

Central England temperature since AD 1850: the potential of stable carbon isotopes in British oak trees to reconstruct past summer temperatures

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ABSTRACT: In regions with seasonal temperate climatic regimes, tree growth is rarely controlled by any single environmental factor. As a consequence, the development of robust palaeoclimate reconstructions has proved challenging. Tree-ring stable carbon isotope ratios ($\delta^{13}\text{C}$), however, are controlled primarily by photosynthetic rate, not by net growth. Therefore, at sites where climatic controls on tree-ring growth are not strongly expressed, a robust (isotopic) palaeoclimate signal may still potentially be preserved. This hypothesis was tested using a 160-year record of $\delta^{13}\text{C}$ measured from the pooled latewood cellulose of six *Quercus petraea* L. (sessile oak) trees from Allt Lanlas in West Wales, UK. Raw $\delta^{13}\text{C}$ values were corrected for changes in the isotopic ratio of atmospheric carbon dioxide and for changes in the behaviour of trees due to the increasing availability of atmospheric CO_2 since AD 1850. Strong correlations with local summer temperature and sunshine are reported, and also with the Central England Temperature record over the full length of the isotopic chronology (AD 1850–2010) ($r = 0.69$, $P < 0.001$). We conclude that tree-ring stable isotopes can be used to extract strong palaeoclimate signals even from oak trees growing in a temperate maritime climate. This demonstrates the potential for extracting robust palaeoclimatic information from the very long and well-replicated oak chronologies which have been developed in western and central Europe primarily for dating rather than palaeoclimatic research purposes. Copyright © 2012 John Wiley & Sons, Ltd.

KEYWORDS: British Isles; carbon isotopes; Central England Temperature; oak (*Quercus*); tree-rings.

Introduction

Late Holocene high-resolution climate reconstructions, calibrated and verified using meteorological measurements, are generally limited to the diverse range of proxy climate information contained within the tree-ring archive (ring-widths, relative wood density/reflectance, height increment, needle dynamics, vessel area and stable isotope ratios). High statistical correlations with instrumental climate data (Pearson's r -values > 0.6) are, however, typically restricted, geographically, to trees sampled from locations near to their ecological limits for growth. At such near-tree-line locations, tree growth is typically constrained by one or a small number of characterizable environmental variables (e.g. temperature or moisture availability) (Fritts, 1976). As a result, tree growth proxies at these locations can be strongly linked, both statistically and theoretically, to these limiting environmental factors. For example, trees growing at cool, non-water-stressed, altitudinal and latitudinal tree-line locations are often strongly controlled by growing season temperatures, while at xeric tree-line sites, antecedent or growing season precipitation/moisture availability is more often the primary growth-limiting factor. There are numerous examples of numerically robust calibrations with, and reconstructions of, climate at such locations [for both temperature (e.g. Kirchhefer, 2001; Gunnarson and Linderholm, 2002; Wilson and Luckman, 2003; Büntgen *et al.*, 2005; Linderholm and Gunnarson, 2005; Luckman and Wilson, 2005; Grudd, 2008; Lindholm *et al.*, 2009) and precipitation (e.g. Cook *et al.*, 2004; Linderholm and Chen, 2005; Salzer and Kipfmüller, 2005; Wilson *et al.*, 2005; Meko *et al.*, 2007; Helama *et al.*, 2009)]. Such tree-line locations are often remote and relatively undisturbed by human activity. This, in combination with slow tree growth and good conditions for timber preservation, enables the construction of long tree-ring

chronologies with suitable levels of annual replication (sample depth) to allow robust climate reconstructions to be developed for defined regions. A relatively large body of palaeoclimatic data therefore exists for remote, climatically extreme and sparsely populated regions (e.g. the northern Eurasian tree-line and high-latitude locations in the European Alps and western North and South America). There is, however, much less information from more densely populated temperate areas, such as Western Europe. This has led to a geographical imbalance in the tree-ring-based climate reconstructions which have been used to determine the rate and magnitude of climatic change over the late Holocene (Jansen *et al.*, 2007). The paucity of robust tree-growth-based temperature reconstructions from temperate areas has resulted in reconstructions of temperature at hemispheric scales, reliant in part upon indirect information from proxies that are not strongly correlated with local temperature records (e.g. Mann *et al.*, 1999).

In addition to diverse physical measures, the tree-ring archive contains a number of chemical proxies, including tree-ring stable carbon isotope ratios ($\delta^{13}\text{C}$) which may also be interrogated for palaeoenvironmental information. In common with the tree growth proxies, $\delta^{13}\text{C}$ often exhibits a statistically significant relationship with environmental variables such as temperature (Gagen *et al.*, 2007; Treydte *et al.*, 2009; Loader *et al.*, 2010), sunshine (McCarroll *et al.*, 2003; Gagen *et al.*, 2011b), cloud cover (Young *et al.*, 2010, 2012), precipitation and drought (Kress *et al.*, 2010; Bale *et al.*, 2011). Where the aim is to reconstruct long-term environmental variability, tree samples for isotopic analysis are typically sought from the same tree-line locations as the physical proxies and they appear to contribute valuable additional information (e.g. Treydte *et al.*, 2009; Kress *et al.*, 2010; Bale *et al.*, 2011; Gagen *et al.*, 2011b; Seftigen *et al.*, 2011; Young *et al.*, 2010, 2012). Tree-ring $\delta^{13}\text{C}$ is, in essence, controlled by the balance between stomatal conductance and photosynthetic rate (McCarroll and Loader, 2004). Where water stress is low, photosynthetic rate should dominate, and annual $\delta^{13}\text{C}$ measurements are likely to

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correlate with measured climate variables such as temperature, sunshine and cloud cover (the major controlling factor is likely to be photosynthetically active radiation, PAR). At xeric locations and where trees suffer from moisture stress, stomatal conductance may play a more important role in carbon isotopic fractionation, leading to statistically significant relationships with antecedent or growing season moisture supply (e.g. Leavitt, 1994; Feng and Epstein, 1995; Gagen *et al.*, 2004; Bale *et al.*, 2011). Tree-ring isotopic theory would therefore suggest that to find a strong relationship between $\delta^{13}\text{C}$ and temperature or sunshine there is little need to seek out tree-line locations. Less extreme locations, with a well-defined annual growing season and little or no evidence of moisture stress, should prove to be equally suitable. If this hypothesis is correct, regions with seasonal temperate climatic regimes may be opened up for isotopic dendroclimatology. Importantly, these are also areas with a long history of human habitation where climatic changes have impacted and will probably continue to impact upon large populations.

At tree-line locations in Europe, *Pinus sylvestris* L. (Scots pine) and *Larix decidua* Mill. (European larch) are often the key archive species. In more temperate regions, the genus *Quercus* (oak) and especially the species *Quercus robur* L. (pedunculate oak), *Quercus petraea* L. (sessile oak) and their hybrids are the most common species used for building long tree-ring chronologies, primarily developed for archaeological dating purposes (e.g. Pilcher *et al.*, 1984; Becker, 1993; Friedrich *et al.*, 2004). Oak tree-ring widths in temperate areas do not typically exhibit a strong numerical relationship with growing season climate. They have therefore been largely dismissed as archives of information on past climate (e.g. Pilcher and Baillie, 1980a,b; García-Suárez *et al.*, 2009), although there is now evidence that it may be possible to reconstruct regional precipitation variability using the ring-width measurements from a very large number of trees (e.g. Büntgen *et al.*, 2011; Cooper *et al.*, 2012; Wilson *et al.*, 2012). Temperature reconstructions from temperate oak tree-ring chronologies are almost wholly absent.

Oak at temperate locations has, however, been used with some success in isotope dendroclimatology studies. In the UK, Switsur *et al.* (1995) and Robertson *et al.* (1997) identified statistical links with growing season temperatures in the high-frequency domain. More recently, Loader *et al.* (2008) were able to demonstrate a robust climatic association between multiple stable isotopes and oak from southern Scotland, highlighting the potential for oak as an isotopic dendroclimatology archive. Rinne *et al.* (2010) and Hemming *et al.* (1998) both identified links between stable carbon isotopes in oak and growing season climate, but also showed that local point

sources of pollution could (temporarily) affect the stability of this signal during the recent past. Larger scale studies of isotopes from temperate tree-ring chronologies in Europe (including oak) have shown a strong common signal, which may be indicative of climate forcing (Treydte *et al.*, 2007; Saurer *et al.*, 2008).

If a strong climate signal can be found contained within oak tree-ring stable carbon isotopes, its wide geographical distribution combined with its suitability as a long chronology-building genus would make it a potentially very valuable and powerful palaeoclimatic archive. We therefore seek to test the suitability of $\delta^{13}\text{C}$ values from oak in a moist temperate European location for reconstructing environmental parameters linked to photosynthetic rate (temperature, sunshine and cloud cover).

Location and methodology

Sampling was carried out at Allt Lanlas [52°13'N, 4°13'W (SN477 604)] situated in the county of Ceredigion, West Wales, UK (Fig. 1). The site comprises 8 ha of sessile oak woodland in the grounds of the National Trust-owned Llanerchaeron Estate. The trees grow on a hillside with a south-westerly aspect rising from 35 to 140 m OD (Fig. 1). A previous tree-ring width study established a local ring-width chronology but reported no strong links between ring-width and temperature (Bale, 2005). Meteorological data from the nearest meteorological station at Aberporth (52°08'N, 04°33'W, c. 25 km south-west of Allt Lanlas) confirm the temperate, maritime climate of the study site (Table 1). Tree-ring widths from such locations typically give a poor climate signal (Pilcher and Baillie, 1980a,b), and so this site provides an ideal test of the ability of $\delta^{13}\text{C}$ from oak tree-rings to capture environmental variability. Cores of 5 mm in diameter were taken at c. 1.4 m height from six healthy, mature trees. All six trees span the 160-year period analysed (AD 1850–2010). Samples were surfaced, air-dried and cross-dated using standard isotopic dendroclimatology methods. The complete sequence of growth rings in each sample was measured to an accuracy of 0.01 mm using a microscope and horizontally travelling stage (Tyers, 2004). The ring sequences were dated dendrochronologically through correlation with each other and also tested against the Allt Lanlas site (Bale, 2005) and regional reference chronologies from Britain and Northern Europe. The dating can therefore be considered accurate and precise.

The latewood from each annual growth ring was cut with a scalpel using a binocular microscope and combined (pooled) for each year to create an annualized record. The earlywood of the rings is not used because it is formed using stored photosynthates rather than those fixed in the current year

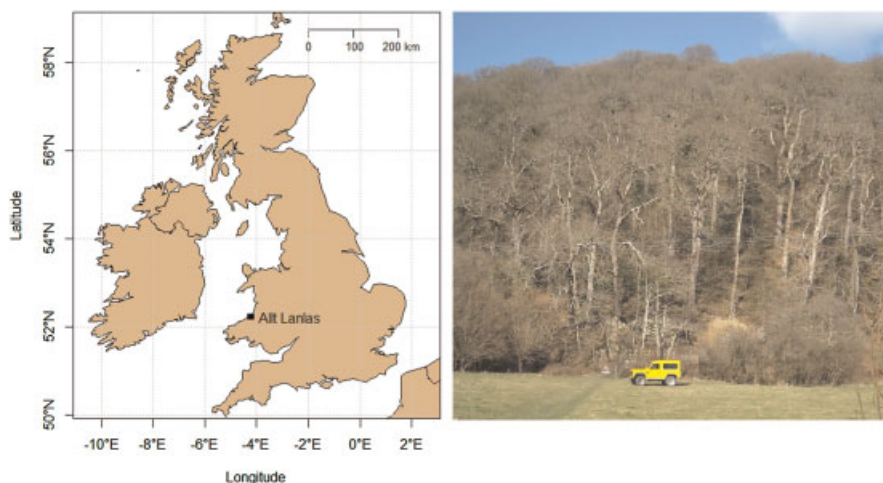


Figure 1. Location (left hand panel) and example photograph (right hand panel) of Allt Lanlas field site (52°13'N, 4°13'W). This figure is available in colour online at wileyonlinelibrary.com.

Table 1. Summer (June–August) and annual meteorological data for Aberporth, AD 1942–2010.

	Temperature (°C)		Precipitation (mm)		Bright sunshine (h)	
	Summer	Annual	Summer	Annual	Summer	Annual
Mean	14.4	9.7	191.1	906.7	570.5	1562.4
Max.	16.6	10.8	314.7	1292.1	780.1	1919.4
Min.	12.8	8.6	25.5	655.2	434.6	1324.6

(Switsur *et al.*, 1995). The pooling approach has the advantage of reducing sample preparation time and cost, whilst previous studies show that pooled chronologies closely approximate the mean of the $\delta^{13}\text{C}$ values from the same trees analysed separately (Leavitt, 2008; Woodley *et al.*, 2012). No isotopic measurements were made for any of the first 50 annual growth rings of the trees sampled, to avoid anticipated 'juvenile' effects (McCarroll and Loader, 2004). After this initial juvenile phase the majority of published studies to date (albeit from the genus *Pinus*) suggests that there are no long-term age related trends in $\delta^{13}\text{C}$ from tree-rings (Gagen *et al.*, 2007, 2008; Loader *et al.*, 2007; Young *et al.*, 2011), although Esper *et al.* (2010) have identified a possible longer-term age-related trend from *Pinus uncinata* in the Spanish Pyrenees.

The annualized pooled samples were extracted to α -cellulose (Loader *et al.*, 1997; Rinne *et al.*, 2005) and 0.30–0.35 mg was weighed into tin capsules. Isotope ratios were measured online using a 20/20 isotope ratio mass spectrometer interfaced to a Europa GSL elemental analyser; analytical error is typically $< 0.1\text{‰}$ (σ_{n-1} $n=10$) based upon results of inter-laboratory comparisons and replicate analysis of in-house laboratory cellulose standards (Loader *et al.*, 2003; Boettger *et al.*, 2007). Results are expressed as $\delta^{13}\text{C}$, in per mille (‰) relative to the Vienna Pee Dee Belemnite (VPDB) standard.

The raw $\delta^{13}\text{C}$ values were corrected for changes in the isotopic ratio of atmospheric carbon dioxide (atmospheric CO_2 correction), which has been declining since c. AD 1850 due to the release of isotopically depleted CO_2 into the atmosphere from the large-scale burning of fossil fuels (Freyer and Belacy, 1983). Trees respond passively to changes in the isotopic ratio of atmospheric CO_2 ($\delta^{13}\text{C}_{\text{atm}}$). The anthropogenically induced decline in $\delta^{13}\text{C}$ of atmospheric CO_2 since c. AD 1850 (c. 1.5‰) is therefore directly reflected in the $\delta^{13}\text{C}$ of tree-rings. To account for this decline an additive correction can therefore be made to the tree-ring $\delta^{13}\text{C}$ values using annual values for $\delta^{13}\text{C}_{\text{atm}}$. We use the values suggested by McCarroll and Loader (2004), assuming a pre-industrial value for $\delta^{13}\text{C}_{\text{atm}}$ of -6.4‰ to produce a corrected tree-ring series.

A second adjustment was applied to account for changes in the behaviour of trees due to the increasing availability of atmospheric CO_2 . As the amount of CO_2 in the atmosphere (c_a) has increased, most trees have reacted actively by increasing their water-use efficiency, therefore maintaining a stable ratio of internal (c_i) to ambient CO_2 concentrations (c_a), despite the large increase in c_a . As tree-ring $\delta^{13}\text{C}$ values are a function of the ratio c_i/c_a , they have remained stable for most of the industrial period (Saurer *et al.*, 2004). There is, however, increasing evidence that many trees have reached the limits of this plastic response, and are now behaving more passively, causing internal concentrations of CO_2 to rise and tree-ring $\delta^{13}\text{C}$ values to decline (Treydte *et al.*, 2001, 2009; Waterhouse *et al.*, 2004; Sidorova *et al.*, 2010; Gagen *et al.*, 2011a). Although there is general agreement as to the need for such a correction, a number of differing approaches to the actual correction procedure have been employed and discussed (e.g. Feng and Epstein, 1995; Loader *et al.*, 2007; Treydte *et al.*, 2009; McCarroll *et al.*, 2009; Wang *et al.*, 2011). We use the correction proposed by McCarroll *et al.* (2009) as it appears to be the most objective, and has been widely accepted and taken-up within the tree-ring isotope research community (e.g. Loader *et al.*, 2008, 2010; Sidorova *et al.*, 2009; Wils *et al.*, 2010; Andreu-Hayles *et al.*, 2011; Bale *et al.*, 2011; Daux *et al.*, 2011; Gagen *et al.*, 2011b; Hafner *et al.*, 2011; Seftigen *et al.*, 2011; Young *et al.*, 2012). This conservative 'correction' was applied to the $\delta^{13}\text{C}$ data from AD 1850 ($\delta^{13}\text{C}_{\text{pin}}$) using a loess regression span (stiffness) of 0.7. The affect of the correction is, in this instance, minimal (maximum correction year AD 2010, 0.64‰; see Fig. 2).

Climate relationship

Stable carbon isotope fractionation within plants has been extensively researched and the major environmental controlling factors are well recognized (Vogel, 1980; Farquhar *et al.*, 1982). A number of measured environmental parameters may be expected to display a numerical relationship with annual tree-ring $\delta^{13}\text{C}$ values (e.g. temperature, sunshine, cloud cover, precipitation and relative humidity). At moist temperate locations, such as West Wales (Fig. 1, Table 1), environmental variables linked to photosynthetic rate (sunshine, cloud cover and temperature) are likely to dominate annual carbon isotope fractionation, rather than variables linked to stomatal conductance (precipitation and relative humidity) (McCarroll and Loader, 2004).

In West Wales the local climate station records are too short for a reliable split period calibration/verification, but the UK Met Office (<http://www.metoffice.gov.uk/>) has produced a longer composite record for Wales which includes temperature and precipitation back to AD 1910 and bright sunshine back

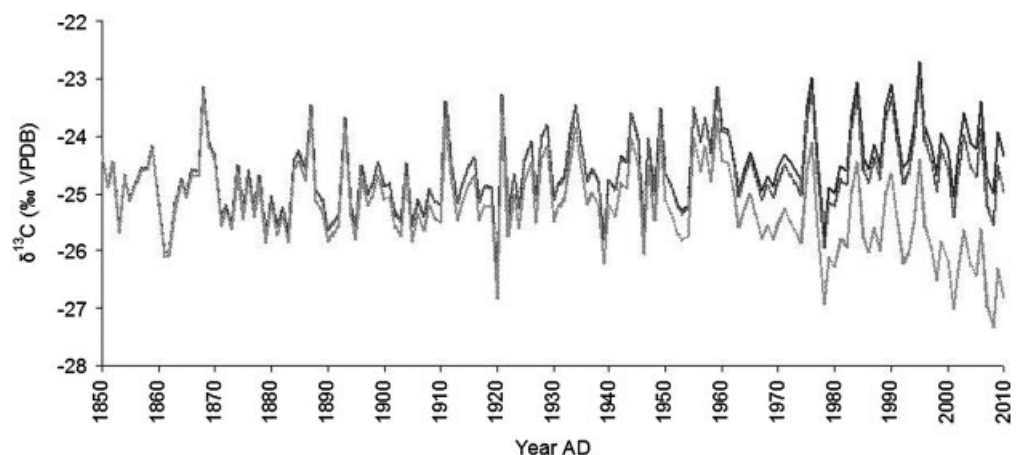


Figure 2. Pooled $\delta^{13}\text{C}$ time series, showing the effect of the corrections: $\delta^{13}\text{C}_{\text{raw}}$, broken grey line (bottom); $\delta^{13}\text{C}_{\text{atm}}$, broken grey line (middle); $\delta^{13}\text{C}_{\text{pin}}$, broken grey line (top).

to AD 1929. The $\delta^{13}\text{C}_{\text{pin}}$ results are significantly ($P < 0.01$) correlated with July/August temperature ($r = 0.70$), bright sunshine ($r = 0.66$) (Fig. 3A,B) and precipitation ($r = -0.49$). These three parameters are, however, highly autocorrelated. Over the period AD 1929–2010 summer (July and August) temperature correlates with sunshine at $r = 0.76$ ($P < 0.001$); temperature with precipitation at $r = -0.58$ ($P < 0.001$); and sunshine with precipitation at $r = -0.66$ ($P < 0.001$). To determine whether any of the correlations between $\delta^{13}\text{C}_{\text{pin}}$ and the three climatic variables are a result of the autocorrelation between these climatic variables, a stepwise multiple regression was undertaken. In the final model, precipitation was rejected as insignificant, while both temperature and sunshine were retained. In theory, the fractionation of carbon at such a moist site should be dominated by photosynthetic rate and the strongest climatic control should be PAR. PAR is likely to be strongly linked with, but not identical to, hours of bright sunshine, cloud cover and temperature. However, when tree-ring $\delta^{13}\text{C}$ has been used for climate reconstruction in Arctic regions over longer timescales, the indirect link with summer temperature (via PAR) has proved problematic. This is because although temperature and sunlight are strongly coupled at inter-annual timescales, it appears that they can become de-coupled over longer timescales reflecting changes in local circulation/air-mass dominance. During the 17th and 18th centuries ('Little Ice Age'), for example, a prolonged period of cold summers was associated with drier air and less cloud cover, perhaps linked to an expansion of the zone of Arctic high pressure (Young *et al.*, 2012). This uncoupling of sunshine and temperature is also found in some of the meteorological records of Arctic Europe, which show a divergence between records of summer temperature and cloud cover (Young *et al.*, 2010). When these parameters diverge, the $\delta^{13}\text{C}$ of tree-rings appears to track cloud cover (sunshine) rather than temperature. West Wales,

however, lies far from the direct influence of the Arctic high-pressure system and so it may be assumed that the relationship between summer temperature and sunshine at both high and low frequencies will be preserved, and therefore also that between temperature and $\delta^{13}\text{C}$. Testing this hypothesis, however, requires a temperature record longer than the composite series available for Wales. Fortunately, the composite record for Wales is nearly identical ($r = 0.97$, $P < 0.001$) to the Central England Temperature (CET) record (Fig. 3D) (Manley, 1974; Parker *et al.*, 1992). This allows the full isotope record back to AD 1850 to be statistically compared with summer temperatures and examined for divergences. The CET comprises homogenized data from a number of geographically and temporally overlapping English climate stations covering a roughly triangular area from Lancashire in the north to London in the south-east and Herefordshire on the border with Wales in the south-west. Monthly standard errors in the CET have been estimated for the period matching the $\delta^{13}\text{C}_{\text{pin}}$ record as 0.4°C from AD 1850 to AD 1877 and 0.2°C from AD 1878 to the present (Parker and Horton, 2005; Parker, 2010). The long CET record allows split-period verification statistics (NRC, 2006; McCarroll *et al.*, 2011) to be used to test the reliability of $\delta^{13}\text{C}$ as a proxy for past summer temperature.

A scatterplot showing the relationship between $\delta^{13}\text{C}_{\text{pin}}$ and the CET from AD 1850 to 2010 can be seen in Fig. 3(C). To further test this relationship two additional statistical tests were applied. The reduction of error (RE) and coefficient of efficiency (CE) statistics (see NRC, 2006, and references therein) are based on splitting the available climate data into a calibration period, on which a regression model is based, and a verification period where the predictive ability of the model is checked. The RE statistic tests whether the model has a better predictive ability than simply using the mean temperature of the calibration period as the best estimate for every year in the verification

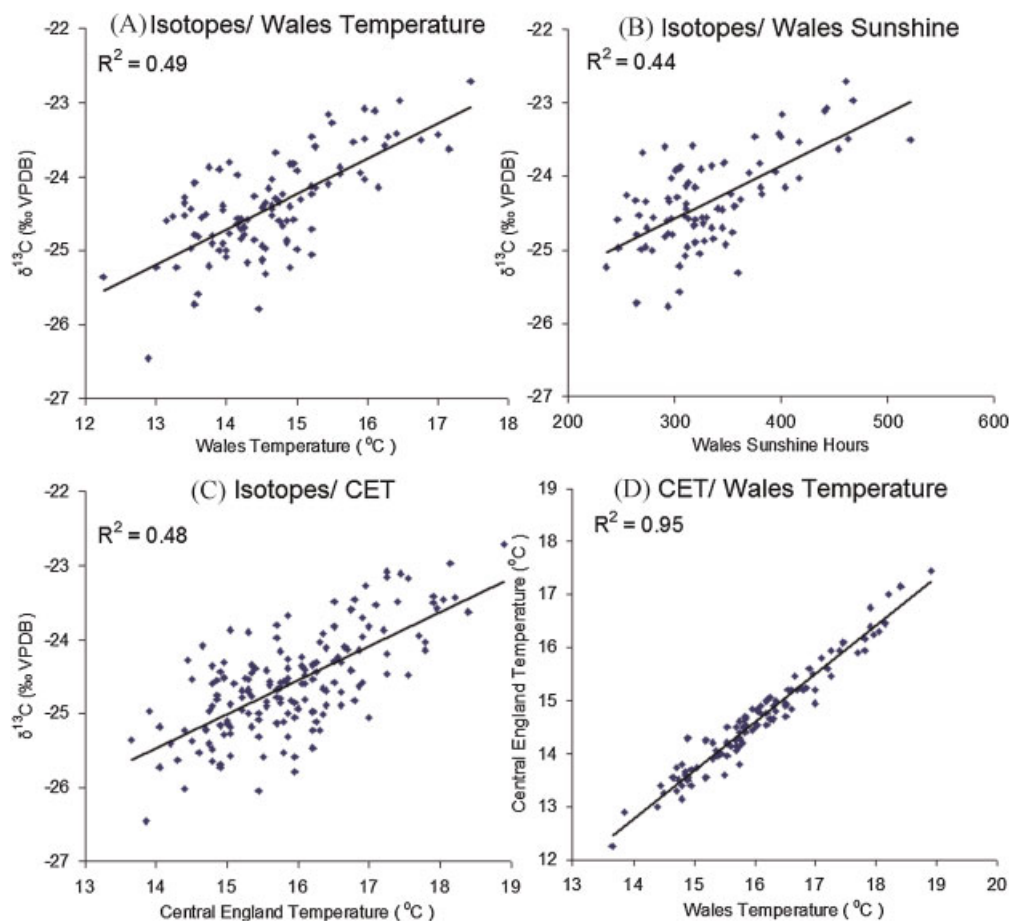


Figure 3. Scatterplots showing the squared correlation coefficients (R^2) between: (A) $\delta^{13}\text{C}_{\text{pin}}$ and July and August mean temperature AD 1910–2010; (B) total July and August total bright sunshine hours (direct solar radiation exceeding 120 W/m^2), AD 1929–2010; (C) $\delta^{13}\text{C}_{\text{pin}}$ and mean July and August CET, AD 1850–2010; and (D) July and August mean Welsh and CET, AD 1910–2010. This figure is available in colour online at wileyonlinelibrary.com.

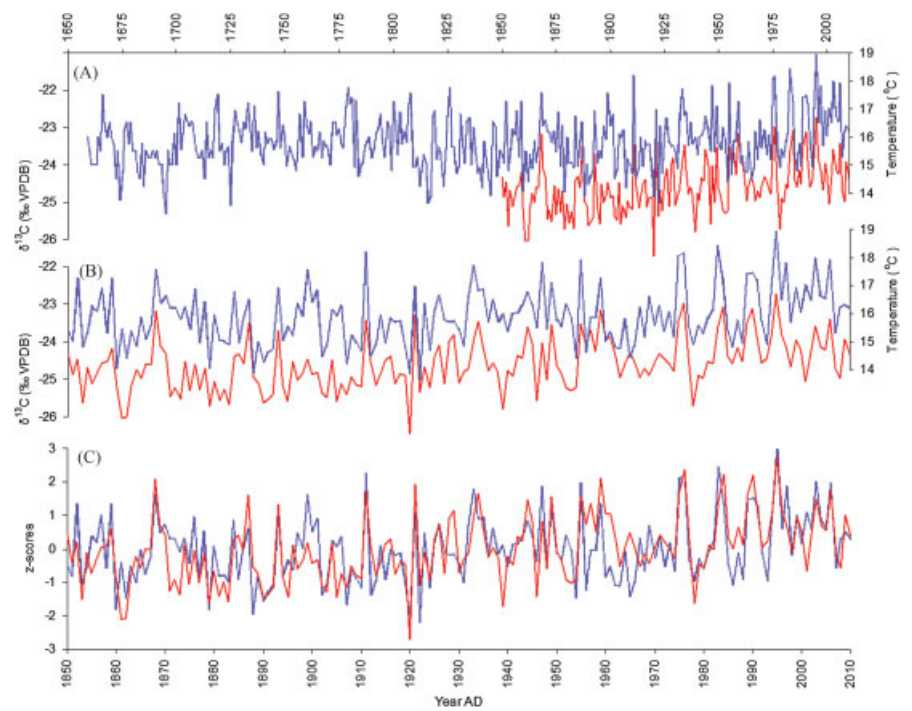


Figure 4. Stable carbon isotope ratios ($\delta^{13}\text{C}_{\text{pin}}$) from Allt Llanlas (red) compared with summer (July–August mean) Central England temperatures (CET) (blue). Over (A) the full length of the CET; (B) with the common period AD 1850–2010 expanded; and (C) with $\delta^{13}\text{C}_{\text{pin}}$ and summer CET both z-scored to mean of zero and a standard deviation of one. The squared correlation between the two series is $R^2 = 0.48$.

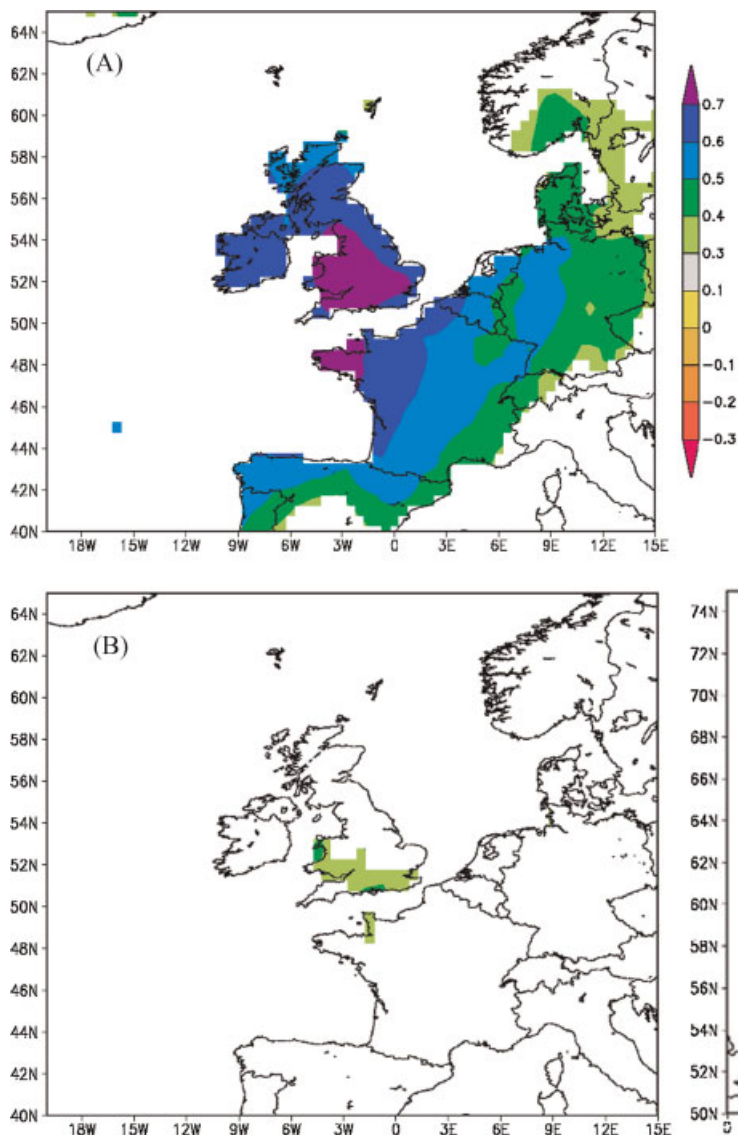


Figure 5. Spatial correlations (Pearson's r , $P < 0.01$) between the University of East Anglia Climate Research Unit (CRU) TS 3.1 (land) 0.5° gridded data set in conjunction with the Royal Netherlands Meteorological Institute KNMI online 'Climate Explorer' tool (<http://climexp.knmi.nl>) (Oldenborgh *et al.*, 2009) for: (A) July and August mean maximum temperature and $\delta^{13}\text{C}_{\text{pin}}$ from six pooled oak trees at Allt Llanlas, Wales, over the period AD 1901–2009; (B) July and August precipitation and ring-width measurements from a mean of 30 trees from the same location over the period AD 1901–2006; and (C) July and August mean maximum temperature and $\delta^{13}\text{C}_{\text{pin}}$ from Forfjorddalen in north-western Norway over the period AD 1927–2001 (see Young *et al.*, 2010), presented to demonstrate the signal strength from a tree-line site.

period. The CE statistic follows the same logic but uses the mean temperature of the verification period, and so is the more demanding of the two tests. The theoretical range for both statistics is $-\infty$ to 1, with all results less than zero being considered failures. In this case a regression model built using the calibration period AD 1930–2010 and verification period AD 1850–1929 gives RE and CE statistics of 0.57 and 0.42, respectively. When these calibration and verification periods are reversed the values are 0.57 and 0.44. These results, together with a comparison of the temperature and $\delta^{13}\text{C}$ values plotted in Fig. 4(C) as indexed values (z-scored to a mean of zero and standard deviation of one), strongly suggest that the signal is robust, over at least the past 160 years. Figure 4 compares $\delta^{13}\text{C}_{\text{pin}}$ and actual summer Central England temperatures, and both the interannual and the low frequency variability appears to be very similar. These results, in conjunction with the high positive RE and CE statistics, show that $\delta^{13}\text{C}_{\text{pin}}$ is able to capture the variability in the summer CET over the period AD 1850–2010 with the high degree of accuracy usually only associated with tree-ring proxies from high-altitude or high-latitude sites.

The strong statistical match with the CET suggests that the $\delta^{13}\text{C}_{\text{pin}}$ results from Allt Lanlas are able to capture summer temperature variability over a considerable geographical range, due to the spatial homogeneity of temperature. To test the geographical area of temperature encompassed by $\delta^{13}\text{C}_{\text{pin}}$ from the Allt Lanlas oaks a spatial correlation map over the period AD 1901–2009 was constructed (Fig. 5) using the University of East Anglia Climate Research Unit (CRU) TS 3.1 (land) 0.5° data set (New *et al.*, 1999, 2000, 2002) in conjunction with the Royal Netherlands Meteorological Institute KNMI online 'Climate Explorer' software (van Oldenborgh *et al.*, 2009). The KNMI software can be used to correlate point proxy time-series data (in this instance tree-ring $\delta^{13}\text{C}_{\text{pin}}$ data from West Wales) with CRU July–August mean land temperatures for every grid cell (0.5°) in the world over the period for which both climate and proxy data are available (in this case AD 1901–2009). Cells with similar levels of significant correlation are joined, and smoothed, to produce coloured geographical correlation bands (e.g. the purple colour in Fig. 5 represents areas with correlations between 0.6 and 0.7). The resulting figure (Fig. 5) shows correlations in excess of (Pearson's) $r=0.7$ ($P<0.01$) with July–August mean CRU gridded temperatures over most of Wales, Western and Central England and the Breton peninsula for the period AD 1901–2009. Correlations in excess of $r=0.6$ extend over most of Great Britain and Ireland and a substantial area of France and Belgium. These correlations are placed into context by comparison with Fig. 5(B,C). Figure 5(B) shows the spatial correlations for a ring-width chronology developed from measurement of 30 trees at the Allt Lanlas site (compared with carbon isotopes from only six trees). The strongest correlation is with July and August precipitation of $r=0.4$ ($R^2=0.16$). Figure 5(C) shows the relationship between tree-ring stable carbon isotopes from *Pinus sylvestris* L. also at a westerly site but at a tree-line (69°N) location in Norway (see Young *et al.*, 2010). The strength and spatial extent of the correlations for the Welsh results compare very favourably with these tree-line results and serve not only to demonstrate the potential of the isotopic approach in temperate maritime regions, but also the potential for development of spatial isotopic/palaeoclimate mosaics based upon multiple tree-ring chronologies.

Discussion

Previous studies of $\delta^{13}\text{C}$ from oak tree-rings in the UK have found significant numerical relationships with measured

climate variables, but none as strong and consistent as those reported here. Robertson *et al.* (1997) reported a very good relationship between summer temperature and tree-ring $\delta^{13}\text{C}$ ($r=0.75$) at Sandringham Park in eastern England, but only after a 10-year Gaussian filter had been applied to the data. A strong relationship between a proxy and climate that is limited only to the very high frequency is of limited use for palaeoclimate reconstruction. Loader *et al.* (2008) found a lower ($r=c. 0.45$) but significant ($P<0.01$) statistical relationship between tree-ring stable carbon isotope ratios from Scotland and unfiltered July temperature, although this signal was enhanced through combination with other isotopic data. Rinne *et al.* (2010) have suggested that poor correlations between tree-ring $\delta^{13}\text{C}$ and climate data during the recent past can result from sulphur dioxide pollution, which was very high near most British urban areas until legislation forced a reduction in emissions in the early 1950s, after which time a recovery was noted. The Welsh site used here is in a rural area far from such sources of pollution. It is also located to the west of major industrial centres and therefore upwind of potential pollution sources.

The tree-ring $\delta^{13}\text{C}$ results from West Wales presented in this paper confirm the hypothesis that a strong and significant climate signal can be found archived within the stable carbon isotope ratios of oak tree-rings growing in a temperate climate. The strength of the correlation with summer sunshine and temperature is equivalent to those more typically observed at high-latitude or high-altitude tree-line locations. The robust verification statistics suggest that the relationship between $\delta^{13}\text{C}$ and summer temperature is consistent at both high and low temporal frequencies (at least for 160 years of the $\delta^{13}\text{C}$ record). There is therefore no suggestion here of the decoupling in the relationship between $\delta^{13}\text{C}$ and summer temperature often observed at high-latitude sites. This decoupling has been linked to low-frequency divergences between temperature and sunshine in these regions (Young *et al.*, 2012), due possibly to long-term expansions and contractions of the Arctic high-pressure zone. Therefore, while the mechanistic control on carbon fractionation for oak trees in West Wales remains sunshine rather than temperature, the position of the site (Fig. 1), far from the direct influence of Arctic high pressure, allows for a strong and consistent link between sunshine and temperature to be maintained. The result is that $\delta^{13}\text{C}$ and temperature are also linked at both high and low frequencies. It therefore appears that tree-ring stable carbon isotopes, at this location, can be used as a powerful and reliable proxy for summer temperature.

Oak trees are very widespread and can live to a great age. Oak timbers are also preserved in archaeological structures, peat bogs, lakes, submerged forests and river gravels. These archives have already produced very long tree-ring chronologies for archaeological dating purposes, extending for >7000 years in Ireland (Pilcher *et al.*, 1984, 1995) and >10 000 years in Germany (Becker, 1993; Friedrich *et al.*, 2004). The results presented in this study are based upon the pooled latewood of only six trees from a single site, yet the resulting isotope series correlates strongly with summer temperature measured over a very wide area (Fig. 5). The implication of this is that just a few suitable sites would be required to produce palaeotemperature curves for much of temperate Western Europe. The availability of long oak tree-ring chronologies suggests that these archives could be exploited, with care, to reconstruct summer temperature at annual resolution for most or even all of the Holocene. The same may also be true of other temperate areas where oak trees are not moisture-stressed. Palaeotemperature reconstructions from such sites would do much to redress the current

geographical imbalance of climate reconstructions and greatly enhance our knowledge and understanding of global environmental change.

Conclusions

The annual pool of stable carbon isotopes from Allt Llanlas in West Wales presented here shows a very strong correlation with summer temperature over the 160-year period from AD 1850 to 2010. The $\delta^{13}\text{C}_{\text{pin}}$ data appear to capture both the low- and the high-frequency elements of the instrumental climate data available and the strong correlation with temperature extends over the whole of the British Isles and beyond. These data demonstrate the clear potential for statistically verifiable annualized reconstructions of climate at such locations. The availability of long oak tree-ring chronologies in Western Europe means that there is potential to reconstruct climate at an annual resolution, and with a high degree of statistical confidence, for much of the Holocene.

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Abbreviations. CE, coefficient of efficiency; CET, Central England Temperature; CRU, University of East Anglia Climate Research Unit; PAR, photosynthetically active radiation; RE, reduction of error.

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