Testing for climate signal age effects at two treeline sites in the European Alps and Tatra Mountains

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Introduction

Age-related fluctuation in the sensitivity of tree-ring data to climate variability has been reported for different tree species, climatic zones and environmental envelopes (see Konter et al. 2016 for an overview). The resulting age-related growth-climate response patterns are, however, often inconsistent and different to compare. Some studies describe a stronger climate sensitivity of young trees (Rozas et al. 2009, Dorado Liñán et al. 2011, Konter et al. 2016) whereas others report stronger coherence between the growth of old trees and climatic parameters (Carrer & Urbinati 2004, Esper et al. 2008, Yu et al. 2008, Linares et al. 2013). Moreover, some authors consider these climate signal age effects (CSAE) negligible (Linderholm & Linderholm 2004, Esper et al. 2008, Dorado Liñán et al. 2011), while others find a significant impact on proxy calibration and the subsequent climate reconstructions (Carrer & Urbinati 2004, Rossi et al. 2008, Yu et al. 2008, Rozas et al. 2009, Linares et al. 2013). Any straightforward comparison of the impact of CSAE suffers from idiosyncratic differences of the existing study designs, including different tree species, geographical locations, environmental conditions, age class categories, and a combination thereof (Konter et al. 2016).

Here, we analyze CSAE at two upper treeline sites in the European Alps and the Tatra Mountains. This newly developed dataset incorporates temperature-sensitive tree-ring width (TRW) series of *Larix decidua* Mill. and *Pinus cembra* L. from the southern Swiss Alps and the northern Slovakian Tatra Mountains. Age-related trends in climate sensitivity are assessed by fitting linear regression models to the seasonal temperature correlations of the individual trees. This approach enables the assessment of CSAE and associated trends particularly focusing on the role of species and geographical origins.

Material and methods

Study design and chronology development

The Valais Alps in southern Switzerland and the High Tatra Mts in northern Slovakia provide the environmental settings for tree growth of the temperature-sensitive conifers: larch and pine. For this analysis we aggregated previously published 317 series of *Larix decidua* Mill. and 314 series of *Pinus cembra* L. from the Alps (Hartl-Meier et al. 2016), as well as 163 and 155 series from the Tatras, respectively (Konter et al. 2015a). Ring widths were measured and crossdated using a LinTab device and COFECHA software (Holmes 1983, Rinn 2007). Power transformation was applied to the raw TRW series to remove biological/age-induced spread-versus-level relationships (Cook & Peters 1997). Non-climatic juvenile growth trends, due to adjoining new rings to an increasing stem girth, were removed by fitting negative exponential functions or linear curve fits with negative slopes using the software ARSTAN and calculating residuals between the power transformed values and the smoothing curves (Fritts 1976, Cook 1985, Cook et al. 1990). Chronologies were compiled using robust bi-weight mean, while stabilization of temporal variance changes was achieved with contemplating sample size and varying interseries correlations (rbar) (Frank et al. 2007b).

Meteorological data and age-related calibration setups

TRW data were calibrated against monthly-resolved meteorological observations from nearby instrumental stations in both regions. The station 'Gr. St. Bernhard' (45.80N, 6.10E, 2070 m asl) provides temperature measurements for the southern Swiss Alps over the period 1850-2011, while the nearby station in the Tatra region 'Poprad' (49.07N, 20.25E, 695.0m asl) only reaches back to 1951. Due to this rather short period we additionally used the a gridded temperature product from CRUTEM 4 (Jones et al. 2012) extending back to 1901, and accessible via the KNMI Climate Explorer (http://climexp.knmi.nl) from 47.5N/7.5E in the Alps and 47.5N/22.5E in the Tatras.

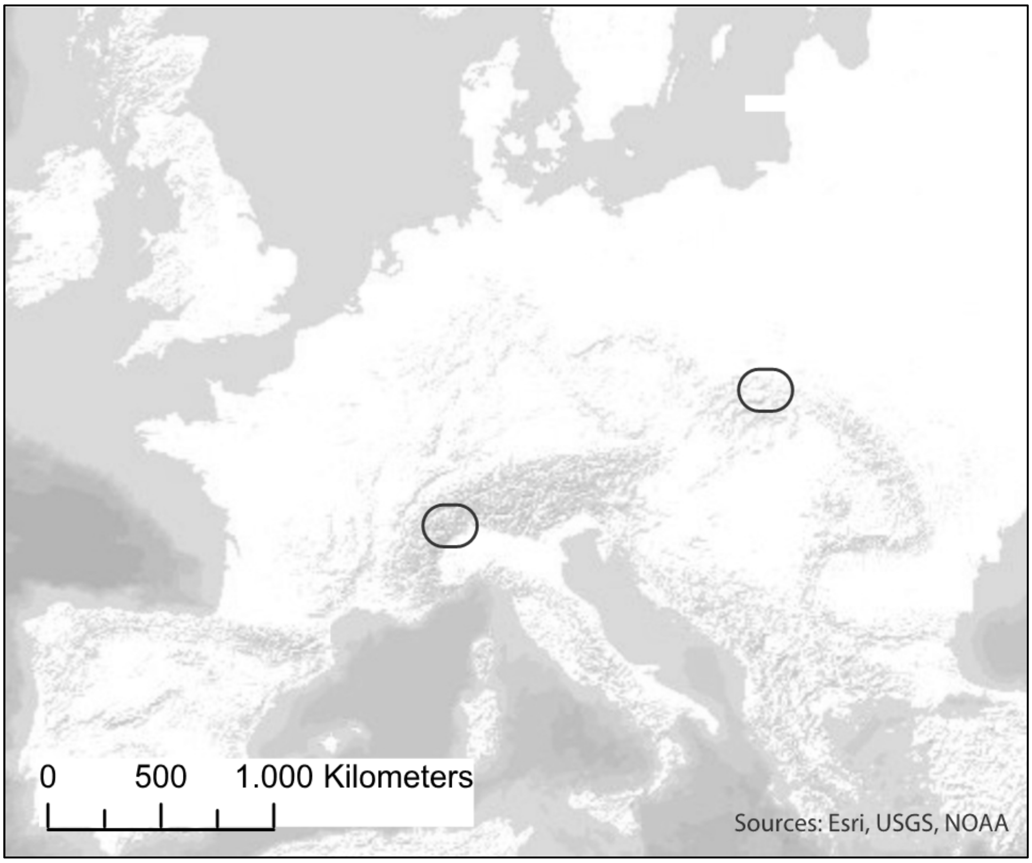

Figure 1: Sampling sites in the Alps and Tatra Mountains (ovals).

Growth-climate relationships were assessed using *Pearson's* correlation coefficients (*r*) between the TRW chronologies and individual core samples from both regions and the corresponding temperature means (Konter et al. 2015a, Konter et al. 2015b, Hartl-Meier et al. 2016). Correlations with seasonal temperatures of the individual cores were aligned by cambial age (Esper et al. 2003) and linear regression functions were applied to these age-aligned climate correlations using R 3.1.1(R Development Core Team 2014), the package dplR (Bunn et al. 2016) and treeclim (Zang & Biondi 2015). Positive and negative slopes of the predicted linear regression functions indicate the presence and orientation of CSAE trends, while associated p-values denote significance levels of these trends. Gradient 'g' signifies the slope of the linear regression functions over 100 years. Temporal robustness of growth-climate relationships and CSAE trends are assessed by splitting the centennial period 1901-2010/11/12 into an early split period (1901-1958), a late split period (1959-2010/11/12) and a station/grid overlap period (1951-2010/11/12).

Results and discussion

Larch and pine TRW chronologies reflect distinct mean summer/growing season temperature signals in their respective habitats (Fig. 2). The detrended larch chronology from the Alps is well in agreement with June-August temperatures, which is detected with significant correlation values at $p<0.001$ during all calibration periods (Table 1). The same behaviour is found for pine from the Alps, except that the seasonality of the signal is extended from May-August. Similarly, the pines from the Tatras respond best to May-July, while larch TRW is most sensitive to a shorter May-June interval.

Correlation values of larch and pine TRW from the Tatras are positively significant, but fall below the corresponding values from the Alps (Table 1) (Büntgen et al. 2007, Büntgen et al. 2010, Büntgen et al. 2013). The signals are generally weaker in the early calibration periods (1901-1959), particularly in the Tatras ($r_{Larix}=0.30$, $p<0.05$; $r_{Pinus}=0.28$, $p<0.05$). This effect might also refer to the reduced quality of early instrumental measurements systematically impacting the calibration exercise (Parker 1994, Frank et al. 2007a, Böhm et al. 2009).

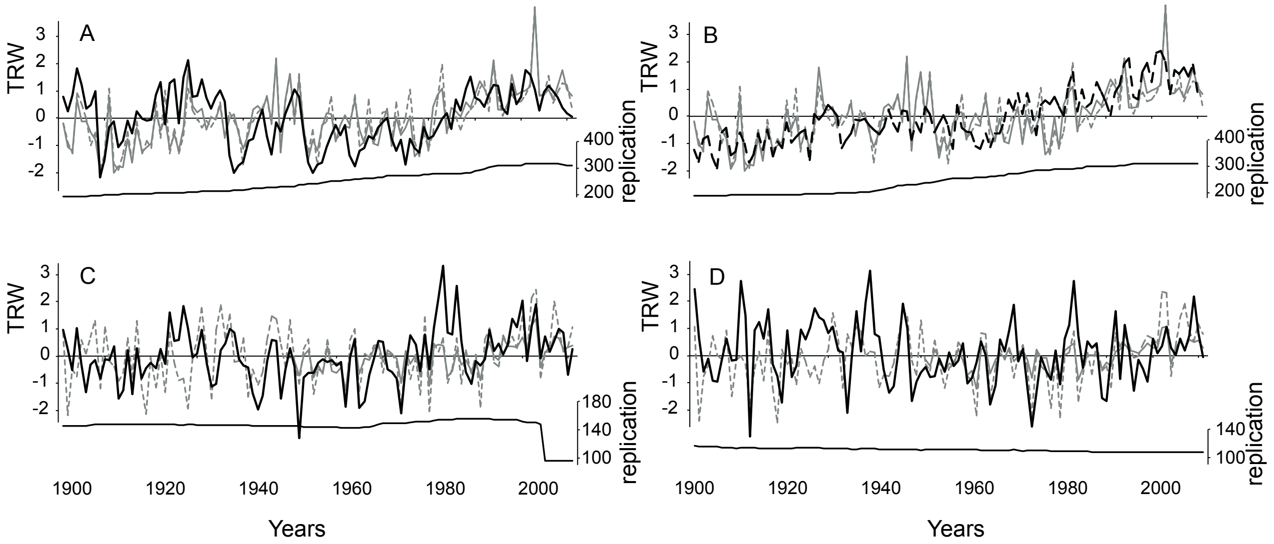

Figure 2: Larch and pine TRW chronologies (black) and seasonal temperatures (grey) from station (solid) and gridded data (dashed) in the Alps and the Tatra Mountains. A: Larix decidua TRW from the Alps and JJA temperature, B: Pinus cembra TRW from the Alps and MJJA temperature, C: Larix decidua TRW from the Tatras and MJ temperature, D: Pinus cembra TRW from the Tatra and MJJ temperature.

Table 1: Chronology and calibration statistics. 'Temperature Signal' indicates seasonality of highest growth-climate relationships. Numbers in Centennial, Early split, and Late split periods refer to correlation values r (using station data / gridded data). Values denoted in black reach p < 0.001, values in grey p < 0.05. Station/Grid period specifies the overlapping period of instrumental with gridded data.

Region	Species	Chronology Length	Temperature Signal	Centennial Period	Early Split Period	Late Split Period	Station/Grid Overlap
Alps	*Larix decidua*	1474-2011	JJA	0.48 / 0.42	0.38 / 0.35	0.65 / 0.55	1901-2011 0.48 / 0.42
	Pinus cembra	1428-2010	MJJA	0.65 / 0.61	0.53 / 0.46	0.66 / 0.65	1901-2010 0.65 / 0.61
Tatras	*Larix decidua*	1612-2012	MJ	-- / 0.44	-- / 0.30	0.60 / 0.56	1951-2012 0.60 / 0.55
	Pinus cembra	1687-2012	MJJ	-- / 0.39	-- / 0.28	0.54 / 0.53	1951-2012 0.54 / 0.52

Most of the TRW correlation values against instrumental or gridded data are near similar, thereby enabling gridded data for analysing CSAE trends throughout the centennial calibration period in the Tatras, where instrumental data are shorter.

In the Alps, both larch and pine individual core climate correlations between larch and JJA-temperatures reveal significantly increasing trends with increasing age, which are also present considering pine cores (Fig. 3). Particularly larch tends to be more prone to CSAE and is more sensitive to temperature variations at higher cambial ages. These results highlight the importance of geographical location over tree species and support previously published evidence from the Eastern Italian Alps (Carrer & Urbinati 2004). The weaker sensitivity of younger trees in the region mostly refers to a higher between-tree competition in juvenile life stages, which can cause a prolonging of the vegetation period or higher assimilation at a greater risk of mortality (Bond 2000). Hence, the impact of temperature variations in a shorter period can be reduced, which culminates in lower temperature correlation values of several young individuals (Carrer & Urbinati 2004).

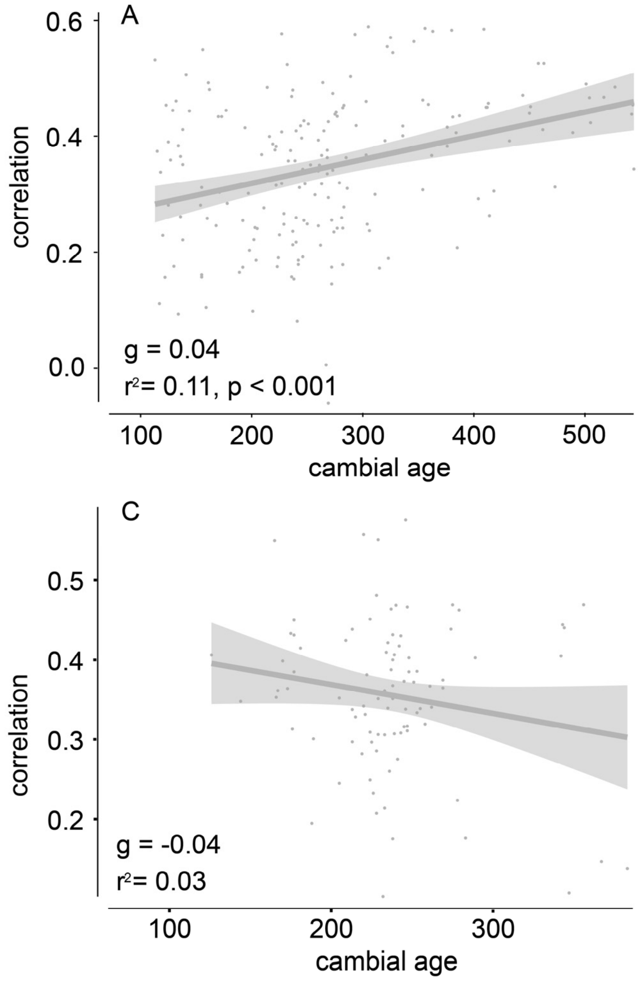

Figure 3: Correlations of individual cores aligned by cambial age with gridded temperatures data since 1901 and associated linear regressions. A: Larix decidua TRW from the Alps and JJA temperature, B: Pinus cembra TRW from the Alps and MJJA temperature, C: Larix decidua TRW from the Tatras and MJ temperature, D: Pinus cembra TRW from the Tatra and MJJ temperature. Shaded areas indicate 95% confidence limits of the predicted linear regression, g = regression slope over 100 years, r^2= adjusted coefficient of determination and p = significance level.

In contrast, both species from the Tatras show consistent negative trends with increasing age, though these trends lack significance and only a very small portion of the variance is explained by changing cambial ages (r^2_{Larix}=0.03, r^2_{Pinus}=0.01). So far, CSAE have not been analysed in this region, but negative CSAE trends in TRW data have also been reported for *Pinus sylvestris* from northern Fennoscandia (Konter et al. 2016), *Pinus nigra* and *Pinus uncinata* from eastern Spain and the Pyrenees (Dorado Liñán et al. 2011), and *Juniperus thurifera* from central Spain (Rozas et al. 2009). Older trees tend to have shorter vegetation periods and produce fewer but larger cells per ring compared to young trees, which results in slower and shorter xylogenesis, making older trees more rigid to temperature variations (Rossi et al. 2008, Carrer et al. 2015, Konter et al. 2016). In addition, older trees can face hydraulic constraints due to tree height and long root-leaves path length, which can decrease temperature correlations of certain individuals, particularly under favourable conditions (Ryan & Yoder 1997).

These pronounced differences between the regions and, in contrast, consistency between the species at the same site become even more obvious when considering split calibration periods (Fig. 4). For all calibration periods the CSAE trends of larch individuals from Alps are increasing with age, with only the early split period (1901-1958) exhibiting non-significant results. CSAE trends of pines show comparable significant positive slopes in the linear regression functions, except for the non-significant trend in the late split period (1959-2011). Independent of the species, the growth-climate relationship of conifer trees in the Alps appears to be more distinct with tree individuals of older cambial ages.

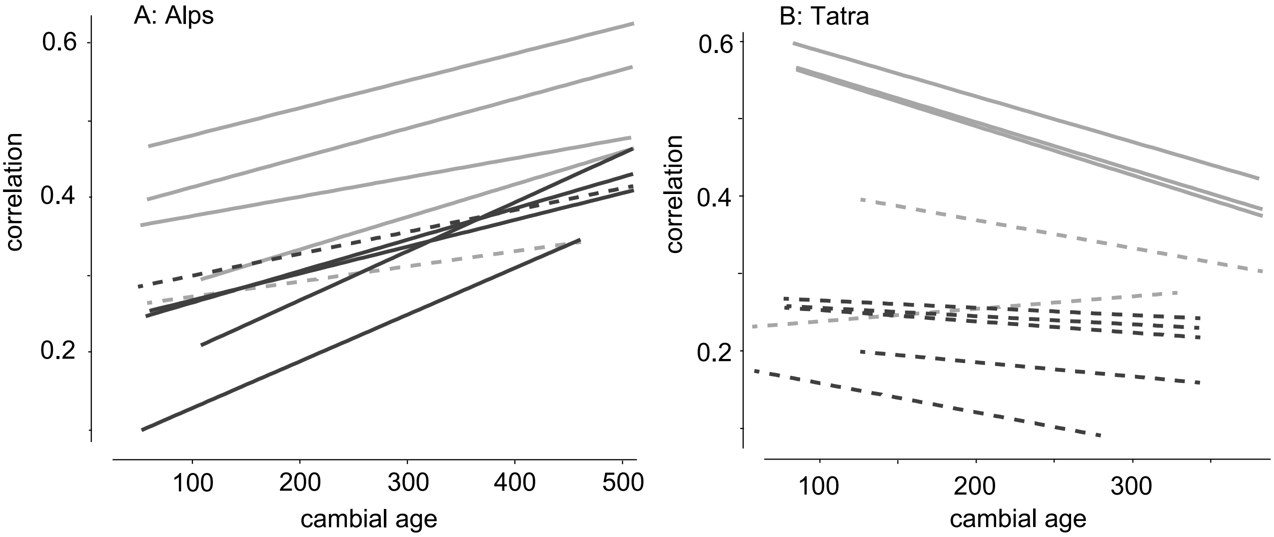

Figure 4: CSAE linear trends of Larix decidua (grey) and Pinus cembra (black) for correlations against corresponding best seasonal temperatures over variable calibration periods (see Table 1). Solid lines indicate significant linear regressions, dashed lines indicate insignificant linear regressions.

The larch CSAE trends from the Tatras are consistently negative with increasing age, however, one positive but insignificant trend (g=0.02) is detectable in the larch data for the early calibration period 1901-1958. These findings are independent of trees species since the pine CSAE trends are also consistently negative, although insignificant for all calibration periods. Contrary to the Alps, the climate sensitivity of conifer trees in the Tatra Mountains decreases with age, proving the greater importance of geographical location compared to tree species.

It has to be noted, that the early calibration period 1901-1958 in almost all cases exhibits the lowest correlation values against the best-responding season and the weakest CSAE trends. This could be related to varying temperature trends over the 20th century (Konter et al. 2016) and contribute to the on-going discussion about the overall reliability of early meteorological measurements (Parker 1994, Frank et al. 2007a, Böhm et al. 2009).

Conclusions

Age-related variations in the growth-climate relationships are present in many TRW datasets, but the magnitude of their impact and the orientation of trends seem to vary among species and geographical origins. The results from this study reveal the higher importance of geographical locations. Whereas the climate sensitivity of two species, *Larix decidua* and *Pinus cembra*, in the Alps increase with increasing age, it decreases in the Tatras with the trends being consistent in both species, but only significant for *Larix decidua*. More research is needed on this topic, since lack of clarity in physiological and climatological explanations for these opposed CSAE trends complicate the aggregation of larger networks including multiple species.

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References

Böhm, R., Jones, P. D., Hiebl, J., Frank, D., Brunetti, M. and Maugeri, M. (2009): The early instrumental warm-bias: a solution for long central European temperature series 1760–2007. *Climatic Change* 101, 1-2: 41-67.

Bond, B. (2000): Age-related changes in photosynthesis of woody plants. *Trends in Plant Science* 5: 349-353.

Bunn, A., Mikko, K., Biondi, F., Campelo, F., Mérian, P., Qeadan, F. and Zang, C. (2016). dplR: Dendrochronology Program Library in R. R package version 1.6.4.

Büntgen, U., Frank, D. C., J., K. R., Verstege, A., Zwijacz-Kozica, T. and Esper, J. (2007): Growth responses to climate in a multi-species tree-ring network in the Western Carpathian Tatra Mountains, Poland and Slovakia. *Tree Physiology* 27: 689-702.

Büntgen, U., Brázdil, R., Frank, D. and Esper, J. (2010): Three centuries of Slovakian drought dynamics. *Climate Dynamics* 35, 2-3: 315-329.

Büntgen, U., Kyncl, T., Ginzler, C., Jacks, D. S., Esper, J., Tegel, W., Heussner, K. U. and Kyncl, J. (2013): Filling the Eastern European gap in millennium-long temperature reconstructions. *Proceedings of the National Academy of Science USA* 110, 5: 1773-1778.

Carrer, M. and Urbinati, C. (2004): Age-Dependent Tree-Ring Growth Responses To Climate In Larix Decidua And Pinus Uncinata. *Ecology* 85, 3: 730-740.

Carrer, M., von Arx, G., Castagneri, D. and Petit, G. (2015): Distilling allometric and environmental information from time series of conduit size: the standardization issue and its relationship to tree hydraulic architecture. *Tree Physiology* 35, 1: 27-33.

Cook, E., Briffa, K., Shiyatov, S. and Mazepa, V. (1990). Tree-ring standardization and growth-trend estimation. Methods of Dendrochronology. E. R. Cook and L. A. Kairiukstis. Dordrecht, The Netherlands, Kluwer Academic Publishers: 104-123.

Cook, E. R. (1985). A Time Series Analysis Approach To Tree Ring Standardization. Ph.D. Thesis, University of Arizona.

Cook, E. R. and Peters, K. (1997): Calculating unbiased tree-ring indices for the study of climatic and environmental change. *The Holocene* 7, 3: 361-370.

Dorado Liñán, I., Gutiérrez, E., Heinrich, I., Andreu-Hayles, L., Muntán, E., Campelo, F. and Helle, G. (2011): Age effects and climate response in trees: a multi-proxy tree-ring test in old-growth life stages. *European Journal of Forest Research* 131, 4: 933-944.

Esper, J., Cook, E. R., Krusic, P. J., Peters, K. and Schweingruber, F. H. (2003): Tests of the RCS method for preserving low-frequency variability in long tree-ring chronologies. *Tree-Ring Research* 59, 2: 81-98.

Esper, J., Niederer, R., Bebi, P. and Frank, D. (2008): Climate signal age effects—Evidence from young and old trees in the Swiss Engadin. *Forest Ecology and Management* 255, 11: 3783-3789.

Frank, D., Büntgen, U., Böhm, R., Maugeri, M. and Esper, J. (2007a): Warmer early instrumental measurements versus colder reconstructed temperatures: shooting at a moving target. *Quaternary Science Reviews* 26, 25-28: 3298-3310.

Frank, D., Esper, J. and Cook, E. R. (2007b): Adjustment for proxy number and coherence in a large-scale temperature reconstruction. *Geophysical Research Letters* 34, 16: n/a-n/a.

Fritts, H. C. (1976): Tree Rings and Climate. Academic Press, 567.

Hartl-Meier, C., Büntgen, U. and Esper, J. (2016): On the occurrence of cyclic larch budmoth outbreaks beyond its geographical hotspots. *TRACE 14* 14: 86-92.

Holmes, R. L. (1983): Computer-assisted quality control in tree ring dating and measurement. *Tree Ring Bulletin* 43: 69-78.

Jones, P. D., Lister, D. H., Osborne, T. J., Harpham, C., Salmon, M. and Morice, C. P. (2012): Hemispheric and large-scale land surface air temperature variations: An extensive revision and an update to 2010. *Journal of Geophysical Research* 117.

Konter, O., Esper, J., Liebhold, A., Kyncl, T., Schneider, L., Düthorn, E. and Büntgen, U. (2015a): Tree-ring evidence for the historical absence of cyclic larch budmoth outbreaks in the Tatra Mountains. *Trees* 29, 3: 809-814.

Konter, O., Rosner, K., Kyncl, T., Esper, J. and Büntgen, U. (2015b): Spatiotemporal variations in the climatic response of *Larix decidua* from the Slovakian Tatra Mountains. *TRACE* 13.

Konter, O., Büntgen, U., Carrer, M., Timonen, M. and Esper, J. (2016): Climate signal age effects in boreal tree-rings: Lessons to be learned for paleoclimatic reconstructions. *Quaternary Science Reviews* 142: 164-172.

Linares, J. C., Taïqui, L., Sangüesa-Barreda, G., Seco, J. I. and Camarero, J. J. (2013): Age-related drought sensitivity of Atlas cedar (Cedrus atlantica) in the Moroccan Middle Atlas forests. *Dendrochronologia* 31, 2: 88-96.

Linderholm, H. W. and Linderholm, K. (2004): Age-dependent climate sensitivity of Pinus sylvestris L. in the central Scandinavian Mountains. *Boreal Environment Research* 9: 307-317.

Parker, D. E. (1994): Effects Of Changing Exposure Of Thermometers At Land Station. *International Journal of Climatology* 14: 1-31.

R Development Core Team (2014). R: A language and environment for statistical computing. R Foundation for Statistical Computing. Vienna, Austria.

Rinn, F. (2007): TSAP Win Professional. Zeitreihenanalysen und Präsentation für Dendrochronologie und verwandte Anwendungen. Benutzerhandbuch. Rinntech, 91.

Rossi, S., Deslauriers, A., Anfodillo, T. and Carrer, M. (2008): Age-dependent xylogenesis in timberline conifers. *New Phytologist* 177, 1: 199-208.

Rozas, V., DeSoto, L. and Olano, J. M. (2009): Sex-specific, age-dependent sensitivity of tree-ring growth to climate in the dioecious tree Juniperus thurifera. *New Phytol* 182, 3: 687-697.

Ryan, M. G. and Yoder, B. J. (1997): Hydraulic limits to tree height and tree growth. *BioScience* 47: 235-242.

Yu, G., Liu, Y., Wang, X. and Ma, K. (2008): Age-dependent tree-ring growth responses to climate in Qilian juniper (Sabina przewalskii Kom.). *Trees* 22, 2: 197-204.

Zang, C. and Biondi, F. (2015): treeclim: an R package for the numerical calibration of proxy-climate relationships. *Ecography* 38, 4: 431-436.