Latewood Width, Maximum Density, and Stable Carbon Isotope Ratios of Pine as Climate Indicators in a Dry Subalpine Environment, French Alps

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Abstract

Pine latewood width, density, and stable carbon isotope ratios were measured at two sites, separated in altitude by 400 m, close to the forest limit on a south-facing slope in the western French Alps. The signal to noise ratio in the δ^{13}C series from each site is higher than that of either of the growth proxies. When the sites are combined, the high-frequency climate signal in the δ^{13}C series is enhanced, whereas in both the ring width and density series it is weakened. Because regional climate dominates over local site conditions, δ^{13}C ratios from long pine chronologies will provide a better indicator of past climate than either ring widths or densities. At dry Alpine sites, δ^{13}C values are controlled mainly by stomatal conductance, which is linked to summer moisture stress and thus antecedent precipitation.

Introduction

The annual rings of trees provide one of the most useful high-resolution paleoclimatic archives (Fritts, 1976; Jones et al., 1998). The parameters measured most commonly, ring widths and density, are essentially proxy measures of annual growth, but the relationship between tree growth and environment is complex, encompassing variables such as competition and disease as well as climate. Thus measurements obtained from two trees, even growing in close proximity, are never exactly the same because each tree responds to a wide variety of factors. At many sites local conditions exert a much stronger control than regional climate, and in some cases ring-width and density measurements contain no paleoclimatic information at all (Fritts, 1991). This problem can be alleviated by choosing sites where climate is likely to strongly limit growth, or by combining results from many sites so that the common signal is dominated by regional climate and local variations tend to cancel each other out. In this way, large-scale networks of ring-width and density series now provide hemispheric scale climate reconstructions (e.g., Schweingruber and Briffa, 1996; Briffa et al., 2002; Esper et al., 2002). However, such a strategy cannot be applied to develop climate reconstructions on smaller spatial scales; constructing long chronologies using subfossil or building timbers, where the conditions of growth are not well constrained, it may not be possible to obtain sufficient replication through time. If chronologies constructed using "sensitive trees" in the modern period are extended using trees that are in effect sampled randomly, modern climate calibrations may become unrealistic when used to extend climate reconstructions back in time.

An alternative strategy might be to use some tree-ring parameter that is strongly linked to climate in a way that does not vary greatly between sites or even between closely related tree species. A possible candidate is the ratio of the stable isotopes of carbon that, rather that recording net growth, varies directly in response to the influence of climate on the rate of photosynthesis and stomatal control of moisture loss (Farquhar et al., 1989).

This paper provides a comparison between latewood width, density, and stable carbon isotope ratios (δ^{13}C) from a high-altitude site in the western French Alps, where moisture stress is known to be growth-limiting (Keller et al., 1997; Rolland et al., 2000). Differences in growth response to climate are known to exist for Alpine *Pinus sylvestris* (see Rigling et al., 2002) and *Pinus uncinata* (see Rolland and Florence-Schueller, 1998), as well as same-species site to site differences, but these parameters have not been similarly evaluated for δ^{13}C series. Here we carry out an evaluation of signal strength and climatic sensitivity in all three proxies. Stable carbon isotopes are not a measure of net growth, but of variation in internal CO_2 pressure, a parameter far less sensitive to local site factors.

We investigate signal strength and climatic sensitivity in three proxies from two different sites and two different species. We asses whether or not stable carbon isotope ratios are less influenced by local site conditions and species differences than growth proxy series, or whether the relationships between δ^{13}C and climate at the field site are also site/species specific. The strength of the correlation between trees provides a useful measure of the proportion of variation that is common, and therefore likely to reflect the local climate. A measure of common signal between sites/species can be gained by combining series and investigating how this affects common signal strength.

STUDY SITE AND METHODS

The field site was located at Montgenèvre, east of Briançon, in one of the driest areas of the French Alps. The forests of this area are dominated by *Pinus sylvestris* L., *Pinus uncinata* Mirb.,*Pinus cembra* L., and *Larix decidua* Mill. Norway spruce (*Picea abies* L.) also occurs but is insufficiently drought-tolerant to form true forest (Rolland et al., 2000).

An upper site was placed near the treeline at 2200 m, where fragmented stands of *Pinus cembra*, *Pinus uncinata*, and *Pinus sylvestris* are scattered with at least 4 to 6 m between nearest neighbors. A lower site, immediately down-slope at 1800 m, was placed in true forest with a mixture of *Pinus sylvestris* and *Pinus uncinata* growing in close proximity but with a fairly open canopy. Both sites are located on a south-facing slope.

At each site 15 dominant or co-dominant trees were cored for density and ring-width measurement. For the stable carbon isotope series, four trees at the upper site and two trees at the lower site were analyzed from breast-height cut disks. Common signal strength within the δ^{13}C series was high enough to keep sample replication low. In all

cases, *Pinus uncinata* were sampled at the upper site and *Pinus sylvestris* at the lower. These two-needle pines are very closely related in terms of ecological requirements. They are commonly found growing in close proximity in similar bioclimatic zones, as seen here. Variability and range at the site is typical of the common European pine species; *Pinus uncinata* in the Pyrenees is typically mesic with *Pinus sylvestris* in warmer and drier localities (see Camerero et al., 1998) while in the dry central Swiss Alps, *Pinus sylvestris* is found on strongly xeric sites (Rigling et al., 2002). Generally *Pinus sylvestris* occupies lower altitudes than *Pinus uncinata* (so-called mountain pine) as seen in the patterns of dominance at our field sites. The two species commonly cross-fertilize to produce hybrids. French sub-Alpine treeline populations of *Pinus sylvestris* and *Pinus uncinata* have been used extensively in dendroclimatic investigations (Tessier, 1986; Fauquette and Talon, 1995; Petitcolas and Rolland, 1996; Edouard et al., 1999; Rolland et al., 2000).

Core samples were sectioned and chemically treated to remove resins and heartwood substances prior to X-ray densitometry (see Edouard et al., 1999, for details). Pine tree rings comprise earlywood, formed in the spring largely from stored photosynthates (Livingston and Spittlehouse, 1996), and latewood formed during the summer. In order to retain an annual signal, without strong lag effects, only latewood parameters are used in this study.

For carbon isotopic analyses, latewood was removed from two sides of each disk and processed to holo cellulose using Soxhlet extraction for the removal of resins and waxes (Hoper et al., 1998), followed by bleaching for lignin removal, using the method of Loader et al. (1997). CO_2 samples were prepared using an offline combustion and cryogenic distillation system followed by analysis on a VG Micromass 602C dual inlet isotope ratio mass spectrometer. Measurement precision was $\pm0.05‰$. The isotope ratios are expressed using the conventional δ (delta) notation (McCarroll and Pawellek, 1998).

CHRONOLOGY DEVELOPMENT

Tree rings were securely dated by reference to regional chronologies (Edouard et al., 1999) and all series were standardized using a high pass filter to highlight only interannual variation (10-yr filter), followed by subtraction from the mean to produce high-frequency indices (using software PPPBase; Guiot and Goeury, 1996). This aggressive high-frequency detrending method was used on all three series in order to allow cross proxy comparisons of high-frequency signal quality. With relatively short series standardization to retain low-frequency signals is not possible (Cook et al., 1995). The $\delta^{13}C$ series do not require statistical standardization in the same manner as growth proxy series. Tree ring $\delta^{13}C$ series include a decline in $\delta^{13}C$ raw ratios due to the anthropogenic increase in isotopically light CO_2 (Friedli et al., 1986) which is commonly corrected by subtraction from an atmospheric $\delta^{13}C$ CO_2 curve (e.g., Saurer et al., 1997; McCarroll and Pawellek, 2001). However, in the context of this study our wish to evaluate signal strength and climatic sensitivity between proxies required the same standardization to be used for all three proxies and a high-pass (10-yr) filter was thus used on all series (Fig. 1). The common practice of pooling wood from several trees prior to isotopic analysis (Leavitt and Long, 1984; Borella et al., 1998; Treydte et al., 2001) was avoided because it precludes removal of age trends and calculation of signal strength.

Different trees were used for the measurement of widths, density, and $\delta^{13}C$ series due to the differing requirements of sample preparation, although all trees grew in close proximity. The chronologies therefore vary in sample length. For the purposes of these analyses a common overlap period of 1895–1995 was used.

Mean monthly maximum and minimum temperatures (1961–1995) and monthly precipitation totals (1967–1995) were available

from a Meteo France climate station at Briançon (44°54′5N, 6°38′1E), 14 km from the field site. Longer climate data series (1904–1980) are available from the Hautes Alps regional climate station at Gap. However, this site is approximately 100 km from the field area in a highly mountainous region, where precipitation in particular can be spatially highly variable. Climate data from Gap correlates poorly with that from Briançon and would not be a good reference for conditions at the field site. Regional climate at Briançon is characterized by high insolation (3064 h yr^{-1}, Petitcolas and Rolland, 1996) and annual precipitation (900 mm) only 300 mm higher than that of the driest regions of the Alps (Cebon et al., 1998). Mean annual temperature is 7.7°C. Summer monthly maximum averages commonly reach 30°C. January is the coldest month and July the driest and hottest.

Results and Discussion

SIGNAL STRENGTH

Signal strength was investigated for the proxy series, comparing within-site and between-site signal strength, a common period of 100 yr was used (1895 to 1995). Correlation matrices (Table 1) reveal that, for both latewood widths and density, between-tree correlations are much stronger at the upper site. At the lower site the average between-tree correlation for maximum density is only 0.29 ($P < 0.05$), compared to 0.61 ($P < 0.01$) for the upper site. Although fewer trees were sampled for carbon isotopic analysis, the between-tree correlations are strong and consistent, and the average within-site correlations (0.66, $P < 0.01$) are stronger than for either widths or densities despite being based on only four trees at the upper site and two at the lower.

Perhaps more significant is the difference in intersite correlations between trees. The mean intersite correlation is r = 0.61 ($P < 0.01$) for the $\delta^{13}C$ series (based on eight tree combinations) compared to r = 0.11 for the density series and r = 0.27 for width, neither of which are significant ($P < 0.05$) despite being based on 121 tree combinations. Of the eight intersite correlations in the $\delta^{13}C$ matrix, six are the highest ranked out of all three series. The probability of the top six ranked intersite correlation values (out of 250) randomly falling in the $\delta^{13}C$ data set is less than one in a million, a strong indication that, when examining high-frequency variability, the $\delta^{13}C$ series is much less sensitive to local site conditions and random between-tree variation than either of the growth proxies.

In addition to insensitivity to site conditions, the high-frequency variability in $\delta^{13}C$ is insensitive to species. This is particularly noteworthy as the traditional view of $\delta^{13}C$ tree-ring work has been that, when using isotopic analysis to derive tree-ring climate proxies, trees would need to be analyzed species by species as isotopic fractionation is species dependent (Schweingruber, 1996). In fact fractionation variability in trees from our two species shows no greater range than between individuals from the same species. When investigated using nonparametric analysis of variance (two-way rank ANOVA performed in SPSS), results are not significant at $P < 0.02$ using raw $\delta^{13}C$ values, indicating that the trees yield stable carbon isotope series that are statistically from the same population. There is a small difference in mean $\delta^{13}C$ value between the two species (*Pinus uncinata* −22.65‰, *Pinus sylvestris* −22.69‰) but this is considerably lower than typical same-species within-site level differences, often in the region of 2 to 3‰ (see McCarroll and Loader, 2004, and references therein).

The number of trees required to provide a representative sample for climatological investigation can be assessed by calculating the expressed population signal (EPS) in individually standardized series, which is a function of the number of trees and the strength of the correlations between them (Wigley et al., 1984; McCarroll and Pawellek, 1998). Samples of trees yielding EPS values below 0.85 are generally regarded as unsuitable for paleoclimatic reconstruction
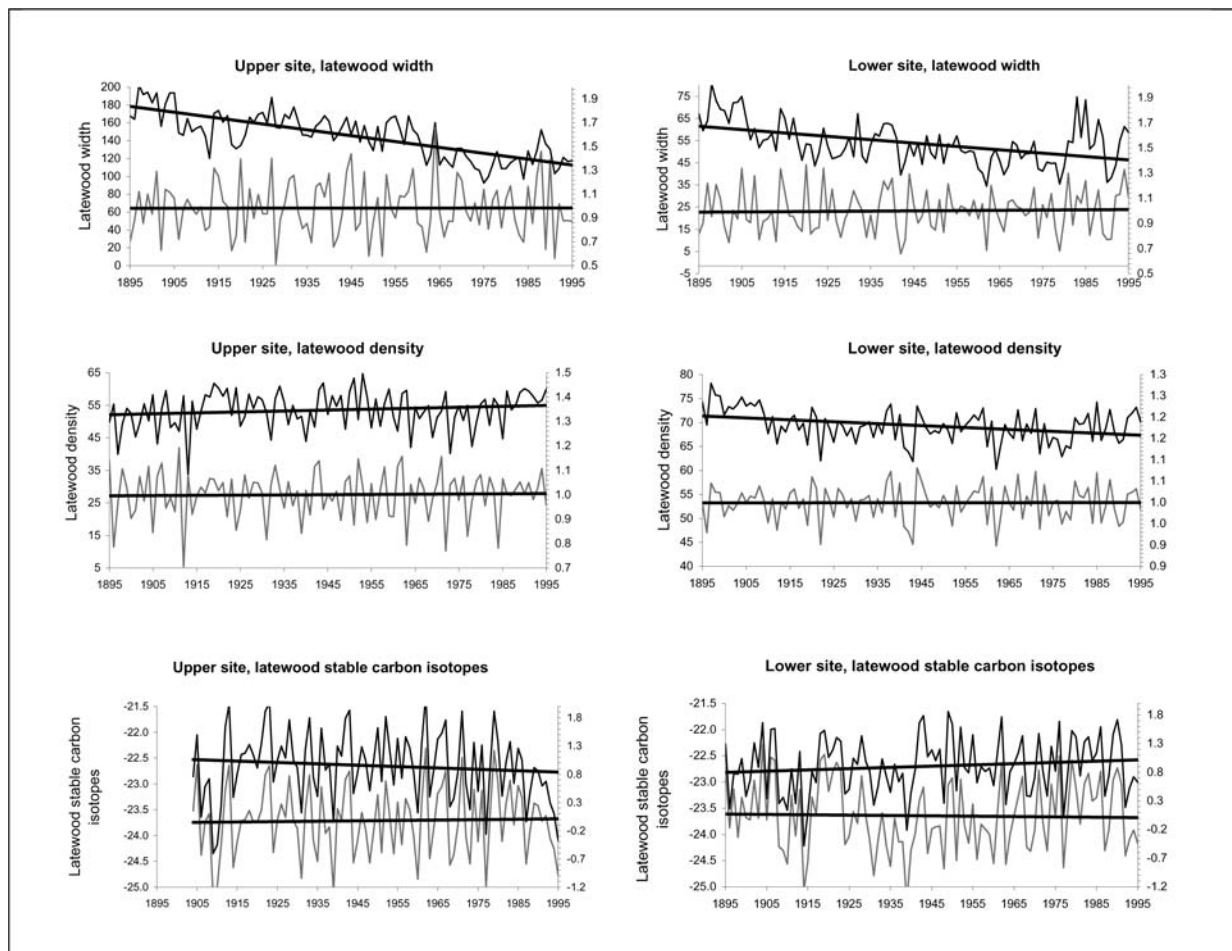
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FIGURE 1. *Raw (black) and indexed (gray) series, upper and lower sites, latewood stable carbon isotopes, density, and width. A 10-yr filter was used to produce high-frequency indices.*

(McCarroll and Pawellek, 1998). Using samples of 15 trees, width and density measurements yielded EPS > 0.85 at all but one site (lower site density series; Table 2). The results can be used to estimate that six and eight trees would be required to obtain an EPS value of at least 0.85 for width measurements at the upper and lower sites, respectively. For density measurements only five trees would be required at the upper site but 15 at the lower site, assuming the average between-tree correlations remain constant. At the upper site, where $\delta^{13}C$ are available from four

trees this small sample is sufficient to provide an EPS of 0.88. These results suggest that stable carbon isotopic analysis requires fewer trees to provide a representative average series for a site than the more traditional growth proxies.

The most striking difference between $\delta^{13}C$ and the growth proxies is the effect of combining trees from both sites to produce a single mean series. The effect on both width and density is to markedly reduce the expressed population signal, despite doubling the sample

TABLE 1

Correlations between the trees. Within site and between site maximum, minimum, and mean correlation coefficients for width and density and between all possible pairs of trees for $\delta^{13}C$ (U = upper site, L = lower site). Correlations were carried out on a 50-yr sample, coefficients ≥ 0.36 are significant at P < 0.01, and ≥ 0.28 at P < 0.05

	Latewood width n = 15			Latewood Density n = 15			Latewood $\delta^{13}C$ n = 4 (upper) n = 2 (lower) n = 6 (inter)		
	mean	max	min	mean	max	min	mean	max	min
Upper plot	0.52	0.71	0.3	0.61	0.83	0.33	0.66	0.77	0.49
Lower plot	0.42	0.69	0.1	0.29	0.56	0.05	0.68	—	—
Interplot	0.27	0.57	−0.01	0.11	0.42	−0.17	0.61	0.74	0.42

Latewood $\delta^{13}C$					
	U-02	U-03	U-04	U-05	L-11
U-03	0.77				
U-04	0.71	0.76			
U-05	0.49	0.57	0.68		
L-11	0.68	0.74	0.72	0.51	
L-12	0.68	0.62	0.57	0.42	0.68

TABLE 2

Expressed Population Signal (EPS): upper, lower, and combined latewood width, density, and stable carbon isotopes. Figures in parentheses show the number of trees in each series

	Upper site	Lower site	Combined
Latewood width	0.92 (15)	0.88 (15)	0.87 (30)
Latewood density	0.95 (15)	0.81 (15)	0.73 (30)
Latewood stable carbon isotopes	0.88 (4)	0.80 (2)	0.90 (6)

size to 22 (Table 2). In the case of density the EPS falls below 0.85 and the combined series could not be used reliably to reconstruct past climate. In contrast, combing the six $\delta^{13}C$ series raises the EPS value of the combined mean above that of either of the individual site means. Based on these results, a minimum of 18 trees would be required to provide a representative mean series in a combined-site chronology using width, and 46 using density. Only four trees are required to achieve the same common signal strength using $\delta^{13}C$ and these could be from either site. In this context the number of useful samples at a site is potentially far higher for $\delta^{13}C$ because a number of different sites

within a region could be sampled and the series combined. This is a clear contrast to alpine growth proxy series where a loss of climate signal often occurs below the uppermost treeline (Schweingruber, 1988). In a wider context climate reconstructions based on tree-ring networks often exclusively use material from boundary environments such as treelines. There is a potentially powerful advantage to tree-ring $\delta^{13}C$ as they are clearly far less sensitive to ecological conditions. It seems this insensitivity to site conditions can extend over larger areas, as Treydte et al. (2001) find high intersite correlations for sites in the Swiss Alps which varied in elevation, moisture conditions, and exposure.

CLIMATE RESPONSE

Simple linear correlations were calculated with monthly climate variables using a period from January to November of the current year. This is a conservative time window chosen as, even at high altitude in the Hautes Alps, the growth season can occasionally extend into November (Edouard et al., 1999). Correlation coefficients (Fig. 2) show marked differences in climatic response between the proxies, and in the case of the growth proxies, between the two sites. The lower site width series is most strongly correlated with May precipitation,
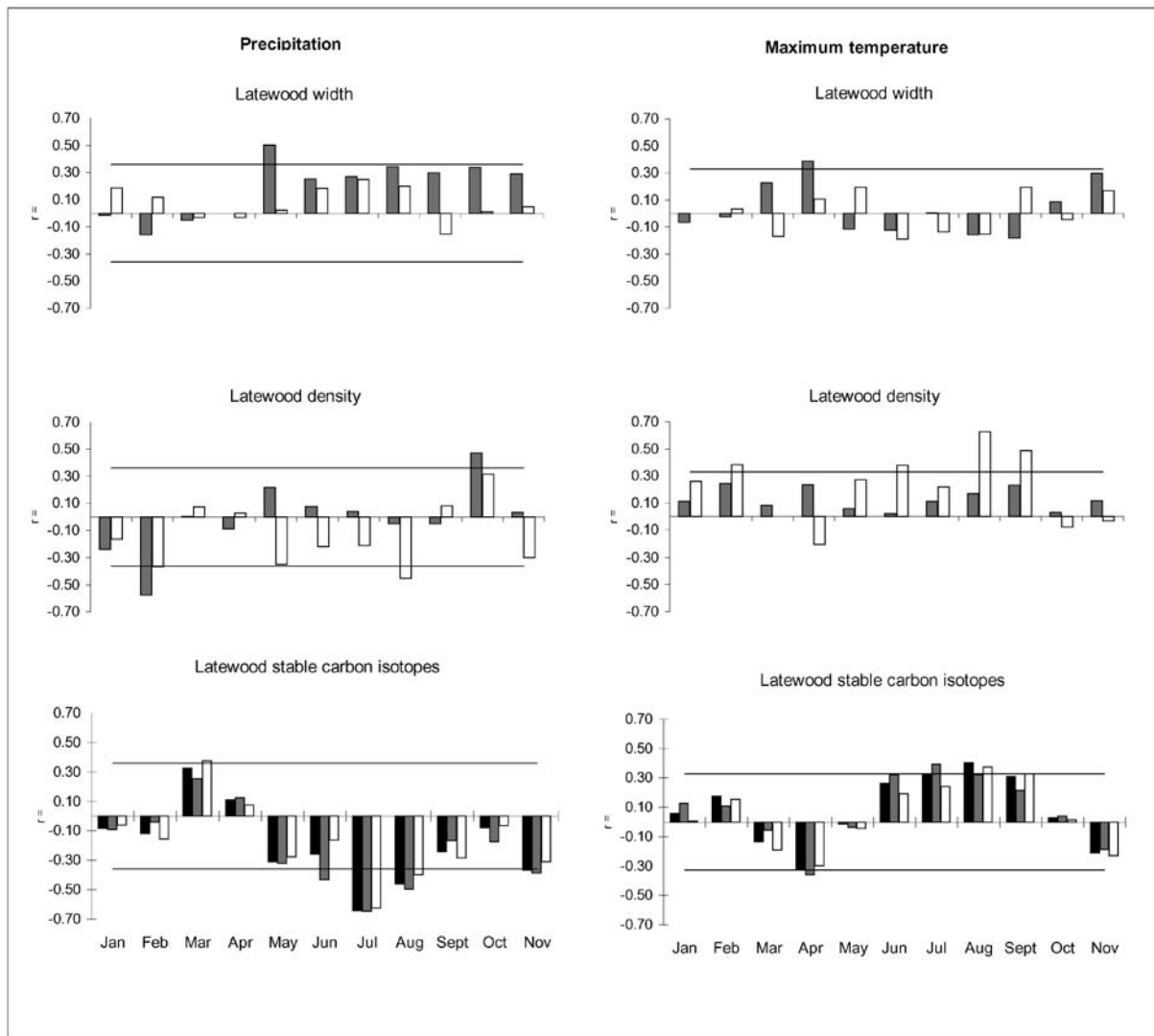

FIGURE 2. Simple linear correlations with Briançon monthly climate variables and latewood width, density, and stable carbon isotope series. Dark gray shows lower site series, white upper site series, black combined upper and lower sites (stable carbon isotopes only). Significance levels (P < 0.05) are shown for each series.

whereas the upper site shows no significant correlations with any of the precipitation variables. At the lower site the strongest correlations, between width and temperature, are with April and November whereas for the upper site the strongest correlation is with May. However, only the correlation with lower site width and April maximum temperature is significant. The density series show even more marked differences between the sites, as is common for Alpine series (Schweingruber, 1988). At the upper site the strongest correlations are with the temperatures of August and September ($P < 0.01$) whereas the lower site shows no significant correlations with temperature, responding rather to the precipitation of February ($P < 0.01$) and October ($P < 0.05$). At the upper site the strongest correlations with monthly precipitation are for May and August, with only August statistically significant ($P < 0.05$).

Since combining the δ^{13}C results from the two sites increases the strength of the common signal, it is valid to use the mean of all six trees for calibration with climate data. The signal is clearly dominated by the climate of July and August, with hot dry conditions during mid summer leading to the highest ratios (indicative of stomatal response to moisture-stress leading to reduced internal concentration of CO_2 and ultimately to ^{13}C enriched cellulose). This is revealed as a strong negative relationship with July and August precipitation, lower precipitation being associated with higher δ^{13}C ratios, and a weaker positive correlation with August maximum temperatures. The strongest signal is the total precipitation of July and August, with a correlation of 0.75 ($P < 0.02$). These results are comparable to those from several other tree-ring δ^{13}C studies, in central Switzerland (Saurer et al., 1995, 1997; Anderson et al., 1998) and the Swiss Alps (Treydte et al., 2001). The consistency in the correlations between the δ^{13}C results from individual trees and the monthly climate data (Table 3) confirms that trees from the two sites retain the same climate signal, as found by Treydte et al. (2001) for six ecologically differing sites in the Swiss Alps. In our case, the same pattern and strength of climate signal is also displayed by the two different species sampled.

Conclusions

Investigating the high-frequency variation at two dry sites in the western French Alps, where summer moisture stress is growth limiting, the three different potential paleoclimate proxies retain different paleoclimate signals, and their sensitivity to local conditions varies. The growth proxy series show less similarity between sites than the δ^{13}C series do. Latewood width and density are sensitive to local site conditions, so that when trees from two sites on the same hillside, separated in altitude by only 400 m, are combined, the effect is to weaken the common regional signal, a common feature of high-elevation chronologies. Comparison of the individual sites with regional climate data reveals that this reflects, not just between-site differences in sensitivity to climate, but differences in the climatic parameters that influence those proxies. This finding has important implications for the use of ring width and density series to reconstruct paleoclimate using long chronologies constructed from subfossil and building timbers, where the provenance of individual trees that comprise sequences may be varied or unknown. This is a long-identified issue in dendroclimatology and, as such, it has become commonplace to use high numbers of series to build growth proxy networks, averaging out local effects and producing spatially smoothed climate reconstructions. While this produces excellent reconstructions at large spatial scales (e.g. Briffa et al., 1998) the same strategy cannot be applied to produce regionally specific climate reconstructions back through the Holocene. The significance of the lack of site dependency in climatic signals from δ^{13}C series may be considerable if it means that climate signal quality is less dependent upon sampling locality and species.

Although sampling replication was not high at the lower of the two

	Upper site				Lower site	
	U-02	U-03	U-04	U-05	L-11	L-12
Mean series correlation r = −0.64						
July Precipitation	−0.62	−0.62	−0.48	−0.50	−0.51	−0.60
Mean series correlation r = −0.75						
Total July+August Precipitation	−0.62	−0.64	−0.64	−0.58	−0.68	−0.73

sites, the climatic signal in all six δ^{13}C series is remarkably consistent. It would appear that, by measuring a proxy not controlled by growth, the effect of different ecological requirements on proxy response to climate is minimized. The lack of sensitivity to local conditions in δ^{13}C is probably enhanced at treeline sites where mean sensitivities tend to be high enough to reduce the impact of site differences. Rigling et al. (2001) note that, despite differences in climatic zone and soil substrate, *Pinus sylvestris* ring widths from dry sites in the central Swiss Alps and central Siberia all respond to preseason and growth season precipitation. However, δ^{13}C insensitivity to site conditions does not seem to be limited to high elevation alpine zones. In a study in northern Finland McCarroll and Pawellek (2001) find that signal coherence is high enough in pine δ^{13}C for series to be combined over a 100 km north–south transect. Combining series over a geographical region is particularly useful as it gives us more realistic modern analogs for the kind of series which are used to build longer Holocene chronologies (see McCarroll and Pawellek 2001; McCarroll and Loader, 2004).

Stable carbon isotope ratios from the latewood cellulose of pine trees growing in dry subalpine environments provide a powerful proxy measure of past changes in summer moisture stress. Where trees experience low precipitation, the isotopic ratios are controlled mainly by the rate of stomatal conductance and so are sensitive to moisture availability during the growth season, with hot dry summers producing the highest δ^{13}C values, a relationship found elsewhere in Alpine Europe (e.g., Saurer et al., 1997; Treydte et al., 2001). Because the regional climate signal is strong, and is not greatly influenced by local site conditions, regional δ^{13}C chronologies are likely to provide stronger and more stable high-frequency climate signals than tree-ring growth proxies.

These results show considerable potential for developing high-frequency climate reconstruction from tree-ring δ^{13}C. The response of the proxy to low frequency variability, both climatic and nonclimatic, is still unknown. It is noteworthy that quantifying tree response to low-frequency shifts, which may be age related, will require analysis of single series rather than samples pooled prior to analysis.

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