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# Climate sensitivity and parameter coherency in annually resolved $\delta^{13}C$ and $\delta^{18}O$ from *Pinus uncinata* tree-ring data in the Spanish Pyrenees

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ABSTRACT

We explore the 20th century climate sensitivity of annually resolved carbon and oxygen isotope ratios in five *Pinus uncinata* individuals from the upper treeline in ~2400 m asl of the Spanish Pyrenees. Time series of $\delta^{13}C$ and $\delta^{18}O$ are calibrated against temperature, precipitation, and drought indices over the period 1901–2009. Negative correlations of $\delta^{13}C$ with summer precipitation and drought indices, as well as positive correlations with summer temperatures, confirm previous evidence from similar habitats in the Pyrenees. In contrast to this summer climate signal in the carbon isotopes, the $\delta^{18}O$ record reveals mainly negative correlations with spring precipitation and drought. We explore the coherence between $\delta^{13}C$ and $\delta^{18}O$ time series derived from individual trees and assess the influence of widely applied $\delta^{13}C$ correction procedures on the climate signal strength. Spatial correlation patterns and decomposition of the time series into high- and low-frequency components are used to develop a calibration setup for carbon and oxygen isotope ratios, which will improve long-term climate reconstructions in a region, where classical tree-ring width and density data are limited.


## 1. Introduction

The influence of temperature on the formation of tree-ring width (TRW) and maximum latewood density (MXD) is well known towards altitudinal and latitudinal treelines, where annually resolved measurements from living trees and relict material allow millennium-long reconstructions to be developed (Büntgen et al., 2008, 2011; Esper et al., 2012). Dendroclimatological studies in the European Mediterranean region reveal temperature-induced growth variations at high-elevation treeline sites (Gutiérrez, 1991; Camarero et al., 1998; Tardif et al., 2003), with MXD generally providing more reliable results in comparison to a reduced sensitivity in TRW (Büntgen et al., 2008, 2010, 2012).

Stable isotope ratios preserved in xylem cells contain information on past environmental conditions and became an important proxy in paleoclimate studies (Helle and Schleser, 2004; Treydte et al., 2007; Planells et al., 2009; Schollän et al., 2013a). However, the climate–isotope relationships for trees growing in high elevation Mediterranean environments are much less explored than in the European Alps, arid regions in the US, or sites in the northern high latitudes, for example (McCarroll and Loader, 2004; Heinrich et al., 2013). The $^{13}C/^{12}C$ ratio of pine trees from different sites in the Spanish Pyrenees revealed positive correlations with June–October temperatures and negative correlations with June–July precipitation (Andreu et al., 2008; Dorado-Liñán et al., 2011b), but the associations are relatively weak compared to evidence from other regions (Dorado-Liñán et al., 2011a).

Dorado-Liñán et al. (2011a) also demonstrated that calibration studies based on pooled isotope time series (that is the combination of wood samples before isotopic analysis) may be biased by non-climatic low-frequency trends. Other work revealed such limitations to be particularly significant, if the number of pooled trees is <5 (Konter et al., 2013).

We here address these issues, and present 20th century, annually resolved, time series of individually measured $\delta^{13}C$ and $\delta^{18}O$ from five *Pinus uncinata* trees from high elevation environments in the Spanish Pyrenees. The measurement series are used to explore the coherency among trees, and to assess their common climatic signal. $\delta^{13}C$ and $\delta^{18}O$ climate signals are evaluated by using instrumental temperature, precipitation and drought data to achieve a deeper understanding of the drivers of tree's isotope fractionation in high elevation environments. Larger scale spatial patterns of climate as well as the effects of $\delta^{13}C$ correction procedures are assessed to evaluate the utilization of tree-ring stable isotope data for reconstruction purposes.

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## 2. Material and methods

### 2.1. Study site and sample design

The sampling site is situated at ~2400 m asl near Lake Gerber at the northern border of the 'D'Aigüestortes Estany de Sant Maurici National Park' in the Spanish central Pyrenees, west of Andorra (Fig. 1). The prevailing tree species is *P. uncinata*, which aggregates as a shade-intolerant conifer in an open forest ecotone (Camarero et al., 1998). Tree heights vary between 3 and 6 m, and stem circumference at breast height ranges from 0.80 to 3.38 m. The poorly developed soils accumulate in shallow basins and can be identified as skeletal leptosols with no access to ground water (Esper et al., 2010). Between-tree distances vary from 2 to 12 m and the canopy is sparse (about 10%). Annual mean temperature fluctuates around ~4 °C, with maxima in July (~13 °C) and minima in January (~−3 °C) (Büntgen et al., 2008). Monthly precipitation totals (mean annual sum at ~1200 mm) are highest in May (12%) and lowest in July (~6%). Since soils are poorly developed at the sampling site, only a small amount of snowmelt is stored in reservoirs accessible to the trees.

A total of 23 *P. uncinata* trees, growing under similar ecological and climatological conditions, were sampled for initial TRW measurements. Four cores per tree were extracted in a radial configuration at breast height, two parallel and two perpendicular to the slope.

### 2.2. Stable isotope ratio measurements

For stable isotope measurements, a subset of five trees was selected and each tree-ring from 1901 to 2009 dissected using a scalpel (Leavitt and Long, 1984). Two cores per tree were used and combined to develop five annually resolved wholewood time series spanning the 1901–2009 period. The α-cellulose was extracted from the wholewood samples following procedures detailed in Wieloch et al. (2011). The α-cellulose samples were homogenized by using an ultrasonic device (Laumer et al., 2009), freeze dried prior to analyzing (1) $^{13}C/^{12}C$ ratios using an IsoPrime Isotope Ratio Mass Spectrometer (IRMS) with an interfaced elemental analyzer, and (2) $^{18}O/^{16}O$ ratios using a TC/EA pyrolysis furnace (Thermo Finnigan) coupled online to a Delta V Advantage IRMS. Both devices were operated in continuous flow mode, allowing combusting (carbon) or pyrolizing (oxygen), purifying and transporting the sample on a continuous carrier gas flow at the GFZ in Potsdam. The isotope ratios are expressed in the conventional δ notation and in parts per thousand (‰), relative to the VPDB (Vienna Pee Dee Belemnite) standard for carbon ($\delta^{13}C$) and the VSMOW (Vienna Standard Mean Ocean Water) standard for oxygen ($\delta^{18}O$) (Craig, 1957). Sample replication resulted in a reproducibility of ±0.1‰ for $\delta^{13}C$ and ±0.25‰ for $\delta^{18}O$.

### 2.3. Time series analyses and corrections

All tree-rings were crossdated and assigned to calendar years, starting with the most recent, fully developed increment in 2009 (trees were sampled in summer 2010). TRW was measured with an accuracy of 0.01 mm using a LinTab measurement device and TSAP software (Rinn, 2007). TRW crossdating was verified by using COFECHA (Holmes, 1983), and different detrending methods (Regional Curve Standardization RCS, 100-year spline) applied using the ARSTAN program (Cook, 1985; Esper et al., 2003).

#### 2.3.1. Tree-ring carbon isotopes

Photosynthetic discrimination of $^{13}CO_2$ against $^{12}CO_2$ is related to the ratio of leaf internal to external $CO_2$ partial pressure ($C_i/C_a$), jointly controlled by the stomatal conductance and rate of $CO_2$ assimilation (Farquhar et al., 1982). Since changes in the atmospheric carbon isotopic source signal are reflected in the tree-ring cellulose, these trends need to be removed in climate studies (Farquhar et al., 1982; Treydte et al., 2009). Accordingly, all tree-ring $\delta^{13}C$ values were corrected to account for the depletion of $^{13}C$ in the atmosphere's $CO_2$, due to the burning of fossil fuels and deforestation since ~AD 1850, and resulting values termed $\delta^{13}C_{atm}$.

Exposure to increasing atmospheric $CO_2$ also leads to changes in internal $CO_2$ concentrations of the needles, resulting in adaptations of stomatal conductance, water-use-efficiency, and photosynthetic assimilation rate (Farquhar et al., 1982). These processes require consideration before assessing climate–isotope relationships (McCarrol et al., 2009; Treydte et al., 2009; Schubert and Jahren, 2012), and are here corrected considering fixed amounts of isotope fractionation per unit $CO_2$ increase, following procedures detailed by Feng and Epstein (1995) based on oak tree greenhouse studies, and Kürschner (1996) based on juniper, pine and oak studies in SW-USA and Egypt. Application of the Feng and Epstein (1995) correction alters the $\delta^{13}C_{atm}$ time series by a factor of 0.02‰ per ppm $CO_2$ change (resulting time series termed $\delta^{13}C_{FE}$), which is quite sizeable compared to the Kürschner (1996) correction of 0.0073/ppm $CO_2$ (hereafter $\delta^{13}C_K$). These

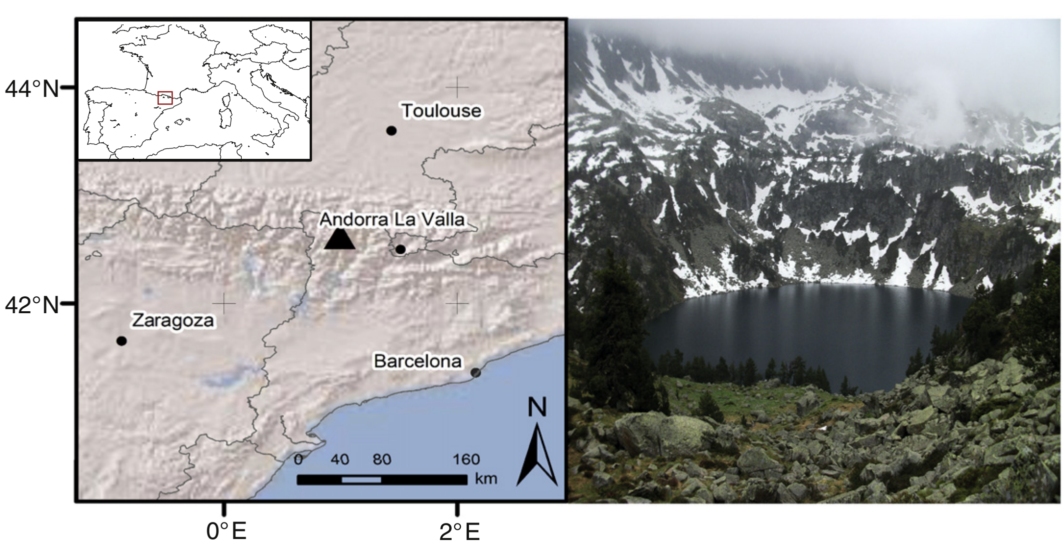


**Fig. 1.** *Pinus uncinata* study site at lake Gerber (right) located in the Spanish Pyrenees (left, triangle).