

Climate signals in width, density, $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ tree-ring series at two Iberian sites.

I. Dorado Liñán^{1,2}, E. Gutiérrez¹, I. Heinrich², L. Andreu-Hayles^{3,1}, E. Muntán¹, F. Campelo^{1,4} & G. Helle²

¹ *Departament d'Ecologia, Universitat de Barcelona. Spain*

² *Potsdam Dendro Lab, German Center for Geoscience-GFZ. Section 5.2, Potsdam .Germany*

³ *Tree-Ring Laboratory. Lamont-Doherty Earth Observatory of Columbia University. Palisades NY .USA*

⁴ *Centro de Ecologia Funcional. Universidad de Coimbra. Coimbra. Portugal*

Introduction

Tree-rings proxy based climate reconstructions have largely proven to be an accurate assessment of past climate variations at local, regional and hemispheric scales. For this purpose, the characterization of the influence of climate on tree growth is a necessary and crucial step. Sensitive trees would record the climate variable and period that limit their annual growth and this information is then used to reconstruct climate based on tree-ring proxies (Fritts 1976). The existing reconstructions based on tree rings are dominated by temperature signals. The reason is because dendroclimatological studies are usually conducted in high altitudes or high latitudes, where long-lived individuals can be found more easily because of the lower anthropogenic pressure and where harsh conditions shape very sensitive trees.

Existent literature reports that, in general terms, species growing under temperate climate response positively to summer warmth (Etien *et al.* 2008; Büntgen *et al.* 2006, 2008) since precipitation is generally not a limitation whereas cold temperatures stops cell division and development in the trunk (Rossi *et al.* 2003). On the other hand, species living under Mediterranean climate are usually described to depend on moisture availability (Touchan *et al.* 2005, 2007, 2008a). This often leads in combination with temperature effects to a drought sensitivity signal (Esper *et al.* 2007, Nicault *et al.* 2008; Touchan *et al.* 2008b, 2010).

The Iberian Peninsula has a predominant Mediterranean climate which is characterized by cool temperatures in winter and dry and hot summers. In addition, there is high spatial and temporal variability in precipitation (Rodríguez-Puebla *et al.* 1998) and ecosystems dynamics are basically controlled by moisture availability (Piñol *et al.* 1998). Previous work on the climate-growth relationship at high altitudes in this area reports a sensitivity mainly to temperature in the northern part (Pyrenees, Tardiff *et al.* 2003, Andreu *et al.* 2007, Büntgen *et al.* 2007) which loses its positive influence on tree growth towards the south but, in turn, no clear influence of precipitation is found (Parque Natural de Sierra de Cazorla, Martín Benito *et al.* 2008). Except for the Pyrenees area, tree-ring climate relationships in the Iberian Peninsula are still rather unclear and dendroclimatological investigations in old forests to assess their potential for climate reconstructions are scarce. Moreover, the usefulness of proxies such as tree-ring stable isotopes has barely been explored.

With the aim of assessing the strength of the climatic signal in each tree-ring record and thus, their potential for climatic reconstructions, we analyze the climatic significance of several tree-ring series from two pine-species stands growing at high elevations in the Iberian Peninsula: Pyrenees and South of Spain.

Six tree-ring variables were used: tree-ring width (TRW), earlywood width (EWw) and latewood width (LWw), maximum latewood density (MXD), stable carbon ($\delta^{13}\text{C}$) and oxygen ($\delta^{18}\text{O}$) isotopes.

Material and Methods

The two study sites are *Parc Natural del Cadí-Moixeró* (UPF) located in the Pre-Pyrenees and *Parque Natural Sierra de Cazorla, Segura y las Villas* (NCZ) in the South of Spain. Both locations

are under the influence of Mediterranean climate (Fig. 1): the UPF site is on the transitional boundary from Mediterranean to Eurosiberian climatic regions and the NCZ site is characterized by a typical high elevation Mediterranean climate. The pine species sampled at UPF was *Pinus uncinata* Ramond ex DC. in Lam. et DC and at NCZ *Pinus nigra* Arn. spp. *salzmannii* var. *salzmannii* (Dunal).

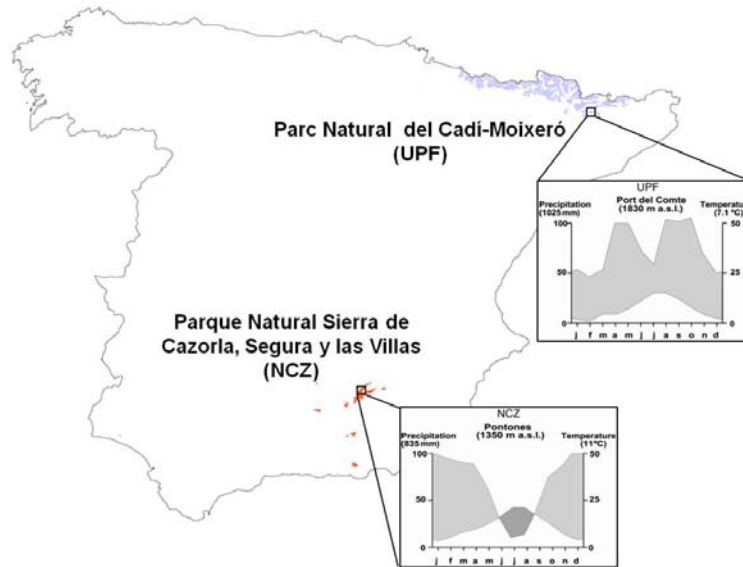


Figure 1: Location of the two study sites and their climate diagrams. The shaded areas indicate coverage of *P. uncinata* and *P. nigra*, respectively

Sampling was carried out during summer of 2006. Cores were taken with an increment borer and preparation and analysis followed dendrochronological procedures described by Stokes and Smiley (1968). Ring widths (TRW) were measured on 89 series at NCZ and 75 at UPF. The accuracy of the cross-dating and measurements were verified using the computer program COFECHA (Holmes 1983).

From the set of cores, 32 and 28 samples were selected for density analysis at NCZ and UPF respectively. Lathes perpendicular to the wood fibres were extracted from the cores and analyzed following X-ray microdensitometric techniques developed by Polge (1965). As results, series of measurements of earlywood width (EWw), latewood width (LWw) and maximum density (MXD) were obtained.

Standard dendrochronological techniques were used for chronology developments (Fritts 1976, Cook and Kairiukstis 1990). For each proxy and site, chronologies were built with TurboArstan[®]. Individual series were standardized to remove trends in the mean but preserving multi-decadal scale wavelengths by fitting a negative exponential curve or cubic smoothing spline of 67% of the series length with a 50% frequency response cut-off to the raw series. Chronologies based on the different variables were built by using a bi-weight robust mean to reduce bias caused by extreme values.

In general, stable isotope chronologies require fewer trees to provide a representative average series for a site and 10 cores were selected at each site for stable carbon ($\delta^{13}\text{C}$) and oxygen ($\delta^{18}\text{O}$) isotope individual analysis. Tree rings were split manually with a scalpel under a stereomicroscope and then α -cellulose was extracted. The $^{13}\text{C}/^{12}\text{C}$ isotope ratios were measured as CO_2 by combusting the α -cellulose samples in an elemental analyzer (Fisons NA 1500NC). Similarly, oxygen isotopes were measured on CO utilizing a TC/EA pyrolysis furnace. The isotope ratios are given in the conventional delta (δ) notation, relative to the standards VPDB ($\delta^{13}\text{C}$) and VSMOW ($\delta^{18}\text{O}$).

We applied the atmospheric correction to the $\delta^{13}\text{C}$ series because of the decreasing trend of atmospheric CO_2 signature from increasing fossil fuel burning since the industrialisation (see details and values at McCarroll and Loader 2004). After the correction of the stable carbon isotope measurements, individual series of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ were z-transformed and averaged to build the final chronologies.

Homogenized mean monthly temperatures (T) and total monthly precipitation (P) were available from nearby stations. The influence of climate on each tree-ring variable was investigated by computing simple linear correlations (r) with monthly climate variables from July of the year previous to growth ($t-1$) to October of the current year (t).

Results and Discussion

At the pre-Pyrenees site UPF, all tree-ring width variables are affected positively by previous autumn (October-November) temperatures (Fig. 2), as has already been reported by Gutiérrez (1991), Tardiff *et al.* (2003), Büntgen *et al.* (2007) and Andreu *et al.* (2008). In temperature controlled environments such as UPF with enough moisture available to the trees, higher temperatures in autumn can favour net photosynthesis and increase food storage that will be available for next year's growth (Fritts 1976). Consequently, cold temperatures in autumn are likely to limit the formation of metabolic reserves and affect radial growth in the following year. We could also identify significant influences of the current year's temperatures on growth similar to those described by Tardiff *et al.* (2003) (May temperature) or Büntgen *et al.* (2007) (late spring to summer temperatures). For instance, TRW respond positively to March to June temperatures, EWw to April, June, September and October and LWw to the very early year temperatures (January to May). Similarly, MXD is discontinuously affected by temperature from early spring to summer (February, May, and September) and stable isotopes also show high and positive correlations with spring to summer ($\delta^{18}\text{O}$) and late summer ($\delta^{13}\text{C}$) temperatures of the year of growth. Thus, at UPF tree growth is controlled by temperature during the growing season since warm conditions allows stems cell division and differentiation. Actually, growing season temperature (May to September) has already been reconstructed at the Pyrenees based on TRW width and MXD records by Büntgen *et al.* (2008, 2010).

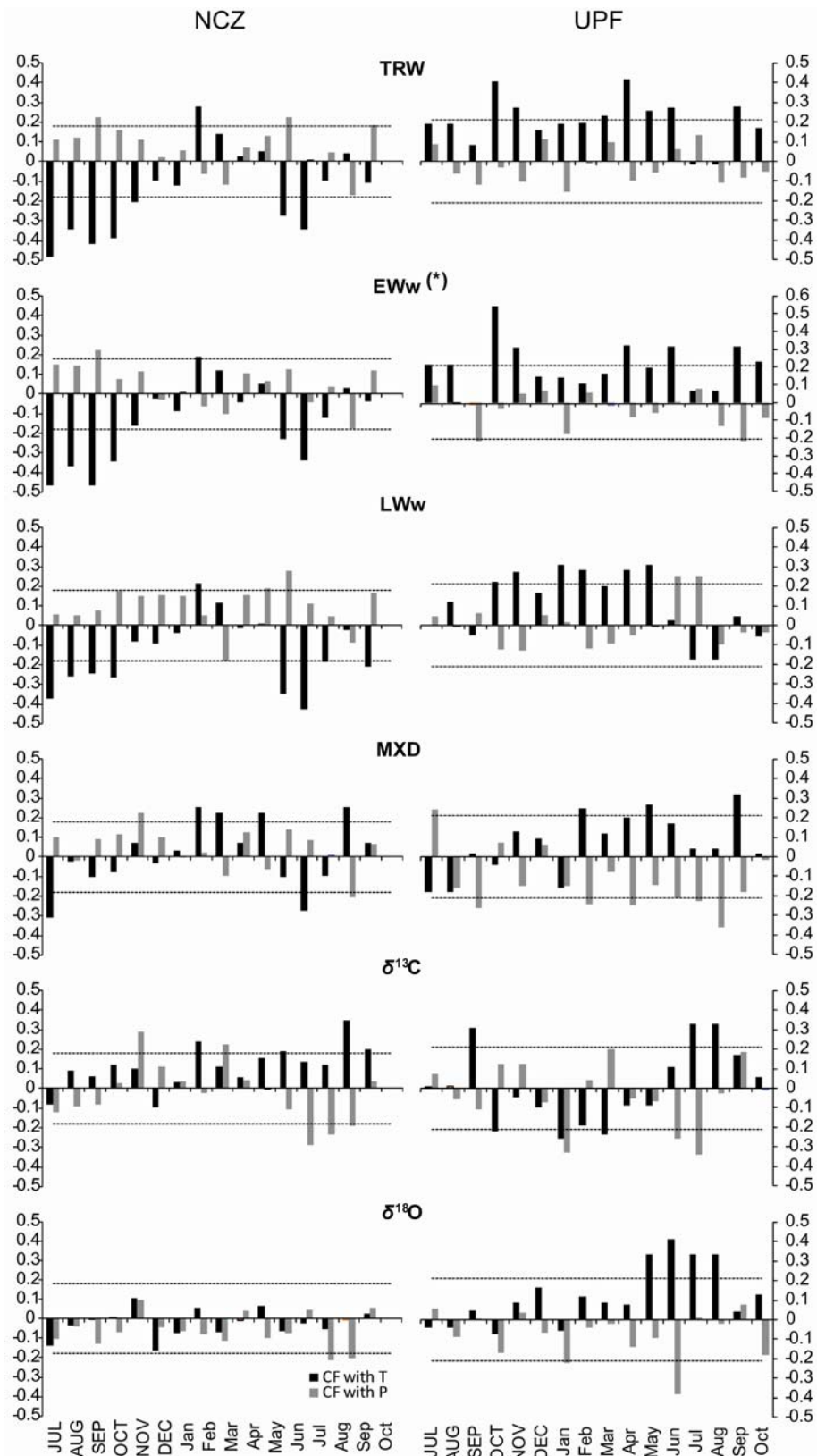


Figure 2: Monthly correlation coefficients between climate and tree-ring proxies from Cazorla (NCZ) and Pedraforca (UPF) for the period July of the previous year ($t-1$) to October of the current year (t). Grey bars indicate correlation with precipitation and black bars with temperature. Abbreviations: Total ring width (TRW); early-wood width (EWw); late-wood width (LWw); maximum density (MXD), stable carbon isotope ratios ($\delta^{13}\text{C}$) and stable oxygen isotope ratios ($\delta^{18}\text{O}$). Dashed lines indicate 95% significance level. (*) Notice different scale.

Precipitation signals are not as consistent across different tree-ring variables as the temperature signals. This is expected in an alpine climate where enough moisture is available throughout the whole year and the proximity of UPF to Mediterranean Sea favours a higher amount of precipitation during summer. Nevertheless, LWw show a slight positive influence of summer precipitation; while MXD, $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ display negative summer precipitation signals. Precipitation does not seem to be a limiting factor for tree-growth, but its availability during summer can prolong the growing season thereby increasing LWw but decreasing MXD, since wetter conditions favour wider lumen sizes and thinner cell walls (Larson, 1994).

Besides, high summer temperatures promote high evapotranspiration rates which increases when rainfall occurs and result in lower tree-ring $\delta^{13}\text{C}$ (Farquhar *et al.* 1982; Leavitt and Long, 1989; Saurer *et al.* 2008).

The $\delta^{18}\text{O}$ -climate relations found at UPF are consistent with earlier reports from the Swiss Alps (Saurer *et al.* 2008; Battipaglia *et al.* 2009) and they are also in accordance with regional patterns described by Treydte *et al.* (2007) for a European network of $\delta^{18}\text{O}$. They found a common physiological response to summer conditions in temperate climates: low moisture combined with higher temperatures increases transpiration rates; which enhances leaf water enrichment resulting in higher $\delta^{18}\text{O}$ values.

At NCZ, the previous summer to autumn temperature exerts a negative influence on tree growth in *P. nigra* individuals which is consistent with reports of previous studies concerned with TRW, EWw and LWw at the Cazorla Range (Martin-Benito *et al.* 2008, Andreu *et al.* 2008). This negative influence of temperatures in combination with a positive influence of precipitation of the previous September on TRW and EWw suggests a strong dependency of the metabolic reserves from the previous year since warm late summers can prolong the growing season, limiting the number of photosynthates stored for next year's growth (Fritts 1976). High summer temperatures (June to July) during the year of growth also exert a negative influence on TRW, EWw and LWw probably as a consequence of the strategic stomata closure adopted in order to avoid xylem embolism due to the high transpiration rates. This may also limit tree production and the food storage for next year growing season would be reduced.

In general, the climate at NCZ is harsh (Fig 1), i.e., winters are very cold with absolute minimum temperatures that can be far below zero and often considerable snow fall occurs while in summer extreme maximum temperatures over 40°C in the shade can be reached (Creus-Novau 1998). The combination of high temperatures and low rainfall amounts theoretically suggests that at NCZ summer droughts may occur. Consequently, a summer precipitation signal in the tree ring series would be expected. However, the dependency of tree growth on precipitation was surprisingly low at NCZ and no significant correlations were found with the Palmer Drought Severity Index (Palmer 1965) (results not shown). Previous studies analysing tree-ring width series from this region did not find a clear summer precipitation signal; we found a non significant positive effect of previous summer autumn precipitation on TRW and EWw. The mean total annual precipitation amount is 835 mm (Fig. 1), a relatively high value for the Mediterranean, which denotes a rather moist character of the climate. Indeed, NCZ is one of the highest rainfall zones in Spain, surrounded by typical low-moist areas from southeast of the Iberian Peninsula (Heywood 1961). Moisture levels are generally quite high throughout the year, so water may be still available to trees during the above-mentioned dry period of July-August. Additionally to the water storage in the soil profile, occasional summer thunderstorms and fogs that may appear anytime of the year (Creus-Novau 1998) can also contribute to the minimisation of the hydric stress on trees in summer.

Only $\delta^{13}\text{C}$ seems to record a certain degree of hydric stress in summer denoted by significant negative correlations with July, August and September rainfall. This is probably related to the increased stomatal closure under dry conditions which affects directly the isotope fractionation and results in a negative correlation between $\delta^{13}\text{C}$ and precipitation. In fact, negative correlations of $\delta^{13}\text{C}$ with summer precipitations have been reported for different pine species across the Iberian Peninsula (Andreu *et al.* 2008; Voltas *et al.* 2008), in the French Alps (Gagen *et al.* 2004; Gagen *et*

a.l. 2006) with *Picea abies* (L.) Karst., in the Swiss Alps (Treydte *et al.* 2001) and for individuals of *Pinus sylvestris* L. in Finish Lapland (Gagen *et al.* 2007). This common summer precipitation signal of stable carbon isotopes ratios across different locations in Europe was already explored by Treydte *et al.* (2007).

Surprisingly MXD at NCZ did not show a consistent pattern of correlation with temperature, just a slight influence of some dispersed months during previous and current year of growth. Moreover, $\delta^{18}\text{O}$ did not display significant correlations with any of the climatic parameters although we expected some signal related to summer hydric stress since stable isotope ratios of oxygen in tree-ring cellulose have been demonstrated to correlate well with climatic factors such as temperature (McCarroll and Loader, 2004) and vapour pressure deficit (Ferrio and Voltas 2005).

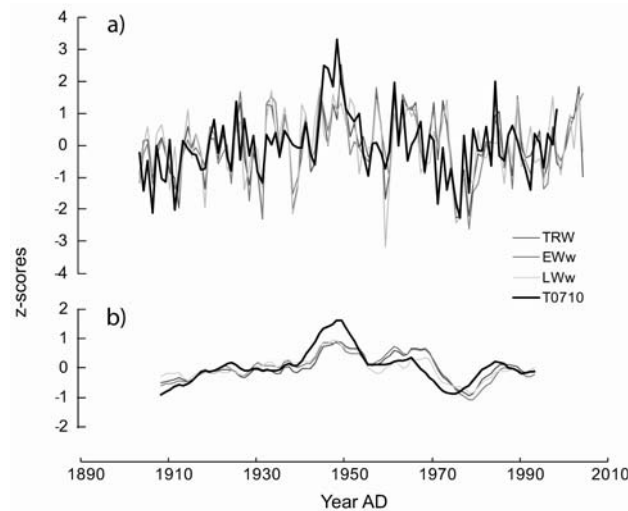


Figure 3: Comparison of NCZ tree-ring width chronologies and target temperature data. a) Inverse indices of TRW, EWw and LWw from NCZ and July to October temperature indices (T0710) of previous year ($t-1$). b) Medium to low frequencies highlighted by a 10-year moving average.

Both UPF and NCZ trees appear to be strongly dependent on lagged physiological effects caused by temperatures but with the difference that the effect exerted on tree ring variables is positive in the northern site (UPF) and negative in the southern site (NCZ). This opposed effect of temperature on tree-ring variables is consistent with the geographical pattern of temperature variation across the Iberian Peninsula. Temperature dynamics in the two different Mediterranean sites seem to play the key role, limiting tree growth by cold temperatures in the more temperate site of the pre-Pyrenees. Temperature response is reversed at the drier and hotter site NCZ, located at high elevations as well, but where tree growth is also limited by high summer temperatures.

The dependence on the temperature of the previous growing season, which is the clearest for ring-width related variables (TRW, EWw, LWw), is not only consistent at inter-annual but also at inter-decadal wavelengths (Figs. 3 and 4). At NCZ (Fig. 3), the climatic information recorded by all three variables is almost identical and agrees in the different frequency domains with the July to October temperature record of the previous year. At UPF (Fig. 4), the tree-ring proxy EWw best records October to December temperatures of the previous year. The comparison of the smoothed tree-ring and temperature records shows a generally better agreement at NCZ. The synchrony is remarkably high except for an offset during the 1940s, where tree rings did not record the magnitude of the increase in temperatures. This could be either due to local differences in the magnitude of the warmth between the sampling site and the location of the weather station, or to inability of the trees to react to such increased warmth. A test with regional climate data will help to answer such a question and to establish the potential suitability of the tree-ring proxies to reconstruct temperatures at both locations.

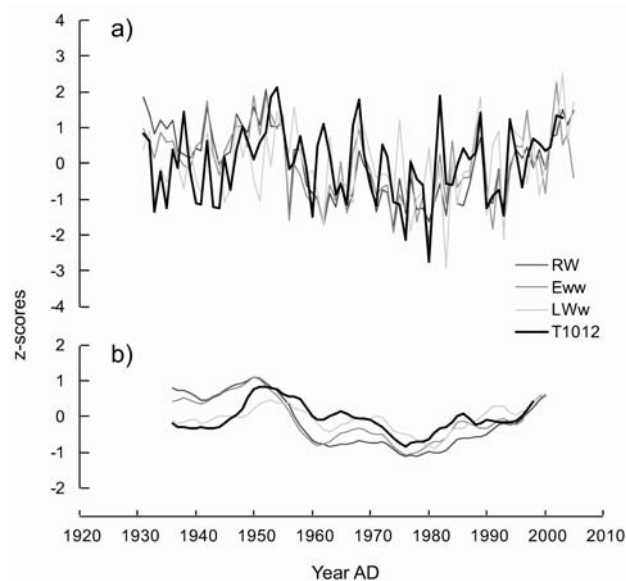


Figure 4. Comparison of UPF tree-ring width chronologies and target temperature data. a) TRW, EWw and LWw from UPF and October to December temperature indices (T1012) of previous year ($t-1$). b) Medium to low frequencies highlighted by a 10-year moving average.

Conclusions

At both sites a dominant temperature signal was found while the influence of precipitation was shown to be limited to the summer period, evidencing a slight drought stress. The significant temperature signals at UPF and NCZ are recorded at both inter-annual and inter-decadal timescales by TRW, EWw and LWw pointing out their potential for climate reconstructions. Tree-ring stable isotopes provide additional information regarding the tree growth-climate relationship but further investigations are needed in order to clarify the absence of significant correlations with climate for some parameters, e.g., $\delta^{18}\text{O}$ at NCZ.

Acknowledgements

We thank Carmen Bürger and Christoph Küppers for isotope analysis and Björn Günther for performing all the density measurements. This research was funded by EU project MILLENNIUM (017008-2).

References

- Andreu, L., E. Gutiérrez, M. Macias, M. Ribas, O. Bosch and J.J. Camarero. 2007. Climate increases regional tree-growth variability in Iberian pine forests. *Global Change Biology* 13: 804-815.
- Andreu, L., O. Planells, E. Gutiérrez, G. Helle and G.H. Schleser. 2008. Climatic significance of tree-ring width and $\delta^{13}\text{C}$ in a Spanish pine forest network. *Tellus* 60B: 771-781.
- Battipaglia, G., M. Saurer, P. Cherubini, R.T.W. Siegwolf and M.F. Cotrufo. 2009. Tree rings indicate different drought resistance of a native (*Abies alba* Mill.) and a nonnative (*Picea abies* (L.) Karst.) species co-occurring at a dry site in Southern Italy. *Forest Ecology and Management* 257: 820-828.
- Büntgen, U., D.C. Frank, D. Nievergelt and J. Esper. 2006. Summer Temperature Variations in the European Alps, A.D. 755–2004. *Journal of Climate* 19: 5606-23
- Büntgen, U., D.C. Frank, A. Verstege, D. Nievergelt and J. Esper. 2007. Climatic response of multiple tree-ring parameters from the Central Spanish Pyrenees. *Trace* 5: 60-72.
- Büntgen, U., D.C. Frank, H. Grudd and J. Esper. 2008. Long-term summer temperature variations in the Pyrenees. *Climate Dynamics* 31: 615-631.

- Büntgen, U., D.C. Frank, V. Trouet and J. Esper. 2010. Diverse climate sensitivity of Mediterranean tree-ring width and density. *Trees, Structure and Function* 24: 261-273.
- Cook, E.R. and L.A. Kairiukstis. 1990. Methods of dendrochronology: applications in the environmental sciences. International Institute for Applied Systems Analysis, Boston, MA, USA: Kluwer Academic Publishers.
- Creus Novau, J. 1998. A propósito de los árboles más viejos de la España peninsular: los *Pinus nigra* Arn. ssp. *salzmannii* (Dunal) Franco de Puertollano-Cabañas Sierra de Cazorla, Jaén. *Revista Montes* 54: 68-76.
- Esper, J., D.C. Frank, U. Büntgen, A. Verstege, J. Luterbacher and E. Xoplaki. 2007. Long-term drought severity variations in Morocco. *Geophysical Research Letters* 34, L17702.
- Etien, N., V. Daux, V. Masson-Delmotte, M. Stievenard, V. Bernard, S. Durost, M. T. Guillemin, O. Mestre, and M. Pierre. 2008. A bi-proxy reconstruction of Fontainebleau (France) growing season temperature from A.D. 1596 to 2000. *Clim. Past* 4: 1-16.
- Farquhar, G.D., M.H. O'Leary and J.A. Berry. 1982. On the relationship between carbon isotope discrimination and the intercellular carbon dioxide concentration in leaves. *Australian Journal of Plant Physiology* 9: 121-137.
- Ferrio, J.P. and J. Voltas. 2005. Carbon and oxygen isotope ratios in wood constituents of *Pinus halepensis* as indicators of precipitation, temperature and vapor pressure deficit. *Tellus B* 57: 164-173.
- Fritts, H.C. 1976. *Tree Rings and Climate*. Academic Press, New York.
- Gagen, M., D. McCarroll and J.L. Edouard. 2004. The effect of site conditions on pine tree ring width, density and $\delta^{13}\text{C}$ series. *Arctic, Antarctic and Alpine Research* 36(2): 166-171.
- Gagen, M., D. McCarroll and J.L. Edouard. 2006. Combining tree ring width, density and stable carbon isotope series to enhance the climate signal in tree rings: an example from the French Alps. *Climatic Change* 78: 363-379.
- Gagen, M., D. McCarroll, N.J. Loader, I. Robertson, R. Jalkanen and K.J. Anchukaitis. 2007. Exorcising the 'segment length curse': summer temperature reconstruction since AD 1640 using non-detrended stable carbon isotope ratios from pine trees in northern Finland. *The Holocene* 17: 435-446.
- Gutiérrez, E. 1991. Climate tree-growth relationships for *Pinus uncinata* Ram. in the Spanish pre-Pyrenees. *Acta OEcologica*, 12(2): 213-225.
- Heywood, V.U. 1961. The Flora of the Sierra de Cazorla, 8. E. Spain. *Feddes Repert.* 64: 28-73.
- Holmes, R.L. 1983. Computer-assisted quality control in tree-ring dating and measurement. *Tree-Ring Bulletin* 43:69-78.
- Larson, P.R. 1994. The vascular cambium: development and structure. Springer series in Wood science. Springer-Verlag, Berlin, 725 pp.; J 581.417.
- Leavitt, S.W. and A. Long. 1989. Drought indicated in carbon-13/carbon-12 ratios of southwestern tree rings. *Water Resources Bulletin* 25: 341-347.
- Martin-Benito, D., P. Cherubini, M. Del Río and I. Cañellas. 2008. Growth response to climate and drought in *Pinus nigra* Arn. trees of different crown classes. *Trees* 22: 363-373.
- McCarroll, D. and N.J. Loader. 2004, Stable isotopes in tree rings, *Quaternary Science Reviews*, 23, 771-801.
- Nicault, A., S. Alleaume, S. Brewer, M. Carrer, P. Nola, E. Gutiérrez, J. L. Edouard, C. Urbinati and J. Guiot. 2008. Mediterranean drought fluctuation during the last 500 years based on tree-ring data *Climate Dynamics* 31:227-245.
- Palmer, W. 1965. Meteorological drought. U.S Weather Bureau, Washington D.C. Research paper No 45.
- Piñol, J., J. Terradas and F. Lloret. 1998. Climate warming, wildfire hazard, and wildfire occurrence in coastal eastern Spain. *Climatic Change*, (38) 345-357.
- Polge, H. 1965. Study of wood density variations by densitometric analysis of X-ray negative of samples taken with a pressler auger. Paper presented at Meeting of IUFRO Section 41.

- Rodríguez-Puebla, C., A.H. Encinas, S. Nieto and J. Garmendia. 1998. Spatial and temporal patterns of annual precipitation variability over the Iberian peninsula. *International Journal of Climatology*. 18: 299-316.
- Rossi, S., A. Deslauriers and H. Morin. 2003. Application of the Gompertz equation for the study of the xylem cell development. *Dendrochronologia* 21/1: 33-39.
- Saurer, M., P. Cherubini, C.E. Reynolds-Henne, K.S. Treydte, W.T. Anderson and R.T.W. Siegwolf. 2008. An investigation of the common signal in tree-ring stable isotope chronologies at temperate sites. *Journal of Geophysical Research Biogeosciences* 113: G02019.
- Stokes, M.A. and T.L. Smiley. 1968. Introduction to tree-ring dating. Chicago, IL, USA: University of Chicago Press.
- Tardiff, J., J.J. Camarero, M. Ribas and E. Gutiérrez. 2003. Spatiotemporal variability in tree growth in the Central Pyrenees: climatic and site influences. *Ecological Monographs* 73: 241-257.
- Touchan, R., E. Xoplaki, G. Funkhouser, J. Luterbacher, M.K. Hughes, N. Erkan, Ü Akkemik and J. Stephan. 2005. Reconstructions of spring/summer precipitation for the Eastern Mediterranean from tree-ring widths and its connection to large-scale atmospheric circulation. *Climate Dynamics*. 25:75-98.
- Touchan, R., Ü. Akkemik, M.K. Hughes MK and N. Erkan. 2007. May–June precipitation reconstruction of southwestern Anatolia, Turkey during the last 900 years from tree rings. *Quaternary Research*. 68:196-202.
- Touchan, R., D.M. Meko and A. Aloui. 2008(a). Precipitation reconstruction for Northwestern Tunisia from tree rings. *Journal of Arid Environments* 72:1887-1896.
- Touchan, R., K.J. Anchukaitis, D. M. Meko, S. Attalah, C. Baisan and A. Aloui. 2008(b). Long term context for recent drought in northwestern Africa. *Geophysical Research Letters*. 35, L13705.
- Touchan, R., K.J. Anchukaitis, D.M. Meko, M. Sabir, S. Attalah and A. Aloui. 2010. Spatiotemporal drought variability in northwestern Africa over the last nine centuries, *Climate Dynamics*. DOI 10.1007/s00382-010-0804-4.
- Treydte, K., G.H. Schleser, F.H. Schweingruber and M. Winiger. 2001. The climatic significance of $\delta^{13}\text{C}$ in subalpine spruces (Lötschental, Swiss Alps), *Tellus* 53B, 593-611.
- Treydte, K.S., D. Frank, J. Esper *et al.* 2007. Signal strength and climate calibration of a European tree-ring isotope network. *Geophysical Research Letters* 34 (24): L24302.
- Voltas, J., M.R. Chambel, M.A. Prada and J.P. Ferrio. 2008. Climate-related variability in carbon and oxygen stable isotopes among populations of Aleppo pine grown in common-garden tests. *Trees* 22 (6): 759-769.