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Stable isotope coherence in the earlywood and latewood of tree-line conifers

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ABSTRACT

Annually resolved and replicated tree-ring stable isotope series have the potential to reconstruct growing season environmental parameters over multi-millennial timescales. As this archive may require only minimal statistical detrending, it has the potential to preserve a large portion of low frequency climate signals. To date, many studies have utilised only the latewood portion of the tree ring, in an attempt to minimize carry-over effects from previous year reserves and maximise the annual nature of the climate signal preserved. However, the old trees from tree-line locations, necessary to build long chronologies, often display narrow ring-widths (<0.5 mm), making accurate earlywood–latewood separation difficult and particular time consuming. The resulting samples may also be too small for efficient cellulose purification or multiple isotopic determinations. As photosynthates from the current year are predominantly used in conifer ring formation at marginal sites with short growing seasons, latewood separation may not be especially advantageous in determining a useful climate signal and therefore unnecessary where resources are limited. To test this hypothesis, Scots pine from Northern Norway and European larch from the Swiss Alps are used. Both sites are tree-line locations where growth is predominantly temperature limited. Tree rings were cut and extracted to cellulose for both the earlywood and latewood of each annual growth ring and stable carbon isotope ratios were measured. Our results demonstrate a very high common carbon isotope signal between earlywood and latewood in both species ($r_{\mathrm{larch}} = 0.68$ and $r_{\mathrm{pine}} = 0.79$), which also show high correlations with summer temperature over the investigated period (AD 1980–2004 for larch and AD 1929–1978 for pine). High turnover rates and small reserve pools at these tree-line locations may account for these high common signals. These results suggest that for European tree-line conifers, the separation of earlywood from latewood is unnecessary to resolve an annual isotopic signal and make a reliable climate calibration. Using the whole ring may provide additional analytical advantages and consequently even improve climate calibrations.

1. Introduction

Stable carbon isotopes ($\delta^{13}C$) from tree rings are frequently used in environmental research, as they provide a continuous, annually resolved record of environmental conditions during growth (e.g. Anderson et al., 1998; McCarroll and Loader, 2004). Carbon isotopic ratios are controlled by the balance between stomatal conductance and photosynthetic rate (Farquhar et al., 1982; Leavitt and Long, 1988). In dry environments, the former is likely to dominate and stable carbon isotopes will correlate with air humidity and antecedent precipitation. In moist environments, where water stress is rare, the rate of photosynthesis is likely to dominate, which results in strong correlations with irradiance factors and growing season temperature (Loader et al., 2008; McCarroll et al., 2003).

Stable carbon isotopes may, therefore, offer potential for reconstructing long-term climatic information, as after a brief juvenile period, they appear to contain no long term age related trends (Gagen et al., 2007) and may therefore require only minimal statistical detrending to account for atmospheric changes in CO_2 during the industrial period (McCarroll et al., 2009). Although a topic of ongoing scientific debate, tree-ring stable carbon and oxygen isotopes are now being used to reconstruct lower frequency climate change (Gagen et al., 2007; Treydte et al., 2006). This is not to say that important lower-frequency environmental information cannot be extracted from physical proxies, a number of highly sophisticated well replicated millennial length reconstructions have been made using tree-ring widths and maximum latewood density, which include a high degree of low frequency variability (e.g., Büntgen et al., 2005; Büntgen et al.,

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2006; Grudd, 2008). It appears likely, therefore, that a combination of multiple proxies from tree rings may yield the best estimate of both low and high frequency climate variably (e.g., Hilasvuori et al., 2009).

To develop such isotope reconstructions, and to contribute to the current climate change debate, it is necessary to produce millennial length isotope tree-ring records with sufficient replication to robustly capture low-frequency trends, and produce statistically defined confidence intervals. This requires isotope measurements on a large scale, especially where annual resolution is required. Increasing isotope sample throughput, without compromising signal quality, is therefore highly desirable. One method of advancing this aim would be to utilize the whole ring (WR) rather than merely the latewood (LW) of individual tree rings. A problem with this approach is, however, that significant intra-annual variability has been recognised for carbon isotopes ratios (Helle and Schleser, 2004; Kagawa et al., 2006; Li et al., 2005; Loader et al., 1995; Schulze et al., 2004). This may be due to seasonal changes in micrometeorology (Barbour et al., 2002; Leavitt, 1993; Livingston and Spittlehouse, 1996; Schulze et al., 2004) or caused by the use of photosynthates from the previous year during the production of earlywood (EW), especially for deciduous hardwood species where the EW formation may commence prior to budburst (Pilcher, 1995). Carbon values in EW are, in this case, likely to be more associated with LW isotope values of the previous year rather than with LW of the current year (e.g. Hill et al., 1995; Switsur et al., 1995). Although some studies also find isotopically enriched EW in conifer species, others suggest that conifers do not seem to rely on stored carbon reserves (Barbour et al., 2002; Dickmann and Kozlowski, 1970; Glerum, 1980; Helle and Schleser, 2004). EW production would therefore use only the current years photosynthates, making the separation of EW from LW unnecessary for an annually resolved isotope signal.

Several authors suggest that the use of LW is preferable to produce climate reconstructions (e.g. McCarroll and Loader, 2004; Switsur et al., 1995). However, while some studies use only LW from both deciduous and conifer species for climate reconstructions (e.g. Etien et al., 2008; Gagen et al., 2007) others utilize LW of deciduous species but WR of conifer species (e.g. Treydte et al., 2007) or WR for deciduous and conifer species (e.g. Reynolds-Henne et al., 2007). Published guidance on the subject is often contradictory. For example, while Kagawa et al. (2006) emphasize the need of EW/LW-separation for climate reconstruction work with narrow boreal rings, Weigl et al. (2008) suggest that stable isotopes from all tree ring components (EW, LW and WR) are suitable as climate proxies.

In this study, we assess the relationship between the carbon isotopic signatures of EW and LW from tree rings of two conifer species at two European temperature-limited tree-line locations. Our aim is to determine whether (1) a sufficiently homogeneous annualised isotope signal can be obtained from WR ring cellulose, and (2) whether this signal correlates sufficiently well with climate parameters to allow palaeoclimate reconstruction.

2. Materials and methods

We considered two European conifer species from two different tree-line locations, one latitudinal and the other altitudinal (Fig. 1). Scots pine (*Pinus sylvestris* L.) from Forfjord, in coastal northwestern Norway, is close to its northern growth limit; while, European larch (*Larix decidua* Mill.) in the Lötschental, southwestern Switzerland, at ~2100 m a.s.l., is located near the inner Alpine tree line. Both sites have short vegetation periods, which, combined with low summer temperatures, produce distinct but narrow annual growth rings (typically ~0.5 mm). Details of the site characteristics are given in Kirchhefer (2001) and Kress et al. (2009). In selecting conifer species for this study, Scots pine was identified as it retains its needles for several years and provides typical conifer characteristics. In contrast, European larch is a deciduous conifer and therefore possesses some characteristics of deciduous broad-leaf trees that may be reflected in the isotopic composition of the earlywood and latewood during ring formation. Both species are widely distributed and utilised in the production of millennial-long tree-ring series from tree-ring width (Büntgen et al., 2005; Kirchhefer, 2001) and maximum latewood density (Büntgen et al., 2006).

At both sites, mature trees were selected (one ~300-year old specimen at the Norwegian site, two 250 to 300-year old specimens at the Swiss site) and cored at approximately 1.2 m using an increment borer. After surface preparation, tree-ring widths were measured (0.01 mm resolution) and cross-dated (Stokes and Smiley, 1968) against the local master chronologies (Büntgen et al., 2005; Büntgen et al., 2009; Kirchhefer, 2001). The program COFECHA (Holmes, 1983) was used to verify this cross-dating. The mean ring width was slightly larger for larch (0.92 mm) than for pine (0.68 mm) with a highly variable LW fraction of 17–25% in average for both species. All tree rings were separated into EW and LW before α-cellulose was extracted following standard procedures (Boettger et al., 2007; Loader et al., 1997). Cellulose samples of EW and LW were weighed for each year from AD 1929 to 1978 (Norwegian site) and AD 1980 to 2004 for two individual trees (Swiss site).

Carbon isotope ratios were measured online using a mass spectrometer interfaced with an elemental analyser, with samples combusted to CO_2 prior to mass spectrometric analysis. Analytical precision is typically ~0.1‰ (σ_{n-1} $n=10$), with results expressed as $\delta^{13}C$, in per mille (‰) relative to the Vienna Pee Dee Belemnite standard (VPDB). All $\delta^{13}C$ values were corrected for the atmospheric $\delta^{13}C$ decrease due to fossil fuel burning since the beginning of the industrialisation (McCarroll and Loader, 2004).

For climate comparisons, instrumental temperature data from Andenes (~60 km distance from Forfjord; see Fig. 1) were used for the Norwegian samples (AD 1929–1978), while for the Swiss site instrumental temperature data from 19 Swiss stations (Auer et al., 2007) was applied for the period AD 1980 to 2004.

3. Results

The $\delta^{13}C$ results for EW and LW cellulose are presented in Table 1 and Fig. 2, with comparison statistics shown in Table 2. Fig. 2 demonstrates a highly significant agreement ($p<0.001$) between the $\delta^{13}C$ values for EW and LW at both sites, with no major offsets throughout the series: while comparison statistics (Table 2) confirm the close similarity of EW and LW at both sites. The results from the Norwegian site (mean squared error – MSE of 0.11, an absolute difference – ABS of 0.28 and a coefficient of variance of R^2 of 0.79, $p<0.001$) indicate a slightly closer agreement between EW and LW compared to the Swiss site. The Swiss results, however, display a high correlation between the two series ($R^2_{EW}=0.57$; $R^2_{LW}=0.76$) and the associated errors are low for both trees. When a mean of the two Swiss trees is taken, the comparison statistics improve (MSE = 0.20, ABS = 0.35 and $R^2=0.68$, $p<0.001$). This is important as a mean of several trees is generally used when reconstructing climate and suggests that the addition of more trees may further reduce the difference between the mean EW and LW values. Moreover, the low squared correlation coefficients of current year EW with previous year LW of $R^2=0.03$ for the Swiss site and $R^2=0.08$ for the Norwegian site (Table 2) illustrate that the $\delta^{13}C$ signature of the current year EW is not significantly related to LW of the previous year.

Comparison with instrumental temperature data indicates the highest correlations between $\delta^{13}C$ and monthly temperature for the summer months at both sites. Only current year July, August, and July–August mean temperatures have significant correlations with $\delta^{13}C$ at both sites (at either $p<0.001$ or 0.01, see Table 3). At the Norwegian site EW-$\delta^{13}C$ correlates more strongly with July than August temperature, while for LW it is *vice versa*. Both EW and LW correlate most strongly with July–August mean temperatures. A mean of the $\delta^{13}C$ values from EW and LW, approximating the whole ring average,