

Irish Geography

November 2016

ISSN: 0075-0778 (Print) 1939-4055 (Online)
<http://www.irishgeography.ie>



Stable oxygen isotopes in Irish oaks: potential for reconstructing local and regional climate

Hazel Vallack, Neil Loader, Giles Young, Danny McCarroll and David Brown

How to cite: Vallack, H., Loader, N.J., Young, G., McCarroll, D. and Brown, D. (2016) 'Stable oxygen isotopes in Irish oaks: potential for reconstructing local and regional climate'. *Irish Geography*, 49(2), 55-70, DOI: 10.2014/igj.v49i2.1234

Stable oxygen isotopes in Irish oaks: potential for reconstructing local and regional climate

Hazel Vallack^{1,2}, Neil J. Loader^{1*}, Giles H.F. Young¹, Danny McCarroll¹, David Brown³.

¹*Department of Geography, Swansea University, Swansea SA2 8PP, Wales.*

²*School of Geographical Sciences, University of Bristol, Bristol BS8 1SS, England.*

³*Queens University, Belfast BT5 4NQ, Northern Ireland.*

Abstract: The long Irish oak tree-ring chronology, developed for archaeological dating and radiocarbon calibration, is the longest of any in northwest maritime Europe, spanning most of the Holocene (7,272 years). Unfortunately, the rings' widths do not carry a strong climate signal and the record has yet to be satisfactorily applied for dendroclimatic reconstruction. This pilot study explores the potential for extracting a climate signal from Irish oaks by comparing the stable oxygen isotopes ratios from ten oak tree cores (*Quercus robur* and *Quercus petraea* L.) collected across the Armagh region of NE Ireland with local and regional climatic and stable isotopic data. Statistically significant correlations between isotope ratios and the amount of summer precipitation ($r = -0.44$) point to the isotopic composition of summer rainfall as the dominant signal. Including the Armagh data into an extended regional oxygen isotope series did not reduce the correlation coefficient with regional precipitation ($r = -0.68$, $p < 0.01$). Correlations of this magnitude in dendro-hydroclimatology are typically restricted to trees growing at their ecological limits. This research suggests that there is considerable potential for including living trees and ancient timbers from Ireland into a regional composite to reconstruct the summer hydroclimate of Britain and Ireland.

Keywords: Tree-rings, *Quercus*, oxygen isotope, Ireland, dendroclimatology.

*Corresponding author

Introduction

High resolution climate reconstructions have the potential to extend beyond instrumental records, establishing baseline levels of natural variability, quantifying the frequency of extreme climatic events and allowing evaluation of models used for projections of future climate change (Loader *et al.*, 2003; McCarroll *et al.*, 2015; Luterbacher *et al.*, 2016). Most reconstructions rely heavily on tree-rings and focus on physical properties such as: ring-width (Kelly *et al.*, 2002; García-Suárez *et al.*, 2009), latewood maximum density (Briffa *et al.*, 1988; McCarroll *et al.*, 2013), blue-intensity (McCarroll *et al.*, 2002; Campbell *et al.*, 2011; Björklund *et al.*, 2013) and vessel area (Tardif and Conciatori, 2006; Campelo *et al.*, 2010; Matisons and Brümelis, 2012). More recently, chemical proxies have been exploited, such as the stable isotope ratios of carbon, oxygen and hydrogen (Saurer *et al.*, 1995; Rinne *et al.*, 2010; Seftigen *et al.*, 2011; Young *et al.*, 2012, 2015).

For long-lived tree species, continuous time series can be constructed over hundreds or even thousands of years (Hantemirov and Shiyatov, 2002; Cook *et al.*, 2006; Bale *et al.*, 2011). However, when using shorter-lived species, long chronologies are constructed through the synchronisation of living, archaeological and sub-fossil samples (Loader *et al.*, 2008) to build a composite chronology, extending back beyond the lifespan of any individual tree (Kelly *et al.*, 1989; Briffa *et al.*, 1999; Gagen *et al.*, 2011). The most common species used to construct long chronologies in European temperate regions, belong to the *Quercus* (oak) genus, in particular *Quercus robur* (pedunculate oak), *Quercus petraea* (sessile oak) and their hybrids. Oaks are long-lived trees and the ring-porous structure means that rings are generally clear and unambiguous, so false or missing rings are rare (Baillie, 1973) allowing successful cross-dating (Hilasvuori and Berninger, 2010). Although such long chronologies have been extremely valuable for archaeological dating (Baillie, 1990) and for calibrating the radiocarbon timescale (Friedrich *et al.*, 2004), oak ring-widths are not strongly correlated with climate. Hence, they have been largely rejected for use in palaeoclimate reconstruction (García-Suárez *et al.*, 2009; Young *et al.*, 2012). This is unfortunate, since the Irish oak tree-ring chronology is the longest in NW maritime Europe, extending back 7,272 years (Kelly *et al.*, 2002; Pilcher *et al.*, 1984). Successful characterisation of a robust climate record from this archive could potentially extend annually-resolved climate reconstructions for Ireland over much of the Holocene where at present there are few annually-resolved records and facilitate linkage between the terrestrial, lacustrine and speleothem archives (McDermott *et al.*, 2011, Turner *et al.*, 2015, Swindles *et al.*, 2010, Roland *et al.*, 2015).

In contrast to measures of tree growth, stable isotope ratios within the tree-rings of oaks growing in a temperate climate have been shown to produce strong correlations with climate parameters (Hilasvuori and Berninger, 2010; Labuhn *et al.*, 2013). Hence, this chemical archive provides the potential for extracting palaeoclimate data from localities or species that show weak correlations between climate and physical tree-ring properties such as ring-width. Carbon and oxygen

isotope ratios extracted from cellulose have been employed successfully to reconstruct climate parameters such as temperature, sunshine and precipitation for temperate regions in Europe (Loader *et al.*, 2008; Young *et al.*, 2012, 2015; Rinne *et al.*, 2013). The $\delta^{18}\text{O}$ value of cellulose is controlled by the $\delta^{18}\text{O}$ of precipitation, which is a product of atmospheric circulation, and evaporative enrichment at the leaf surface. Fractionation does not occur when water is taken up by the roots; instead, the critical site for fractionation is within the leaf (Wershaw *et al.*, 1966). Relative humidity and temperature affect transpiration and can cause a difference in vapour pressure between the air and leaf resulting in an evaporative enrichment of $\delta^{18}\text{O}$ at the leaf surface, by as much as 20‰ (Saurer *et al.*, 1998; Roden *et al.*, 2000). Photosynthetic sugars reflect the isotopic signature of leaf water, although they are enriched in ^{18}O by 27‰ in comparison (Labuhn *et al.*, 2013). During the formation of tree-rings, cellulose is formed from sugars which are transported down the trunk where they exchange between 20 and 50% of their oxygen with the source water being carried through the xylem (Barbour and Farquhar, 2000; Labuhn *et al.*, 2013). Therefore, the dominant climatic signal preserved in the $\delta^{18}\text{O}$ of cellulose is a combination of the $\delta^{18}\text{O}$ of precipitation and relative humidity, which is controlled by air mass characteristics and trajectories (Dansgaard, 1964, Treydte *et al.*, 2014, Young *et al.*, 2015, McCarroll and Loader, 2004).

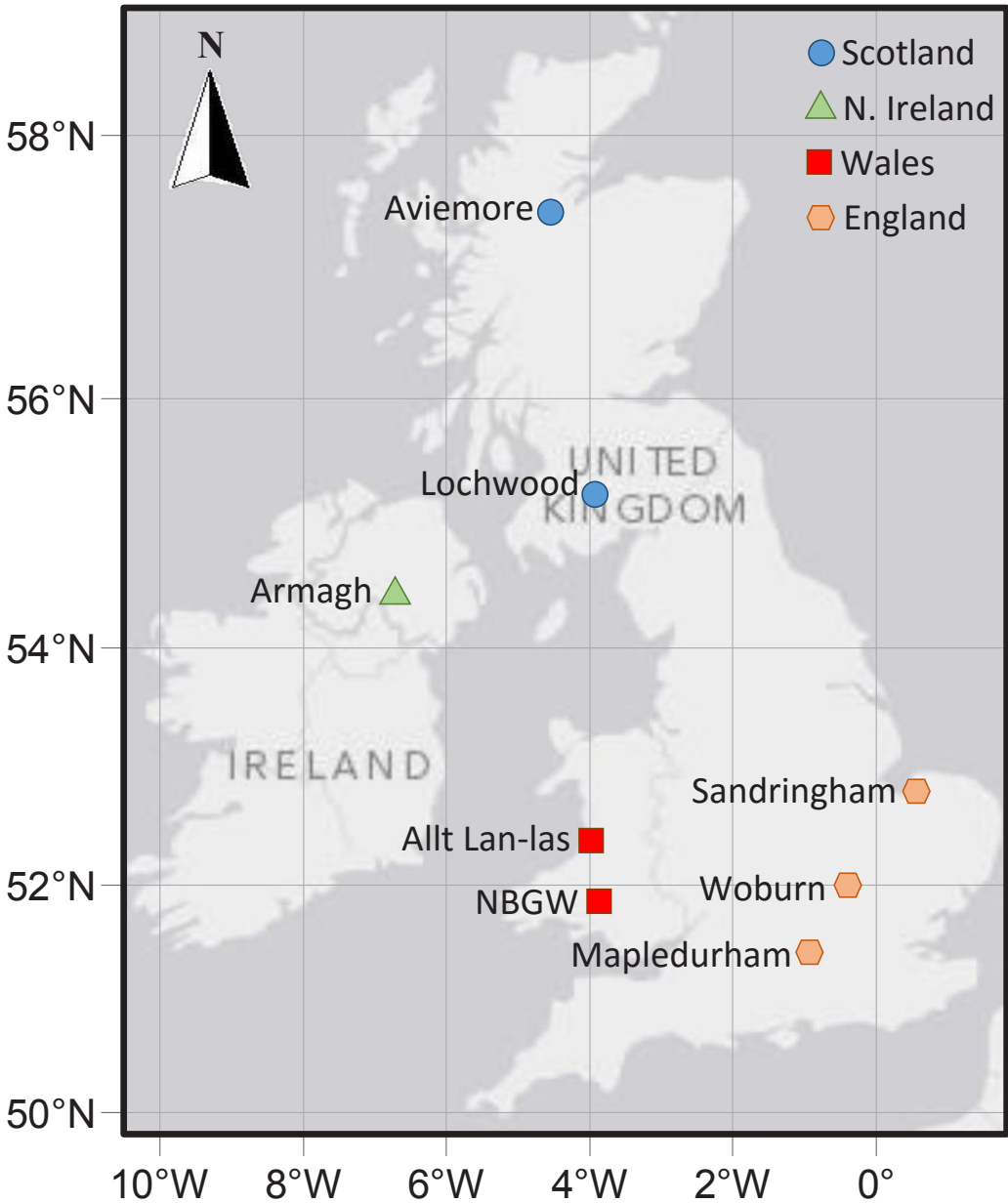
The aims of this study are:

1. To determine whether stable oxygen isotope ratios in Irish oaks carry a climate signal.
2. To determine if the stable isotope ratios from Ireland can be combined with British records to form a composite isotope series for reconstructing climate.

Study site and methodology

Samples of oak were selected from within a 10km radius of the Armagh Observatory (García-Suárez *et al.*, 2009) approximately 700m north-east of the small city of Armagh. The region has a typical temperate, maritime climate (Butler and Coughlin, 1998). Mean annual maximum and minimum temperatures are 12.8°C and 5.6°C respectively, with mean annual precipitation at 816mm and an average annual relative humidity of 85% for the period of AD 1844-2001.

Figure 1: The locations of the Armagh Observatory in Northern Ireland and of the eight $\delta^{18}\text{O}$ chronologies used to form the UK composite.



In order to determine if it is reasonable to include Irish results in a wider reconstruction, the Armagh $\delta^{18}\text{O}$ series was combined with previously published data sets from around the United Kingdom (UK) to form a composite chorology. The seven annually resolved isotope series are well replicated over the common period AD 1880-2001; Lochwood ($55^{\circ}16'\text{N}$ $3^{\circ}26'\text{W}$) (Loader *et al.*, 2008); Sandringham ($52^{\circ}50'\text{N}$ $0^{\circ}30'\text{E}$) (Robertson *et al.*, 2001); Woburn ($51^{\circ}59'\text{N}$ $0^{\circ}35'\text{E}$) (Rinne *et al.*, 2013) and Aviemore ($57^{\circ}19'\text{N}$ $3^{\circ}92'\text{W}$), Allt Lan-las ($52^{\circ}38'\text{N}$ $3^{\circ}92'\text{W}$) and Mapledurham ($51^{\circ}49'\text{N}$ $1^{\circ}26'\text{W}$) (Young *et al.*, 2015). Climate data were obtained from the Armagh Observatory meteorological station ($54^{\circ} 21.2'\text{N}$ $6^{\circ}38.8'\text{W}$) the archives of which contain measurements since AD 1784, and represents the longest continuous meteorological records in Ireland, and one of the longest in the UK (Butler, 1990; Butler and Coughlin, 1998). The UK $\delta^{18}\text{O}$ composite series was calibrated and verified with the 'England and Wales precipitation (EWP) record' (Wigley *et al.*, 1984).

Wood cores of 4mm diameter were obtained using a standard increment borer, and prepared by García-Suárez *et al.*, (2009) using standard dendrochronological methods as described by Stokes and Smiley (1968). The cores were cross-dated against each other using TSAP (RINNTEC, Germany) and of the 14 cores provided, 10 were selected for isotopic analysis based upon their consistent inter-tree cross dating ($t \geq 3.5$) (Baillie and Pilcher, 1973), tree-age and ring-clarity. Using a razor blade and microscope, the latewood portion of each annual ring was then removed as thin slivers. Ring porous trees like oak use reserves to build earlywood, so the latewood was targeted to provide true annual resolution (Switsur *et al.*, 1995, Kimak and Leuenberger, 2015, McCarroll *et al.*, in review). The samples were then pooled prior to chemical treatment.

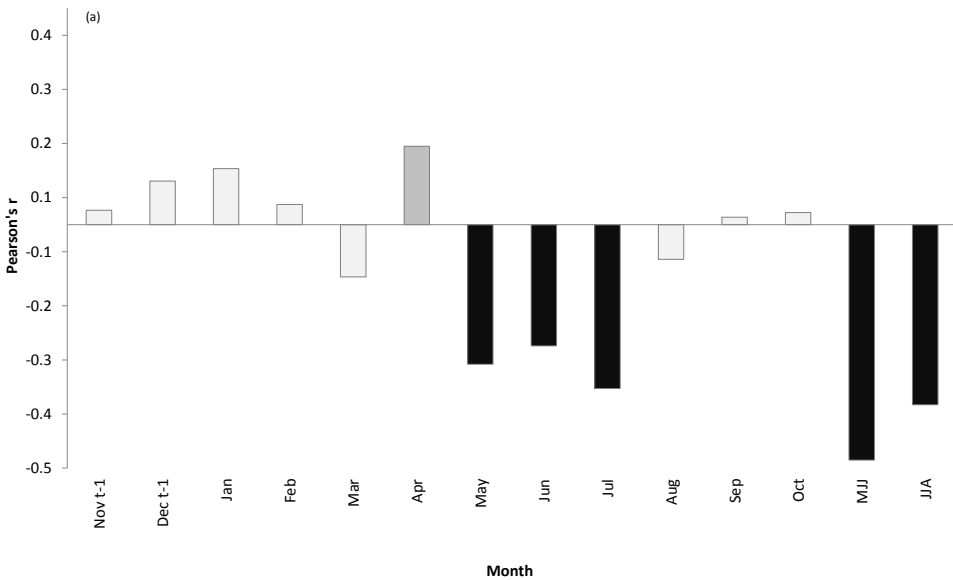
Alpha-cellulose (α -cellulose) was isolated from the pooled latewood samples using standard methods (Loader *et al.*, 1997) and homogenised and freeze-dried (Laumer *et al.*, 2009; Loader *et al.*, 2013). For oxygen isotope analysis, 0.30 to 0.35mg of α -cellulose was weighed into silver foil capsules and then pyrolysed over glassy carbon at 'high temperature' (1400°C) using a Flash HT elemental analyser, interfaced with a Thermo Delta-V isotope ratio mass spectrometer (Thermo Fisher Scientific Inc.) with typical analytical error of $<0.3\text{‰}$ for oxygen. The stable isotope ratios were expressed using delta notations (δ) as per mille (‰) relative to the Vienna Standard Mean Ocean Water (VSMOW) (Coplen, 1995).

Results

Correlations (Pearson's r -values) were calculated between the $\delta^{18}\text{O}$ chronology and mean monthly meteorological parameters obtained from the Armagh observatory for the period AD 1880-2001. The highest values were obtained with precipitation summed over May to July (MJJ) ($r = -0.44$, $p < 0.01$). Weaker correlations were found with July temperature ($r = 0.40$), relative humidity ($r = -0.24$) and sunshine hours ($r = 0.30$) and with the average MJJ temperature ($r = 0.30$), relative humidity ($r = -0.21$) and sunshine ($r = 0.25$). However, step-wise multiple regression, using

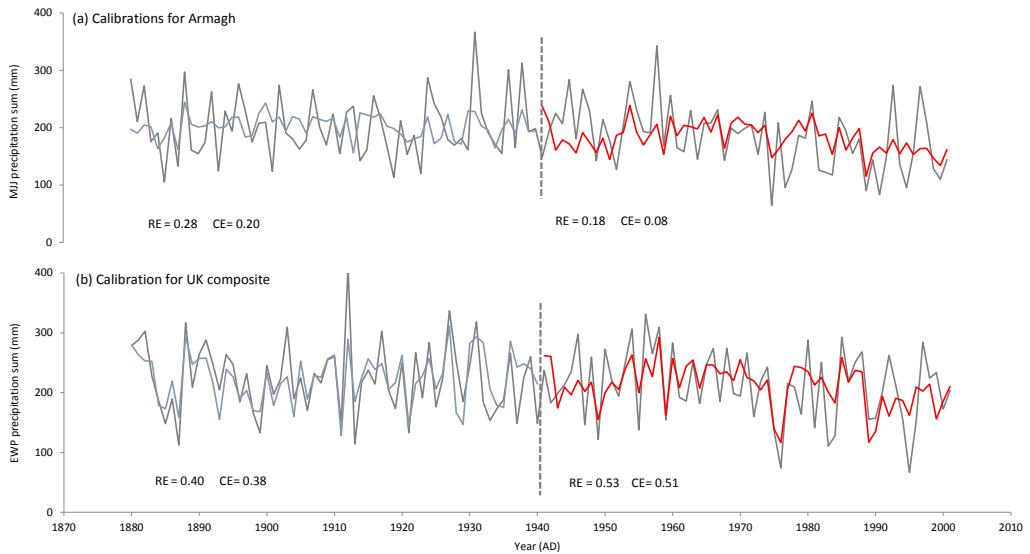
a Bayes' information criterion, discarded these, leaving precipitation as the only climate parameter explaining variance in the Armagh $\delta^{18}\text{O}$ time series ($p < 0.001$).

Figure 2: (a) Composite correlation diagram showing simple linear correlation (Pearson's r) between Armagh $\delta^{18}\text{O}$ and the annual variability of the instrumental data obtained from Armagh Observatory for precipitation. Grey shaded bars represent correlations that are statistically significant with a 95% confidence level and black shaded bars represent correlations with a 99% confidence level. (b) The relationship between Armagh $\delta^{18}\text{O}$ and MJJ precipitation.



Split period calibration and verification, using $\delta^{18}\text{O}$ to reconstruct MJJ precipitation, produced positive values for both Reduction of Error (RE = 0.18 and 0.28) and Coefficient of Efficiency (CE 0.08 and 0.19). When linear regression is applied over the full period (1880-2001), 19% of the variance is explained (Figure 2b). Thus, the correlation between the Armagh $\delta^{18}\text{O}$ record and local rainfall amount is strongly statistically significant ($p < 0.01$), and as high as some other correlations that have been used for climate reconstruction (McCarroll *et al.*, 2015). However, it falls below the threshold recommended for producing climate reconstructions using variance scaling (McCarroll *et al.*, 2015), so a local reconstruction would have to rely on regression methods, with the loss of variance that ensues.

Figure 3: (a) Calibrations for the Armagh $\delta^{18}\text{O}$ time series; first half calibration period (1941-2001) (red), second half calibration period (1880-1940) (blue), with the sum of MJJ precipitation (mm) from Armagh Observatory (grey); (b) Calibrations for the UK $\delta^{18}\text{O}$ composite time series, first half calibration period (1941-2001) (red), second half calibration period (1880-1940) (blue) with the sum of EWP precipitation (mm) from Armagh Observatory (grey).



An alternative to producing a local reconstruction is to include Oxygen isotope data from Ireland into a large regional composite. The individual sites $\delta^{18}\text{O}$ series and the $\delta^{18}\text{O}$ composites were correlated against the Armagh MJJ precipitation sum and the precipitation sum for June to August (JJA) for the England Wales Precipitation series (EWP), which acts a true representation of summer precipitation across southern Central England and Wales (Table 1). There was no statistically significant difference between the correlation coefficients for the Armagh $\delta^{18}\text{O}$ series and both local and regional precipitation ($p > 0.01$).

Table 1: Simple linear correlations (Pearson's r) between $\delta^{18}\text{O}$ series and the Armagh MJJ precipitation record and JJA EWP at various sites across the UK and composite of those sites. (NBGW = National Botanic Gardens Wales).

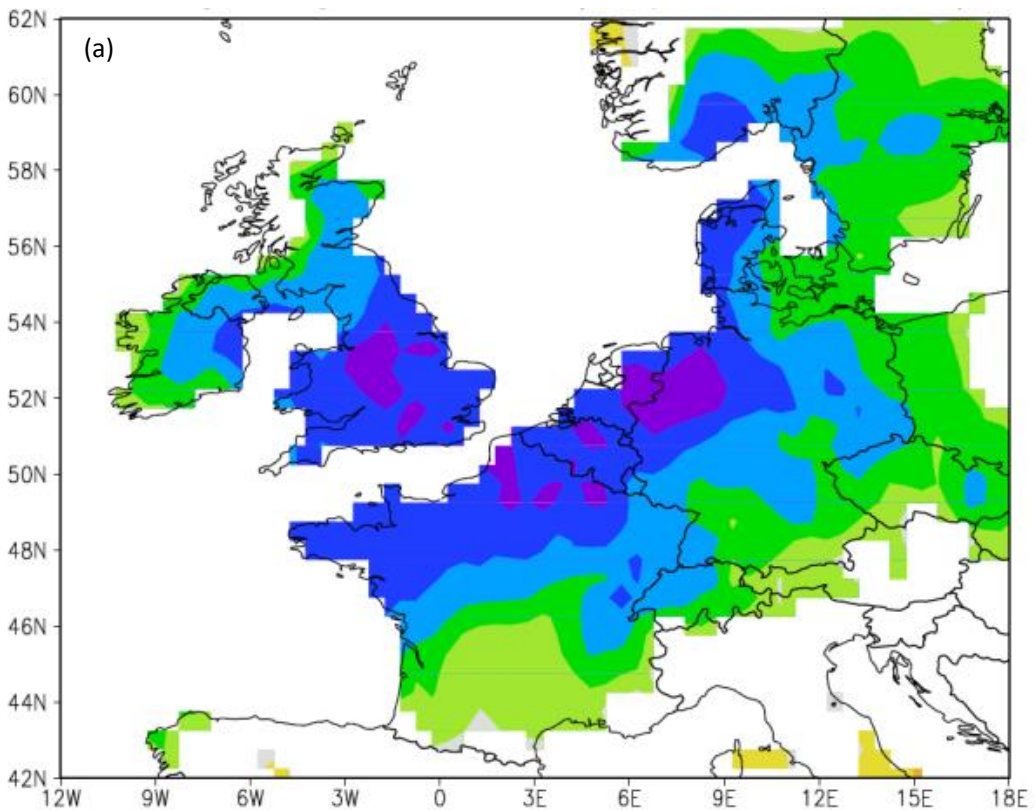
	Armagh MJJ	JJA EWP
Armagh	-0.44	-0.37
UK composite	-0.45	-0.68
Aviemore	-0.15	-0.33
Lochwood	-0.23	-0.47
Allt-Lanlas	-0.44	-0.56
NBGW	-0.13	-0.39
Sandringham	-0.30	-0.53
Woburn	-0.29	-0.50
Oxford	-0.40	-0.50

The individual time series from across the UK were z-scored, and were then averaged to produce $\delta^{18}\text{O}$ composites and then z-scored again. In order to determine the impact of including Armagh, two $\delta^{18}\text{O}$ composites were formed over the common period of 1880-2001. The first covered the UK but excluded the Armagh record, and the second included Armagh. When correlated against JJA EWP both $\delta^{18}\text{O}$ composite series produced the same values, ($r = -0.68$, $p < 0.01$). The skill of the $\delta^{18}\text{O}$ regional composite series (including Armagh) as a proxy for summer precipitation was tested using split period calibration and verification. During the calibration period, 39% of the variance in summer precipitation is explained by the $\delta^{18}\text{O}$ series, and both RE and CE statistics are positive (0.53 and 0.51) (Figure 3b). Over the verification period 53% of the variance is explained with positive RE and CE values (0.40 and 0.38). This demonstrates that a regional $\delta^{18}\text{O}$ composite provides a strong and temporally stable proxy for summer precipitation. Once linear regression was applied over the full series, 46% of the variance was explained.

One of the negative effects associated with using regression-based techniques to reconstruct climate is that it produces a bias towards the mean, and, therefore, underestimates variability and the magnitude of extremes (McCarroll *et al.*, 2015). To avoid this problem, variance scaling (Esper *et al.*, 2005) was used to adjust the $\delta^{18}\text{O}$ composite series to have the same mean and variance as the EWP series. Given the strong correlation, the loss of skill due to scaling (McCarroll *et al.*, 2015) is only 10%. The ability of the scaled reconstruction to capture extreme events was tested using a simple non-parametric test for 'Extreme Value Capture' (McCarroll *et al.*, 2015). Using a 10% threshold to define extreme years, it was found that the UK $\delta^{18}\text{O}$ composite series produced six years above and below the threshold that matched the extreme years in the EWP series which is highly significant ($p < 0.001$) and symmetrical; wet and dry extreme years being captured with equal skill.

Spatial field correlations produced using the new composite $\delta^{18}\text{O}$ time series show large areas of strong correlation. Correlation with summer precipitation is strongly negative (between $r = -0.5$ and $r = -0.6$) for the whole of England and Wales as well as parts of Ireland and the northern regions of France and Germany. Correlations with air pressure at 850mb ($r = 0.5$) now extend across the majority of Britain and Ireland.

Figure 4: Spatial field correlations of the UK composite $\delta^{18}\text{O}$ time series (including Armagh) and gridded JJA climate data using (a) the CRU TS3.22 (land) 0.5° precipitation for AD 1901-2001, and (b) 850mb air pressure during the period AD 1870-2001, produced using 20th century Reanalysis V2 data provided by PSD, Colorado, USA. Coloured bars represent correlation based on Pearson's r ($p < 0.01$). Maps were produced using Climate Explorer (<http://climexp.knmi.nl/>) (Trouet and van Oldenborgh et al., 2013).



Discussion and conclusions

Young *et al.*, (2015) have argued that the dominant control on the stable oxygen isotope ratios of UK oak trees is the oxygen isotopic composition of summer rainfall. Strong correlations between oxygen isotope results occur because dry summers are dominated by cyclonic conditions that produce high isotope ratios in precipitation, whereas wet summers are dominated by anticyclonic conditions (Lamb, 1972) and lower ratios in precipitation. Evaporative enrichment at the leaf level accentuates rather than attenuates the signal. Thus, the dominant control on the isotope ratios is the circulation pattern during the summer. The results from Armagh support these conclusions and since the dominant summer circulation patterns affect large regions it is reasonable to include isotope results from Ireland with those from Great Britain to produce a large scale regional composite series. The results suggest that even with a sparse combination of sub-optimal sites, spread over a relatively large geographic region, there is still a strong relationship between the composite $\delta^{18}\text{O}$ series and both regional summer precipitation amount and summer air pressure.

The Armagh $\delta^{18}\text{O}$ reconstruction for precipitation sum was developed from cores sampled and prepared initially for conventional dendrochronology (García-Suárez *et al.*, 2009). The variance explained was comparable to several other individual sites across the UK. For example, Loader *et al.*, (2008) found a correlation ($r = -0.52$) between cellulose $\delta^{18}\text{O}$ of oak trees and July precipitation at Lochwood, Scotland which was not significantly different to that obtained from Armagh ($p = 0.28$, $P > 0.1$). In contrast, the correlation coefficient from Armagh was significantly different to that found by Rinne *et al.*, (2013) between cellulose $\delta^{18}\text{O}$ and precipitation for southern England ($r = -0.71$). Without knowing specific details about the locations of the samples for this study, it is hard to speculate as to why correlations between $\delta^{18}\text{O}$ and precipitation from Armagh may be lower than other sites in the UK. One possible explanation may relate to the relatively low slope on which the trees were situated (less than 10°), meaning there is the potential for trees to access deep groundwater. This could cause changes in $\delta^{18}\text{O}$ associated with climate to be masked or distorted by sampling 'old' precipitation that is not a true representation of the source water. Other factors including sampling and archival methods, replication, atmospheric pollution, woodland management and ecological amplitude (Fritts, 1976) could also help to explain the relatively lower correlation observed in these trees. Total summer precipitation is not a direct control on the oxygen isotopic composition of cellulose, rather $\delta^{18}\text{O}$ reflects a larger range of external physiological and climatic controls; hence a stronger precipitation signal may be expressed at some sites more than others, such as those where the amount of rainfall does correlate well with the $\delta^{18}\text{O}$ of precipitation. This is likely to occur where soil moisture levels are relatively low, but not low enough to induce moisture stress. Precipitation reconstructions are generally weaker and more variable than those of temperature, possibly due to the localised variations in precipitation and soil moisture levels (Briffa *et al.*, 2002; García-Suárez *et al.*, 2009). Ideally, trees would be selected from sites known to

favour strong isotopic signals such as those located on steep slopes. However, an inherent part of reconstructing climate beyond the period of instrumental data means relinquishing a level of control over sample selection. Thus, this study provides a more realistic representation of potential palaeoclimate reconstructions produced using archaeological and sub-fossil trees in the long Irish oak chronology. By combining multiple sites over a wide region the non-climatic ‘noise’ is averaged out, producing a stronger correlation with the climate data target. The inclusion of Armagh in a UK composite made no difference to the correlation with summer rainfall ($r = -0.68$, $p < 0.01$), with such high results typically being restricted to trees growing at their ecological limits (Loader *et al.*, 2008). This suggests that there is considerable potential for including trees from Northern Ireland into a large regional composite to reconstruct summer precipitation and past changes in circulation. Such a composite might include living trees, building timbers and sub-fossil oaks.

Acknowledgements

This work was funded by the European Social Fund (Access to Masters Programme) at Swansea University. We thank the National Botanic Garden of Wales and the Leverhulme Trust (RPG-2014-327) for additional research support.

References

- Baillie, M.G.L. (1973). A recently developed Irish tree ring chronology. *Tree-Ring Bulletin*, 33, 15-28.
- Baillie, M.G.L. (1990). *Tree-ring Dating and Archaeology*, University of Chicago Press.
- Baillie, M.G.L. and Pilcher, J.R. (1973). A Simple Cross-dating Program for Tree-Ring Research. *Tree-Ring Bulletin*, 33, 7-13.
- Bale, R.J., Robertson, I., Salzer, M.W., Loader, N.J., Leavitt, S.W., Gagen, M., Harlan, T.P. and McCarroll, D. (2011). An annually resolved bristlecone pine carbon isotope chronology for the last millennium. *Quaternary Research*, 76, 22-29. doi:10.1016/j.yqres.2011.1005.1004.
- Barbour, M.M. and Farquhar, G.D. (2000). Relative humidity- and ABA-induced variation in carbon and oxygen isotope ratios of cotton leaves. *Plant, Cell and Environment*, 23(5), 473-485. doi:10.1046/j.1365-3040.2000.00575.
- Björklund, J.A., Gunnarson, B.E., Seftigen, K., Esper, J. and Linderholm, H.W. (2013). Is blue intensity ready to replace maximum latewood density as a strong temperature proxy? A tree-ring case study on Scots pine from northern Sweden. *Climate of the Past Discussions*, 9(5), 5227–5261. doi:10.5194/cpd-9-5227-2013.

- Briffa, K.R., Jones, P.D. and Schweingruber, F.H. (1988). Summer temperature patterns over Europe: A reconstruction from 1750 A.D. based on maximum latewood density indices of conifers. *Quaternary Research*, 30(1), 36-52. doi:10.1016/0033-5894(88)90086-5.
- Briffa, K.R., Jones, P.D., Vogel, R.B., Schweingruber, F.H., Baillie, M.G.L., Shiyatov, S.G. and Vaganov, E.A. (1999). European tree rings and climate in the 16th century. *Climatic Change*, 43, 151-168.
- Briffa, K.R., Osborn, T.J., Schweingruber, F.H., Jones, P.D., Shiyatov, S.G., Vaganov, E.A. (2002). Tree-ring width and density data around the Northern Hemisphere: Part 1, local and regional climate signals. *Holocene*, 12, 737-757
- Butler, C.J. (1990). *History and Archives of Armagh Observatory*. Retrieved August 24, 2014, from <http://star.arm.ac.uk/history/history.html>.
- Butler, C.J. and Coughlin, A.D.S. (1998). Precipitation at Armagh Observatory 1838-1997. *Biology and Environment – Proceedings of the Royal Irish Academy*, 98(2), 123-140.
- Campbell, R., McCarroll, D., Robertson, I., Loader, N.J., Grudd, H. and Gunnarson, B. (2011). Blue Intensity in *Pinus sylvestris* Tree Rings: A Manual for A New Palaeoclimate Proxy. *Tree-Ring Research*, 67(2), 127-134. doi:10.3959/2010-13.1.
- Campelo, F., Nabais, C., Gutiérrez, E., Freitas, H. and García-González, I. (2010). Vessel features of *Quercus ilex* L. growing under Mediterranean climate have a better climatic signal than tree-ring width. *Trees*, 24(3), 463-470. doi:10.1007/s00468-010-0414-0.
- Cook, E.R., Buckley, B.M., Palmer, J.G., Fenwick, P., Peterson, M.J., Boswijk, G. and Fowler, A. (2006). Millennium-long tree-ring records from Tasmania and New Zealand: A basis for modelling climate variability and forcing, past, present and future. *Journal of Quaternary Science*, 21(7), 689-699.
- Coplen, T.B. (1995). Discontinuance of SMOW and PDB. *Nature*, 375 (6529), 285. doi:10.1038/375285a0.
- Dansgaard, W. (1964). Stable isotopes in precipitation. *Tellus*. 16(4) 436-468.
- Esper, J. (2005). Effect of scaling and regression on reconstructed temperature amplitude for the past millennium. *Geophysical Research Letters*, 32(7), L07711. doi:10.1029/2004GL021236.
- Friedrich, M., Remmele, S., Kromer, B., Hoffmann, J., Spurk, M., Kaiser, K.F., Orsel, C. and Küppers, M. (2004). The 12,460-year Hohenheim oak and pine tree-ring chronology from Central Europe – a unique annual record for radiocarbon calibration and paleoenvironment reconstructions. *Radiocarbon*, 46, 1111-1122.

- Fritts, H.C. (1976) *Tree Rings and Climate*. Academic Press, London.
- Gagen, M., McCarroll, D., Jalkanen, R., Loader, N.J., Robertson, I. and Young, G.H.F. (2011). A rapid method for the production of robust millennial length stable isotope tree ring series for climate reconstruction. *Global Planet Change* 82-83, 96-103. doi:10.1016/j.gloplacha.2011.1011.1006
- García-Suárez, A.M., Butler, C.J. and Baillie, M.G.L. (2009). Climate signal in tree-ring chronologies in a temperate climate: A multi-species approach. *Dendrochronologia*, 27(3), 183-198. doi:10.1016/j.dendro.2009.05.003.
- Hantemirov, R. and Shiyatov, S. (2002). A continuous multi-millennial ring width chronology from Yamal, north-western Siberia. *The Holocene*, 12, 717-726.
- Hilasvuori, E. and Berninger, F. (2010). Dependence of tree ring stable isotope abundances and ring width on climate in Finnish oak. *Tree Physiology*, 30(5), 636-47. doi:10.1093/treephys/tpq019.
- Kelly, P.M., Munro, M.A.R., Hughes, M.K. and Goodess, C.M. (1989). Climate and signature years in west European oaks. *Nature*, 340 (6228), 57-60. doi:10.1038/340057a0.
- Kelly, P.M., Leuschner, H.H., Briffa, K.R. and Harris, I.C. (2002). The climatic interpretation of pan-European signature years in oak ring-width series. *The Holocene*, 12(6), 689-694. doi:10.1191/0959683602hl582rp.
- Kimak, A. and Leuenberger, M. (2015). Are carbohydrate storage strategies of trees traceable by early-latewood carbon isotope differences? *Trees* (2015), 29:859-870. doi: 10.1007/s00468-015-1167.
- Labuhn, I., Daux, V., Pierre, M., Stievenard, M., Girardclos, O., Féron, A., Genty, D., Masson-Delmotte, V. and Mestre, O. (2013). Tree age, site and climate controls on tree ring cellulose $\delta^{18}\text{O}$: A case study on oak trees from south-western France. *Dendrochronologia*, 32(1), 78-89. doi:10.1016/j.dendro.2013.11.001.
- Lamb, H.H. (1972). *Climate: Past, Present and Future* (p. 613). Methuen, London: Routledge.
- Laumer, W., Andreu, L., Helle, G., Schleser, G.H., Wieloch, T. and Wissel, H. (2009). A novel approach for the homogenization of cellulose to use micro-amounts for stable isotope analyses. *Rapid Communications in Mass Spectrometry*, 23, 1934-1940.
- Loader, N.J., Robertson, I., Barker, A.C., Switsur, V.R. and Waterhouse, J.S. (1997). An improved technique for the batch processing of small wholewood samples to α -cellulose. *Chemical Geology*, 136(3-4), 313-317. doi:10.1016/S0009-2541(96)00133-7.

Loader, N.J., Robertson, I. and McCarroll, D. (2003). Comparison of stable carbon isotope ratios in the whole wood, cellulose and lignin of oak tree-rings. *Paleogeography*, 196, 395-407. doi:10.1016/S0031-0182(03)00466-8.

Loader, N.J., Santillo, P. and Woodman-Ralph, J. (2008). Multiple stable isotopes from oak trees in southwestern Scotland and the potential for stable isotope dendroclimatology in maritime climatic regions. *Chemical Geology*, 252, 62-71. doi:10.1016/j.chemgeo.2008.01.006.

Loader, N.J., Young, G.H.F., Grudd, H. and McCarroll, D. (2013). Stable carbon isotopes from Torneträsk, northern Sweden provide a millennial length reconstruction of summer sunshine and its relationship to Arctic circulation. *Quaternary Science Reviews*, 62, 97-113.

Luterbacher, J., Werner, J.P., Smerdon, J.E., Fernández-Donado, L., González-Rouco, F.J., Barriopedro, D., Ljungqvist, F.C., Büntgen, U., Zorita, E., Wagner, S., Esper, J., McCarroll, D., Toreti, A., Frank, D., Jungclaus, J.H., Barriendos, M., Bertolin, C., Bothe, O., Brázdil, R., Camuffo, D., Dobrovolný, P., Gagen, M., García-Bustamante, E., Ge, Q., Gómez-Navarro, J.J., Guiot, J., Hao, Z., Hegerl, G.C., Holmgren, K., Klimentko, V.V., Martín-Chivelet, J., Pfister, C., Roberts, N., Schindler, A., Schurer, A., Solomina, O., von Gunten, L., Wahl, E., Wanner, H., Wetter, O., Xoplaki, E., Yuan, N., Zanchettin, D., Zhang, H. and Zerefos, C. (2016). European summer temperatures since Roman times. *Environmental Research Letters* (024001), 1-13. doi:10.1088/1748-9326/11/2/024001.

Matisons, R. and Brūmelis, G. (2012). Influence of climate on tree-ring and earlywood vessel formation in *Quercus robur* in Latvia. *Trees*, 26(4), 1251-1266. doi:10.1007/s00468-012-0701-z.

McCarroll, D. and Loader, N.J. (2004). Stable Isotope in Tree Rings. *Quaternary Science Reviews*, 23, 771-801.

McCarroll, D., Pettigrew, E., Luckman, A., Guibal, F. and Edouard, J.L. (2002). Blue reflectance provides a surrogate for latewood density of high-latitude pine tree-rings. *Arctic, Antarctic and Alpine Research*, 34(4), 450-453.

McCarroll, D., Loader, N.J., Jalkanen, R., Gagen, M.H., Grudd, H., Gunnarson, B.E., Kirchhefer, A.J., Friedrich, M., Linderholm, H.W., Lindholm, M., Boettger, T., Los, S.O., Remmele, S., Kononov, Y.M., Yamazaki, Y.H., Young, G.H. and Zorita, E. (2013). A 1200-year multiproxy record of tree growth and summer temperature at the northern pine forest limit of Europe. *The Holocene*, 23(4), 471-484. doi:10.1177/0959683612467483.

McCarroll, D., Young, G.H.F. and Loader, N.J. (2015). Measuring the skill of variance-scaled climate reconstructions and a test for the capture of extreme values. *The Holocene*, 25, 1-24. doi: 10.1177/0959683614565956.

- McCarroll, D., Whitney, M., Young, G.H.F., Loader, N.J. and Gagen, M.H. (in review). Scottish oak trees display strong and consistent reliance on young reserves for early-wood formation. *Trees Structure and Function*.
- McDermott, F., Atkinson, T.B., Fairchild, I.J., Baldini, L.M., Matthey, D.P. (2011). A first evaluation of the spatial gradients in $\delta^{18}\text{O}$ recorded by European Holocene speleothems. *Global and Planetary Change*, 79, (3-4) 275-287.
- Pilcher, J.R., Baillie, M.G.L., Schmidt, B. and Becker, B. (1984). A 7,272-year tree-ring chronology for Western Europe. *Nature*, 312(5990), 150-152. doi:10.1038/312150a0.
- Rinne, K.T., Loader, N.J., Switsur, V.R., Treydte, K.S. and Waterhouse, J.S. (2010). Investigating the influence of sulphur dioxide (SO_2) on the stable isotope ratios ($\delta^{13}\text{C}$ and $\delta^{18}\text{O}$) of tree rings. *Geochimica et Cosmochimica Acta*, 74(8), 2327-2339. doi:10.1016/j.gca.2010.01.021.
- Rinne, K.T., Loader, N.J., Switsur, V.R. and Waterhouse, J.S. (2013). 400-year May to August precipitation reconstruction for Southern England using oxygen isotopes in tree rings. *Quaternary Science Reviews*, 60, 13-25. doi:10.1016/j.quascirev.2012.10.048.
- Robertson, I., Waterhouse, J., Barker, A.C., Carter, A.H.C. and Switsur, V.R. (2001). Oxygen isotope ratios of oak in east England: implications for reconstructing the isotopic composition of precipitation. *Earth and Planetary Science Letters*, 191 (1-2), 21-31.
- Roden, J., Lin, G. and Ehleringer, J. (2000). A mechanistic model for interpretation of hydrogen and oxygen isotope ratios in tree-ring cellulose. *Geochimica et Cosmochimica Acta*, 64(1), 21-35. doi: 10.1016/S0016-7037(99)00195-7.
- Roland, T.P., Daley, T.J., Caseldine, C.J., Charman, D.J., Turney, C.S.M., Amesbury, M.J., Thompson, G.J. and Woodley, E.J. (2015). The 5.2ka climate event: Evidence from stable isotope and multi-proxy palaeoecological peatland records in Ireland. *Quaternary Science Reviews*, 124, 209-223.
- Saurer, M., Siegenthaler, U. and Schweingruber, F.H. (1995). The climate-carbon isotope relationship in tree rings and the significance of site conditions. *Tellus B*, 47(3), 320-330. doi:10.1034/j.1600-0889.47.issue3.4.x.
- Saurer, M., Robertson, I., Siegwolf, R. and Leuenberger, M. (1998). Oxygen Isotope Analysis of Cellulose: An Interlaboratory Comparison. *Analytical Chemistry*, 70(10), 2074-2080. doi:10.1021/ac971022f.
- Seftigen, K., Linderholm, H.W., Loader, N.J., Liu, Y. and Young, G.H.F. (2011). The influence of climate on $^{13}\text{C}/^{12}\text{C}$ and $^{18}\text{O}/^{16}\text{O}$ ratios in tree ring cellulose of *Pinus sylvestris* L. growing in the central Scandinavian Mountains. *Chemical Geology*, 286(3), 84-93. doi:10.1016/j.chemgeo.2011.04.006.

- Stokes, M.A. and Smilley, T.L. (1968). *An Introduction to Tree-Ring Dating*. Chicago: University of Chicago Press.
- Swindles, G.T., Blundell, A., Roe, H.M. and Hall, V.A. (2010). A 4500-year proxy climate record from peatlands in the North of Ireland: the identification of widespread summer ‘drought phases’? *Quaternary Science Reviews*, 29(13), 1577-1589.
- Switsur, V.R., Waterhouse, J.S., Field, E.M., Carter, A.H.C. and Loader, N.J. (1995). Stable isotope studies in tree rings from oak – techniques and some preliminary results. *Palaoklimaforschung*, 15, 129-140.
- Tardif, J.C. and Conciatori, F. (2006). Influence of climate on tree rings and vessel features in red oak and white oak growing near their northern distribution limit, south-western Quebec, Canada. *Canadian Journal of Forest Research*, 36(9), 2317-2330. doi:10.1139/x06-133.
- Treydte, K.S., Boda, S., Pannatier, E.G., Fonti, P., Frank, D., Ullrich, B., Saurer, M., Siegwolf, R.T.W., Battipaglia, G., Werner, W. and Gessler, A. (2014). Seasonal transfer of oxygen isotopes from precipitation and soil to the tree ring: source water versus needle water enrichment. *New Phytol.* doi:10.1111/nph.12741
- Trouet, V. and van Oldenborgh, G.J. (2013). KNMI Climate Explorer: a web-based research tool for high-resolution paleoclimatology. *Tree-Ring Research*, 69(1), 3-13. doi:10.3959/1536-1098-69.1.3.
- Turner, J.N., Holmes, N., Davis, S.R., Leng, M.J., Langdon, C., Scaife, R.G. (2015). A multiproxy (pollen, stable isotope, chironomid and XRF) record for the Late Glacial to Holocene transition from Thomastown Bog, Ireland. *Journal of Quaternary Science* 30(6) 514-528.
- Wershaw, R., Friedman, I. and Heller, S.J. (1966). Hydrogen isotope fractionation in water passing through trees. In: F. Hobson and M. Speers (eds.), *Advances in Organic Geochemistry* (pp. 55-67). New York: Pergamon.
- Wigley, T.M.L., Lough, J.M. and Jones, P. (1984). Spatial patterns of precipitation in England and Wales and a revised, homogeneous England and Wales precipitation series. *Journal of Climatology*, 4, 1-25.
- Young, G.H.F., Bale, R., Loader, N.J., McCarroll, D., Nayling, N., Vousden, N. (2012). Central England temperature since AD 1850: the potential of stable carbon isotopes in British oak trees to reconstruct past summer temperatures. *Journal of Quaternary Science*, 27(6), 606-614. doi:10.1002/jqs.2554.
- Young, G.H.F., Loader, N.J., McCarroll, D., Bale, R.J., Demmler, J.C., Miles, D., Nayling, N., Rinne, K.T., Robertson, I., Watts, C. and Whitney, M. (2015). Oxygen stable isotope ratios from British oak tree-rings provide a strong and consistent record of past changes in summer rainfall. *Climate Dynamics*, 45(11), 3609-3622. doi: 3610.1007/s00382-00015-02559-00384.