Dendroclimatic signal in managed Mediterranean forests. A case study in SW Spain

F. Natalini, J. Vázquez-Piqué & R. Alejano

Departamento de Ciencias Agroforestales, Escuela Técnica Superior de Ingeniería, Universidad de Huelva, Spain
E-mail: *fabio.natalini@dcaf.uhu.es; fabionatalini@gmail.com*

Introduction

Processes and dynamics of the natural environment can be studied through the information stored in tree rings. Since radial stem increment is influenced by a number of external factors (Cook & Briffa 1990), extracting from a tree-ring chronology the information related to one of those factors requires the retention of the chronology variance linked to that single factor and the removal of the variance linked to the others. The climatically explained ring-width variance common to an ensemble of trees is the "signal" of interest in dendroclimatology. The extraction of the climatic signal is done through the standardization procedure, which involves three steps: (1) "detrending", i.e. removing the growth variability which is not related to climate from individual series of measured tree-ring parameters, (2) "indexing", i.e. computing a-dimensional tree-ring data from the detrended series, (3) estimating a master chronology containing the common climatic signal of the ensemble of trees by averaging the indexed series (see Cook & Briffa 1990). Detrending methods are crucial in dendroclimatology and typically involve fitting a smoothing function to the tree ring series. They are defined "deterministic", when the fitted function is an a priori defined mathematical model (e. g. straight lines, exponential functions), or "stochastic", when a data-adaptive running function is fitted to the series (e.g. splines) (Cook et al. 1990a). When deterministic models are used, the goodness-of-fit can vary with time because of the middle-frequency perturbations commonly found in ring-width series of trees growing within stands owing to stand dynamics. For that, data-adaptive models can be more appropriate to find the best fitting (Cook et al. 1990a). However, care must be taken when using a stochastic model because, the more it closely follows the fluctuations of the ring width series (i.e. more the smoothing function is flexible), the more the variance is removed at the low-frequencies. Long-term climatic changes are recorded in low-frequency growth variability which hence should be also retained as climatic signal (Briffa et al. 1996).

In the Mediterranean forests of the Iberian Peninsula, dendroclimatological studies can provide valuable information about forests dynamics in relation to climate change (e.g. Gea-Izquierdo et al. 2011, 2014). However, the Iberian Mediterranean forests are systematically managed, thus anthropogenic disturbances influence tree growth. *Pinus pinea* L. is an important tree species of Iberian Mediterranean forests. In Spain, it forms monospecific or mixed woodlands which occupy more than 500,000 ha. Most of these woodlands originated from plantations during the 20th century and present even aged stand structure. In *P. pinea* forests of Southwestern Spain, the production of timber and pine nuts are among the main purposes of silvicultural measures, which typically involve thinning for improving wood production and crown development. Therefore, forestry-related variability in growth patterns can be expected in these forests.

We tested detrending criteria based on smoothing functions in managed *P. pinea* woodlands in SW Spain. Ring-width series were smoothed by fitting functions with different degree of flexibility. We hypothesized that flexible curves would provide a better climatic signal at the high frequencies by smoothing the stochastic growth oscillations related to silvicultural measures, while more conservative criteria would retain higher amounts of climate change-related low-frequency growth trends.

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Materials and methods

Study site, samples and measurements

The samples were collected from two *Pinus pinea* monospecific stands with flat sandy terrains located in Valverde del Camino (37.53°N, 6.78°W; 200 m a.s.l.) and Hinojos (37.28°N, 6.39°W; 100 m a.s.l.), SW Spain. The stand in Valverde presents a mean tree height of 19 m, a mean DBH of 60 cm and a density of 150 trees/ha. The stand in Hinojos presents a mean tree height of 20 m, a mean DBH of 70 cm and a density of 200 trees/ha. The climate of the region is Mediterranean and summer drought normally lasts for 3 months (Jun-Aug). Hence, we expected to find a chronology signal related to water availability as a limiting growth factor. When selecting the study sites, we searched for the oldest stands, which could provide chronologies long enough for climate investigation, and site homogeneity, which enhanced the common chronology signal (Pilcher 1990). The samples were extracted from 20 dominant trees in each site with an increment borer at breast height (two samples per tree). Individual ring-width series were measured and cross-dated (Pilcher 1990, Grissino-Mayer 2001). Since we found chronologies of different lengths, in the subsequent analyses we only included the trees older than 110 years to ensure the use of the oldest trees only and thus to buffer the possible differences in the response to climate between trees of different age (Carrer & Urbinati 2004). The confidence of the chronology was verified through the Expressed Population Signal (EPS) (Briffa & Jones 1990).

Detrending criteria and computation of the master chronologies

We used 4 criteria to detrend the tree-ring width series:

1) Spline with a wavelength equal to the 67% of the series length expressed in years (SP67). This method enables the retention of some portion of growth variability at medium/low frequencies (Cook et al. 1990a).

2) Double detrending (DDET). This criterion follows the 2-step method introduced by Holmes et al. (1986). We computed tree-ring indices through a negative exponential curve, which fits well the descending juvenile portion of the ring-width series, and then we detrended a second time by applying to the indices a spline with a wavelength equal to the 67% of the series length, which was meant to remove the growth trends that were not smoothed in the first step.

3) Spline with a wavelength that maximized the signal-to-noise ratio (MSNR). This was proposed by Cook et al. (1990a) as an objective criterion to choose the proper flexibility of a digital filter. The signal-to-noise ratio (SNR) is an expression of the strength of the chronology signal (Briffa & Jones 1990). This criterion produces short wavelengths that emphasize the high-frequency response to climate (see e.g. Piermattei et al. 2014).

4) Spline with a fixed wavelength of 32 years ("SP32"). Wavelengths approaching 30 years produce quite flexible splines which can properly filter tree-ring series from closed-canopy stands and managed woodlands, where medium/low-frequency growth oscillations are expected as a result of competition, stand dynamics and silviculture (e.g. Gea-Izquierdo et al. 2009). The wavelength of 32 years is generally used as a default spline rigidity to accomplish the optimum job of discovering errors in cross-dating (Grissino-Mayer 2001) and was chosen here as a reference against the other criteria.

Since we were mainly interested in testing detrending methods, we followed the same indexing procedure and master chronology estimation for all the four detrending criteria (Cook et al. 1990b): firstly, the indices were computed as ratios of the measured ring widths to the values estimated by the fitted detrending model; secondly, an autoregressive model was fitted to the indexed series to remove the autocorrelation; finally, two master chronologies were computed as biweight robust means for each site, i.e. a standard chronology (computed from the indexed series, without autoregressive model), and a residual chronology (calculated from the prewhitened series). The standard and the residual chronologies were used in the subsequent analyses.

Statistical comparison of the master chronologies

To evaluate the quality of the standard chronologies in terms of common signal among trees captured through detrending, we used the EPS, the SNR and the mean inter-series correlation (r) (Briffa & Jones 1990).

The standard deviation (SD), the 1st–order autocorrelation (AC) and the mean sensitivity (MS) were used as measures of the retained growth variability in the standard chronologies. The SD was used as a measure of the dispersion of the dataand to evaluate the reduction of dispersion after detrending. We calculated the AC to examine the capacity of the detrending criteria to reduce the noise deriving from the one-year lag persistence in growth (Cook et al.1990b). The MS, defined as the average of the relative differences from one ring to the next (Fritts 1976), was used to assess the amount of retained year-to-year growth variability after detrending.

The power spectra of the standard chronologies were studied to determine how the power of the chronology signal was distributed across the range of frequencies after each detrending criterion.

A growth-climate correlation analysis was performed to examine the dendroclimatic signal at the high frequencies. We used monthly cumulative precipitation and averages of minimum and maximum temperatures from a close meteorological station (Fig. 1) as independent variables and residual chronologies as dependent variables to compute bootstrapped correlations with a statistical critical value $\alpha = 0.05$. Through the significance test we searched for the months in which climatic conditions had more influence on annual growth, and we expected to find out some differences in the pattern of significant months depending on the detrending method applied to obtain the chronology used in the analysis.

We compared the suitability of the residual chronologies for climate reconstruction through a calibration-verification procedure (Fritts & Guiot 1990). We used mean annual values of self-calibrated Palmer Drought Severity Index (PDSI) (Dai et al. 2004). The overlap period between the chronologies and the PDSI series was divided into two intervals of equal length: the first interval was the dependent set for calibration, and the second was the independent set for verification. The independent set included the recent decades because we wanted to test the capacity of the chronologies to estimate the increase of aridity over recent decades previously documented for the region (Romero et al. 1998). In the calibration phase, the relationship between PDSI and chronologies was modeled through a simple linear regression (Fritts & Guiot 1990). The regression coefficients obtained in the calibration phase were applied to the tree-ring data of the independent set to obtain PDSI estimates. In the verification phase, the actual PDSI values of the independent set were compared with the PDSI estimates through correlation coefficients and the reduction of error (RE) (see Blasing et al. 1981).

Results and discussion

The chronology lengths ranged from 90 to 139 years in Valverde and from 70 to 150 in Hinojos. The trees older than 110 years were 15 in Valverde and 16 in Hinojos. The raw ring width series and the master chronologies are plotted in figure 1. Residual fluctuations remained after standardization at the low frequencies, with higher amplitudes in the case of DDET and SP67. The statistics of the standard chronologies are reported in table 1. The EPS was above the minimum threshold of 0.85 (Briffa & Jones 1990) and rather similar among the four standard chronologies, indicating that reliable chronologies were obtained with all four criteria. However, we found that the lowest values of r and SNR were brought by the stiffer smoothing functions, which in contrast produced the highest values of SD, AC and MS.

Table1. Statistics of the standard chronologies (r: inter-series correlation, AC: 1st order autocorrelation; SNR: signal-to-noise ratio; EPS: expressed population signal; MS: mean sensitivity)

			Hinojos			Valverde		
	MSNR	SP32	DDET	SP67	MSNR	SP32	DDET	SP67
r	0.61	0.60	0.59	0.59	0.55	0.51	0.49	0.49
AC	0.10	0.32	0.53	0.53	0.29	0.44	0.57	0.57
SNR	22.96	22.28	21.17	21.43	16.63	14.27	13.06	13.37
EPS	0.96	0.96	0.95	0.95	0.94	0.93	0.93	0.93
SD	0.26	0.32	0.34	0.33	0.19	0.22	0.25	0.25
MS	0.30	0.37	0.39	0.39	0.22	0.25	0.27	0.27

The power spectra (Fig. 2) show that the amounts of signal power at the lowest frequencies were higher for the SP67 and were almost eliminated by the MSNR criterion, in accordance with the different amplitudes observed in the oscillations retained in the master chronologies (Fig. 1). The higher amounts of variance at the low frequencies found with DDET and SP67 in Hinojos can be related to the growth release in the 1960s-70s, which was originated by thinning.

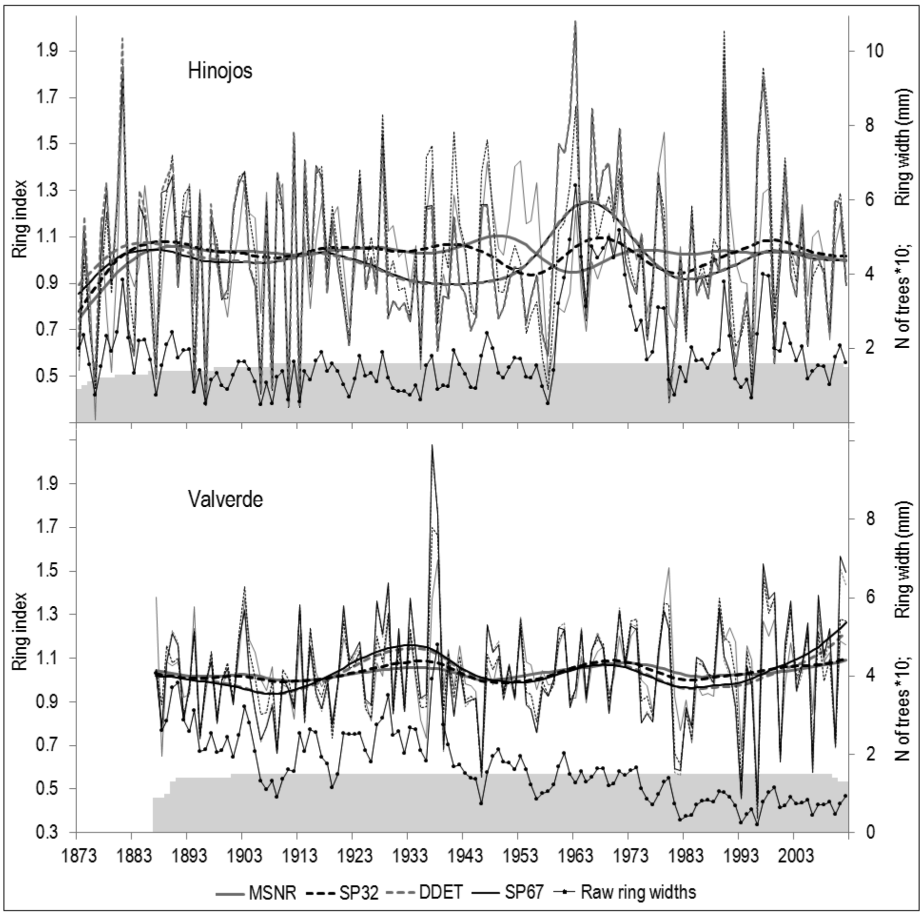

Figure 1 Residual chronologies, mean ring-width series and sample depth

The correlation analysis between the master chronologies and meteorological covariates (Fig. 3) indicates that flexible splines accomplish a better job in analyzing the high-frequency growth response to climate. Correlation between radial growth and winter (Dec-Jan-Feb) rainfall was found with all four detrending criteria. It is probably explained by the winter maximum precipitation in the study area and may reflect the importance of soil recharge for improving water availability and subsequent growth in spring (Campelo et al. 2006). We also observed in all cases (except for

MSNR in Hinojos) a positive response to mild temperatures in winter, suggesting that in evergreen trees the ring formation is linked to the photosynthesis and carbohydrates produced during this season (Baldocchi 2010). In Valverde, the contribution of spring rainfalls, an important factor for the formation of rings (Campelo et al. 2006, De Luis et al. 2013) were well indicated by the relationship between the MSNR chronology and precipitation from March to May, while significant correlations were found only in May with the other detrending criteria. The correlation with rainfall of the previous autumn, indicating the importance of soil water reserves for the formation of rings (Di Filippo et al. 2010), and with precipitation in the autumn of the current year, reflecting the activity of the cambium in Mediterranean species in this season (e.g. Camarero et al. 2010), was found only in the case of MSNR chronology. Furthermore, the dendroclimatic signal related to the negative effect of high temperatures in May and June, which can be explained by the reduction of stomatal conductance and photosynthetic inhibition induced by water stress (Vaz et al. 2010), was better assessed with the SP32 master chronology. Negative responses to high temperatures in spring and summer were not detected in Hinojos, but the positive relationship with temperatures in April and June was found with the DDET and SP67 criteria, that was surprising because high temperatures in these seasons induce water stress and inverse (or not significant) responses by trees should be expected (e.g. Campelo et al. 2006; De Luis et al. 2013), and seems to indicate that stiff detrending models were not appropriate to study the relationships with climate in this site.

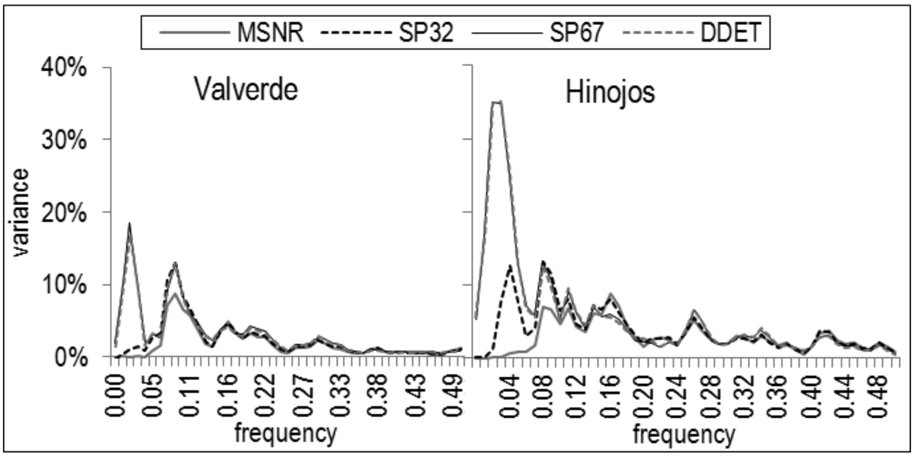

Figure 2 Power spectra of the standard chronologies

The RE and the correlation coefficients between the actual PDSI and the PDSI estimates are listed in table 2. Both statistics indicate that the MSNR method was the least effective in estimating climate. For Valverde, the correlation coefficient increased slightly when the detrending methods were applied in the order SP32-SP67-DDET, but the SP32 brought the highest RE. In Hinojos, the RE was higher with SP67, but the correlation coefficients obtained with SP67 and SP32 were equal. The actual PDSI and the PDSI estimates are plotted in figure 4: the actual values showed fluctuations in the mid/low frequencies, which were induced by an arid period in the 1980s and 1990s and were matched by the PDSI series estimated from the SP32, DDET and SP67 residual chronologies. Our results suggest that good climate reconstructions can be accomplished by the use of stiff detrending functions. The verification analysis involving the SP32 chronology suggested that good estimates can be provided by flexible splines as well, but very flexible splines are not appropriate for climate reconstructions. This is confirmed by the PDSI estimated by the MSNR chronology, which was positively correlated with the actual PDSI and produced positive RE, but showed no coherence at the low frequencies with the actual data.

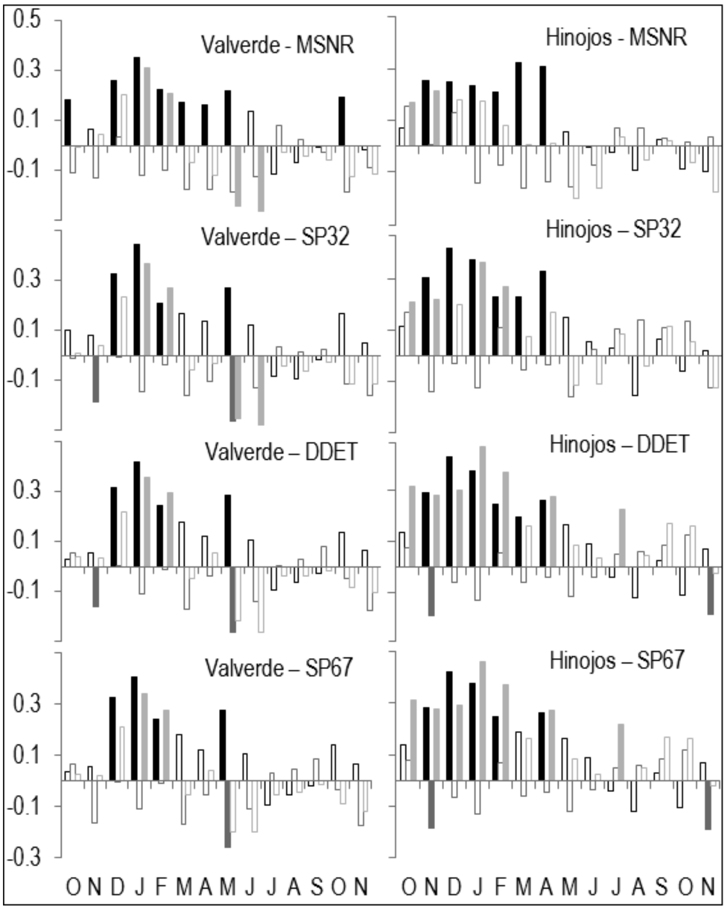

Figure 3 Bootstrapped correlations between residual chronologies and monthly values of climatic covariates from the previous October to the current November (precipitation, maximum temperature and minimum temperatures: first, second and third bar, respectively). Filled bars indicate statistically significant relationships (p< 0.05).

Table 2 Statistic verification of the climate reconstruction: reduction of error (RE) and correlation coefficients between the actual climatic records of the indipendent period and the climate values estimated from the residual chronologies.

			Hinojos			Valverde		
	MSNR	SP32	DDET	SP67	MSNR	SP32	DDET	SP67
Correlation	0.38	0.70	0.66	0.70	0.56	0.66	0.68	0.67
RE	0.13	0.44	0.36	0.47	0.19	0.29	0.28	0.27

Conclusions

Conservative detrending methods retain higher amounts of low-frequency growth variability, which can reflect the impacts on growth of long-term climatic changes, but can fail in removing non-climatic anomalies that could be wrongly interpreted as exceptional climatic events. In managed closed-canopy woodlands, detrending methods involving flexible smoothing functions properly filter the middle/low-frequency growth variance deriving from stand dynamics and provide meaningful results when climate-growth relationships are analyzed. However, very flexible functions can even entirely remove the low-frequency variance, so they could fail in conserving growth responses to long-term climatic changes. The choice of the detrending method should be done on the basis of a careful evaluation of the stand characteristics and frequency domain of the resulting standardized chronology. In our study case, the SP32 criterion was appropriate to preserve as much low frequency as possible and yet remove the noise deriving from stand dynamics, indicating that smoothing functions with wavelength approaching 30 years are suitable for dendroclimatic studies in the managed woodlands in our region.

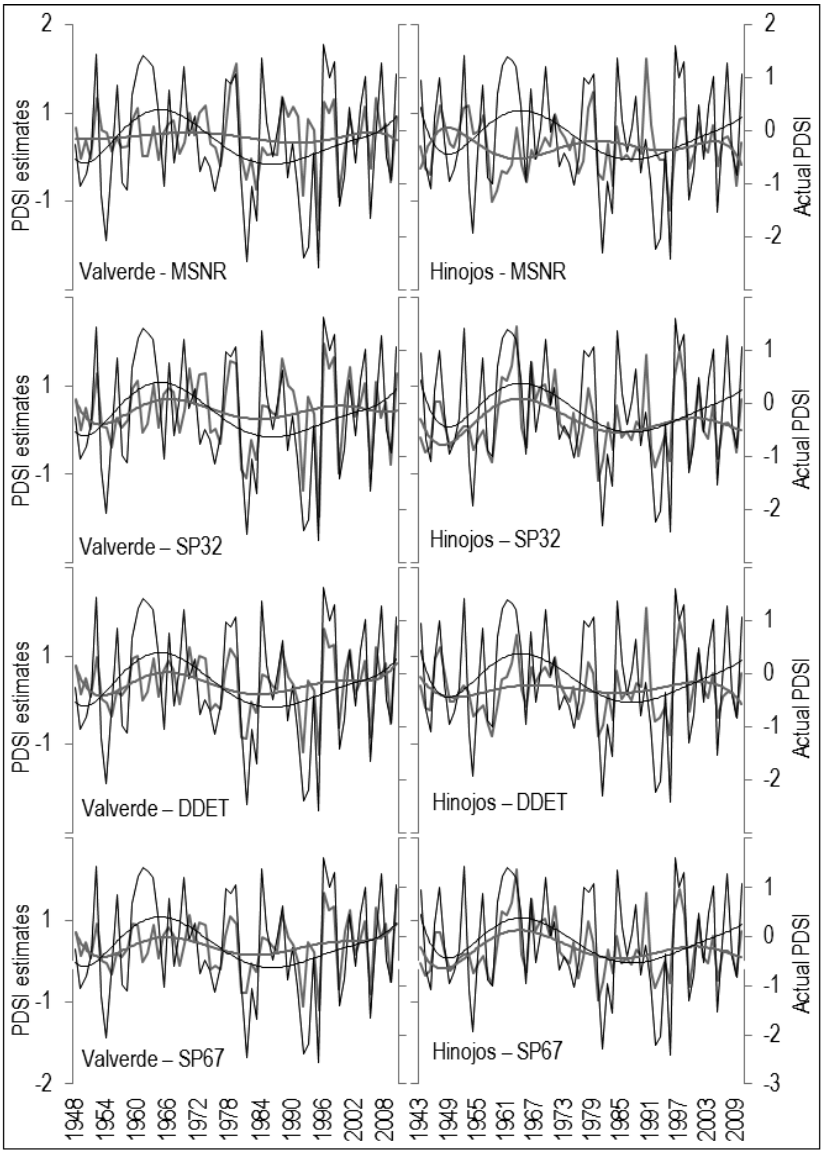

Figure 4 Climate reconstructions. Black lines are the actual PDSI values of the indipendent period; grey lines are the climate values estimated from the residual chronologies. The fitted curves are 6^{th}-degree polynomials.

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