

High-elevation inter-site differences in Mount Smolikas tree-ring width data

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Introduction

Tree-ring chronologies of maximum latewood density (MXD) of *Pinus heldreichii* CHRIST, an endemic species of the Balkan Peninsula, are most suitable to reconstruct annually resolved late summer temperatures and further our understanding of past climate variability in the Eastern Mediterranean (Klesse et al. 2015, Trouet et al. 2012, Trouet 2015). In contrast, studies of tree-ring width (TRW) of *P. heldreichii* reported relatively weak and temporarily unstable climate signals (Panayotov et al. 2010, Seim et al. 2012, Todaro et al. 2007) owing to a temporarily unstable drought signal or the complex interaction of high temperatures and low precipitation. To assess tree-ring/climate associations in this old-growth species, we here present TRW records from a northwest- and a south-facing *P. heldreichii* site located near treeline in the Pindus Mountains in Greece and explore the importance of changing slope aspect on growth and climate signal.

Data and Methods

Study area and data collection

Mt. Smolikas (2637m a.s.l., 40.1N, 20.9E), situated in northern Greece (Fig.1), is the highest peak of the Pindus range stretching from southern Albania to the Peloponnese. Geologically, the range is an extension of the Dinaric Alps and consists of serpentine (ophiolitic) rocks (Hughes et al. 2006, Stevanovic et al. 2003). One hundred and one samples from 51 living *P. heldreichii* trees were collected at two sites near treeline on NW- and S-exposed slopes of Mt. Boghdhani (2236m a.s.l.) (Fig. 1), an eastern foothill of Mt. Smolikas, using 5 mm increment corers. The mean number of rings per sample is 446 and 372 with a minimum of 229 and 215 years and a maximum of 866 and 553 years at the NW- and S-facing sites, respectively.

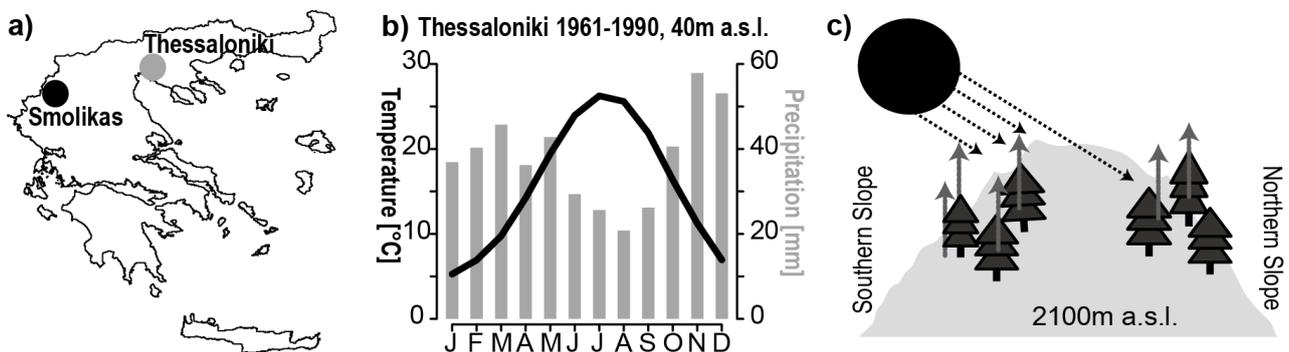


Figure 1: a) Map of Greece indicating the location of the investigation area (black circle) and the climate station (grey circle) and b) climate diagram of the meteorological station in Thessaloniki (40 m a.s.l., 1961-1990) and c) sampling design with sites according to slope exposure.

Meteorological data

Due to limited availability and time-series length of nearby meteorological records (e.g. Ioannina, Metsovo), TRW chronologies were calibrated against temperature and precipitation data from the meteorological station in Thessaloniki (Fig.1) over the period 1931-2014. To estimate the influence of drought on tree growth, the 1- and 2- month standardized precipitation evaporation index (SPEI-1, SPEI-2), which integrates precipitation and temperature, was calculated and calibrated against the TRW chronologies (Vicente-Serrano et al. 2010).

Chronology development and statistics

TRW was measured with an accuracy of 0.01mm using the TSAP-Win software (Rinn 2003) and a subsequent quality check of the crossdating was performed visually and with the help of the program COFECHA (Holmes 1983). Prior to standardization using a cubic smoothing spline with a 300-year low-pass filter (Fig.2, Cook 1985), the data were power-transformed to remove non-climatic differences in variance (Cook & Peters 1997). Variance stabilization was applied according to Frank et al. (2007) considering the number of samples and average correlation coefficients. The final chronology was calculated using a robust bi-weight mean (Cook 1985) and signal strength was estimated using the inter-series correlation and EPS statistics in a 30-year moving window with 15-year overlap (Wigley et al. 1984). High-frequency variability was assessed using the mean sensitivity (Cook 1990) and growth was compared using the series average growth rates of the first 300 years of the trees life as well as the means of the age-aligned individual series, the Regional Curves (Esper et al. 2003). Pith-offset estimates were considered for growth analysis. For the study of climate-growth relationships, the standardized chronologies, precipitation, and temperature data were additionally high-pass filtered by computing residuals between the original data and their corresponding 10-year cubic smoothing splines.

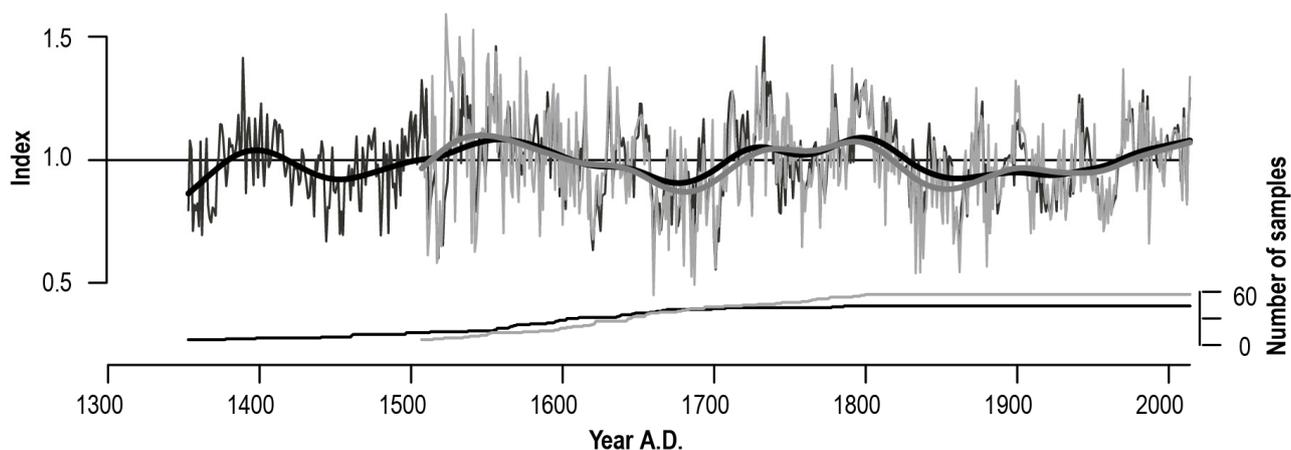


Figure 2: NW-facing (black) and S-facing (grey) power-transformed 300-year smoothing spline standardized tree-ring width chronologies (thin lines) and their corresponding 50-year smoothing splines (bold lines). Chronologies were truncated at $n > 5$ series. The lower panel displays number of samples.

Results and Discussion

Intra- and inter-site (growth) coherence

The site chronologies date back to 1353 and 1507 ($n > 5$) and are reliable after 1495 for the NW- and 1575 for the S-facing stand, respectively (Fig.2), when EPS increases above the widely-accepted threshold of 0.85. The raw chronologies correlate at $r = 0.89$, the 300-year spline-detrended chronologies at $r = 0.86$ ($p < 0.01$, 1575-2014). A temporally stable and strong correspondence with *P. heldreichii* TRW chronologies from Albania (Seim et al. 2012, 968-2008)

and Greece (Mt. Olympus, Klesse et al. 2015, 1470-2008) with correlation coefficients ranging between 0.57 and 0.84 among 300-year spline detrended chronologies ($p < 0.01$, common period $n > 5$ 1515-2008, Schweingruber 1981, Klesse TRW not published) points to comparable environmental conditions and similar growth forcing. The correlation coefficients increase with decreasing distance indicating a coherent pattern of climate-growth signals over the Balkan Peninsula (Panayotov et al. 2010, Seim et al. 2012).

Tab. 1: Site chronology statistics.

Site	Chronology AD	n	MSL	AGR ¹	SD ^{1,2}	MS ^{1,2}	RBAR ^{1,2}	EPS ^{1,2}	AC1 ^{1,2}
NW	1353-2014	44	446	0.89	0.33	0.21	0.38	0.95	0.82
S	1507-2014	57	372	0.75	0.37	0.27	0.39	0.95	0.79

Chronology AD (truncation > 5 series), MSL: mean segment length in years, AGR: average growth rate (mm) of the first 300 years of growth, SD: standard deviation, MS: mean sensitivity, Rbar: inter-series correlation, EPS: mean expressed population signal, AC1: first order auto correlation, ¹common period ²1507-2014.

Despite a strong covariance between the site chronologies, we found significant growth differences. The S-facing stand shows higher mean sensitivity and lower growth rate denoting a higher degree of high-frequency climatic information (Table 1, Fritts 1976). Focusing on the first 300 years of growth, statistically significant differences between the average growth rates appear. Annual increment is significantly higher and variance more heterogeneous at the NW-facing site, whereas in the S-facing stand 75% of the individual growth rates appear below the median growth of the NW-facing site (Fig.3a). The means of the age-aligned individual series, the Regional Curves (RC; Esper et al. 2003), show opposing growth trends in the first 150 years of growth and the differences in absolute growth level are independent of tree age. The RC of the NW-facing stand initially increases and moderately decreases, whereas the RC of the S-facing stand decreases exponentially (Fig.3b). The growth increase over the first 150 years in the NW-facing site is likely related to ecological conditions, e.g. shading effects and competition for resources, masking the regular age trend (Chi et al. 2015, Muthuchelian et al. 1989). The significant differences in growth prove that differently exposed stands do not necessarily belong to the same biological growth population (Esper et al. 2003), thus perhaps also implying differences in the climatic response.

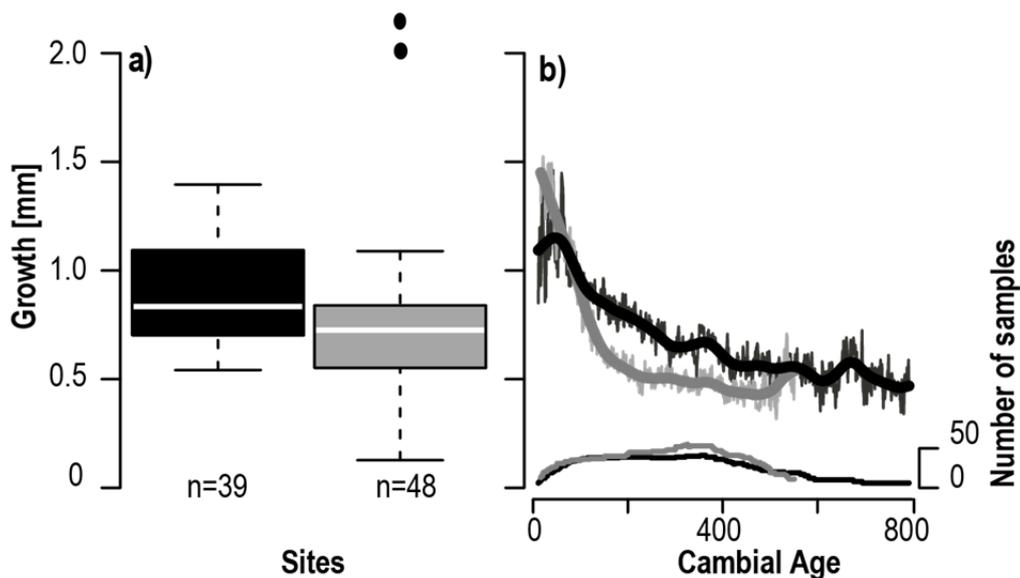


Figure 3: Growth characteristics of NW-facing (dark grey) and S-facing (light grey) sites. a) Mean growth rates over the first 300 years of cambial age, and b) regional curves and 100-year cubic smoothing splines truncated at $n < 10$ series.

Climate response

In the high-frequency domain, growth is significantly controlled by temperature, precipitation, and drought in April and June-July. This is the case at both sites. Positive correlations with April temperature ($r_{1931-2014} = 0.39/\text{NW}$ and $0.43/\text{S}$, $p < 0.01$) and negative correlations with SPEI-1 ($r_{1931-2014} = -0.36/\text{NW}$ and $-0.35/\text{S}$, $p < 0.01$) and precipitation ($r_{1931-2014} = -0.34/\text{NW}$ and $-0.33/\text{S}$, $p < 0.01$) demonstrate that dry and warm spring conditions support growth. These conditions stimulate timely snowmelt and early cambial activity and elongate the vegetation period and time of cell formation (Vaganov et al. 1999, Moser et al. 2010). The negative response to June-July temperature ($r_{1931-2014} = -0.34/\text{NW}$ and $-0.18/\text{S}^*$, $p < 0.01$, *not significant) and associated positive responses to precipitation ($r_{1931-2014} = 0.34/\text{NW}$ and $0.29/\text{S}$, $p < 0.01$) and SPEI-2 ($r_{1931-2014} = 0.34/\text{NW}$ and $0.25/\text{S}$, $p < 0.01$) synchronize with the beginning of the Mediterranean dry season that triggers increased water depletion, drought stress, and reduced metabolic activity (Vieira et al. 2013, Chaves 2002). The uniform seasonal response of differently exposed sites strongly suggests that the Mediterranean climate regime enforces growth synchronicity (Bolle 2003, Loukas et al. 2002, Luterbacher et al. 2012).

However, the absolute monthly climate signal strength appears to be associated with slope exposition. The S-facing site, receiving most insolation, is more sensitive to April temperatures and SPEI-1 as the trees benefit from warmer spring temperatures and an early growth onset (Rossi et al. 2007). The NW-facing site surprisingly shows a stronger response to June-July temperature, precipitation, and SPEI-2 (Fig.5). From a physiological point of view, S-facing trees were expected to suffer more from high temperatures and drought in June-July (Panayotov et al. 2010, Fritts 1976, Måren et al. 2015). The actual response is a product of biological memory effects, which artificially reduce the absolute strength of preserved climatic information. We hypothesize that potential biomass losses during high summer are masked by early season biomass gains and reduce the June-July climate sensitivity of S-facing trees. These findings highlight the importance of site selection even in high elevation environments (Frank & Esper 2005, Dũthorn et al. 2016).

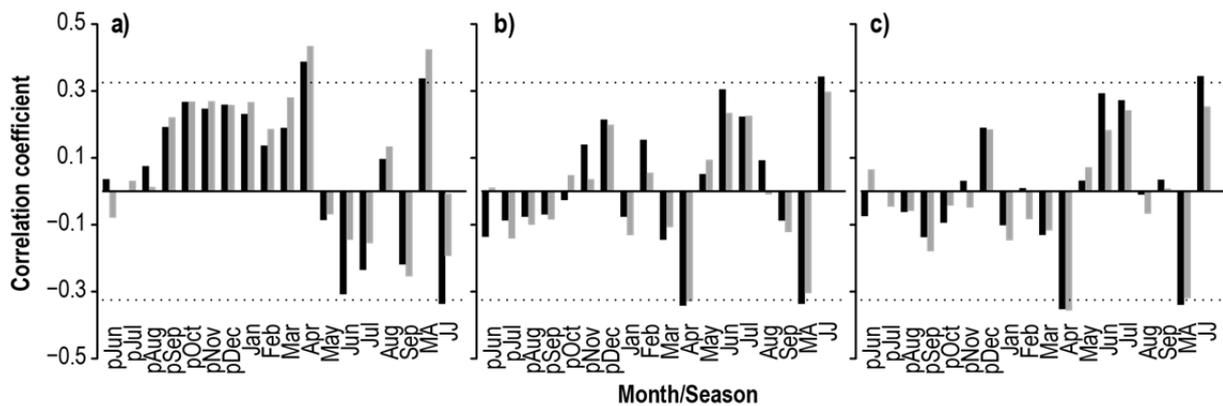


Figure 4: Correlation coefficients between site chronologies (NW-/black and S-/grey) and meteorological data (both 10-year high-pass filtered) using monthly and seasonal **a)** temperature, **b)** precipitation, and **c)** SPEI-1/-2 data from the station in Thessaloniki (40.52N, 23.00E, 40m) for the period 1931-2014. Dashed lines indicate 99% significance levels. p- indicates month of the previous year, MA= March-June and JJ= June-July.

In contrast to previous studies on *P. heldreichii* TRW data revealing variable climate signals (e.g. Todaro et al. 2007, Panayotov et al. 2010, Seim et al. 2012), we find temporally robust signals after 1950 (Fig.5). Post-1950 April temperature and SPEI-1 correlations are fairly stable, whereas June-July precipitation sensitivity gradually decreases. However, for all meteorological parameters and months, we find a shift in climate sensitivity in the 1950s, in both tree sites, pointing to potential biases in the early observational data. The scarcity of meteorological data prior to the Second

World War complicate testing this hypothesis, but we suggest to use post-1950 data for calibration trials in northern Greece.

The significant, site-independent, and temporally robust temperature and SPEI-1 correlations underscore the potential of *P. heldreichii* TRW data for climate reconstruction. We hypothesize that the notable signal strength in comparison to previous *P. heldreichii* studies is related to i) the standardization approach including the application of a high-pass filter, ii) slope exposition effects, and c) site elevation. Splitting the data according to slope exposition allows maximizing the seasonal climatic response, as signal differs in single months of the growing season. Panayotov et al. (2010) collected *P. heldreichii* on a S-facing slope and report a weak association with summer precipitation. This study shows that S-facing trees are least suitable to analyze summer drought and precipitation, as the influence of drought stress and growth cessation is likely masked by compensating growth gains earlier in the season. Further tests on the inter-dependency between spring warmth and summer drought need to be conducted to support this hypothesis. Seim et al. (2010) suggested that the absence of a robust climate signal in Albania is associated with site elevation as the natural thermal tree line is 500 m above their sampling location resulting in a reduced climate growth control. The Smolikas sites analyzed here are located at the thermal treeline (Brandes 2006) and are therefore exposed to a harsher climate that likely supports the stronger climate signals.

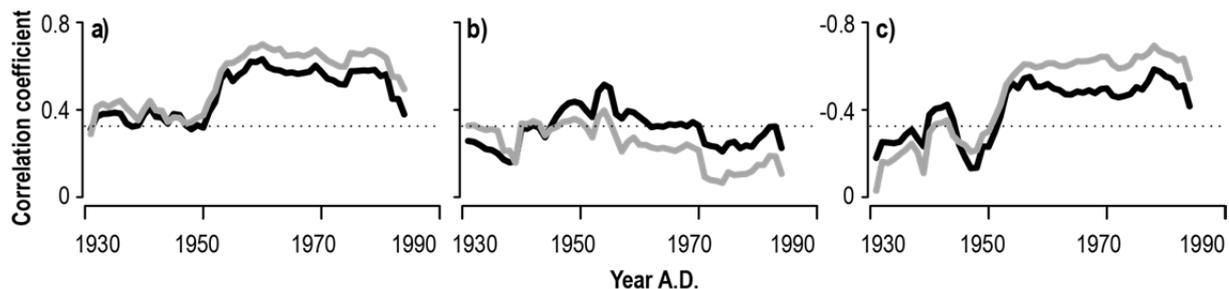


Figure 5: 31-year moving window correlation coefficients between high-pass filtered TRW chronologies of the NW- (black) and S-exposed (grey) sites and climate data displayed in Fig. 4 for a) April temperature, b) June-July precipitation, and c) April SPEI-1. Dashed lines indicate 99% significance levels.

Conclusion

TRW data from NW- and S-exposed high-elevation sites in northern Greece are characterized by different growth rates, with the S-exposed trees being more growth limited. In addition, we found distinct aspect effects of the climate sensitivity of *P. heldreichii* associated with higher insolation rates on S-facing slopes. Due to the positive temperature and negative SPEI-1 and precipitation responses in April which stimulates early cell formation, a potential summer season signal cannot be properly resolved. The negative temperature and positive SPEI-2 and precipitation signal strength is strongly influenced by the previous month's cell productivity. Further work will focus on (i) including relict material to prolong the chronology back in time, (ii) extending the spatial scope including east- and west-facing sites, (iii) establishing a climate reconstruction using MXD measurements.

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