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Are pooled tree ring $\delta^{13}C$ and $\delta^{18}O$ series reliable climate archives? — A case study of *Pinus nigra* spp. *laricio* (Corsica/France)

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ABSTRACT

Stable carbon and oxygen isotopes in tree rings are considered as reliable climate archives as they provide past environmental information with high resolution. However, recent studies have shown that isotope chronologies may reveal a long-term age trend and be influenced by non-climatic factors as other tree-ring parameters as well. These trends can only be identified in chronologies measured on individual trees but not on pooled sample chronologies consisting of several trees. In order to test whether pooled chronologies from pine trees from the Island of Corsica (Mediterranean/France) can be used for climatic reconstructions, we compared calculated mean values from 5 individual trees with pooled chronologies from the same 5 individuals. Carbon and oxygen isotope chronologies for a 50-year interval with annual resolution and 400 years with decadal resolution were analysed in order to document secular changes in inter-tree variability and to test for age related trends in the isotope ratios. Pooled carbon and oxygen isotope series correspond well to chronologies based on mean values calculated from analyses of individual trees. Inter-tree variability in oxygen isotope ratios is higher than in carbon isotope ratios but remains relatively constant over time. Similarities between the isotope series of individual trees are stronger over the 400-year time scale documenting a common long-term signal in the isotope values. No long-term age related trends are observed. Oxygen isotope values of the juvenile phase are characterised by a remarkable decrease over 40–50 years, interpreted to be related to the less developed root system of the young trees. This age effect can be avoided by not considering the first 50 years from the chronologies. Our results confirm that pooled carbon and oxygen isotope chronologies from *Pinus nigra* can be used for environmental reconstructions without statistical detrending.

1. Introduction

Tree rings are a widely used archive for palaeoclimate reconstructions since they provide high dating accuracy and annual or even seasonal resolution of the reconstructed climatic signal (e.g. Serre-Bachet, 1994; Briffa et al., 2002; Griggs et al., 2007; Büntgen et al., 2011). Tree-ring parameters such as tree-ring width and maximum latewood density, have proven their potential for analysis and reconstruction of past climate conditions (Bräuning, 1999; Briffa et al., 2002; Esper et al., 2002; Bräuning and Mantwill, 2004; Frank and Esper, 2005). However, extracting low-frequency climate signals remains challenging since these parameters are also influenced by non-climatic factors such as endogenous and exogenous disturbances as well as tree age (Cook and Kairiukstis, 1990; Hughes et al., 2011). Before a thorough climatic interpretation is possible, these non-climatic effects must be minimized or removed by 'detrending' procedures, i.e. the application of statistical methods that transfers the original values to dimensionless index series that are largely free of the biological age trend (Fritts, 1976; Briffa and Jones, 1990; Cook and Kairiukstis, 1990; Esper et al., 2003). Depending on the selected detrending algorithm, part of the climatic information contained in tree-ring series may be lost during the detrending process, especially in the lower frequency domain which is of particular interest in the study of long-term climate change (Cook et al., 1995; Briffa et al., 1996; Melvin and Briffa, 2008).

In recent years, a considerable number of studies using stable isotopes from tree rings were performed to overcome the weaknesses of ring widths and density series and to allow the reconstruction of climate parameters during other seasons (e.g. Robertson et al., 2001; Danis et al., 2006; Gagen et al., 2007). Since stable isotope series from single trees often contain a stronger common signal, a smaller sample number (usually 4 to 5 trees) is sufficient to build reliable chronologies (Leavitt and Long, 1984; Treydte et al., 2001; Gagen et al., 2004, 2007; Leavitt, 2010). Additionally, some studies suggested

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that stable isotope ratios from annual tree rings appear to be insensitive to the influence of defoliation caused by insect attack (Kress et al., 2009a) and are not showing long-term age related trends (McCarroll and Loader, 2004; Young et al., 2011).

Instead, other studies did describe age related trends in carbon and oxygen isotope series (e.g. Treydte et al., 2006; Esper et al., 2010). The existence of a carbon isotope age trend in the juvenile phase of trees was already observed in early studies by Bert et al. (1997) and Francey and Farquhar (1982) and more recently confirmed by investigations of Esper et al. (2010), Gagen et al. (2007, 2008), and McCarroll and Pawellek (2001). According to the earlier studies, the isotope age trend seemingly only affects the first years after tree germination and is expressed by a significant increase in $\delta^{13}C$. The magnitude of observed age trends is variable and ranges from 1–1.5‰ (Leavitt and Long, 1985) up to 1.5-2‰ (Freyer, 1979). The duration of the age-related change in the isotope ratios seems to depend on tree longevity and can last from 20–30 years (Stuiver, 1978; Freyer, 1979) up to 200 years or more for long-living and very tall trees like *Agathis australis* (Jansen, 1962) and *Sequoia* (Craig, 1954; Stuiver et al., 1984). Treydte et al. (2006) were the first to observe an age-related effect in $\delta^{18}O$ characterised by decreasing values of~2‰ over nearly 300 years. The recent study by Esper et al. (2010) reported a systematic decline in $\delta^{13}C$ and $\delta^{18}O$ time series over the first 100 to 400 years after germination. Since a thorough correction of age trend effects is only possible if isotope values are measured on individual trees, Esper et al. (2010) highlight the necessity of individual tree analysis for stable isotope-derived climate reconstructions.

As sample preparation and stable isotope analysis of tree ring cellulose are time and labour intensive, a common approach to reduce the number of samples is the pooling of contemporaneous tree-ring material of several trees. Several studies have shown that isotope values measured on pooled tree samples are within the uncertainty range of single tree analyses (Saurer et al., 1997; Borella et al., 1998; Treydte et al., 2001; Leavitt, 2008). An important constraint of pooled chronologies is that any information on inter-tree variability is lost (Saurer et al., 1997). Inter-tree variability in the isotope ratios of different tree species has been shown to range generally from 1 to 3‰ for $\delta^{13}C$ and 1 to 4‰ for $\delta^{18}O$ (for a review see Leavitt, 2010). Microenvironmental factors like moisture, light and temperature, which can influence rates of photosynthesis or stomatal conductance, are interpreted as the main causes of different isotope values among neighbouring trees (Leavitt, 2010). Inter-tree variability can further result from circumferential variability in a single tree. The circumferential variability can be rather high (up to 4.5‰ in $\delta^{13}C$ and up to 5‰ in $\delta^{18}O$; Tans and Mook, 1980), but usually ranges from 0.5 to 1.5‰ for $\delta^{13}C$ and 0.5 to 2.0‰ for $\delta^{18}O$ (Leavitt, 2010). Circumferential variability is attributed to microenvironmental factors and root architecture of individual trees (Leavitt, 2010). The determination of circumferential variability is important for an estimation of the error when interpreting inter-tree variability and annual variations in the isotope ratios.

By pooling several trees, it is neither possible to identify non-climatic effects nor to define confidence limits for calculated mean values (McCarroll and Loader, 2004). To avoid these restrictions in the use of pooled chronologies, several authors recommend analysing several years separately for each tree (e.g. Leavitt and Long, 1992; Leavitt and Lara, 1994) or applying modified pooling techniques (e.g. Tang et al., 2000; Boettger and Friedrich, 2009). Another issue is whether pooled chronologies represent well the calculated mean of single tree chronologies. Only few studies compared pooled chronologies with chronologies based on averaged values of single trees. High synchronicities in both chronologies were observed for carbon isotopes by Treydte et al. (2001) and for carbon and oxygen isotopes by Dorado Liñán et al. (2011) and Kress et al. (2010).

Documentation of non-climatic trends in isotope chronologies and inter- and intra-tree variability in the isotope ratios are of major importance for evaluating the significance of isotope chronologies for climate reconstructions. This study evaluates the potential of stable carbon and oxygen isotope series derived from pine trees (*Pinus nigra* ssp. *laricio*) growing on the island of Corsica for the development of long-term climate reconstructions by focussing on the questions whether (i) pooled isotope series are equivalent to calculated mean values from single tree isotope analyses, (ii) how inter-tree variability in the isotope values changes over time, and, (iii) whether carbon and oxygen isotope series show any age-related long-term trends.

2. Study site

Corsica is a mountainous island located in the western Mediterranean Basin between 41–43° N and 8–10° E (Fig. 1). The main mountain range runs from North to South with several peaks above 2000 m asl, composed of Variscan basement dominated by calc-alkaline and alkaline granites (Rossi and Cocherie, 1991). Local climate is strongly influenced by rugged mountains and deep valleys. The climate close to the coast can be classified as subtropical Mediterranean with dry and warm summers and temperate and wet winters. In general, mean annual precipitation increases from the coast to the mountains from around 600 mm/a up to more than 1500 mm/a above 1000 m asl. However, differences in precipitation occur within the mountain ranges, with northeastern Corsica being drier than central and southern Corsica (Bruno et al., 2001; Kuhlemann et al., 2008). The dominating tree species in the mountains is Corsican pine (*Pinus nigra* ssp. *laricio*) which forms a forest belt between 1000 and 1800 m asl and often builds the upper tree-line (Kuhlemann et al., 2009).

We sampled upper timber line Corsican pine trees at the sites Capannelle at around 1700 m asl and close to Col de Bavella at around 1300 m asl (Fig. 1). Capannelle is located in the central part of the main mountain range on the southeast exposed slopes of the Monte Renoso massif (2352 m asl). The forest is a mixed stand of *Pinus nigra* ssp. *laricio* and European beech (*Fagus sylvatica*) with *F. sylvatica* dominating the upper timber line at north exposed slopes and *P. nigra* at south exposed slopes. The local climate of Capannelle is relatively cool and wet compared to other mountain locations on Corsica. Air masses from the east coast can reach the site nearly unhampered and are responsible for high local precipitation conditions. Snow cover during winter months plays an important role with single snow fields remaining until the end of May. The vegetation period lasts approximately from May to October. Climate and ecologic conditions at Col de Bavella are similar to Capannelle, as documented by high similarities between two tree-ring width chronologies from both sites (Pearsons correlation coefficient $r = 0.89$). Col de Bavella is affected by strong winds and relatively humid conditions due to nearly daily occurring fog. The most obvious difference to the Capannelle site is that the forest consists predominantly of *P. nigra*.

3. Material and Methods

To test for inter-tree variability and age trend effects, we sampled five trees at the site Capannelle. In order to minimize tree specific disturbances, we selected trees of comparable height and circumference from a homogenous site, a small grove of around ten *P. nigra* trees within stands of *F. sylvatica*. The mean tree age of the sampled five trees is 348 years with two trees being significantly younger (Table 2). Five cores per tree were extracted with Swedish increment corers to get sufficient material for extraction and isotope analysis of tree-ring cellulose on the individual tree level. The trees were mainly cored from two different directions perpendicular to the slope direction in order to avoid wood anomalies, as e.g. compression wood,