlywood vessel studies have proved useful and have demonstrated their capacity to capture a diverse range of environmental information relating to spring and early summer flooding (Astrade and Bégin, 1997; George and Nielsen, 2000; Meko and Therrell, 2020; St George et al., 2002) as well as other ecological events (e.g. mass movement; Arbellay et al., 2013; forest fire; Kames et al., 2011). Most studies, however, have been on climatic variables.

Both current and previous year climatic conditions can affect earlywood vessel development with the latter being hypothesised to be a result of climatic influences on carbohydrate storage and tree structure (García-González et al., 2016). Relationships with precipitation

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(Eilmann et al., 2006; García-González and Eckstein, 2003), drought conditions (e.g. Corcuera et al., 2004; Fonti and García-González, 2008; Pumijumnong and Park, 1999), temperature (Fonti and García-González, 2004; Jevšenak et al., 2018; Matisons et al., 2012; Matisons and Brūmelis, 2012; Pritzkow et al., 2016) and soil water excess (e.g. González-González et al., 2015) have also been documented. Eilmann et al. (2006) provided a number of explanations that could account for these studies reported response to differing climatic variables, including: distinct species-related response to water availability, different site characteristics, and internal controls on earlywood production (Sass and Eckstein, 1995). Earlywood vessel characteristics appear to have the advantage of being buffered from non-climatic events – unlike other tree-ring proxies – thus retaining climatic information that may otherwise have been lost (García-González et al., 2016). However, while being resistant to non-climatic extreme events, there is also evidence to suggest that the vessel response to extreme climatic events may also be muted or absent (e.g. Puchałka et al., 2016).

The suitability of earlywood vessels as an environmental proxy in many regions is not yet fully established however, as it is frequently reported that the statistical quality of vessel series is poor in comparison to ring-width chronologies. For instance, Fonti and García-González (2008) who compared ring-, latewood- and earlywood-width to mean vessel area at three locations, found that the common variability, signal and mean sensitivity was reduced in the vessel chronologies, compared to standard ring-width measurement series. Similar findings are reported across the literature (e.g. Campelo et al., 2010; García-González and Eckstein, 2003; Pritzkow et al., 2016; Souto-Herrero et al., 2017). However, the relatively weak series quality could be due to a blurring of environmental signals as demonstrated by García-González and Fonti (2006).

Relative to other tree-ring parameters, the use and study of earlywood vessel area as a climatic proxy is still in its early stages. There have been few studies over a limited spatial extent and to the best of our knowledge, none published for the UK. Although there are now a growing number of longer time-series of earlywood vessels (e.g. 201 years; Pritzkow et al. (2016); 481 years; Souto-Herrero et al. (2017)), the majority remain exploratory in nature or based upon short periods (e.g. 25 years; García-González and Fonti (2008), 22 years; Alla and Camarero (2012)). To date and to the best of our knowledge, only Pritzkow et al. (2016) have used statistics such as the Reduction of Error (RE) and Coefficient of Efficiency (CE) on a vessel time-series which are recommended to evaluate the skill of a climate reconstruction (National Research Council, 2006). Little is also known about the extent of the spatial correlation field of any environmental signal captured, although Pritzkow et al. (2016) identify a spatial correlation field comparable to other tree-ring based proxies.

Within the UK the use of oak earlywood vessels as a climatic proxy has great potential. There is already a well replicated database of oak series in the UK, which would allow for vessel chronologies to be produced that cover many hundreds of years. The distribution of oak is not limited to extreme areas within the UK and is commonly found growing near regions of human populations both now and in the past. If it was demonstrated that vessel area contained a climatic signal in climatically non-marginal locations, there is the potential to interrogate this archive to directly examine how climatic change has occurred in relation to well-documented historical and societal changes in the UK.

This study will develop oak earlywood vessel chronologies of differing vessel sizes from trees growing in south Wales (UK) and evaluate their statistical properties. It will then identify the relationship between instrumental climate data and the different combinations of earlywood vessel sizes. The suitability and spatial field of any climate-vessel relationships identified will be tested statistically with a view to their application to reconstruct the climate of the past for the UK.

2. Material and methods

2.1. Location

Samples were collected from the National Botanic Gardens of Wales (NBGW) and the adjacent Waun Las National Nature Reserve (51°50′ N, 04°08′ W; 87 m a.s.l.). The vegetation is dominated by semi-improved grassland and dense scrub woodland as described by the National Vegetation Classification System (Rodwell, 1992, 1991). There is evidence of minor management of the larger vegetation within the NBGW, while it appears minimal or absent in the nature reserve. Average annual temperature is 9.8 °C, while average annual total precipitation is 1365 mm (measurement period: 1961–1990).

2.2. Sample selection, preparation and measurement

10 pedunculate oak trees (*Quercus robur* L.; Table S1) were selected and dual 5 mm cores were obtained at breast height (1.3 m). Samples were obtained perpendicular to the topographic slope to minimise reaction wood (Fonti et al., 2009). Cores were left to air-dry, before the transversal surface was progressively prepared with sandpaper (P80, P400 and P600 grades). Prior to analysis, vessel lumina were first cleared with compressed air, then the wood matrix of each core was stained black; and vessel lumina were in-filled with white chalk (after Alla and Camarero, 2012; Fonti et al., 2007; Fonti and García-González, 2008; see supplementary information).

Ring-widths were measured for cross-dating purposes using a binocular microscope (Nikon SMZ645) and horizontally travelling Velmex stage. Cross-dating was conducted using the software TSAP (Rinn, 2003; see supplementary information). Digital images were captured using an EPSON Perfection V750 scanner at 6400 DPI and vessel analysis conducted with WinCELL PRO (version 2013; Régents Instruments Inc., Québec, Canada). To optimise correct identification of earlywood vessels, several filters were applied (Table S2). The output was visually inspected to identify and to remove any false classifications (e.g. merger of vessels) following application of the different filters. WinCell PRO also calculated ring-width measurements which were used to validate the TSAP measurements used for cross-dating and were further used in the chronology construction.

2.3. Chronology construction, evaluation and climate response analysis

The expression of a climate signal in earlywood vessel area was investigated with 4 average vessel time-series. For comparison, a standardised ring-width series was also produced using the same trees studied for vessel characteristics. These series are identified as follows:

1) MAX – A series comprising of the largest annual earlywood vessel area,
2) 5MAX – A series comprising of the annual average of the 5 largest earlywood vessel areas,
3) 10MAX – A series comprising of the annual average of the 10 largest earlywood vessel areas,
4) MEVA – A series comprising of the annual average of earlywood vessel area,
5) RW – A standardised tree-ring width series.

Non-climatic trends were removed from each individual ring-width and vessel series with a 32-year cubic smoothing spline with 50 % cut-off (Fonti and García-González, 2008, 2004; Souto-Herrero et al., 2017), using the R (version 3.6.2; R Core Team, 2018) package DetrendeR (version 1.0.4; Campelo et al., 2012). Prior to chronology construction, vessels were measured for each annual ring of the tree's dual cores and combined (García-González and Eckstein, 2003). Each cell chronology variant was then calculated and data detrended for each individual tree prior to their combination by averaging to create a site chronology.

A common set of statistics used to evaluate chronologies were selected: the mean inter-tree correlation (Rbt), the expressed population signal (EPS) (Wigley et al., 1984), mean sensitivity and first-order autocorrelation. These were calculated using the dplR package (version 1.7.0; Bunn, 2008) in R. By rearranging the EPS equation, an estimation of the sample depth required to attain an EPS value of 0.85 was made. The association between the vessel chronologies and RW were evaluated by correlating each vessel chronology and RW (RW r), while the coefficient of determination (r^2) was used to quantify the shared variability (RW r^2). Climatic influences were tested with the Pearson correlation coefficient. Precipitation and temperature data were sourced from the CRU TS3.24.01 0.5° gridded dataset (University of East Anglia Climatic Research Unit et al., 2017). Monthly Relative humidity data were extracted from the gridded 5-km^2 observed UK Climate Dataset (Met Office, 2017). The nature of the climatic signal for the period prior to the earlywood growing season was tested by offsetting August to December meteorological measurements by one year. For current year correlations the period of 1947–2012 was used for temperature and precipitation, while 1961–2011 was used for relative humidity. For previous year correlations, 1946–2011 from the temperature and precipitation datasets was used, while for relative humidity 1961–2010 was used again but there was a reduced number of paired data. Seasonal data was constructed by summing monthly precipitation values and averaging monthly relative humidity and temperature measurements. The meteorological seasons were calculated as: autumn – (-) September, (-)October and (-)November, winter – (-)December, January and February, spring – March, April and May and summer – June, July and August, with (-) indicating previous year data.

2.4. Examining chronology suitability for climate reconstructions

The strongest climate correlations were modelled through reverse linear regression. This allowed for the evaluation of earlywood vessel chronologies as a climatic proxy through use of the statistical tests: RE, CE and r^2 using split-window calibration and independent verification periods with half of the data in each window. The footprint of the most reliable correlation was then investigated using spatial correlation analysis computed using Climate Explorer (Trouet and Van Oldenborgh, 2013).

3. Results

3.1. Vessel and tree-ring characteristics

Dual core coverage varied for each sampled tree, with the longest period between 1823–2012 (NBGW06; Figure S2). With the exception of NBGW07 and NBGW14, all samples had dual coverage for the 1947–2012 period used for calibration and verification.

Between 1823–2012; 45,628 earlywood vessels were measured with the frequency distribution positively skewed (0.47). Vessel area ranged between 10,002 μm^2 and 148,642 μm^2 with a mean of 50,162 μm^2.

3.2. Chronology evaluation

The 5 chronologies are presented in Fig. 1 with their statistical characteristics summarised in Table 1. The EPS and Rbt values demonstrate that RW contained the strongest common signal in comparison to the vessel chronologies. MEVA contained the weakest common signal; however, subsets of earlywood vessels demonstrated an improvement in chronology cohesion with the addition of earlywood vessels reflected in a reduction of ESD. All earlywood vessel chronologies were similarly muted in their annual variability, while RW in comparison was more pronounced. First-order autocorrelation was low for all vessel series, while RW demonstrated a stronger preceding year influence. Apart from MEVA, all vessel chronologies were significantly correlated with RW. On

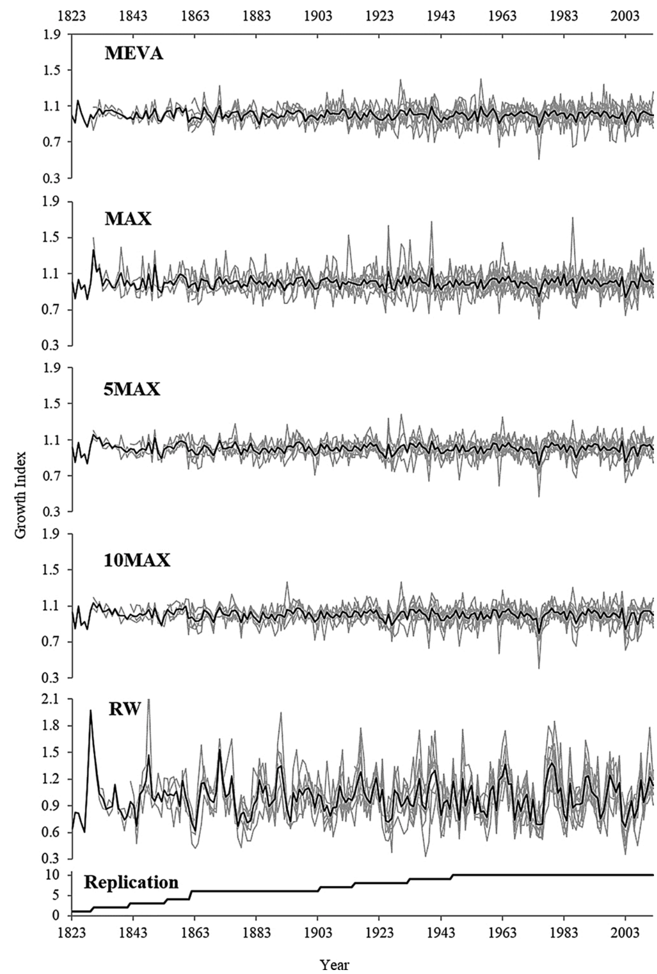

Fig. 1. Constructed chronologies for the period 1823 – 2012. Grey line represents individual series and black line is the sample mean.

Table 1
Expressed population signal (EPS), estimated sample depth for an EPS of 0.85 (ESD), mean correlation between standardised chronologies (Rbt), mean sensitivity (MS), first order autocorrelation coefficient (AC1), correlation with RW (RW r) and vessel variability explained by RW (RW r^2) for the common period (1947 – 2012) for each chronology.

Chronology	EPS	ESD	Rbt	AC1	MS	RWr	RW r^2
MEVA	0.41	80	0.06	0.01	0.05	0.15	0.02
MAX	0.53	49	0.10	−0.04	0.06	0.37*	0.14
5MAX	0.62	34	0.14	0.07	0.05	0.43*	0.18
10MAX	0.66	29	0.16	0.07	0.06	0.45*	0.20
RW	0.91	6	0.51	0.37	0.18	–	–

* significant at p <0.01.
n = 10 trees.

average, 14 % (average RW r^2) of the variation in the vessel chronologies could be explained by the RW series.

3.3. Climate response

Climate-growth correlations are presented in Fig. 2. As a factor controlling growth, precipitation had a lesser influence on earlywood vessel area than temperature or relative humidity. Springtime relative humidity demonstrated the closest relationships to vessel development, with March exhibiting the strongest correlations. The weakest vessel match with March relative humidity was found when all vessels were included in the chronology (MEVA; r = 0.39, p < 0.01, n = 51). By

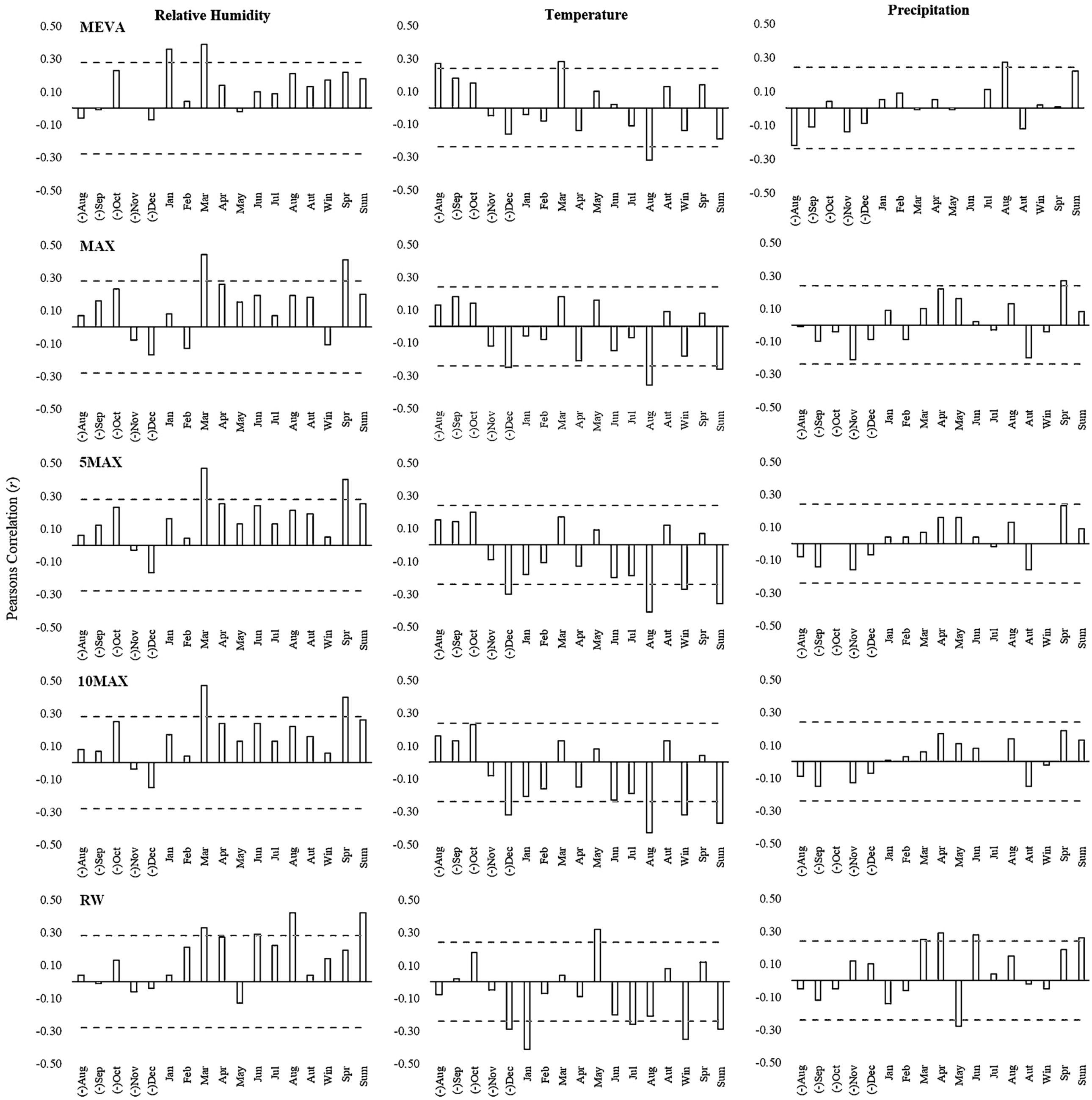

Fig. 2. Composite correlation diagrams (Pearson's correlation coefficient) between constructed series and monthly relative humidity (1961 – 2011), temperature (1947 – 2012) and precipitation (1947 – 2012). For temperature and precipitation, the previous year correlation period utilised the climatic data for 1946 – 2011 and for relative humidity 1961 - 2010. (-)Aug – Aug represents monthly correlations beginning with August of the previous year running to August of the year of vessel growth. (Aut = Autumn, Win = Winter, Spr = Spring and Sum = Summer).

controlling the number of vessels, there was an improvement in correlation strength with 5MAX and 10MAX performing best (MAX; $r = 0.44$, $p < 0.01$, n = 51, 5MAX; $r = 0.47$, $p < 0.01$, n = 51, 10MAX; $r = 0.47$, $p < 0.01$, n = 51). In contrast, the RW series had the weakest correlation with March relative humidity ($r = 0.33$, $p < 0.05$, n = 51). The strongest correlation with RW was also with relative humidity, but this was limited to the summer season ($r = 0.42$, $p < 0.01$, n = 51) and August ($r = 0.42$, $p < 0.01$, n = 51). There was also a highly significant correlation between January relative humidity and MEVA ($r = 0.36$, $p < 0.01$, n = 51). In comparison, the strongest correlation with the vessel chronologies for temperature was with August (r = -0.43, $p < 0.01$, n= 66) and, but weaker, with combined summer months (r = -0.37, $p < 0.01$, n= 66). There were also highly significant correlations between the vessel chronologies and wintertime temperatures peaking with 10MAX (r = -0.32, $p < 0.01$, n = 66). The strongest correlation with precipitation was with August ($r = 0.27$, $p < 0.05$, n = 66) and spring ($r = 0.27$, $p < 0.05$, n = 66). A similar pattern was observed in temperature and precipitation as with the relative humidity correlations, with a general improvement in signal strength by controlling vessel sizes. Although, this was not the case for the correlations between MAX and precipitation where the strongest match was observed with spring ($r = 0.27$, $p < 0.05$, n = 66) and weakened in 5MAX ($r = 0.23$, $p < 0.05$, n = 66) with insignificant correlations for the chronologies 10MAX ($r = 0.19$, $p > 0.05$, n = 66) and MEVA ($r = 0.01$, $p > 0.05$, n = 66).

3.4. Suitability for climate reconstructions

The strongest correlations – between March relative humidity and

5MAX and 10MAX – were modelled and examined to evaluate the proxy's ability to capture the climate signal (Table 2). For both the forward and reverse models the RE and CE demonstrate a stable signal in the calibration and verification periods between the target climate and both vessel chronologies and the results can be considered significant as the test values are greater than zero. However, the results demonstrate that 10MAX was the strongest vessel series in terms of its inter-series and climate signal strength, and the stability of the reconstruction (Figs. 3 and 4). This series was therefore used to examine the spatial field of the correlation with relative humidity. Fig. 5 demonstrates that 10MAX is significantly correlated ($p < 0.05$) with March relative humidity for much of the western UK.

The results demonstrate that the vessel chronologies were able to capture a significant and stable climatic signal in addition to being correlated with a large spatial area. However, when critically assessing the ability of the chronology to reconstruct past environmental changes, in this case, the low inter-series common signal, the authors could not justify presentation of a formal reconstruction.

4. Discussion

For earlywood vessels to be useful as a proxy in the UK there are a number of conditions that should be met: 1) a strong shared common signal between constituent trees (Fonti and García-González, 2008), 2) a better or unique environmental signal in comparison to easier to obtain tree-based proxies (Fonti and García-González, 2004), 3) a climate signal that is representative of a large spatial area, and 4) the reconstruction passes climate reconstruction verification statistics.

The stronger inter-series coherence that ring-width series contain, in comparison with vessel chronologies is frequently reported (Campelo et al., 2010; Fonti and García-González, 2008, 2004; García-González and Eckstein, 2003). The results here are no different and can be explained by biological controls having a strong influence on vessel development (Eilmann et al., 2006; Fonti and García-González, 2004; Woodcock, 1989) to ensure sufficient annual hydraulic conductivity (Alla and Camarero, 2012; Bréda and Granier, 1996; Fonti et al., 2009). To overcome this natural variability, as demonstrated by the ESD, it may be necessary to increase sample size, thereby allowing the weaker common signal to be enhanced. However, this is not a trivial task and the low inter-tree correlation would remain even where the EPS exceeded 0.85 as the number of trees was increased. Where such limits are strongly expressed this could prevent the ability of a vessel chronology to capture extreme events (e.g. Puchałka et al., 2016). It does appear that vessel area chronologies have the advantage of low autocorrelation (i.e. reduced influence of the previous year's climate) in comparison to ring-width series, which could offer some practical advantages over ring-widths.

Humidity has previously been linked with vessel area size variations (Kondoh et al., 2006), and the relationship with moisture availability is widely acknowledged (e.g. Corcuera et al., 2004; Eilmann et al., 2006; Fonti and García-González, 2004; García-González and Eckstein, 2003; Pumijumnong and Park, 1999) as it is believed to be linked to turgor pressure within the trees hydro-system (Boyer, 1985; Eilmann et al., 2006; Ray et al., 1972). Vessels begin development prior the first-flush of leaves, which in South Wales commonly occurs at the end of March and start of April (Forestry Comission, 2001), hence a correlation with March relative humidity is not unexpected. In the Iberian Peninsula it has also been observed that in *Q. robur* that earlywood vessel development begins in early March, with cell maturation occurring in late March and mid-May (Pérez-de-Lis et al., 2016). In contrast, tree growth is controlled by the totality of environmental factors over a longer period, so it is perhaps not unsurprising that the vessel series contain a different climatic signal to the ring-width chronology developed for the same trees.

Table 2
Analysis of climatic reconstruction stability of 5MAX and 10MAX with March relative humidity for the period 1961 – 2011 using the Reduction of Error (RE), Coefficient of Efficiency (CE) and Coefficient of Determination (r^2).

	RE	CE	r^2 Calibration Period
		5MAX	
Forward[1]	0.23	0.23	0.18
Reverse[2]	0.11	0.11	0.27
		10MAX	
Forward[1]	0.20	0.20	0.23
Reverse[2]	0.22	0.22	0.21

[1]Calibration Period: 2011 – 1986, Verification Period: 1985 – 1961.
[2]Calibration Period: 1985 – 1961, Verification Period: 2011 – 1986.

During earlywood development, the size of new vessels decreases as the seasons progress. By controlling the vessels incorporated into the chronologies by size, it was possible to improve both the common inter-series and climatic signals (correlations and reconstruction stability). This suggests that vessels that have developed at the beginning of the earlywood may contain different signals to those formed later (see García-González and Fonti, 2006) and the capture of this signal can be improved by selecting vessels of a similar size within each ring (i.e. formed at a similar time). By using an alternative method based on percentage of vessels (García-González and Fonti, 2006; González-González et al., 2014) it may be possible to enhance and *fine-tune* the measurement of the climatic signal further, which may improve climate and inter-tree correlations. However, this may not be the case for all species (González-González et al., 2014).

The results show that our vessel chronologies from south Wales hold a climatic signal that passes verification and validation statistics, a prerequisite of any proxy-based climate reconstruction (National Research Council, 2006). In fact, by altering the number of vessels incorporated into the chronologies it was possible to improve the reconstruction stability – again highlighting the promise of fine-tuning vessel selections based on size in chronology building. *Q. robur* in Poland has also been found to contain a climatic signal within average earlywood vessel area that is stable enough for a reconstruction (Pritzkow et al., 2016). To date, only Pritzkow et al. (2016) has demonstrated the ability of vessel area chronologies to contain a climatic signal that is representative of a large spatial area that is comparable to other tree-ring proxies (e.g. Treydte et al., 2007; Wilson et al., 2017; Young et al., 2015). The results presented here reinforce this finding. Considering the relatively weak inter-series correlation between constituent trees, this is encouraging. Together, our results and those of Pritzkow et al. (2016) would suggest that vessel series may be useful in reconstructing regional climatic variability, as well as local environmental factors.

With reference to the suitability of average vessel area as a proxy in the UK, the results are encouraging, but do not support the reporting of a reconstruction yet. The trees sampled are from a location that is rarely moisture limited (c.1,365 mm rain per annum), which may influence year-to-year variability in vessel area and correlations with climatic data. Nevertheless, there is scope for further research, the method could be applied to oaks growing in “drier” parts of the UK, for example East Anglia, which might yield stronger hydro-climate and inter-series correlations and with a longer-term perspective, the UK has a rich supply of living oak and archaeological samples that would allow development of long vessel area chronologies with high levels of replication. Finally, through process studies (e.g. Puchałka et al., 2017) and the refinement of the selected vessel groups (i.e. percentages) it may be possible to further enhance the recorded climatic signal to a point of more routine application. We cannot ignore that it may be the case that in low moisture-stress regions such as the UK, the best use of oak earlywood vessel area may be as part of a multi-parameter approach, combining vessel area with stable carbon isotopes to provide a clearer understanding of tree hydro-system dynamics (Locosselli et al., 2013; Ponton et al., 2001).

The results presented here are promising and should be seen to

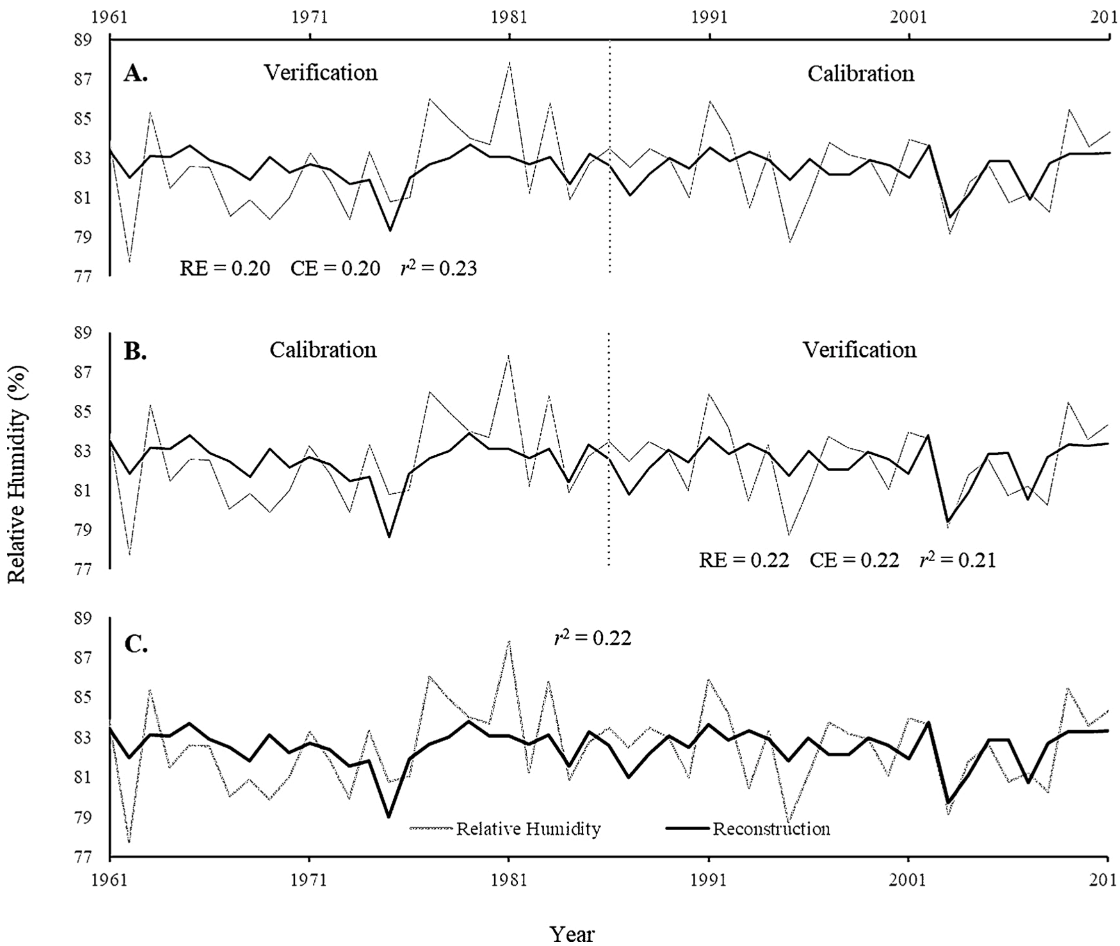

Fig. 3. Calibration and Verification results. RE – Reduction of Error, CE – Coefficient of Efficiency and r^2 – Coefficient of Determination. Grey line – Relative humidity; Black line – Reconstruction based on 10MAX. Analysis periods: 1961-1985 and 1986-2011. Plot A: Forward calibration, Plot B: Reverse calibration and Plot C: Full reconstruction.

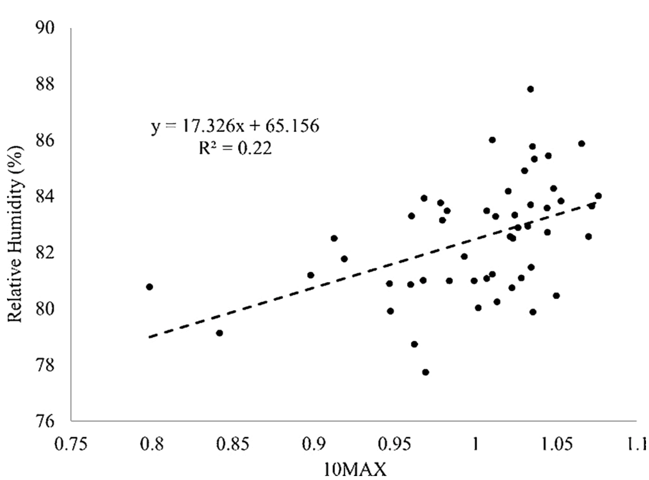

Fig. 4. Scatter plot illustrating the regression line used to reconstruct March relative humidity (%) using 10MAX over the common period (1961 – 2011).

stimulate further efforts in the UK. However, by critically assessing our methodology several issues have been identified which may have impacted our results and should also be considered here and when conducting future vessel analyses. Sample preparation and image quality are paramount in visual-based techniques. Efforts were taken to remove debris from vessel lumina, such as the use of dry compressed air.

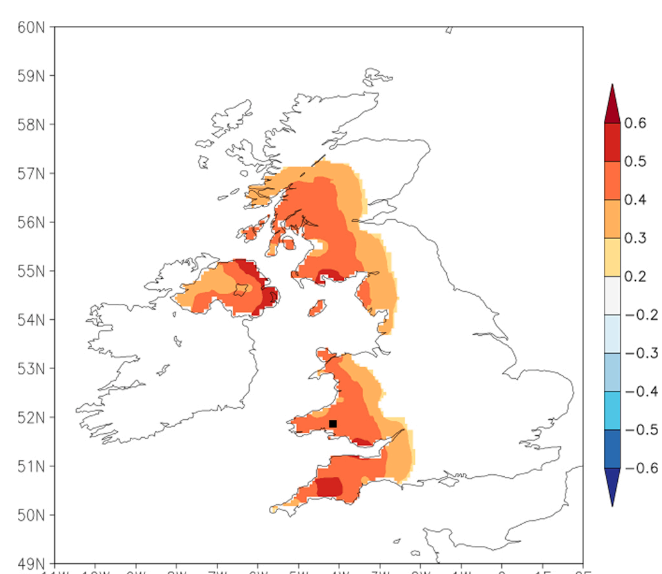

Fig. 5. Spatial field correlation between 10MAX and the 5-km^2 gridded observed UK Climate Relative Humidity Dataset (Met Office, 2017). Produced using Climate Explorer (Trouet and Van Oldenborgh, 2013). The location of the study site is marked as a black square. Data available for UK only.

However, these were not 100 % effective as analysis of the images shows that there are instances where tyloses have remained. In such cases, this could increase vessel measurement inaccuracies. Future work in the UK may benefit from making use of image analysis algorithms, microtoming or manual exclusion to correct inaccurate measurements caused by the retention of tyloses.

In this study, where merged vessels were missed by the filters, they were removed from the analysis by the operator to prevent measurement bias. Image analysis software may offer a less subjective approach for the separation of merged vessels. Indeed, it is possible that if these additional steps had been applied to our dataset that the presented results may have improved. However, as the measurement errors are random, and as we average numerous vessel records from multiple cores and trees, the impact on the overall result is believed to be small. Even with this simpler method, our results are not notably different from other similar vessel area studies (e.g. García-González and Eckstein, 2003). Incorporating these additional sample preparation and image analysis protocols where appropriate/feasible, and increasing sample replication (number of trees) represent the most practicable first steps to advancing the vessel area method in the UK.

5. Conclusion

Annually resolved climate proxies are critical for understanding the long-term behaviour of our climate system. This research has investigated the suitability of earlywood vessel area of *Q. robur* L. in the UK as such a proxy. It was demonstrated that vessel area in the UK contains a distinct climatic signal compared to that identified within a ring-width series and that this signal could be enhanced by removing vessels that had developed later in the growing season. The relative humidity signal captured was representative of a significant area of the UK, comparable to other tree-ring proxies. However, inter-tree signal strength was relatively low which precluded the reporting of a full climatic reconstruction. Further methodological refinements and high levels of sample replication will undoubtedly be required. However, given the encouraging results obtained, future investigation into the use of earlywood vessel area as a climate proxy in the UK is recommended, both in isolation and as part of a multi-parameter approach.

Declaration of Competing Interest

None.

Acknowledgements

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.dendro.2020.125777.

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